Advances in Agroforestry 9

P.K. Ramachandran Nair
Dennis Garrity *Editors*

Agroforestry - The Future of Global Land Use

Springer

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Advances in Agroforestry

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Aims and Scope

Agroforestry, the purposeful growing of trees and crops in interacting combinations, began to attain prominence in the late 1970s, when the international scientific community embraced its potentials in the tropics and recognized it as a practice in search of science. During the 1990s, the relevance of agroforestry for solving problems related to deterioration of family farms, increased soil erosion, surface and ground water pollution, and decreased biodiversity was recognized in the industrialized nations too. Thus, agroforestry is now receiving increasing attention as a sustainable land-management option the world over because of its ecological, economic, and social attributes. Consequently, the knowledge-base of agroforestry is being expanded at a rapid rate as illustrated by the increasing number and quality of scientific publications of various forms on different aspects of agroforestry.

Making full and efficient use of this upsurge in scientific agroforestry is both a challenge and an opportunity to the agroforestry scientific community. In order to help prepare themselves better for facing the challenge and seizing the opportunity, agroforestry scientists need access to synthesized information on multi-dimensional aspects of scientific agroforesty.

The aim of this new book-series, *Advances in Agroforestry*, is to offer state-of-the art synthesis of research results and evaluations relating to different aspects of agroforestry. Its scope is broad enough to encompass any and all aspects of agroforestry research and development. Contributions are welcome as well as solicited from competent authors on any aspect of agroforestry. Volumes in the series will consist of reference books, subject-specific monographs, peer-reviewed publications out of conferences, comprehensive evaluations of specific projects, and other book-length compilations of scientific and professional merit and relevance to the science and practice of agroforestry worldwide.

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Preface

Agroforestry ranks high among the significant initiatives in improving land management that have occurred the world over during the past few decades. The establishment of ICRAF (World Agroforestry Centre) in 1977 signified the beginning of organized global efforts to transform the age-old forms of agroforestry from a "*set of practices in search of science*" to its present status as a science-based, integrated approach that is vigorously addressing many of the world's most serious land-management challenges. The developments in the discipline during this period have been quite substantial. Today, agroforestry has carved out a distinct niche as a robust land-management discipline, and it is now recognized as being at the heart of the global community's commitment to banish hunger and poverty and rebuild resilient rural environments. This is not surprising given that nearly a billion hectares of agricultural landscapes already have more than 10 % tree cover, and an estimated total of 1.6 billion ha of land worldwide has the potential to be under agroforestry management in the foreseeable future. The drivers underpinning such a transformation are increasingly favorable.

An important set of events that stand out in the impressive developmental pathway of agroforestry is the World Congress of Agroforestry (WCA) series. The inaugural congress (WCA1) was held in Florida, USA, in 2004. It was a highly successful event in terms of the numbers of participants (nearly 600), countries (82), and organizations represented, and in the breadth and scope of presentations and discussions. The 2nd World Congress (WCA2) was held in Nairobi, Kenya, in 2009 (http://www.worldagroforestry.org/wca2009/). It eclipsed WCA1 in every aspect, with the participation of about 1,200 delegates from 96 countries.

Significant outputs from these world congresses include many professional publications on different aspects of agroforestry, including high-quality books and special issues of peer-reviewed, international scientific journals. For example, four such books and journal special issues have been published out of presentations at WCA2. Although outstanding in their disciplinary merits, these publications do not fully represent all the deliberations at the congress. For example, keynote speeches by world leaders and comprehensive reviews covering a variety of subjects related agroforestry with a regional focus do not fit well into the thematic mode and style of disciplinary journals. We, the congress organizers, felt the need for a book to encompass the above topics and outputs of the congress. This book was developed to meet that need.

This volume is organized into three parts: an Introduction part consisting of the summaries of six keynote speeches at WCA2, followed by two parts of thematic chapters grouped as "Global Perspectives" (seven chapters) and "Regional Perspectives" (11 chapters). Finally, there is a Conclusion chapter, in which we, the editors, present some forward-looking thoughts about the pathways and directions to be pursued for realizing the promise of agroforestry in the future.

We want to record our deep sense of gratitude and respect to Nobel Laureate Professor Wangari Maathai, who unfortunately passed away in September 2011 before this book was finalized. She was a tireless champion of tree planting and natural resource conservation, and we were fortunate to have her with us during the congress and to witness her inspiring keynote address calling for accelerated efforts of everyone to turn the tables on the path of environmental destruction that the world is following today.

All other chapters were specifically commissioned for the book. We requested the lead organizers of the various WCA2 symposia to each prepare a comprehensive chapter, with the input and cooperation of other presenters in their respective symposia. These required updating and expansion of contents, to make each chapter a state-of-the-art review on the subject. Additionally, we requested a group of leading professionals currently spearheading significant agroforestry-related initiatives worldwide to contribute similar comprehensive chapters on the developments in their domain of activities. We are very pleased that many of these professional leaders could undertake the task in spite of their busy work schedules. The chapters in these two major parts, all of which were rigorously peer-reviewed by high-caliber professionals in the respective fields, deal with issues of a global nature or regional focus, as their headings indicate. The specific regions of focus included parts of Africa, the Amazon basin, and other parts of Latin America, South Asia, Japan, Latin America, Canada, Europe, and the United States. The chapters cover a range of aspects related to agroforestry development within those regions. A total of 98 professionals representing institutions located in 27 countries contributed as authors, and 41 from institutions in 23 countries served as reviewers. Accounting for some authors who also served as reviewers, a total of 130 professionals from institutions in 33 countries around the world contributed to the book as chapter authors and reviewers. With the inclusion of chapters from both the developing countries and the industrialized temperate regions, the book presents a global picture of the status of agroforestry. Thus, although the book originates from WCA2, it does not constitute the proceedings of the congress or any of its sections; instead, it contains a solid body of the current state of knowledge on the various themes and activities in agroforestry worldwide compiled by distinguished leaders in their respective areas of expertise.

The tedious task of putting together such a book would not have been possible without the cooperation and support of a number of collaborators. First of all, we thank the chapter authors, who, in spite of being extremely busy with their crowded schedules, showed the highest level of commitment and professionalism in coping with repeated requests for revisions and improvement following rigorous peer review of their manuscripts. The reviewers (list attached) did a splendid job of providing insightful comments and valuable suggestions, often at very short notice, which helped enhance the professional quality of the chapters. We also thank the publishers and other copyright holders of the original publications for permission to reproduce some of the tables and figures as indicated in the respective chapters. Once again, we sincerely thank all the authors, reviewers, and others who directly or indirectly supported and cooperated with us in bringing out this publication.

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Part I
Introduction
Keynote Presentations at WCA2

Agroforestry, Climate Change and Habitat Protection

Wangari Maathai (1940–2011)

Wangari Maathai was awarded the Nobel Peace Prize in 2004 for her work on community-based tree planting and its role in democratization and peace-building. The first woman in East and Central Africa to earn a doctorate degree, Professor Maathai founded the Green Belt Movement in 1986 as a grassroots organization, whose main focus is poverty reduction and environmental conservation through tree planting. Professor Maathai was internationally recognized for her persistent struggle for democracy, human rights and environmental conservation.

Abstract The agricultural systems most vulnerable to climate change are those already affected by unsustainable management and land and resource degradation. Trees have an important role to play not only in climate change mitigation but also in reducing vulnerability to climate-related risks. The value, role and contributions of agroforestry and the protection of endemic habitats, in the light of current global environmental challenges, cannot be overemphasized. African negotiators in global discussions must form a unified position and show how important agroforestry and indigenous agricultural practices are for climate change mitigation and adaptation on the continent.

Keywords Habitats • Evergreen agriculture • Green belt movement • Food security • Carbon credits

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W. Maathai (✉)
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The theme of this Congress “Agroforestry – The Future of Global Land Use” is very appropriate and timely, especially to Kenya and Africa as a whole. Today, when we are faced with the grave challenges of climate change, environmental degradation, food shortages, poverty and global financial downturn, it is important more than ever before to redouble our efforts to protect and rehabilitate the environment, reduce emissions of greenhouse gases and provide smallholder farmers with sustainable ways of increasing their production and meeting their livelihood needs. Expanding our existing, time-tested, integrated, tree-based practices and promoting rain water harvesting – in short, combining conservation agriculture and agroforestry to create an “evergreen agriculture” and promoting it – would make a huge positive impact on the environment and related global problems. For the past three decades, the Green Belt Movement, working in collaboration with ICRAF and UNEP, the two major Nairobi-based international organizations and co-sponsors of this Congress, has been involved in this area of activity through urging and encouraging citizens to plant appropriate trees on smallholder farms in Africa. Thus, it is very satisfying for me to participate in this important global event.

One of the promising areas of research in agroforestry is the domestication of wild fruit trees. Selecting superior trees from the wild; improving their desirable characteristics such as early bearing, taste, quality and nutritive value; and popularizing them among farmers will go a long way in ensuring food and nutritional security of the local people. Smallholder farm families in some countries in Africa have traditionally been following this approach and benefitting from it. Some small-scale farmers in Western and Southern Africa are diversifying into higher value enterprises that involve production, processing and commercialization of fruits from indigenous fruit trees and their products.

In rural Malawi, lack of food security is directly linked to declining soil fertility, with nitrogen being the main limiting factor. Thanks to an effort coordinated by the World Agroforestry Centre in partnership with a consortium of national institutions, the Malawi Agroforestry Food Security Programme has enabled hundreds of thousands of families to increase food production and enhance nutrition by improving soil fertility and restoring degraded farmland through incorporation of nitrogen-fixing trees such as *Faidherbia albida* and other agroforestry technologies on their farms. It is also important that as we select trees for fruit, medicine, fodder and soil services, their adaptation to climate change is taken into consideration. For example, we need to know how seed sources and tree ecology will be affected by climate change, and we should be able to assess the carbon sequestration potential of different agroforestry species under various growing conditions.

Climate change is increasing inter-annual rainfall variability and the frequency of extreme events, leading to accelerated rates of degradation of soil and water resources upon which farming communities depend for their livelihoods. As we all know, it is the poor people in developing countries who will bear the brunt of climate change and suffer most from its negative impacts. The agricultural systems most vulnerable to climate change are those already affected by unsustainable management and land and resource degradation. Yet, even as the climate changes, food production, environmental services and rural livelihoods must improve – not just be maintained – if we are to meet the demands of the population that is growing at an exponential rate. Trees have an important role not only in climate change mitigation but also in reducing vulnerability to climate-related risks. The Green Belt Movement is working closely with institutions such as the World Agroforestry Centre to improve the resilience of farming systems and livelihood strategies of smallholder farmers to current climate variability.

Another important issue to be considered in the context of agroforestry promotion is habitat protection and biodiversity conservation. Agroforestry by its very nature encompasses integration of diverse plant and to some extent animal communities, and promotes biodiversity conservation. Here in Kenya, we have been involved in long-term campaigns to urge farmers and government alike to respect and protect, conserve and restore biodiversity in forests so that we can benefit from the environmental services they provide.

If the principles of agroforestry are to be applied to many countries in Africa through a massive up-scaling with real impact, it will require training and a huge extension effort with serious donor commitment. Furthermore, by linking farmers and communities to markets, their capacity to learn and adopt new innovations is enhanced. These families and communities are in urgent need of the knowledge that science generates and the policies and practices that governments and technocrats help legislate and implement. All of us – scientists, extension workers, policymakers, academicians, students and civil society – have vital roles to play in addressing this and in providing practical and sustainable solutions to the challenges we face today. As we work with farmers in Africa, we are also learning a lot about the constraints to adopting environmentally sustainable ways of farming.

In Kenya, and indeed in many other countries, there is a destructive culture of removing vegetation, including trees and shrubs, from road reserves, riverine areas and local green spaces. The potential of road reserves to be reservoirs of biodiversity, slowing down water run-off and thereby reducing soil erosion and road destruction, especially during the rainy season, is greatly underestimated. In areas where land is intensively cultivated, such as in highly populated areas of Central and Eastern Kenya, road reserves, riverine borders and local hills are the only areas where wilderness and genetic reservoirs are still available. Protecting the vegetation and maintaining that wilderness is essential for sustainable agriculture, especially for pollinators, honey production and food security. Therefore, policymakers need a new education and mindset so that they appreciate and accept that trees and bushes on road reserves are good for the environment, for the eye and for mental health. The argument that vegetation in cities promotes insecurity is unbelievably simplistic and misleading. We cannot turn the country into a desert in the mistaken belief that we shall be safer in a concrete desert! Promotion of tree planting in both rural and urban areas to the extent possible is vital to the existence of our society.

The return on investment from trees in agroforestry systems can be substantial but can also take several years to recoup. Subsistence farmers might be more willing to invest in trees if it generated short-term revenue through carbon credits. Africa has long been sidelined in the carbon market, but initiatives such as the Carbon Benefits

Project, funded by the Global Environment Facility (GEF) and implemented by UNEP and the World Agroforestry Centre with other partners, bring hope. In many quarters, where even if agroforestry is accepted as a land management system, it is conceived mainly as a strategy for increasing food security; its role and importance in reducing climate-change vulnerability is not adequately appreciated, and, therefore, agroforestry does not figure prominently in climate change negotiations.

We had been told that there were no reliable methods for measuring carbon stored in trees or soil, particularly if it is stored on small landholdings, such as the farms typical of the central highlands of Kenya. However, I am happy to note that things are changing. In May 2009, the Carbon Benefits Project was launched in Nairobi, as a partnership between UNEP, the World Agroforestry Centre and a range of other key partners, and it seeks to assist local communities execute projects aimed at reducing greenhouse gas emissions. This GEF-funded multimillion dollar project aims to develop tools that will help boost carbon trading in Africa, specifically targeting village communities in Western Kenya, Niger, Nigeria and Western China, and it could become the key to unlocking the multibillion dollar carbon markets for millions of farmers, foresters and conservationists across the developing world. Farming carbon to combat climate change is an exciting prospect, and the consortium of partners involved in the Carbon Benefits Project is developing a cost-effective and scientifically rigorous system – making use of the latest remote-sensing technology and analysis, soil carbon modelling, ground-based measurement and statistical analysis. The implementation of these carbon benefits projects should open the door to more environmentally friendly types of agriculture, such as agroforestry and conservation farming.

The African Union should ensure that African governments work together because climate change has no borders, and countries without forests will be even greater victims of the effects of climate change. They will find it difficult to adapt or adopt. A common voice and a common stand are critically important on the road to progress, and this is an excellent opportunity for us to impact on policy. The prospect of earning revenue from carbon markets can encourage African farmers to more rapidly adopt sustainable and productive practices – much needed in addressing the damaging effects that agriculture can have on the environment. In the lead-up to future global conventions and negotiations on climate change, it is critical that Africa comes together in its position on a post-Kyoto climate regime.

Agroforestry for an Evergreen Revolution

M.S. Swaminathan

M. S. Swaminathan, an outstanding agricultural scientist and statesman, is hailed as the Father of Green Revolution in Asia. Time Magazine recognized him as one of the 20 most influential persons of Asia in the twentieth century. A winner of numerous prestigious recognitions and awards including the First World Food Prize, 1987, Prof. Swaminathan was the chairman of ICRAF Board of Trustees in the early 1980s.

Abstract Africa needs an "evergreen revolution" that increases productivity in perpetuity without causing ecological damage. Agroforestry clearly has a key role to play in this evergreen revolution. Novel solutions and technological advances must be married with ecological thinking to drive a truly sustainable agricultural revolution. Building a successful evergreen revolution requires four components: technology, services, favorable public policies, and farmer enthusiasm.

Keywords Ecological thinking • Africa • Germplasm conservation • Anticipatory research

Today, African agriculture faces two major challenges. First, farmers need higher farm productivity to provide them with a marketable surplus and cash income. In Africa, 80 % of food production is from smallholder farmers, for whom agriculture is the backbone of their livelihood and food security. The productivity of these farms has traditionally been very low. Higher productivity must be achieved, but without

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harming the ecological foundations essential for sustainable agriculture. Second, climate change threatens agriculture in many parts of the world, especially in Africa. Risks rise rapidly with temperature. Once the temperature increases by about 2 °C, up to four billion people could be experiencing growing water shortages. Agriculture could cease to be viable in some parts of the world, particularly in the tropics, and millions more people will be at risk of hunger. To respond to these challenges of climate change, food security, and ecosystem degradation, Africa needs an "evergreen revolution" that increases productivity in perpetuity without causing ecological damage. Agroforestry clearly has a key role to play in this evergreen revolution.

Novel solutions and technological advances must be married with ecological thinking to drive a truly sustainable agricultural revolution. A key aspect of this effort will be conservation of the germplasm of locally available plant materials and their genetic diversity. The conservation continuum in the case of annual crops starts from the field and the farmers and their in situ (on-farm) conservation traditions. For example, today we have about 140,000 varieties of rice. More than 100,000 of them are in the IRRI (International Rice Research Institute) Gene Bank. They are all indigenous land races that farmers had conserved. If these races are lost, we will be losing a lot in intraspecific variability.

Today, we have various kinds of conservation mechanisms for rice, starting with on-farm conservation to gene banks of various kinds including the Svalbard Global Seed Vault, where rice germplasm is retained under permafrost conditions. We need the same continuum of conservation mechanisms for agroforestry and forestry tree species, starting with farmers' conservation complemented by gene banks and other methods of conservation, including tissue culture and so on.

In some of the program areas of the MS Swaminathan Research Foundation in India, we assist farm women and men to conserve their own plant genetic materials because such materials have a high level of resilience and resistance to drought, flooding, and other natural disasters. The farmers are encouraged to create seed banks of their own preferred grains such as *Pennisetum* spp., *Setaria* spp., and so on. These seed banks help rural people overcome the potential danger of the seed source being wiped out by a drought or other such calamities.

The farmers are also encouraged to maintain "water banks" or "rain banks" along similar lines. This overall approach of farm level or in situ conservation won for this group – composed largely of tribal women in the remote areas and lower echelons of the society – the Equator Initiative Award at the World Summit on Sustainable Development, 2002, in Johannesburg, South Africa.

There are several wonderful indigenous plants – medicinal plants, food plants, horticultural species, and so on – that are used in local agroforestry systems that are gradually disappearing. *Prosopis juliflora*, which is a common shrub in the arid and semiarid tropics and is usually considered a weed, is nevertheless a wonderful species that is tolerant to drought and salinity. It is now sought after as a source of genes for drought and salinity tolerance.

It is absolutely critical to conserve these genetic materials. Their conservation can be stimulated through economic rewards to farmers, thus creating economic stake in conservation. Today, when there is a high economic stake in exploitation and destruction, it is time that we reverse the paradigm and create an economic stake in conservation.

Agroforestry opportunities in mangrove areas are another important issue. This has tremendous potential and is attracting attention only now because of the alarm about the rise of sea levels. The sea level obviously is going to rise. In Africa and India, we have long coastal shore lines, and many of our major cities are along the coasts. We at the MSSRF are trying mixed cropping in mangroves as part of our experiments on agroforestry systems along the coastal shoreline of India. Halophyte mangrove trees that tolerate saline conditions, such as *Salicornia* species and *Atriplex* species, have a great deal of value. They could be a wonderful repository of genes for salinity tolerance.

Root and leaf exudates of the mangrove forests that are rich in nutrients support shrimp and fish production. One of the strategies we are testing is integrated sea water farming, or "agro-aqua" farm cultivation with halophytes. The wood needs of the local community will be met by incorporating woody species such as bamboo and casuarina into these systems. After the 2004 tsunami in Asia, people started realizing the great value of mangroves, which acted as speed breakers during that event. The tsunami damage was comparatively less in areas wherever there were dense mangrove forests along the coast, compared with those that did not.

Carbon sequestration has both a direct and an indirect role in agroforestry. Direct carbon sequestration rates vary from species to species. Indirectly, agroforestry also has some other important consequences for carbon sequestration since it helps to reduce the pressure on natural forests and helps to avoid deforestation. The IPCC (Intergovernmental Panel on Climate Change) recognizes that agroforestry systems have the highest carbon sequestration potential among managed land use systems, followed by grazing management, forest management, and crop plant management in that order.

Interest and awareness about the importance of trees and agroforests has increased tremendously in India lately, such that today there is enormous support for it among all sectors of the society – public, media, political, and professional – as a way to regreen India. For the first time, we find not only that we are no longer losing ground but the area in India under tree cover is now increasing, particularly because of the expansion of agroforestry. The Government of India just announced a scheme involving over one billion US dollars per year for the rejuvenation of degraded forests and the planting of trees in new areas, including establishment of agroforestry systems.

In conclusion, as noted by Edward Wilson while acknowledging a copy of my 1974 book on *Evergreen Revolution:* "The problem before us is how to feed billions of new mouths over the next several decades and save the rest of life at the same time." Because the population is growing rapidly and may reach ten billion by 2050, we are very worried that the population supporting capacity of the ecosystem has already been exceeded in many parts of the world. Indeed, it is a daunting challenge to feed the billions of new mouths without compromising our freedom and security.

An "evergreen revolution" is the best approach to address this problem. The aim of this new thrust is to lift food production well above the level attained by the green revolution of the 1960s, but using technology and regulatory policy more advanced and even safer than that used now. Building a successful evergreen revolution requires four components: technology, services, favorable public policies, and farmer enthusiasm. The issue of regulatory policy is very important: With the increasing application of biotechnology, it has become very important to ensure that the new tools are used in a safe and responsible manner, and that the risks and benefits are measured without exaggerating either. We must also embrace regulatory mechanisms so that the ethical dimensions of the use of new technologies are not forgotten.

We need to be proactive so that we remain prepared to address the occurrence of natural calamities such as more droughts, more floods, and higher temperature as a consequence of climate change. That is called anticipatory research. Anticipatory research and participatory research are two pillars of sustainable agriculture. Participatory research refers to involving farmers and their families in the research so that their traditional wisdom is meshed with modern technology. Both of these approaches must be combined together, so that we have opportunities for both of them to contribute their full measure. I hope this congress will show the way for that. Africa urgently needs further research and scaling up to create a real evergreen revolution.

Environmental Resilience and Agroforestry

Richard Leakey

Richard Leakey is a renowned paleoanthropologist and conservationist, Dr. Leakey served as the head of the Kenya Wildlife Services in which capacity he oversaw a reorganization of Kenya's troubled national park system. He was an elected member of the Kenyan parliament.

Abstract Water is at the heart of the crisis facing Africa today, and agroforestry provides some of the tools for restoring tropical aquifers that have been destroyed by years of deforestation and poor land management. When restoration does become a priority, human technologies for reforestation cannot truly mimic nature's complex restoration process. We need to control our species to do less harm rather than trying to control nature.

Keywords Water • Environmental resilience • Restoration • Rehabilitation

Environments can be resilient but they also change very dramatically. Had they not changed dramatically over the last four million years, we would not be here. And, it is the failure of certain ecosystems to survive that forces speciation and that forces change. There are two issues that need to be emphasized here: First, temperature rise per se may not be the real issue in the context of climate change, the biggest environmental threat facing us today. The more critical issue is the effect of temperature on precipitation in the tropical and subtropical regions. Water is at the heart of the crisis facing Africa today, but that issue is missed in many discussions. In our willingness to persist with bad habits in the destruction of water catchment areas and natural

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water dispersion systems, we overlook the depletion of water reserves in the aquifers below us without any regard to where they came from and how long they have been there and how long they will take to recharge. The current practice of sinking more and more bore holes in the tropics totally disregards the needs in the future.

Second, in the discussions on environmental resilience, the resilience of the environment to a given set of conditions is given prominence. That is a very different thing from environmental resilience. For example, it may have been alright to talk about environmental resilience with confidence when the global population was at a maximum of one billion. But today the population of *Homo sapiens* is more than seven billion, and there is little doubt that it will be around ten billion soon. Environmental resilience with the impact of ten billion people is a very, very different issue from that with the impact of one billion people.

Concerns have been raised about possible temperature rises of 2 °C. The mean temperature rise in the western Antarctic along the Atlantic peninsula has exceeded 2 °C within the last decade. Ten years ago, this was expected to happen in maybe 40 years. The interesting paradox that appears from records and recent research is that in East Africa, the soil temperature probably has not risen significantly over four million years, but what has changed dramatically is the hydrology and the precipitation levels and the impact of those changes on the ecosystems. Today, we are concerned, and rightly so, about unborn generations and the livelihoods of existing populations. Yet we must recognize that it is a foregone conclusion that we will fail if we do not pay regard to hydrology and the need for a sustainable way of life that reflects less on temperature and more on water. It is in this context that the issue of agroforestry becomes critically important.

Kenya has vast tracts of forests on the western shoulder of the Great Rift Valley. Human activities have long degraded the aquifers and are therefore undermining any attempts to adapt to climate change impacts or to build a more sustainable way of life. Despite high seasonal rainfall and flash flooding, natural water capture in Kenya has been minimal. This is exacerbated by uncontrolled hydroelectric schemes and extraction of water through boreholes. Water banks, water towers, and catchments, which require healthy forests on them to function properly, are also not sufficiently valued. Agroforestry techniques could perhaps be used to specifically return degraded areas to a capacity where they will begin to trap water and store it by giving some soil cover.

It needs to be noted that when restoration does become a priority, the reforestation technologies that are conventionally used cannot truly mimic nature's complex restoration process. In Kenya's Aberdare National Park, for example, what is now a forested national park used to be farmland. After the area became protected, it eventually reverted naturally to a healthy forest ecosystem. This is an example of nature doing its job remarkably quickly and effectively.

There are vast areas of land that need urgent rehabilitation; they should be protected and fenced and left to get on by themselves, possibly with some aerial dispersion of a mix of seeds of indigenous species, and left undisturbed for 30 years for nature to do its job. Technological interventions alone are not enough to bring a forest or an ecosystem back to life. Experts become so specialized in their areas of specialization that they tend to disregard or even kill off nature's ability to heal itself. We need to control our species to do less harm. Nature has resilience, and agroforestry can help maintain that resilience. Rather than trying to control nature, we should let nature do its job.

Climate Change and Agroforestry

Rajendra K. Pachauri

Rajendra K. Pachauri was the chairman of the IPCC delegation that received the Nobel Peace Prize in 2007. He has won various awards and outstanding recognitions and has been active in several international forums dealing with the subject of climate change and its policy dimensions.

Abstract The worst victims of climate change will be the poorest communities in the world, especially the vulnerable in Africa, where 75–250 million people are projected to live in water-stressed conditions by 2020. Agroforestry should be a key component in climate change mitigation measures. If we work together, collectively, there is no reason to believe that agroforestry cannot bring about mitigation of greenhouse gases but also produce a substantial set of cobenefits.

Keywords Greenhouse gas emissions • Biodiversity • Energy security

At the outset, let me emphasize the enormity of the challenge that we are facing with respect to climate change. We know now that climate change is unequivocal. The impacts that are being felt all through the world, and which are now being observed and recorded very carefully, point clearly to a future that is frightening if not disastrous. If we do not take action, it is now obvious, as the fourth assessment report of the IPCC has brought out, that the impacts of climate change could cause untold hardship and misery to a very large number of people.

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The unfortunate reality is that the worst victims of climate change are going to be some of the poorest communities in the world, and the continent of Africa in particular is very vulnerable. Our projections indicate, for instance, that the stress caused by climate change, together with the existing stresses such as water scarcity, is likely to affect 75–250 million people in Africa as early as 2020. This is something that obviously can lead to a great deal of conflict and will certainly lead to a huge loss of human welfare. It is something that we must prevent. Mitigation of the emission of greenhouse gases (GHGs) is the only way to accomplish that globally.

There are various ways by which we can bring about the level of mitigation that is required, and certainly agroforestry is one such important component. In fact, we have underrated the advantages and the benefits of using biomass cultivation as a means to mitigate GHG emissions. We have been doing just the reverse, i.e., the large-scale deforestation and degradation of forests all over the world has substantially diminished the ability of these natural systems to absorb CO_2. We need to reverse that trend; we need to make sure that we plant more and more trees.

We need to carry out larger scale agroforestry and make sure that this natural bounty of trees that fix atmospheric CO_2 is proliferated and expanded on a much greater scale. Through the efforts of agroforestry, and by ensuring optimal land use changes, we should be able to bring about a revival of biodiversity, and we would certainly be able to make a major impact in terms of water availability as well. It is no mystery that if we bring about resuscitation and revival of any part of an ecosystem, the benefits will be really widespread such that the benefits will be accrued to several other links of the ecosystem.

As in the case of most mitigation measures, there are huge cobenefits from agroforestry as well. Indeed, if we look at mitigation in general, in terms of the greater use of renewable sources of energy and improvements in the efficiency of energy use, there are several cobenefits such as lower levels of pollution at the local level, which bring about major health benefits. Arresting or limiting the impacts of climate change that would take place in the future will certainly bring about a higher level of energy security globally and minimize or avoid the negative impacts of climate change on agriculture. Furthermore, through mitigation measures, we would also be able to expand employment because a large number of these mitigation measures bring about large-scale employment generation.

These benefits of climate change mitigation apply specifically to agroforestry. If we expand agroforestry activities, there would be substantial benefits in terms of the local environment, and as a result, there would be accrued health benefits. There would be much greater energy security too, because agroforestry can also lead to biofuel production, particularly in respect of second-generation biofuels, where the target clearly is to bring about a conversion of cellulosic material to liquid fuels that could ultimately and substantially substitute for petroleum-based products.

There would also be great benefits in terms of agriculture. And we must not also minimize the importance of the revival of biodiversity. After all, all the known food that we get and all the crops that have been developed for human consumption are really the gift of what we obtained by way of the biodiversity that occurs naturally in our ecosystems. Finally, we also know that agroforestry is an important source of great employment.

As far as climate change is concerned, we have two very clear choices which must run in parallel. First, we have to adapt to the impacts of climate change, and some of these adaptation measures can also be carried out through agroforestry activities, particularly in the case of sea level rise that is already affecting several coastal areas and several small island states. Plantation of mangroves can make an enormous difference in terms of providing protection to storm surges, to cyclonic events, and coastal flooding in general.

Agroforestry activities, if carried out in the right locations, will bring about means of adapting to the impacts of climate change. But at the same time agroforestry also gives us an extremely attractive option for mitigation of emissions of GHGs because the net effect of agroforestry would be to see that a large part of the CO_2 that is emitted from our factories, transport vehicles, households, etc., can be absorbed through whatever we grow as a part of agroforestry programs.

It is important to look at not only the direct benefits of agroforestry to mitigation of emissions of GHGs but also the cobenefits that are not always apparent. In any economic decision-making and in any enlightened approach to deal with problems faced by human society, we must examine the totality of costs and benefits. If agroforestry provides substantial net benefits, then it is essential that we clearly identify them, evaluate them, and estimate their contributions. On the basis of that, we would be able to take much more enlightened decisions.

Last, but not the least, this will also give us a basis for informing the public. Each of these programs will require substantial public support, and one way to bring that about is through the presentation of the right facts in the right framework. Informing the public at large about these potential benefits will lead to the generation of a great deal of public support for agroforestry activities. Thus, the challenge is exciting, and the task is very clear. If we work collectively, there is no reason to believe that an option like agroforestry will not only be able to bring about mitigation of GHGs and thereby help in meeting the threat of climate change, but it also will produce a substantial set of other cobenefits for the whole of human society.

Agroforestry and the Transition to the Future

Achim Steiner

Achim Steiner is the executive director of UNEP and under-secretary-general of the United Nations since 2006. Before joining UNEP, Mr Steiner served as director general of the International Union for Conservation of Nature (IUCN) from 2001 to 2006, and prior to that as secretary general of the World Commission on Dams.

Abstract Humanity all too often thinks in boxes, but all too often this can lead to simplistic, short-term solutions.. Complexity needs to be embraced in which the best of indigenous, traditional, and farmers' knowledge is aligned and woven with empirical scientific evaluation. Agroforestry is a shining example of this approach, merging centuries-old knowledge with modern science. The future of global land use is no longer just about land – it is about the future of the atmosphere, of biodiversity, and of water, fuel, and food.

Keywords Ecosystem services • Systems approach • Sustainability • Greenhouse gas emissions • Organic agriculture

Welcome to the 2nd World Agroforestry Congress being held here at the UN Office at Nairobi and jointly hosted by the World Agroforestry Centre and UNEP. The theme "Agroforestry – The Future of Global Land Use" echoes to the challenges but also opportunities of our time.

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How do we, in a world of nearly seven billion people rising to perhaps over nine billion, feed everyone while simultaneously securing the ecosystem services such as forests and wetlands that underpin agriculture, and indeed life itself in the first place? And how do we achieve all this while also overcoming poverty, generating decent jobs for the 1.3 billion underemployed or unemployed, and combating the greatest challenge of this generation – climate change?

Sometimes you have to think small to think big. Humanity all too often thinks in boxes rather than in complexity – thinks keeping it simple rather than using a systems approach is the best way forward. There are those who look for silver bullets – nuclear power and genetically modified organisms might be two examples. Others might wish to consign modern scientific and technological knowledge to the dustbin and seek to turn back the clock to some kind of ideological or mythical rural idyll. The sustainability challenges we are confronted with today will not be amenable to such polarized approaches.

- We must take the best of the indigenous, traditional, and farmers' knowledge, forged over centuries of trial and error, and submit it to empirical, scientific, and rigorous evaluation.
- We must also put our modern, technological prowess under a fresh lens and more wide-ranging scrutiny. It must be subject to broader cost benefit analysis alongside delivering a wider suite of societal and environmental goals.
- Above all, we must bring the best of these worlds together and deploy them in both an integrated and flexible way that recognizes the different circumstances and conditions of the communities they serve.

Agroforestry is in many ways a shining example of this approach, merging centuries-old knowledge with modern science in a systems-led approach – and the concept of thinking small-scale to achieve potentially big and transformative outcomes. Indeed agroforestry's relevance to sustainable development in the twenty-first century has in many ways come of age in part through the lens of climate change.

Forestry needs to be an important element. The proposal for financing Reducing Emissions from Deforestation and Forest Degradation (REDD) must be a key plank of a new emissions reductions agreement. Up to 20 % of greenhouse gas emissions are from deforestation and forest degradation. Without economic incentives to reverse the trend, the emission levels will continue to rise. This will challenge all our efforts in terms of cleaner, renewable energy, including more energy efficient buildings and transportation networks.

However, simply locking away forests to secure their carbon as if they are the Queen's jewels, or putting up the modern equivalent of a Berlin Wall between forests and people, is almost certainly folly and almost certainly a recipe for disaster. REDD should and must reflect the genuine needs of the surrounding communities, including indigenous peoples. UNEP, in collaboration with the Food and Agricultural Organization of the UN and the UN Development Programme, and with funding from Norway, is spearheading the UN REDD Programme with nine pilot countries.

There are several issues that need to be resolved, from verification and monitoring of forests to how to manage payment systems, but also the role and rights of communities and their share in the financial flows. If REDD can be up and running, it may not only be good for combating climate change but also for generating new revenue flows from North to South, and also good for accelerating adaptation in terms of improving the health of water supplies, nutrient flows, soil stabilization, and job creation in areas such as natural resource management. The returns are potentially enormous and wide-ranging. The Economics of Ecosystems and Biodiversity (TEEB), an initiative of the G8+5 of which UNEP is the secretariat, says an investment of just $45 billion in protected areas alone – many of which are forested areas – could secure nature-based services worth trillions of dollars a year.

Agroforestry may have many roles to play in this new landscape of rewarding countries for their natural or nature-based services. First, it offers the potential for maximizing sustainable food production in the zones surrounding natural forests, while also boosting biodiversity and other "natural infrastructure." Second, it offers an opportunity for timber production and thus alternative livelihoods to meet a supply gap that may emerge under a fully fledged REDD regime. Third, these agroforestry areas can also potentially secure flows from carbon finance in their own right, for example, under the existing agreements of the Kyoto Protocol as afforestation or reafforestation projects, or under what one might call carbon farming.

REDD can open the door to even more creative carbon payments for improved land management elsewhere, including on farms, in peatland areas, and in coastal zones such as mangrove forests and perhaps one day even in the oceans themselves. I am delighted that the World Agroforestry Centre and UNEP, with funding from the Global Environment Facility and in collaboration with a broad alliance of academic institutions, are pressing ahead here. The Carbon Benefits Project is underway with an initial focus on communities in the catchments of Lake Victoria, Niger-Nigeria, and China. The missing link is a standardized way of assessing how much carbon is actually locked away in vegetation and in soils under different land management regimes. This is the goal of the project, and we anticipate preliminary findings soon.

In terms of afforestation and reforestation under the existing Kyoto Protocol, UNEP would be keen to learn why less than 1% of existing Clean Development Mechanism projects involve such initiatives. One area that needs to be explored is insurance: The insurance industry manages risk reasonably well for timber plantations, but seems less well geared to natural forests or farmland forests. The role of organic agriculture within farming, but also within agroforestry systems, has also emerged as an area of genuine debate in recent months. It follows a survey by UNEP and the UN Conference on Trade and Development. This survey of 114 agricultural projects in 24 countries shows that yields are often more than double where organic (or near organic) small-scale farming methods are used. The increase in yields in East Africa was well over 120 %.

A University of Michigan study revealed that there was up to three times greater productivity from organic methods, in comparison to other practices, in developing countries. The point here is that even if one is not ideologically in favor of organic food production, we are often force-fed points of view from one set of powerful vested interests. The reality on the ground for the less politically and financially powerful can be quite different.

And there are other possibilities that are in need of increased research and development, such as perennial crops. Experts suggest that “moving back to the future” to these kinds of multiyear crops with deep roots can also boost soil fertility and stability 50-fold while assisting in adapting to climate change. Perennial crops are also 50 % better at carbon capture and storage than their annual cousins, according to some estimates. Because they do not need to be planted every year, they use less farm machinery and require fewer inputs – reducing greenhouse gas emissions further.

In response to the food, fuel, financial, and economic crises, UNEP launched its Global Green New Deal-Green Economy Initiative. The basic concept is that in order to meet current and future challenges, every dollar, Euro, shilling, Yuan, and Rupee needs to work on multiple fronts in order to deliver sustainability. The Green Economy in the context of sustainable development and poverty eradication is now one of the two central themes of Rio+20 taking place in June 2012, two decades after the 1992 Earth Summit.

Agroforestry, with its multiple benefits, is very much a part of this transition to a low-carbon resource-efficient economic future – one able to meet the needs but also the aspirations of communities and countries across the globe. That is why UNEP has been delighted to cohost the 2nd World Agroforestry Congress and why we are equally delighted that all of you are here to make that transition a reality – a transition that merges centuries of knowledge with modern scientific methods – that can turn the challenges facing millions of small-scale farmers into one big opportunity for humankind.

The future of global land use is no longer just about land – it is about the future of the atmosphere and of biodiversity and of water, fuel, and food. Overall, it is about choosing a future of accelerating poverty or one that puts poverty on the run and prosperity into the cockpit and driver’s seat. In short, it is part of the complexity rather that reductionist simplicity that humanity urgently needs to embrace and to more intelligently manage if it is to survive and to thrive in the twenty-first century.

Agroforestry and the Future of Global Land Use

Dennis Garrity

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Abstract Positive forest transitions are now occurring in many countries in both the tropical and temperate zones. During the 1990s, 38% of the world's countries experienced increases in forest cover, particularly in Europe, North America, and East and South Asia. Evidence is also mounting that the number of trees on farms is increasing the world over. About 1 billion ha of agricultural land has more than 10% tree cover. Concerns about the availability and cost of wood resources, the growing awareness about environmental issues, and the opportunities for agroforestry to better address food insecurity will enhance expansion of tree planting on farms in many tropical countries. A substantial increase of trees on croplands, or what we now call EverGreen Agriculture, will be going to be an inevitable phenomenon in the future. The future of trees (and forests) is on farms.

Keywords Forest transitions • EverGreen agriculture • Tree cover • Food security • Faidherbia albida • Niger

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Introduction

Agroforestry has come of age as an integrative science as well as a common land use system around the world. It is recognized as being at the heart of the solution to many of the world's most intractable challenges.

Scientists at the World Agroforestry Centre recently completed an assessment of tree cover on agricultural lands around the world, based on a detailed analysis of full-cover satellite imagery. The results revealed that almost half of all farmed land in the world has more than 10% tree cover. Thus, nearly a billion hectares of agricultural landscapes now have trees on them. In some regions, such as Southeast Asia and Central America, tree cover on farms exceeds 30%.[1]

Unlike their counterparts in temperate areas, smallholder farmers in the tropics have always husbanded trees among their crops. They are doing so for a growing variety of purposes. Evidence is mounting that a counterintuitive phenomenon is widely occurring: that wherever there are relatively more people, there are relatively more trees. This increase in tree cover on farms is crucial in many ways, not least of which is to help protect the forests themselves. The FAO summed it up succinctly a few years ago when it declared: "The proportion of trees on farms and in forests varies considerably among countries, but two trends seem almost universal in the tropics: The number of trees in forests is declining, but the number on farms is increasing."

Forest Transitions

Forest transitions are now occurring in a large number of countries in both the temperate and tropical zones. During the 1990s, 38% of the world's countries experienced increases in forest cover, particularly in Europe, North America, and East and South Asia. China has established millions of hectares of tree plantations, some through agroforestry systems, while in India, village committees have been empowered to expand and restore small community forests and to engage in agroforestry.

The key trends identified as the drivers of these transitions include the following:

1. Demographic shifts of populations from rural to urban environments in the temperate zones, with concomitant increases in labor costs in agriculture. This has influenced farmers to take more marginal land out of production and allow it to go back into forest in North America and Europe.
2. Dwindling forest resources in many developing countries that have raised concerns about future wood supplies, along with increased concerns about watershed protection to reduce flooding risks along river courses.

These factors, along with growing environmental awareness among urban populations, have induced the two most populous countries in the world, China and India, to invest heavily in forestation programs. They have similarly induced many other tropical countries to formulate more conducive policies, invest in protecting catchments, expand tree plantations, and increase tree cover in agricultural areas. There are, however, a number of countries where rapid deforestation is continuing. These countries tend to be nations that perceive themselves to still have abundant forest resources, such as Brazil and Indonesia, or they are countries (or parts of countries) that are experiencing civil conflicts, such as the Congo.

In the medium to long term, we can expect that the drivers that caused the forest transitions in the temperate zones (specifically urbanization and increased rural labor costs) will continue to exert a dominant influence there. These drivers will also take hold in subtropical and tropical countries as economic growth accelerates. Public concerns about the availability and cost of wood resources will grow in many tropical countries as natural forest resources dwindle. Environmental awareness will rise alongside economic growth. The REDD+ (Reducing Emissions from Deforestation and Forest Degradation) agenda is already driving the policies of some forest-abundant countries such as Brazil or Indonesia in positive directions. Its influence is likely to grow, promoting forest protection and reforestation across the tropics. There is also a trend in the decline in the number of countries experiencing civil conflict. These factors will drive government policies toward forest protection and conservation and tree planting in critical watersheds. Thus, in the long run, we may anticipate that forest transitions will be observed as part of a ubiquitous global transformation.

The question is whether the process of a long-term increase in tree cover will be extended to the agricultural and grazing lands of the world. While such a process has hardly been contemplated so far, we can expect that to occur as well, since many of the factors driving a transition toward increased tree cover on farmlands are similar to those driving the forest transitions. There are also some additional factors promoting the increase of tree cover on farmland. These are related to the dynamics of addressing agricultural land degradation and assuring food security in a world of increasing fossil-fuel prices.

Suppose that the world succeeds in stopping deforestation someday soon, and that *all* of the remaining natural forest in the tropics is effectively protected to reduce carbon emissions, protect watersheds, and conserve biodiversity. How would the accelerating demand for timber, fuelwood, and other tree products be met? Without alternative sources of supply, demand will outstrip available resources, leading to a price explosion that negates efforts to protect the remaining natural forests. This demand must be met, and in a world that protects its natural forests effectively, it can only be met from the expansion of tree plantations and agroforestry on farms. Thankfully, the smallholders of the world are already beginning to respond to their local price signals. Tree cover on farms will expand.

In many places, this is already happening. In Kenya, some 70% of all wood is already sourced from farm-grown trees. This is growing rapidly, helping the country with its forest protection efforts. In India, farm-grown timber now supplies about 50% of the country's burgeoning demand for wood. In Bangladesh, farm-grown wood supplies 90% of the country's needs. The story is similar in other countries throughout the tropics.

Across the tropics, smallholder farmers have a huge role to play in meeting demand for tree products and thus saving the last of the natural forest domain. The world will soon be awakening to the crucial imperative of enhancing smallholder tree production systems to supply its voracious needs for tree products. Investments to do so through climate change mitigation funds will be increased. We must be prepared with the science and the practice to enable this enormous transformation. Helping farmers to produce more wood and tree products on their own farms and thus meet market demand must become a priority.

We expect tree cover to grow on farmland in temperate areas, too. Europe and North America are likely to expand tree cover on farms as part of their efforts to reduce carbon emissions. Demand for the next generation of biofuels produced from lignocellulosic woody sources will be grow. In the USA, fuel from woody sources is now estimated to be capable of producing 50% of the fuel needs of the entire transport sector – compared to a potential of only 3% for maize-based ethanol.

When we add to all this the demand for fodder, fruits, nuts, and internationally traded tree crop products like rubber, coffee, tea, and cacao, the area of trees on farms will be further enhanced. At the World Agroforestry Centre, we like to say that "The future of trees is on farm." What we now also realize is that the "future of forests is on farms" as well.

EverGreen Agriculture Transitions

The evidence is beginning to suggest that a massive increase of trees on croplands, or what we now call EverGreen agriculture, is inevitable. Perhaps not everywhere, but the trends suggest that it is likely to occur in many countries. In the tropics, there are a number of prospective drivers, including greater wood scarcity, labor migration off the land, and rapid urbanization. Concerns about watershed degradation continue to grow, inducing more investment in farming with trees on sloping land.

In many tropical countries, farms are rapidly becoming smaller. This encourages farmers to seek alternative income sources, inducing a greater diversity of activities on the farm itself. The need to produce higher value products for cash income (such as fruits and timber), and to supply more of the household's requirements for fodder and fuelwood, becomes ever more acute.

Trees on farms also provide crucial environmental services, such as enhanced soil fertility. Since its price tracks that of oil, nitrogen fertilizer is likely remain expensive by historical standards for the foreseeable future. And concerns are growing that the degradation of land and soil is undercutting food security. Even in the temperate zones, there is growing interest in the environmental services of land use systems. This foretells a shift toward governments investing in farmers' enhancement of those services through subsidy programs and away from commodity support. The European Common Agricultural Policy is now shifting away from discriminating against agroforestry and toward financially encouraging it. The eventual development of markets for farming carbon will add further impetus to EverGreen Agriculture.

There are, however, some serious trends that counterbalance these developments. Conventional wisdom has it that the future of farming in the tropics consists of large-scale commercial operations. There, trees are seen as a nuisance to mechanized operations. This view is accompanied by the impression that small-scale family farming is less productive and will decline in the future. The business opportunities from agroecological farming systems using biological resources are often seen as less lucrative than those flowing from the use of input-driven farming methods based on saleable products (inorganic fertilizers, pesticides, and machinery). Agribusiness multinationals are increasingly influential in setting the agenda for research and development in farming systems. And they are often supported by the agribusiness orientation of some developed country aid organizations. The short time horizons under which development investments are judged often militate against investments in agroforestry. Consequently, the investment in agroecological farming research is meager. A more effective body of solid agroforestry research is needed to counter these negative trends.

Major Themes of the 2nd World Congress of Agroforestry

Let us briefly turn to the three major themes of the 2nd World Congress of Agroforestry: food security, natural resources and the environment, and policy challenges.

Food Security

The entire world is now painfully aware that we face a very serious global food crisis. In the tropics, 70% of hungry people are rural. This crisis is predominantly a hunger crisis on the small-scale farm. Raising the productivity of small-scale farming is thus critical to achieving national and global goals to reduce hunger. Also, there is growing acceptance of the fundamental “right to food,” which puts further impetus on increasing productivity and land regeneration on small-scale farms.

Food imports into the African continent have been growing relentlessly, and food is becoming less and less affordable by the desperately poor. The reasons for this sad situation are many. Fertilizer use is pitifully low in Africa due to high prices and the risks of frequent crop failure in an uncertain climate. Meanwhile, the land is degrading and soil fertility is declining. The standard solutions are simply not working anymore.

The question is: What are we, as agroforestry scientists, going to do about it? How are we going to contribute to sustainable solutions? In Africa, agroforestry scientists have for years been observing the efforts of African farmers to create their own evergreen agriculture, using the biological resources that they already have.

Africa has indigenous tree species, such as *Faidherbia albida* Del. A. Chev., a leguminous nitrogen-fixing acacia species that exhibits a unique property: reverse leaf phenology, enabling it to be highly compatible with food crops. *Faidherbia* defoliates at the beginning of the rains and deposits abundant quantities of organic leaf fertilizer onto the food crops to provide nutrients and increase yields, free of charge. The trees perform as fertilizer factories in the food crop fields. The trees refoliate and produce pods in the dry season, providing a crucial source of fodder for their livestock when other plants are dried up. They are adapted to a wide array of climates and soils from the deserts to the humid tropics.

It is no wonder that millions of farmers across this continent have quietly nurtured these trees in their maize, sorghum, and millet fields. This tree has become an icon of what agroforestry can contribute to food production systems in the tropics. Indeed, were scientists to invent a tree from scratch that combines the ideal characteristics needed to successfully incorporate trees into food crop fields, they would come up with something very much like *Faidherbia*.

We scientists have observed farmers using these trees; we have appreciated their unique qualities, but so far we have failed to do enough to refine, adapt, and extend their unique properties to the millions of food crop farmers who desperately need home-grown solutions to their food production problems. We have failed to inform the policymakers and the farming community about the unique opportunities to exploit this indigenous African solution to the food production crisis.

Agroforestry science has much to offer in overcoming the food security challenges in Africa and elsewhere in the world. It evokes a vision of a double-story evergreen agriculture that will be a beacon to the world on how to farm efficiently and compatibly with trees.

Conservation and Rehabilitation of Natural Resources

We have focused on agroforestry for climate change adaptation and mitigation, water and watershed services, and biodiversity conservation. The role of agroforestry in climate change adaptation and mitigation was a theme of many of the presentations in the symposia and technical sessions. Agroforestry scientists and practitioners are working diligently to build the evidence base, the measurement systems, and the successful projects on the ground to make the case for full inclusion of smallholder agroforestry in climate change investments. We know that agroforestry systems can increase the carbon sequestration capacity of agriculture, above- and belowground, by up to an order of magnitude compared to other agricultural systems. And we know that agroforestry is critical to creating a multifunctional agriculture that can provide better watershed services and enhance the conservation of biological diversity. Many Congress presentations delved into just how this can actually be done. The concept of an evergreen agriculture has enormous implications here as well.

Policies to Enhance Farmers' Incentives to Practice Agroforestry

The World Agroforestry Centre has launched a Global Agroforestry Policy Initiative, in collaboration with FAO and our many international, national, and local partners. Some may ask what difference a policy change can really make to enhance agroforestry. Let me offer a transformative example. In the 1980s, the Sahelian country of Niger, at the edge of the Sahara desert, was in the throes of *catastrophic* desertification. Then, in the 1990s, catastrophe forced some creative thinking. The forestry regulations were relaxed by government. Farmers were no longer prohibited from cutting down trees on their own farms. They now had an incentive to farm more intensively with trees. Farmers across the country responded. They dramatically increased their efforts to regenerate and expand the tree populations on their farms.

Agroforestry spread across over 5 million ha during the past two decades, protecting the land and the crops, enriching the soil, providing fodder, and creating new income sources from wood and other tree products. The Sahel faces a complex crisis of desertification. Yet a single policy change transformed the incentives for millions of farmers and opened up new opportunities for sustainable farming, at the very edge of the Sahara. Encouraged by the experience in Niger, programs to promote the farmer-managed natural regeneration of agroforestry systems are now being established in all the other countries across the Sahel, as part of a coordinated regional initiative to once again regreen the Sahel. Farmers rose to the challenge when they were offered the opportunity to do so.

Conclusion

The future of land use across the world faces many stark challenges – food security, land degradation, desperate poverty, climate change, and others. But agroforesters have the tools to address many of them in an integrated and practical way. Let us take heart from the fact that agroforestry is truly the future of global land use. And let us focus our science and practice in getting on with the job of creating an EverGreen Agriculture throughout the world.

End Note

1. The study underestimated the amount of agricultural land supporting trees because the satellite images it is based on could not readily distinguish between agroforestry areas with full tree cover and forests.

Part II
Global Perspectives
Based on WCA2 Symposia

Climate Change Mitigation: A Low-Hanging Fruit of Agroforestry

P.K.R. Nair

Abstract Agroforestry systems (AFS) have attracted special attention in climate change mitigation and adaptation (M&A) discussions. Various reports on carbon (C) sequestration (and therefore climate change mitigation) potential of different AFSs have been reported from different ecological regions. However, the site-specific nature of AFS and lack of uniformity in C sequestration estimation methods make it difficult to compare the reported results. For convenience of comparative analysis, the various AFS are grouped into five subgroups – tree intercropping, multistrata, protective, silvopasture, and tree woodlots – and the global areas under each are estimated as 700, 100, 300, 450, and 50 million ha, respectively. Tillage, crop residue management, and plant diversity are reported as the major management operations that influence the role of land-use systems in climate change mitigation. The extent of influence of these operations varies considerably in various AFS subgroups; representative values (range) are reported for each. Based on this evaluation, the "strengths, weaknesses, opportunities, and threats" of the role of agroforestry in climate change M&A are presented as a SWOT analysis. On a global scale, while existing multistrata and tree-intercropping systems will continue to provide substantial climate change mitigation benefits, large-scale initiatives in grazing land management, working trees in drylands, and establishment of vegetative riparian buffer and tree woodlots are promising agroforestry pathways for climate change M&A. Clearly, climate change mitigation is a low-hanging fruit of agroforestry; enabling policies and rigorous long-term research are essential for facilitating its timely and sustainable harvests.

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Keywords Agroforestry subgroups • Carbon sequestration • Ecosystem services • Land-management factors • SWOT analysis

Introduction

Terms such as global warming, climate change, and carbon sequestration that used to sound as technical jargon until about a decade ago have now become common parlance in everyday life. While this rapid and widespread usage of the terms signifies their relevance and importance, it has also resulted in the use of the terms ambiguously, erroneously, and sometimes out of context. It is therefore important that the concepts and significance of the terms as used in this chapter are explained right at the outset.

The terms and concepts as used in this chapter are those defined or adopted by the IPCC,[1] and in some cases further elaborated by the UNFCCC[2] (United Nations Framework Convention on Climate Change; United Nations 2010). Accordingly, global warming refers to the increase in temperature of the earth's near-surface air and oceans that has happened in recent decades, estimated as 0.6 °C since 1970 and projected to be between 1.8 °C and 4.9 °C during the twenty-first century (IPCC 2007). This temperature rise (or global warming) that has far-reaching and grave consequences in terms of human life and ecosystem stability is believed to be caused by the increasing concentrations of the so-called greenhouse gases (GHG), among which carbon dioxide (CO_2) is the most abundant one. In IPCC usage, climate change refers to any change in climate over time, whether due to natural variability or as a result of human activity; however, it is viewed as a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods. Carbon sequestration is the process of removing C from the atmosphere and depositing it in a reservoir. It entails the transfer of atmospheric CO_2 and its secure storage in long-lived pools (UNFCCC 2007). The relevance of sequestering CO_2 in long-lived pools is that it could reduce the GHG-induced global warming. Mitigation and adaptation are two terms that are commonly used in climat change discussions. Mitigation refers to addressing the causes (of climate change), while adaptation attempts to tackle its effects. The IPCC defines mitigation as "an anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases" and adaptation as "the adjustment in natural or human systems to a new or changing environment" (IPCC 2011). The goal of climate change mitigation is to reduce net emissions of GHGs, whereas climate change adaptation aims at developing strategies to reduce the negative impacts. In spite of the clear differences in their meanings, the two terms signify interrelated and interdependent activities and processes and are often used together as climate change mitigation and adaptation (M&A).

Climate change and global warming are hotly debated and contested topics; but the debate is not on whether atmospheric temperatures are rising, but to what extent anthropogenic factors are contributing to this rise. Irrespective of the merits of that argument, the fact remains that human activity can affect the concentration of GHGs in the atmosphere. It is also well known that enhancing C content in the soil – the principal way of sequestering C in land-use systems – can contribute to soil productivity in so many ways. Indeed, there is hardly any physical, chemical, or biological property of the soil that is not favorably influenced by its higher organic carbon (organic matter) content.

In order to get a clear understanding of how land-use systems and their management can impact C sequestration (CS) and thereby climate change, it is important to present a brief description of the underlying processes. A major one is the so-called carbon cycle, which involves the fixation of atmospheric CO_2 in plants through photosynthesis and return of part of that C to the atmosphere through plant, animal, and microbial respiration as CO_2 under aerobic and CH_4 under anaerobic conditions (Nair et al. 2010). Direct sequestration of C occurs in soil by inorganic chemical reactions that convert CO_2 into soil inorganic C compounds such as calcium and magnesium carbonates. Aboveground C storage is the incorporation of C into plant matter either in the harvested product or in the parts remaining on site in a living form. The amount of biomass, and subsequently C, that is stored depends to a great deal – apart from the nature of plant itself – on the properties of the soil on which it grows, with higher concentrations of organic matter, nutrients, and good soil structure leading to greater biomass production. Roughly two-thirds of the total C storage occurs belowground, the extent and rate of which are influenced by inherent soil properties and processes, including some that are not influenced by management practices. Decomposition of plant residues and other organic materials in the soil is a source of C and nutrients for new growth of microbial communities and plants. Much of this C is released back into the atmosphere as CO_2 during respiration or is incorporated into living biomass. However, about one-third of soil organic matter (SOM) breaks down much more slowly and could still be present in the soil after 1 year. This SOM represents a significant C store and can remain in the soil for extended periods as a part of soil aggregates. The fraction of SOM that is so “protected” from further rapid decomposition is very important from the point of view of soil C sequestration.

The role of land-use systems such as agroforestry as a climate change M&A strategy has gained considerable importance lately following the realization of the ability of these systems to capture atmospheric CO_2 and store C in plant parts and soil. Agroforestry systems (AFS) have attracted special attention in this regard, especially for climate change mitigation, in view of their perceived advantage of large volumes of aboveground biomass (AGB) and deep root systems of trees. Given that a key mitigation strategy is to reduce the atmospheric concentrations of GHGs such as CO_2 through the process of CS, several estimates and reports on the C sequestration potential (CSP) of various AFS under different ecological regions have become available. Most of them constitute or include some estimates of C stocks: how much C is, or could potentially be, accumulated and stored in above- and belowground compartments of the systems under different conditions of ecology and management (Nair et al. 2009a, 2010). This chapter aims to review the current state of knowledge in this area and evaluate the role of agroforestry as a land-management strategy in climate change mitigation. The primary focus of the chapter is on mitigation, especially to gain an understanding on how and to what extent the common management practices can impact climate change mitigation in agroforestry systems; however, given that mitigation and adaptation are seen as two sides of the same coin as mentioned before, some relevant adaptation strategies that are directly linked with mitigation strategies are also considered. This chapter will first present the relevant information on the effect of land-management practices or operations that are common to many land-use systems on climate change mitigation (primarily C sequestration) and review the available information on them in relation to specific agroforestry practices; a synthesis of that information will then be used to present a general picture on the role of agroforestry in climate change M (& A). Although C sequestration is only one of the several strategies for climate change mitigation (see Box 1), the extent of research and other activities related to it compared with those on other strategies have been so prolific during the recent past that it would appear as the most important – if not the only – issue. Indeed, the terms climate change and C sequestration are used rather synonymously in discussions concerning land-use systems including AFS even in scientific literature. The extent of literature related specifically to AFS, however, is relatively low compared with other land-use systems. Moreover, as discussed by Nair (2011), the site-specific nature of AFS and the lack of uniformity in methods and procedures used to sample, analyze, determine or estimate, and present the data on C sequestration in AFS make it difficult to compare the results from different locations.

Land Management and Climate Change M&A

Given that the goal of climate change mitigation is to reduce net emission of GHGs and enhance sink capacity, land-management practices for accomplishing that goal should aim at avoiding or reducing the emissions as well as increasing the amount of C sequestered in terrestrial sinks (Box 1). Operational strategies for that include increasing the use efficiency of inputs such as nutrients and water and managing tillage and rhizosphere processes, and decreasing the losses of C from soil through desirable soil- and water-management practices such as soil erosion control and water conservation. Strategies for reducing the negative impacts – the goal of climate change adaptation – involve such activities as enhancing soil resilience, adopting efficient land-use systems (such as agroforestry), and improving the net primary productivity through introduction of new germplasm (Box 2).

Voluminous literature is available on the effect of specific management practices on climate change mitigation in various land-management systems: land preparation and tilling, nutrient management and manure/fertilizer use, irrigation, etc., in agricultural systems; fodder species, grazing management, etc., in animal production systems; tree species, silvicultural operations, harvesting regimes, etc., in forestry, to name a few. Understandably, there is enormous variation in the nature of these reports and the extent

Box 1 The major strategies and approaches for climate change mitigation through land-management practices. The various processes involved and factors affecting them are so interlinked and situation-specific that the impact of any specific practice cannot be clearly and independently delineated; the impact of each can best be expressed only in relative terms

Climate change mitigation through land management

Goal: reduce net emissions and enhance sink capacity

1. Avoiding or reducing the emissions
    - Increasing input-use efficiency
        - Management of nutrients, water
        - Tillage, rhizosphere
    - Decreasing losses
        - Soil and water conservation, reducing losses
2. Sequestering CO_2 in terrestrial biosphere
    - Forest/woody biomass
        - Aboveground, belowground
    - Soil C sequestration
        - Aggregation, physical protection, recalcitrant C
        - Plant stand density and species admixture

Box 2 The major strategies and approaches for adapting to climate change through land-management practices. The various processes involved and factors affecting them are so interlinked and situation-specific that the impact of any specific practice cannot be clearly and independently delineated; the impact of each can best be expressed only in relative terms

Climate change adaptation through land management

Goal: develop strategies to reduce the negative impacts

1. Enhancing soil resilience
    - Increasing SOC pool
    - Restoring degraded lands
2. Adopting efficient land-use systems/practices
    - Conservation agriculture
    - Agroforestry
    - INM, IPM, etc.
3. Improving NPP
    - New and improved germplasm
    - GM crops

of information they provide. Based on such information, different reports containing estimates, computations, and conjectures have been prepared by numerous authors and agencies projecting the effect of various practices on climate change mitigation in the long and short terms, and mitigation and adaptation strategies have been proposed to deal with climate change. The literature shows that climate change mitigation is not a simple and easily accomplishable objective or output that can be attained by tweaking and manipulating one or a few factors and practices; instead, it represents the net result of a large number of interacting factors and processes. No wonder that efforts to schematically represent the interplay of the various factors often result in a bewildering array of diagrams and flow charts consisting of a series of arrows, squares, boxes, etc., of various sizes and shapes resulting often in confusing and incomprehensible presentations that attract criticisms for being complex on the one hand and for leaving out essential features on the other. Indeed, almost any land-management practice can be claimed to have an effect – direct or indirect – on climate change, such that climate change mitigation cannot realistically be presented by simple cause–effect models. The bottom line is that adoption of soil- and land-management practices that have been long known as "good" and sustainable is the key to climate change mitigation through land management. Among these, reduced/no-tillage practices, crop residue management, and the use of diverse cropping systems are the most commonly mentioned management practices that have the greatest impact (Rui 2010). A summary of the reported effects of these practices on C sequestration is presented in Table 1, and the salient features are outlined below.

Tillage

Tillage is the agricultural preparation of the soil by mechanical agitation of various types, such as digging, stirring, and overturning. It aids the incorporation of plant material into the soil where it is subject to microbial oxidation; it also enhances gaseous exchange between soil and atmosphere. Minimum, reduced, and zero (or no) tillage are phrases, as their names imply, that are used to describe the various extents of tillage and consequently soil disturbance in crop management. Various reports are available on the C sequestration benefits of various tillage levels under different conditions (Lal 2010). Rees (2005) estimated that, on average, a change from conventional to no-till can result in sequestration of 0.57 Mg C ha^{-1} $year^{-1}$. Since a large portion of the process for secure storage of C occurs belowground when root material and other decaying matter are broken down slowly and incorporated into micro- and macroaggregates, soil disturbances such as tillage break these aggregates apart or expose decaying matter to the aboveground atmosphere, leading to its rapid decomposition and release of C and reducing the amount of C sequestered (Paustian et al. 2000; Bricklemyer 2007). The decrease of C sequestration reported from agricultural soils that follow conventional tillage practices (Alvaro-Fuentes et al. 2009; Cambardella and Elliott 1993; Six et al. 2000, 2002) is related to the rate of microaggregate (>250 μm diameter) production in till versus no-till systems. Although both (conventional and no-till) systems may have similar rates of macroaggregate formation, the level of microaggregates (250 to 53 μm) within macroaggregates of no-till systems has been found to be higher and has been attributed to tillage that caused breakup of up soil aggregates, exposing iPOM (intra-aggregate particulate organic matter) in macroaggregates and hastening their

Table 1 Some reported values of carbon sequestration potential associated with different management factors at various locations

Management practice	Location/ecological region	Carbon sequestration potential (CSP) (Mg C ha^{-1} year^{-1})	Reference	Relevance to AF
Tillage/ reduced till	Predicted global average; temperate grasslands	0.43–0.71; comparison of eight studies of root-derived organic C during a growing season depending on soil texture	Rees (2005)	Most AFS, especially in the tropics, are reduced- tillage systems
No-till (NT)	Canada prairie soils; SW Saskatchewan	0.67–5.12; 0–15 cm depth; six experiments with a range of climates and soil textures	McConkey et al. (2003)	
	Tropical and temperate	2.12–4.38; 0–10-cm depth; 20 years under NT; review of peer-reviewed experiments	Six et al. (2002)	
Manure	Eastern China	0.34 from 26; to 16.5 cm soil depth; long term (avg. 10 years); rice-based	Rui (2010)	Manure use is common in many tropical AFS
	Ludhiana, India; subtropical	23.3 and 31.3 Mg ha^{-1} in rice–wheat and maize–wheat systems; 0–60 cm depth	Kukal et al. (2009)	
Fertilizer	Ludhiana, India; subtropical	0.015–0.12; ($N_{120}P_{30}K_{30}$) rice–wheat and maize–wheat system; to 60 cm depth	Kukal et al. (2009)	Fertilizers are used in some AFS, although quantities are less compared to single-species systems
	New Delhi, India; semiarid and subtropical	5.53 over a 10-year period; 390:105:124 NPK kg ha^{-1} year^{-1}; intensive cropping with maize, wheat, cowpea	Purakayastha et al. (2008)	
	Alabama, USA; temperate	7.30; 10-year experiment; to 20 cm depth; two cotton-based cropping systems	Sainju et al. (2008)	

(continued)

Table 1 (continued)

Management practice	Location/ecological region	Carbon sequestration potential (CSP) (Mg C ha^{-1} year^{-1})	Reference	Relevance to AF
Plant diversity/ crop rotations	Predicted global average	0.08–0.32; 30 cm depth; meta-analysis using a global database of 67 experiments each over 5 years	West and Post (2002)	Plant diversity and species mixtures are very important characteristics of AFS
	Yangtze Delta Plain, Eastern China	0.70; mean depth 16.5 cm; meta-analysis 26 long-term rice-based experiments	Rui (2010)	
	Canada; temperate	0. 27–4.3; 0–15 cm depth; six experiments with a range of climates and soil textures	McConkey et al. (2003)	
Mulching/residue management	Hawaii, USA; humid tropics	5.4; pruning of tree residue pollard from trees at 1 m; to 20 cm depth	Youkhana and Idol (2009)	Quite relevant in AFS that involves tree pruning and litter fall
	Ohio, USA; temperate	14.89–15.53; 8-year experiment, using wheat straw; to 10 cm depth	Duiker and Lal (1999)	
Fallow	US Great Plains; temperate	1.4–2.7; meta-analysis for 8.5–9.1 Mha of US land in fallow; compilation of peer-reviewed papers	Follet (2001)	Relevance is location specific
	Central Zimbabwe; semiarid tropics	5.4 Mg C ha^{-1} natural fallow; to 20 cm depth 1 year after fallow termination	Nyamadzawo et al. (2009)	
	Germany; temperate	1.25; 13 locations, using EPIC model, avg. 10.6 years of grassland fallow with cereal crops in rotation; to 30 cm depth	Billen et al. (2009)	

breakdown (Six et al. 2000). No-till, on the other hand, allowed macroaggregates to persist for longer allowing iPOM to break down slowly into more recalcitrant microaggregates. Thus, although levels of light fraction organic matter (litter that is finely broken up but only partly decomposed and can be separated by ultrasonic dispersion and flotation) are no different between tillage and no-tillage and coarse iPOM only differs slightly, the incorporation of these materials into fine iPOM and microaggregates is greatly affected by breakup of macroaggregates by conventional tillage (Six et al. 1998). However, just as SOC stocks are heavily dependent on factors beyond the control of management, increasing evidence suggests that the effect of reduced/no-tillage on SOC sequestration largely depends on additional soil environment conditions (Ogle et al. 2005; Gregorich et al. 2006).

Although the vast majority of the voluminous research reports available show positive effects of minimum (or no) tillage on C sequestration, it needs to be noted that this conclusion is not unanimous. No-till management may not be effective in some soils and climates, and the role of tillage management in mitigating global warming is highly variable and complex and can be realized only when no-till farming is practiced over the long term (Six et al. 2004). It has been argued that sampling protocol might bias the results of most tillage system comparisons because conventional tillage merely moves the C that can be sequestered below what is considered the surface layer of soil, and the notable difference is found between C levels in soils under the two practices (conventional and minimum tillage) when only surface level measurements are taken (Baker 2007). The authors noted that in all cases where conservation tillage was found to sequester C, soils were only sampled to a depth of 30 cm or less even though crop roots often extend much deeper; in the few studies where sampling extended deeper than 30 cm, conservation tillage did not show consistent accrual of SOC, instead showing a difference in the distribution of SOC, with higher concentrations near the surface in conservation tillage and higher concentrations in deeper layers under conventional tillage. Blanco-Canqui and Lal (2008) reported that no-till usually increased SOC in the upper layers of soils but did not lead to C storage more than tilled soils in the entire soil profile. Nevertheless, other benefits of conservation tillage such as lesser soil erosion, lower cultivation costs, and reduced fossil fuel consumption for machinery are important arguments in support of conservation tillage (Baker 2007).

Residue Management and Nutrient Cycling

Residue management in agricultural systems ranks high among the important management practices in the context of C sequestration (and climate change M&A) and is particularly relevant to agroforestry discussions. Adding as much plant residues as possible back to soil has been known and recommended as a sound land-management practice, the virtue of which has stood the test of time. It is a cardinal rule to be followed in the climate change/C sequestration discussions as well. The principle involved is simple: more plant materials added to the soil means more C added to the soil. The extent to which plant materials added to the soil lead to enhancement of C – more importantly, sequestered C – depends, however, on a whole host of factors. An important one is litter quality, defined by the amount of C, N, lignin, and polyphenols in the litter, and ratios of these constituents, such as C-to-N, lignin-to-N, and (lignin + polyphenol)-to-N; litter-quality parameters have been used to predict decomposition and nutrient release in a number of situations (Nair et al. 1999; Palm et al. 2004; Youkhana and Idol 2009).

Plant materials, when intentionally incorporated into a system (whether produced by plants within it or brought in from external sources), are considered mulch, the addition of which to the soil surface could have both positive and negative effects. Its decomposition can lead to a small amount of short-term C sequestration, but some studies have reported that as much as 70–90% of the C in surface mulch may be respired back to the atmosphere as CO_2 (Flessa et al. 2008; Youkhana and Idol 2009). However, increased soil water content and soil nutrient availability in plots to which mulch has been added may stimulate fine root growth and activity (Batjes 1996), which would result in increased organic matter inputs from root exudation and turnover. Increased soil water and nutrients would also stimulate microbial degradation of organic matter, so the net effect on soil C could be unclear. The complexity of this scenario intensifies when litter fall is created through pruning, as this increases the amount of sunlight received by biomass decomposing on the soil surface. The increased exposure quickens decomposition, potentially reducing the amount of C sequestered. It is generally agreed that the greater the amount of biomass accumulated on the soil surface through operations such as pruning, the greater the CSP for the system; as even though the fraction of the material that may make it into the lower soil layers is small, a larger initial quantity equates to the percentage representing a larger quantity of C ultimately stored. The literature on organic matter decomposition, litter quality, and carbon dynamics is so extensive that it is not feasible to review it here; in fact, such a review is not needed here to emphasize the importance of the all-embracing term “residue management” in the climate change/C sequestration discussion.

Manure Use and Grazing

The use of organic manures either alone or in judicious conjunction with chemical fertilizers is another practice that has also received considerable attention in this regard. Manure application is somewhat related to plant residue management in the sense that both involve surface addition of organic materials. The effects of addition of such materials depend, obviously, on the nature of materials, ecological conditions, land-management systems, and so on. Zou et al. (2004) reported that while the addition of organic materials such as straw and manure to rice (*Oryza sativa* L.) paddy fields can significantly enhance SOC and rice yield, the induced GHG emissions, especially CH_4, have to be considered when judging the net effect of the practice.

Fertilizer application can also influence the formation and stability of soil aggregates. The effect of fertilization practices on SOC can be dependent on the nature of the fertilizer as well as the climate and other site-specific factors. Tripathi et al. (2008) found that nitrogen fertilizer inputs increased the formation of macroaggregates and associated microbial biomass nitrogen in the dry tropical forests in India but caused a decrease in the savanna. Nitrogen in the form of inorganic fertilizer on maize (*Zea mays* L.) fields in Ghana also led to a decrease in soil aggregation (Fonte et al. 2009), while amendments with high C/N ratios compared to low C/N ratios were found to lead to higher levels of SOC and greater aggregate stability in a dryland ecosystem in India (Singh et al. 2009). Similarly, inorganic fertilizer use in combination with C additions resulted in an increase in SOC and aggregate stability as well as nutrient levels in the soil, although inorganic fertilizers by themselves did not have this effect (Xiang et al. 2009). In an experiment comparing an organic farm and conventional farm in England, the main factor affecting aggregate stability was SOM input; organic versus inorganic fertilizers were not significantly different, but there was a trend toward less stable aggregates when using the inorganic fertilizers (Williams and Petticrew 2009).

Although management practices can influence the formation and stability of soil aggregates and thus the amount of C sequestered, there is a limit of C that can enter the soil, and a certain point at which C additions to the soil will not be incorporated into microaggregates, but only into more labile macroaggregates that are not stable. For example, Gulde et al. (2008) found that soil C sequestration did not increase when manure applications were increased from 120 to 180 Mg ha^{-1} $year^{-1}$. They also found that macroaggregate was the only aggregate size class that increased in C across all manure application levels and that was due to an increase in iPOM concentration. This suggests that rates of manure application cannot speed up the rate of C sequestration.

Grazing could have both positive and negative impacts in terms of net effects on climate change. Grazing practices which increase grassland productivity have the potential to increase SOM and C sequestration (Conant et al. 2001). Comparing grazed and ungrazed grasses, Reeder and Schuman (2002) reported that grazing could result in higher soil C due to more rapid annual turnover of shoot material and changes in species composition, while Rees (2005) found that the exclusion of grazing allowed an increase in annual forbs and grasses with less dense and fibrous root systems. An appropriate level of grazing must be determined, however, to maximize these ecological benefits of grazing. While grazing-induced soil biological activity can stimulate net nutrient mineralization and increase nutrient availability, numerous studies are available to show that excessive grazing can affect total C, microbial biomass, enzyme activity, and reduce above- and belowground biomass (Holt 1997; Mayzlish 2005). Cao et al. (2004) attest to the fact that both grazing and manure addition may accelerate soil respiration leading to release of C to the atmosphere. This process must be balanced against the positive attributes of manure application.

Cropping Systems and Plant Diversity

The importance of cropping systems from the standpoint of climate change M&A stems from the premise that providing continuous plant cover and plant residues through appropriate crop rotations and/or cover crop systems protects the soil from erosion and helps promote C input to the soil. In that context, plant diversity, as in mixed stands of species of different growth habits and root configuration, is quite relevant. The relationship between plant diversity and C sequestration has been a subject of scientific interest (Schwartz et al. 2000; Tilman et al. 2001; Srivastava and Vellend 2005); but investigations on this topic are limited. Tilman et al. (1997) and Kirby and Potvin (2007) have suggested that plant assemblages with high species diversity may promote more efficient use of resources compared with those of lesser species diversity and thus lead to greater net primary production (Vandermeer 1989) and consequently higher C sequestration. Saha et al. (2009, 2010) reported higher soil C stock under multispecies homegarden systems compared with single-species systems (rice paddy) in Kerala, India. High plant diversity in a system may also alleviate disturbances (Huston and Marland 2003) such as temporal instabilities caused by climate change; on the other hand, it is widely agreed that more C is better sequestered in systems with lesser disturbance (Six et al. 2002). West and Post (2002) found that increased diversity in crop rotation either through change from monoculture to rotation or by increasing the number of crops in rotation was associated with a change of 0.2 Mg C ha^{-1} $year^{-1}$ in an analysis of data from 67 experiments.

Nitrogen-fixing species are highly valued in land-use systems for their potential to improve soil fertility through and therefore promote the growth and productivity of associated species. Consistent with this, mixed plantings involving N_2-fixing tropical tree species have been reported to produce more aboveground biomass compared to the respective monoculture stands under comparable conditions (Bauhus et al. 2004; Forrester et al. 2006). Major differences in organic C inputs from tree biomass (prunings) of N_2-fixing trees are possible. Oelbermann et al. (2006) noted profound differences in organic matter inputs between two N_2-fixing species, *Gliricidia sepium* (Jacq.) Kunth ex Walp. and *Erythrina poeppigiana* (Walp.) O. F. Cook, both in 19-year-old alley-cropped stands in Costa Rica, implying the need for proper choice of species to augment SOC. The possible impact of N_2-fixing tropical species on atmospheric concentrations of GHGs other than CO_2 such as nitrous oxides (N_2O) is also frequently mentioned (Sharkey and Loreto 1993); but a solid body of research data is not yet available. Thus, the effects on vegetation and SOC accretion may be positive, negative, or neutral, and it is possible to influence biomass and soil C sequestration by selecting appropriate tree species. Since many AFS, especially in the tropics, use fast-growing, and often N_2-fixing, multipurpose tree species, they help increase SOC levels (Nair et al. 1999; Oelbermann et al. 2006) and as such are expected to have high CSP.

Role of Agroforestry Systems in Climate Change Mitigation (and Adaptation)

This section will examine the available literature on the role of AFS in climate change and C sequestration under different ecological conditions in the light of the effects of specific management practices presented in the previous section. The effort is focused on the major management factors rather than the reported quantities of C sequestration for various AFS under different conditions (considering that such values are highly variable depending on the local conditions, system characteristics, management practices, and methods of computation) so that future management strategies could focus on manipulating those factors for optimum advantage. Moreover, for the purpose of this analysis, the multitude of AF systems and practices that are reported in the climate change/C sequestration literature are grouped under fewer categories, each encompassing several systems and practices of a somewhat similar nature. These are intercropping systems (alley cropping, other forms of tree intercropping), multistrata systems (homegardens, shaded-perennial systems), protective systems (riparian buffer, windbreaks, live fence), silvopasture (grazing systems, tree-fodder systems), and tree woodlots (fodder trees, fuelwood trees, degraded land rehabilitation). A summary of the analysis is presented in Table 2.

Intercropping (Alley Cropping and Other Forms of Tree Intercropping)

Alley cropping and various other forms of tree intercropping encompass many of the traits associated with the management practices that are considered favorable for climate change mitigation discussed before (Table 1). All of these systems and practices can be identified with reduced tillage, effective residue management, and species diversity. Efficient nutrient cycling and use of deep rooting/N_2-fixing species are particularly significant in tropical alley cropping, where fast-growing trees and shrubs, especially N_2-fixing ones, are grown as hedgerows in crop fields and are pruned periodically during the cropping season for the biomass to be returned to the soil as a source of nutrients or used as animal fodder (Nair 1993). In moderately sloping lands (<10% slope), alley cropping is also an effective soil erosion control strategy in both the temperate regions (where the trees are not pruned, but are harvested at the end of the tree-rotation cycle) and the tropics (Garrett 2009; Bannister and Nair 1990). Root turnover and decomposition is another process that might be contributing to C sequestration in these systems; estimates of the amounts involved are, however, rare and available figures are highly variable. In extensive intercropping systems under widely spaced or scattered stands of multipurpose trees, as in the parklands system of sub-Saharan Africa, an additional favorable factor is the large stock of C retained in trees both above- and belowground (Takimoto et al.

Table 2 Some reported values of carbon sequestration under various agroforestry systems and possible management factors related to climate change M&A under each in different ecological regions

System/practice	Location/ecological region	Reported values of CSP (Mg ha^{-1} $year^{-1}$)	Reference	Major management factors[a]
Alley cropping and other tree-intercropping systems				
Tropical alley cropping: *Gliricidia sepium* + maize; 10 years old	South Malawi; humid and subhumid tropics	123–149; soil stock to 200 cm depth	Makumba (2006)	RM (NC), PD/PSM, EC, RT
Tropical alley cropping: *L. leucocephala* + maize	Western Nigeria; humid lowland tropics	13.6; above- and belowground; soil depth n/a	Lal (2005)	
Tropical alley cropping: *Erythrina poeppigiana* + maize + beans; 19 years old	Costa Rica; humid and subhumid lowland tropics	162; above- and belowground (to 40 cm soil depth)	Oelbermann et al. (2006)	
Temperate alley cropping	Ontario, Canada; temperate	N/A	Peichl et al. (2006)	RT, EC, RM/NC
Temperate alley cropping	Midwestern USA; (general)	(Estimated)	Udawatta and Jose (2011)	
Multistrata systems (shaded perennials, homegardens)				
Shaded coffee system	SW Togo; trop. humid lowlands to highlands	6.31 in a 13-year-old (above- and belowground)	Dossa et al. (2008)	PD/PSM, RM (NC), EC
	Tropics; humid lowlands	10–20 (belowground to 1 m); 5 years old	Nair et al. (2010)	
	Tropical highlands (general)	10–20 (belowground to 50 cm); 15 years old	Nair et al. (2009b)	
Homegarden	Sumatra, Indonesia	8.00 (above- and below ground); 13 years old	Roshetko et al. (2002)	PD, PSM, NC, EC, RT
	Kerala, India	101–126 Mg ha^{-1}; to 1-m depth; <35 years old; above- and belowground	Saha et al. (2009)	
	Tropics; general projection	5–9; 750 trees ha^{-1}; belowground only	Nair et al. (2010)	
	Western Kenya	16 Mg C ha^{-1} perennial aboveground biomass	Henry et al. (2009)	

Protective systems (windbreaks, riparian buffer)				
Riparian buffer strips	United States; temperate	1.5 Tg C $year^{-1}$ for 0.8 million km by 30 m (above- and belowground)	Montagnini and Nair (2004)	EC, NC, RM
Windbreaks and riparian buffers	United States; temperate	2.9 Tg C $year^{-1}$ for 4.25 million ha (potential) (above- and belowground)	USDA (2011)	
Windbreaks	United States; temperate	4.0 Tg C $year^{-1}$ (above- and belowground)	Montagnini and Nair (2004)	
Live fence; A. *nilotica*, A. *senegal*, B. *rufescens*, L. *Lawsonia inermis*, and *Z. mauritiana*	Ségou, Mali	24 Mg $ha^{-1}$from 0 to 100 cm for an 8-year-old (above- and belowground)	Takimoto et al. (2008)	EC, PD
Silvopasture				
Grazing system	Southern USA; Lake Okeechobee watershed in Florida	350–540 Mg CO_2 ha^{-1} absorbed in southern pine, 20-year rotation	Shrestha and Alavalapati (2004)	PSM, RT, EC
Browsing system	Kerala, India	6.55 for a 5-year-old (above- and belowground)	Kumar et al. (1998)	RT, EC, NC
Acacia mangium Willd. +*Arachis pintoi*	Costa Rica; Atlantic coast, tropical	173 Mg ha^{-1} from 0 to 100 cm for a 10–16-year-old	Amézquita et al. (2005)	
Woodlots				
Improved fallow; various NFTs with maize	East Zambia; tropical	32.2–37.8; to 20-cm depth; 10-year-old system	Kaonga and Coleman (2008)	NC, PSM, RM, RT
Improved fallow; *L. leucocephala*	Central Philippines; tropical lowlands	16 for a 6-year-old system (aboveground)	Lasco and Suson (1999)	
Improved fallow; *Tephrosia candida*	Western Kenya; subhumid highlands	64.2 Mg ha^{-1} for 1.5 years (above- and belowground)	Albrecht and Kandji (2003)	

(continued)

Table 2 (continued)

System/practice	Location/ecological region	Reported values of CSP (Mg ha^{-1} year^{-1})	Reference	Major management factors[a]
Fodder bank; *Gliricidia sepium*, *Pterocarpus lucens* and *P. erinaceus*	Mali, West Africa; semiarid tropics	0.29 in a 7.5-year-old system (above- and belowground)	Takimoto et al. (2008)	NM, EC, PD
Fodder bank; *Acacia auriculiformis*	Kerala, India; humid lowlands	180 Mg C ha^{-1} in a 9-year-old stand, 2,500 trees ha^{-1} (above- and belowground)	Kumar et al. (1998)	NC, PSM, EC, RT
Fodder bank	Tropics; general, humid lowlands	60–95 Mg C ha^{-1} in a 10-year-old system to a 50-cm depth (belowground)	Nair et al. (2009b)	NC, PSM, EC, RM

[a] Possible climate change-related management factors (as identified in the text) for each system/practice: *EC* erosion control, *NC* nutrient cycling, *PD* plant diversity, *PSM* plant-species mixture, *RM* residue management, *RT* reduced (minimum/zero) tillage

2008; Luedeling et al. 2011); benefits derived from factors such as residue management and nutrient cycling, erosion control, and reduced tillage may, however, be expected to be of a low level of magnitude in these systems.

Another agroforestry technology that has been promoted, especially in nutrient-depleted African soils, is improved fallow. Basically, one or a few (mixed) tree species are planted as a substitute to natural fallow, to achieve the benefits of the latter in a shorter time (Buresh and Cooper 1999). The production of biomass in planted fallows as well as the potential of planted fallows to ameliorate soil fertility is controlled by several factors: environmental conditions, soil type, land degradation, length of the fallow period, density of tree planting, tree management, and soil and climatic conditions (Mutuo 2005). Improved fallows, in which leguminous trees and shrubs are grown in association with crops, are reported to sequester substantial amounts of C in plants and soil in the short term (Sanchez 1999; Albrecht and Kandji 2003) and enhance the stabilization of water-stable aggregates, which in turn decreases the risk of erosion in subsequent crop periods, thus contributing to the sustainability of the system (Mutuo 2005). Apart from the N-rich materials directly returned by coppicing, trees also return sizeable quantities of organic C through root detritus, root exudates, and mycorrhizal hyphae (Kaonga and Coleman 2008). The year-round buildup of SOC on the soil surface due to litter fall and/or coppicing increases the C stock at that layer, while belowground long-term C storage potential is improved via the rooting systems. In spite of these promising reports, long-term data on soil C buildup under improved fallows are not available, and the technology still remains “on the shelf” with few reports on its large-scale adoption.

The current distribution as well as future scope for adoption of these intercropping systems is extensive throughout the world. Rigorous statistics on the extent of area under agroforestry are not available; however, given the extensive spread of various forms of tree intercropping, it is reasonable to assume that about 60% of the more than 1 billion ha of land that was estimated to be under agroforestry (Zomer et al. 2009) falls in this category. Somarriba et al. (2012) who estimated the area under various AFS in Latin America did not recognize alley cropping and such other forms of tree intercropping as a major practice in the region. Udawatta and Jose (2011) estimated that the area under alley cropping in North America could be about 18 million ha. Altogether, it seems that 700 million ha is a realistic estimate of the area under this category of AFS (Table 3). In the extensive systems of tree intercropping under scattered trees as in the parkland system of sub-Saharan Africa that constitutes the major share of this category of AFS, the C sequestration rates are expected to be low (<2 Mg ha^{-1} year^{-1}) as suggested by Nair et al. (2009b). In the tropical and temperate alley cropping, the CS rates could be higher than in the extensive systems (>10 Mg ha^{-1} year^{-1}); however, at present the area under such systems is rather low as stated above. Given that this subgroup of AFS seems to have high potential for adoption in both the tropics and the temperate regions, these systems could have a significant role in climate change mitigation in the future.

Multistrata Systems

Intensive, multispecies, tree-based farming systems such as homegardens and shaded-perennial stands are common agroforestry practices, especially in the humid and subhumid lowlands of the tropics. The structural and functional diversity and various other characteristics of these systems have been well described in a variety of publications and summarized in a few (Nair 1989; Kumar and Nair 2006). Homegardens have a long tradition of providing food and nutritional security as well as environmental sustainability in smallholder production systems, often in thickly populated regions of lowland humid tropics in South and Southeast Asia and, to a small extent, in other tropical and subtropical regions. Although a few systems that have some similarities to tropical homegardens can be found in parts of the temperate regions as well (e.g., the satoyama system in Japan, Ichikawa and Toth 2012), intensive multispecies homegardens are a unique agroecosystem of the tropics.

Growing tree crops such as coffee (*Coffea* sp.) and cacao (*Theobroma cacao* L.) under the shade of overstory tree species, known as shaded-perennial systems, is another traditional example of high-intensity crop combination that has some unique ecological features and commercial value. In addition to coffee and cacao, several of the tropical fruit- and nut-producing tree species that are harvested annually or at shorter intervals are often grown in association with understory or overstory species (Elevitch 2006, 2011; Gama-Rodrigues et al. 2011). In many situations, the species combinations and management features of these systems are very similar to those of homegardens such that, at the landscape and village level, there is a continuum of plant associations from homegardens nearer homes to multistrata tree gardens away from the homes.

Characterized as the epitome of sustainability, these multispecies tree-crop combinations are excellent examples of efficient land-management systems from the point of view of climate change M&A. With heavy reliance on human (often family) labor for the farm operations, conventional tillage operations involving machinery are nonexistent in such systems. Some of the distinguishing ecosystem sustainability features of these systems include efficient and "closed" nutrient cycling facilitated by continuous litter fall and decomposition and very little export of nutrients from the system by way of harvested products, the reliance on organic manure and plant materials with consequent avoidance of chemical-fertilizer use, and predominance of deep-rooted trees, which collectively contribute to the high levels of C sequestration and climate change mitigation in these systems, as evidenced by the recent studies by Saha et al. (2010) in the homegardens of Kerala, India, and Gama-Rodrigues et al. (2010) in the shaded cacao systems of Bahia, Brazil.

In terms of the area occupied, these multistrata systems are not as widespread as the tree-intercropping systems. As in most AFS, accurate estimates of area are not available. Nair and Kumar (2006) presented a global map showing the spread of homegardens within the 30ºN and 30ºS parallels with the highest concentrations in the humid and subhumid tropics but did not present an estimate of the area involved. The same applies to shaded-perennial systems too. All told, the total area under all such multistrata systems may not exceed 100 million ha globally, and given the specialty nature of the commodities involved and the relatively high amount of human labor demand in their management, the area under such systems is not likely to increase in the near future. However, over the decades, even centuries, the area under these systems has not declined either. Thus, although the prospects of enhancing the role of these multistrata systems in future scenarios by extending the area under the systems do not appear to be very promising, their area is likely to remain unchanged, and therefore these systems will continue to be quite important in maintaining the status quo of climate change mitigation.

Protective Agroforestry Systems

These systems encompass the use of trees and shrubs for exploiting their ecosystem-protection benefits by planting them as windbreaks, riparian buffers, soil conservation hedges, etc. Windbreak practices include shelterbelts, timberbelts, and hedgerows and are planted and managed as part of a crop or livestock operation. Field windbreaks are used to protect a variety of wind-sensitive row, forage, tree, and vine crops, to control wind erosion, and to provide other benefits such as improved bee pollination of crops and wildlife habitat (Brandle et al. 2009). Livestock windbreaks help reduce animal stress and mortality, feed and water consumption, and odor, while timberbelts are managed windbreaks designed to increase the value of the forestry component, and shelterbelts are planted along sea coast to reduce the impact of sea encroachment and protect crops from saltwater damage. Riparian and upland buffers are strips of permanent vegetation, consisting of trees, shrubs, and grasses that are planted and managed together. Riparian buffers are placed between agricultural land (usually crop land or pastureland) and water bodies (rivers, streams, creeks, lakes, wetlands) to reduce runoff and nonpoint source pollution, stabilize stream banks, improve aquatic and terrestrial habitats, and provide harvestable products. Upland buffers are placed along the contour within agricultural crop lands to reduce runoff and nonpoint source pollution, improve internal drainage, enhance infiltration, create wildlife habitat and connective travel corridors, and provide harvestable products (Schultz et al. 2009). As discussed under alley cropping, frequently pruned rows of trees and shrubs planted across the contour in crop production fields help reduce soil erosion, and the pruned biomass serves as a source of nutrient to crops or can be transported away to be used as animal fodder.

The trees and shrubs planted in these protective tree barriers contribute to climate change mitigation directly through their C sequestration and indirectly and more importantly through the protection they offer by reducing soil erosion by wind and water. Depending on the planting patterns adopted (windbreaks: around crop fields; soil conservation hedges: among crop rows; riparian buffer and fodder banks: along plot and field boundaries; and shelterbelts: along field boundaries in coastal areas), the number of trees/shrubs per unit area and the extent of C sequestration will vary considerably. Jose et al. (2012) estimate that the potential C sequestration could be 4.7 Tg C year^{-1} by riparian buffers along rivers and 8.79 Tg C year^{-1} by windbreaks in the USA.

Riparian buffers are a common feature of the landscape in the US North Central region in particular (Jose et al. 2012), as well as in Canada (Thevathasan et al. 2012). In addition to the benefit of C sequestration, these protective systems could provide additional C benefits due to improved crop and livestock production and energy savings (Kort and Turnock 1999). Recognizing agricultural runoff being a key contributor to nonpoint source pollution (NPSP) of water including hypoxia in the Gulf of Mexico, riparian buffer strips are a heavily subsidized agroforestry practice by US Federal cost-share programs such as the Conservation Reserve Program, Environmental Quality Incentives Program, Forest Stewardship Program, Wetlands Reserve Program, and Wildlife Habitat Incentives Program (Jose et al. 2012).

Silvopasture

Silvopasture that combines trees, forages, and shrubs/trees with livestock operations is another type of agroforestry practice that is popular in both the tropics and the temperate regions. Broadly, there are two major forms of silvopasture: grazing and tree-fodder systems. In grazing systems, cattle are allowed to graze on pasture under widely spaced or scattered trees, whereas in the tree-fodder systems, the animals are stall-fed with fodder from trees or shrubs grown in blocks on farms (Nair 1993; Nair et al. 2008; Kiptot and Franzel 2012). Most silvopastoral systems in Africa and other developing regions of the world involve extensive open grazing by free-roaming animals under scattered natural stands of trees and shrubs mostly in semiarid to arid areas, as in the parklands of sub-Saharan Africa. More intensive grazing systems of silvopasture are practiced in Latin America where animals are penned in barbed-wired parcels and grazing is regulated (Somarriba et al. 2012). Such "organized" silvopastoral systems are also becoming popular in the extensive Cerrado region of Brazil (Nair et al. 2011). The most intensive silvopastoral system is the stall feeding of animals with fodder from trees grown elsewhere, which is a very common practice in smallholder farming systems as described by Kiptot and Franzel (2012). The grazing system of silvopasture has recently gained prominence as an environmentally desirable approach to managing degraded pasture lands in the industrialized countries (Rigueiro-Rodriguez et al. 2008; Garrett 2009).

The extent of C sequestration in any AFS depends largely on the amount and quality of biomass input provided by tree and non-tree components of the system and on properties of the soils, such as soil structure and their aggregates. Howlett et al. (2011a) reported that the soil C stock under cork oak (*Quercus suber* L.) and other trees that are common in the dehesa was higher under the trees near the tree trunks than away (15 m) from the trees. Studying C storage in soils under varying depths in silvopastoral systems (trees + pasture) versus treeless pasture in southern USA, Haile et al. (2010) reported that C3 plants (trees) contribute to more stable C (in the silt- + clay-sized, <53 μm) fractions than C4 plants (warm-season grasses) in deeper soil profiles. In the establishment of silvopastoral systems, some functional consequences are inevitable when trees are allowed to grow in grass-dominated land such as an open pasture (Nair et al. 2011). It also needs to be noted here that in intensive ruminant production systems, energy-containing compounds produced as biomass in primary plant production are converted to desired animal products such as meat and milk and into waste products. Waste comprises fecal and urine outputs as well as the fermentation and respiration gases CO_2 and methane (CH_4). Methane is considered much more harmful than CO_2 to the ozone layer because of its much higher intensity of infrared energy absorption; its contribution to the greenhouse effect, per gram, is around 30 times higher than that of CO_2.

Silvopasture embodies the goals of desirable management practices for climate change mitigation (especially in terms of grazing, rooting, and manure addition) and C sequestration.

Additional benefits of silvopasture include water quality improvement (Nair and Graetz 2004; Michel et al. 2007), soil conservation, aesthetics, and providing shade to cattle (Garrett 2009). Alternative land uses including sustainable forest management, outdoor recreation, and ecotourism, and most encouragingly silvopasture, are considered highly compatible with traditional ranching and include several elements of best management practices for ranchers (Shrestha and Alavalapati 2004; Garrett 2009).

The extent of C sequestration and climate change mitigation in silvopastoral systems will vary, depending, as in other systems, on the nature and level of management of the systems, with rather low levels in the extensive system to relatively high levels in the intensively managed systems. Grierson et al. (1992) suggested that a hectare of southern pine in the USA grown in silvopasture with 20-year rotation could absorb 350–540 Mg CO_2 (4.8–7.3 Mg C ha^{-1} $year^{-1}$). Dulormne et al. (2003) reported a 15% increase in soil C to a 20 cm depth after 10 years of silvopasture with *Gliricidia sepium* in the French Antilles, with an average carbon sequestration rate of 1.9 Mg C ha^{-1} $year^{-1}$. Udawatta and Jose (2011) concluded that silvopastoral systems had the greatest potential among all AF practices to sequester C in the USA. Using a sequestration potential of 6.1 Mg C ha^{-1} $year^{-1}$ on 10% marginal pasture land (23.7 million ha) and 54 million ha of forests, they estimated total CSP for silvopastoral lands in the Unites States as 474 Tg C $year^{-1}$. The dehesa system of southern Mediterranean region of Europe is a traditional silvopastoral system extending over 3 million ha, primarily in Spain and Portugal (Mosquera-Losada et al. 2012; Rigueiro-Rodriguez et al. 2008).

Tree Woodlots and Specialty Crops

These terms are used to denote agroforestry practices that are undertaken for special situations and needs. Examples include growing tree woodlots as fodder banks (for production of cut-and-carry tree fodder); boundary planting of trees for production of firewood, small timber, poles, and fence posts; tree planting for reclamation of degraded lands such as saline soils and mined land (Quinkenstein et al. 2012); establishing tree woodlots for biomass and bioenergy production such as in the Canadian prairies (Kort and Turnock 1999; Thevathasan et al. 2012); growing specialty products such as ornamentals, honey, and high-value crops for niche markets; and a whole host of such out-of-the-mainstream land-use systems. The extent of people and areas involved and the economic benefits derived from such activities are seldom documented. These activities, although important for their economic, social, and cultural benefits, may not count as major activities in terms of carbon sequestration and climate change mitigation, except for any large-scale tree woodlot establishments.

The analyses presented above clearly indicate the effective role of agroforestry practices in mitigating and adapting to climate change. Indeed, several broader analyses of land-use systems in general have also highlighted the important role that agroforestry could play in climate change M&A. Reviewing the various conservation practices, Delgado et al. (2011) has identified agroforestry as an excellent climate change mitigation tool since it can sequester significant amounts of C from the atmosphere and suggested that agroforestry practices such as alley cropping, silvopasture, riparian buffers, tree-grass buffer, and windbreaks could be used to sequester C in North America. Eagle et al. (2010) argue that well-managed agroforestry could also be integrated with bioenergy production and could reduce GHG emissions due to its low use of fertilizer inputs and energy. Several of the management practices identified by Lal et al. (2011) for increasing soil C sequestration such as residue management, cover crops, use of nitrogen-fixing species, soil and water conservation, and riparian buffer management are indeed central to many of the agroforestry practices, as summarized in Table 2. Thus, it is clear that agroforestry systems can be used to mitigate climate change by enhancing C sequestration both above- and belowground and to help us adapt to changes in climate change by minimizing soil erosion and improving soil productivity. Obviously, the extent of benefit that could be realized depends on a large number of site-specific and management factors. Table 3 that has been synthesized based on the analyses presented in Tables 1 and 2 and supplemented by other literature sources shows a summary of the range of C sequestration benefits that can realistically be expected from different agroforestry practices. Again, these values are only indicative.

Agroforestry Pathways to Climate Change M&A

Recognizing the value and importance of a land-management practice such as agroforestry in climate change M&A is only the essential first step in addressing the issue. The real success will come only when the identified practices are adopted and implemented. For example, in spite of the recognition of the importance and availability of a substantial body of research data regarding the desirability of no-till farming for the past several decades, the rate of adoption of no-till farming is low, and it is practiced on only about 7% of crop lands on a global basis, primarily in the mechanized farms in the United States (Kassam et al. 2009; Derpsch 2011). The practice has little or no adoption in developing countries because of various social, political, and cultural reasons. Conservation agriculture promoted by the Food and

Table 3 Approximate global area under different agroforestry system subgroups and the carbon sequestration potential under each[a]

AFS subgroup	Distribution (major regions) including potential	Approx. area, million ha (including potential)	Estimated C stock range (kg ha^{-1} year^{-1})		Estimated CSP in new area (kg ha^{-1} year^{-1})	
			Aboveground	Belowground	Aboveground	Belowground
Alley cropping and other tree-intercropping systems	Humid and subhumid tropics	650	Up to 15	Very low to 150	2–5	25–75
	Temperate (N. America, Europe)	50	Up to 10	Up to 200	2–6	50–150
Multistrata systems (shaded perennials, homegardens)	Mostly tropical humid and subhumid lands, predominantly lowlands, but up to 2,000-m altitude	100	2–18	Up to 300	2–10	100–200
Protective systems (windbreak, riparian buffer, shelterbelts, etc.)	Arid and semiarid lands of the world, primarily sub-Saharan Africa, China, and North and South America	300[b]	2–10	Up to 100	1–8	20–60
Silvopasture	Grazing systems: mostly semiarid and subhumid lands in Africa, India, and the Americas	450	2–15	Up to 250	3–10	80–120
Woodlots (firewood, fodder, land reclamation, etc.)	Firewood and fodder-tree lots are mostly in tropics; land reclamation plantings in special problem areas	50	1–12	Up to 140	1–5	40–70

[a] These are arbitrary estimates based on the reported values in literature, many of which are also arbitrary

[b] Planted in linear rows; the area is expressed in terms of the area protected by the protective plantings

Agriculture Organization of the United Nations (FAO 2009) and others that espouse the principles of minimal disturbance of soils while providing continuous plant residue cover and using diverse rotations and/or cover crop systems are very similar to several of the agroforestry management options that can be used to sequester C and to help mitigate and adapt to climate change (Tables 1 and 2). These principles that could be applied to low-intensity and/or high-intensity systems provide alternatives that can address the challenges presented by climate change. However, the adoption rates of many of these promising alternatives are low. It would therefore appear that it is not the lack of technologies or awareness about their role and value that hinders their application and adoption. That is very true of agroforestry adoption as well (Ajai and Place 2012).

Keeping with the biological focus of this chapter, let us examine briefly some of the major agroforestry-related activities that could have significant impacts on climate change M&A.

Grazing Land Management

Savannas are a major component of the world's landscape, covering one-sixth of the land surface and accounting for 30% of the primary production of all terrestrial vegetation (Grace et al. 2006). Grazing land and pasture cover about 3.4 billion ha globally (Gurian-Sherman 2011), most of which is currently under poor or little management. Undoubtedly, proper management, including diversification of pasture species in this vast area, has a potential role in climate change M&A (Gurian-Sherman 2011). Silvopasture could be a valuable tool for grazing land management in many parts of the world. Recent studies by Howlett et al. (2011a,b) and Mosquera-Losada et al. (2012) have illustrated the role of trees in C sequestration in the dehesa system in Spain and other parts of southern Europe. The Cerrado region of Brazil and other parts of South America are extensive regions where silvopasture could provide a major opportunity. As discussed by Tonucci et al. (2011), the Cerrado, extending over 200 million ha, is the largest neotropical savanna in the Americas. With its ongoing conversion to intensive agriculture since the 1960s, of which cultivated pastures for beef cattle production are a major form, this unique ecosystem is now considered threatened. Following the realization that the silvopastoral system of tree plantation development on pasture lands could be relevant to this region in view of the role of trees in C sequestration and GHG mitigation, eucalyptus-based silvopastoral systems have been established during the past two decades in the Cerrado region by growing agricultural crops [rice (*Oryza sativa* L.) and soybean (*Glycine max* (L.) Merr.)] in the first 2 years followed by the forage species, *Brachiaria brizantha* (Hochst. ex A. Rich.) Stapf., and beef cattle grazing from the third year of plantation establishment. The Brazilian savannas that have characteristically low aboveground C reserves hold considerable stocks of soil organic C, probably as a consequence of previous land use, the history of which is unknown. Most of this C is in a biodegradable form and is likely to be lost to the atmosphere when the soil is disturbed during land conversion to agriculture and pasture. Adoption of sustainable land-use systems such as silvopasture could reduce this potential hazard (Nair et al. 2011; Tonucci et al. 2011).

Working Trees in Drylands

A resurgence of interest in tree planting seems to be sweeping across the dry regions of the world that occupy roughly 40% of land area. Two significant and massive projects that have become talking points not only in conference halls and college classrooms but also in international news media and perhaps in rural villages are the shelter forest of China and the Great Green Wall of Africa. Shelter forest refers to large-scale planting of trees and shrubs to form a long protective shield against desertification and soil and water losses in northern China covering more than 40% of China's land area (Yan et al. 2011). Officially called the "Three-North Shelter Forest Program (TNSFP)" and dubbed as China's "Green Great Wall," the project involves planting deciduous broad-leaved tree species (e.g., *Populus* spp., *Ulmus* spp.) and shrubs (e.g., *Caragana microphylla*, *Hippophae rhamnoides*, *Hedysarum fruticosum*), since 1978 (Yan et al. 2011), and it represents the largest ecological afforestation program in the world. The Great Green Wall Initiative of Africa is a program that aims to regreen the Sahelian countries from Senegal in the west to Djibouti in the east, providing hope for poor farmers and their communities to increase food production and incomes and at the same time to improve their ability to adapt to future climate variability. Backed by the African Union, the program is envisioned to encompass agriculture, livestock, forestry, and agroforestry in a sustainable system, not "a wall made up of trees planted across the Sahara, but rather as a set of cross-sectoral actions and interventions aimed at the conservation and protection of natural resources with a view to achieving development and, particularly, alleviating poverty".[3] News reports and other publications are replete with various examples of "working trees" being regenerated by farmers across the sub-Saharan region to renew land health and transform environments (Garrity 2012; ICRAF 2011).[4] In Niger, more than 5 million ha of farmland are covered predominantly by the fertilizer and fodder tree, *Faidherbia albida*, and in the Seno Plains of Mali, grassroots efforts have resulted in half a million hectares of medium-to-high density tree cover. The agroforests of Ranawa in Burkina Faso that produce shea butter, an important ingredient in the international cosmetics market from the shea butter tree (*Vitellaria paradoxa* C. F. Gaertn.), have been applauded as a shining example of agroforestry just like the assisted natural regeneration of traditional parklands in Senegal. As suggested by Ban Ki-moon the UN Secretary General, on the World Day to Combat Desertification, 17 June 2011, Dakar, Senegal,[5] "the ongoing greening of the Sahel and other success stories around the world show that degraded lands can be reclaimed by agroforestry and other sustainable practices. We need to scale up these interventions." The establishment of shelterbelt plantations of fast-growing temperate tree species in the Canadian prairies (Thevathasan et al. 2012) is yet another example of such a large-scale tree planting initiative. The scope for extending such measures to vast areas of degraded drylands of the world and reaping the resulting benefits of climate change M&A is enormous.

Riparian Vegetative Buffer

Soil erosion and nutrient runoff from agriculture, collectively called by the term nonpoint source pollution (NPSP), remains a major challenge in protecting and restoring water quality in the United States even three decades after the implementation of the Clean Water Act in the 1970s. The US Environmental Protection Agency (2010) has identified agriculture as the leading cause for water pollution, the most common pollutants being sediment, nutrients, pathogens, and organic enrichments. The proportion of forest to agricultural land cover could be a good indicator of NPSP moving to streams and lakes (Jones et al. 2004). Studies during the past three decades have shown that the establishment of perennial vegetation on agricultural watersheds as upland buffers can improve water quality parameters (Udawatta et al. 2002; Schultz et al. 2009). Strategically positioned buffers can enhance environmental benefits by filtering nutrients and reducing sediment losses. This strategy might include conversion of sensitive areas such as variable source areas or areas with greater runoff potential to perennial vegetation or wetlands (Schmitt et al. 1999; Qui 2003). Numerous studies have suggested that a holistic approach that addresses landscape parameters, soil properties, and management provides for the best protection of watersheds, and the implementation of agroforestry practices, especially vegetative riparian buffers, has been recognized as one of those strategies (Udawatta et al. 2009; Schultz et al. 2009). Riparian zones are particularly effective "sinks" for groundwater-borne NO_3 (Hill 1996) and are an essential component of efforts to reduce N delivery to receiving waters in many parts of the world (Lowrance et al. 1997; Mitsch et al. 2001). The main processes underlying the N-sink capacity of riparian zones are denitrification – the anaerobic microbial conversion of NO_3 into the gases NO, N_2O, and N_2 – and plant N uptake. Managing riparian zones to keep them in permanent vegetation including trees and shrubs will increase C sequestration in soils and vegetation (Udawatta and Jose 2011), with nutrient inputs leading to enhancement of this sequestration (Fortier et al. 2010). Given that public demand for ameliorative measures such as establishment of vegetative buffer zones in crop fields to arrest increasing hazards of soil erosion in the US Midwest is increasing,[6] riparian vegetative buffers are expected to be an increasingly adopted best management practice (BMP) in vast areas, especially in the industrialized world, that are increasingly being degraded by chemical agriculture. Considering the benefits of C sequestration, erosion control, and nutrient-use efficiency, such BMPs are an excellent climate change M&A strategy.

Rural Development and Indigenous Systems

Land-use intensification through tree-based production systems on smallholder agricultural lands is a principal rural development pathway of agrarian transformation with significant benefits for greenhouse gas emissions, economic return, provision of ecosystem services, and climate change adaptation in Southeast Asia (Minang et al. 2012) and South Asia (Kumar et al. 2012). As suggested by Verchot et al. (2007), such high-carbon stocks rural-development approach offered through tree integration in agricultural landscapes could play a major role in climate change M&A in the region.

Some of the indigenous land-use systems that have stood the test of time and provided food and nutritional security and environmental sustainability and have been identified with the social and cultural norms and traditions of the local people for centuries are now being recognized and promoted gradually. The satoyama system of Japan (Ichikawa and Toth 2012; Kumar and Takeuchi 2009) is just but one such example of this trend. Plieninger (2011) has illustrated how trees on landscape as embodied in the concepts of agroforestry could be a climate change mitigation strategy in Germany. The emerging appreciation of their hitherto unrecognized value is a promising development that will lead to greater understanding of their role in the overall ecosystem health, of which climate change M&A will be a major component.

Policy, Implementation, and Research Needs

The foregoing discussion leads to a SWOT analysis as presented in Fig. 1 that summarizes the strengths, weaknesses, opportunities, and threats for the role of AFS in climate change M&A.

Even when the strengths and opportunities are formidable as they appear to be in this case, the success of the programs will be determined more by the “weak links” (weaknesses and threats). The weaknesses are internal or inherent to agroforestry, whereas the threats are external in the sense that they are conditioned by factors outside agroforestry. Nevertheless, both categories manifest themselves as weaknesses or impediments, and therefore, they can be clubbed and considered together. Policy, implementation, and research needs are the major weaknesses that could hinder the realization of the potential for climate change M&A offered through AFS.

The REDD+ (Reducing Emissions from Deforestation and Forest Degradation)[7] is currently the most talked-about mechanism for international investments or incentives in emission reductions from the land-use sector. It is based on the understanding that developing countries should be financially supported for reduced emissions from deforestation and forest degradation either through new targeted funding streams or by links to carbon markets. Support for REDD+ is largely due to the common expectation that reducing emissions from land-use change will be cheaper

Strengths

- ✓ High above ground biomass production
- ✓ Deep root systems of trees
- ✓ High litter-fall and ground cover
- ✓ Efficient nutrient cycling
- ✓ More stable C in deeper soil layers
- ✓ Plant diversity and biodiversity
- ✓ Species admixture
- ✓ Control of wind and water erosion
- ✓ Amelioration of non-point source pollutants
- ✓ Biodiversity conservation

Opportunities

- ✓ Enhanced above-ground C storage
- ✓ Increased SOM content
- ✓ More stable C in deeper soil layers
- ✓ More ground cover and litter fall facilitating better nutrient cycling and control of soil erosion
- ✓ More plant diversity leading to "safety net" of nutrients and reduced NPSP
- ✓ Overall, better ecosystem sustainability
- ✓ Increasing global interest in environmental ethics

Weaknesses (Internal)

- ➢ Lack of rigorous and long-term quantitative data on potential benefits
- ➢ Site specific nature of systems making large-scale extrapolation difficult
- ➢ Paucity of standardized methods and procedures for sampling and estimation of C seq in AFS
- ➢ Multiplicity of factors and complex nature of interactions
- ➢ Difficulty in estimating area under different AFS

Threats (External)

- ➢ Lack of adequate recognition of AFS and trees on farms in int'l policy initiatives and mechanisms such as REDD+
- ➢ Insufficient valuation methods for assessing ecosystem service benefits
- ➢ Excessive importance to economic over environmental benefits in adoption incentives
- ➢ Inadequate institutional niche for agroforestry at national and international levels

Fig. 1 A SWOT analysis of the role of agroforestry systems in climate change M & A

than other sectors (Stern 2006). Yet, REDD+ and the previous similar effort, Clean Development Mechanism (CDM) of the Kyoto Protocol (that used to dominate similar discussions until REDD+ attained prominence recently), have so far been slow to deliver sustainable development. Moreover, both REDD+ and CDM only address forestry, afforestation and reforestation, respectively. Smallholder farmers and agriculture are not specifically included, although 46% of agricultural land globally has at least 10% tree cover (Zomer et al. 2009). With at least 30% tree cover in about 50% of agricultural land in Southeast Asia and Central America and in 15% of agricultural land in sub-Saharan Africa, as revealed by the comprehensive study by Zomer et al. (2009), agroforestry ought to have a rightful place as a major afforestation strategy in these global policy agendas and action plans, and it seems to be moving in that direction as indicated by the recent international initiatives such as the CRP 6.[8]

In the discussions on low-input land-use systems such as agroforestry in relation to climate change M&A, the trade-offs and synergies between and among the various benefits will need to be factored in. As Matocha et al. (2012) articulate, the potential of a land-use system for carbon sequestration, the ability of an activity to increase the resilience of that system to climate change, and the capacity of local communities to implement and maintain a project as well as the benefits they would derive from it should be considered while identifying and prioritizing these activities. The trade-off discussions in such cases, however, are often dominated by environmental benefits; the trade-off between the environmental benefits and the potential for reduced commodity production in AFS compared with monocultural systems is seldom considered. But, income generation from crop and other commodity production, rather than the potential climate change mitigation and adaptation benefits, will be the overriding factor in the farmers' decisions on adoption of practices. Matocha et al. (2012) argue that in places where adaptation is needed and there is a risk of trade-offs with mitigation, adaptation should be prioritized as the more site-specific need, with due emphasis on research into strategies that will aid in mitigation. This could be unrealistic, because, as noted before, mitigation and adaptation are so intertwined that they will need to be considered together; moreover, adaptation strategies have to be guided by research results of mitigation efforts. It needs to be emphasized that while mitigation efforts are directed toward manipulating or managing existing systems and practices (e.g., exploitation of nutrient cycling in agroforestry), adaptation may involve introduction of new practices including species and cultivars that are better adapted to climate change than the currently used ones (e.g., agroforestry tree-improvement efforts, Leakey et al. 2012). In practical terms, however, successful mitigation requires that the systems are able to adapt to climate change; the effect of unmitigated climate change might exceed the adaptive capacity of systems even if adaptation measures are fully implemented. Therefore, adaptation strategies should be based on mitigation research, and the two should proceed simultaneously in successful land-management systems.

The claims and conjectures about the role of land-use systems in climate change mitigation and adaptation are riddled with more rhetoric than science and more rote than reason. An examination of the rather prolific literature on the promising virtues and roles of land-use systems in climate change M&A reveals that many of them represent generalized – often global – projections, estimates, and assumptions that are not adequately supported by rigorous research data. Agroforestry systems are no exception. Indeed, it is even more complex in the case of AFS because of their extreme location specificity compared with, say, commercial production systems. Moreover, the lack of standardized procedures for research and estimations in agroforestry makes it difficult to compare the reported data; indeed, some of the variability in the values reported is due to this lack of uniformity in the procedures adopted. While part of this can be attributed to the newness of this field of research, especially in agroforestry, which by itself is a relatively new field for research, it is a serious problem in climate change research in AFS. Nevertheless, all indications based on available scientific evidence suggest that AFS have much greater potential than row-crop agricultural and grazing systems in enhanced climate change mitigation, and introduction of these practices wherever feasible would be a good climate change adaptation strategy. This articulation of potential benefits based on available information from related fields is indeed a good beginning. Although that initial phase has been productive, it is time to move on to the next and more exciting stage, i.e., testing the hypotheses and validating them in the field, while also developing rigorous and standardized research procedures and analytical tools. Fortunately, we now have adequate experience and accrued knowledge to embark on research projects of any magnitude on climate change mitigation depending on resource availability, and we need to do that sooner than later to harvest this seemingly "low-hanging fruit" of agroforestry.

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Segregate or Integrate for Multifunctionality and Sustained Change Through Rubber-Based Agroforestry in Indonesia and China

**Meine van Noordwijk, Hesti Lestari Tata, Jianchu Xu,
Sonya Dewi, and Peter A. Minang**

Abstract Rubber (*Hevea brasiliensis* L.) production systems have conserved forest biodiversity in some parts of Asia and are a threat elsewhere. A holistic view on these two sides of the coin is needed. The roles planted trees and agroforestry play in the transformation of lives and landscapes depend on the stage of "forest transition" and the spatial configuration, segregation or integration, of the landscape. "Forest transitions" need to be understood at the level of the actual *pattern* of change, (one level up) at the level of *drivers* of change, and (one level down) at the level of *consequences* for ecosystem goods and services. To close the loop on a *feedback* mechanism, forest transitions also need to be understood at the level of mechanisms that link desirable or undesirable consequences of changes in tree cover to the drivers, providing positive or negative feedback. "Forest ecosystem services" can be partially fulfilled by agroforests as a form of domesticated forest. We revisit the theoretical framing of agroforests as part of forest transition and discuss a case study of the rise and decline of complex rubber agroforests in lowland

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Sumatra (Indonesia) and the recent expansion of monoculture rubber in China replacing agroforestry systems. Both cases indicate a complex of driving and conditioning factors but also a current lack of incentives to reverse the trend toward landscape segregation. Complex agroforests represent an intermediate stage of intensification, between natural forest and home garden, and may occupy an intermediate stage in the way landscapes develop under the influence of land users and other stakeholders. Although complex agroforests represent considerable value (biodiversity and carbon stocks) of relevance to external stakeholders, incentive systems for the land users need to match these values; otherwise, these systems will disappear when more intensified and simplified tree crop systems take over. Current analysis of the choices in land sparing versus land sharing, and segregation versus integration, emphasizes the convex or concave nature of the bifunctional trade-off curves.

Keywords Biodiversity • Swidden • Sustainagility • Trade-offs • Tree regeneration

Introduction

Multifunctionality Through Integration or Segregation

The title of this book suggests that agroforestry may be the future of land use in at least some parts of the world. In other parts of the world, it is or is on its way to be part of the history of land use. The rise, decline, and continued dynamics of any land use respond to drivers, consequences, and feedback mechanisms. In the context of the debate on sustainability of meeting the ever-increasing demand for food, feed, and fiber production (Tilman et al. 2002) and the similarly increasing scarcity and expressed value of environmental integrity (Kumar 2010), the potential role of complex agroforests and other land use of “intermediate intensity” has caught the attention of researchers (Vandermeer et al. 1998; Swift et al. 2004; Schroth et al. 2004; Michon et al. 2007; Scherr and McNeely 2007; Steffan-Dewenter et al. 2007). Such agroforests may serve as an integrated, multifunctional, or “*land sharing*” solution (Jackson et al. 2010; Tomich et al. 2001) and form an alternative or complement to the segregated “*land sparing*” approach of agricultural intensification and simplification based on substituting ecological functions by technical means and external inputs (Sanchez 1994; Green et al. 2005). In its crudest and simplest form, the hypothesis suggests that intensification will increase supply and decrease farm-gate prices, leading to recovery or avoided clearance of forest and abandonment of marginal land; investment in agricultural intensification might thus, if the hypothesis were true, directly lead to biodiversity conservation and qualify for REDD+funding (under emerging schemes to Reduce Emissions from Deforestation and Degradation, Minang et al. 2012). Evidence supporting the hypothesis is mostly indirect (Angelsen and Kaimowitz 2001; Rudel et al. 2009) and contradictory effects at intermediate scale – profitable forms of intensification attracting migrants to forest margins – exist, but intensification may still be a *necessary though not sufficient* condition for biodiversity, watershed, and carbon stock conservation (van Noordwijk et al. 1995a; Tomich et al. 2001), depending on the direct negative consequences of intensification.

A rapidly increasing literature quantifies the trade-offs between productivity and ecosystem services at various scales (Polasky et al. 2005; Woltmann et al. 2007; Nelson et al. 2009; Perfecto et al. 2009; Fischer et al. 2010; Phalan et al. 2011). Beyond the efficiency and persistence scales of such studies, however, the "sustainagility" aspects of maintaining the options and resource base for continued change (Verchot et al. 2007; Jackson et al. 2010) also need attention. As output per ha will have to keep increasing to match growing demand, however, an input-based operational definition of land-use intensity is needed before dynamic hypotheses on the relationship of intensification with output per ha and other functions can be quantitatively tested (van Noordwijk and Budidarsono 2008). Van Noordwijk et al.[11, 12] analyzed whether a "segregate" or an "integrate" choice would achieve more of a fixed production goal plus a maximized biodiversity goal on a limited area of land. The equations suggest a simple quantitative criterion: if the trade-off curve between productivity and biodiversity is concave, spatial segregation of functions and specialization is the better choice; if the trade-off function is convex, integrated solutions to multifunctionality targets are attractive, at least from a planners' perspective. In this chapter, we will revisit this theoretical framing in the light of the "land pressure" that exists as human needs for both goods and services keep growing and discuss two case studies from Asia, both involving rubber (*Hevea brasiliensis* L.) but in different types of agroforestry systems, one complex and one simple, with different consequences on surrounding biodiversity.

Simple or Complex Agroforestry Systems: Innovation and Multifunctionality

Joshi et al. (2003, 2005) and Pretty et al. (2006) explicitly discussed the type of progress in productivity that is possible in resource-conserving agriculture. Simple systems are in general easier to improve than complex ones and tend to have higher growth rates, making them more interesting for investors (McNerney et al. 2011). Simple systems, however, tend in general to become more complex over time and may get bogged down by complexity, in the same way as tree growth slows down with increased maintenance costs of existing biomass. In research on technological progress, empirical scaling laws suggest that per doubling of cumulative production costs per unit production decrease typically around 20% (for coal plants 12%, ethanol production 20%, photovoltaic cells 23%, and transistors 43% as analyzed by McNerney et al. 2011). From a producer's perspective, the negative exponential decline in costs reflects a decreasing rate of success in innovations, unless market demand keeps growing exponentially at rates faster than the cost decline. Most agricultural or forest products no longer match this type of efficiency gain, and their production cannot keep up with increases in industrial wage rates.

In agriculture, long-term trends toward declining farm-gate prices for primary products imply that labor efficiency has to keep increasing. Recent increases in food prices show that the pattern is not a monotone decrease, however. In ecology, the relationship between complexity and dynamic properties ("stability") has been studied for more than four decades (May 2001) and has led to a redefinition and cross scale refinement of both complexity and "dynamic stability" concepts. It may not be particularly productive to ask whether "complex agroforests" are superior or inferior to simple tree crop production systems unless we can be sure of the evaluation perspective, but we can try to understand the conditions under which they emerge in the landscape and the drivers of their subsequent decline. For resources with a dominantly local use pattern, the farm-gate value per unit product decreases with its frequency of occurrence, and this implies that a diverse portfolio is more valued than a specialized one, supporting the emergence of fine-grained landscape mosaics. For products with a national or global market where demand is not easily satisfied in local production, farm-gate value per unit product increases with frequency of occurrence if there are "economies of scale" linked to transport, processing, know-how, and social linkages along the value chain. A shift from local to national and global markets thus induces loss of globally relevant diversity and coarsening of landscape mosaics.

Forest Transition and the Rise and Decline of Agroforests

While at continental scale Asia has turned the corner on "forest transition" (Rudel et al. 2005) and has reported an increase in forest area during the last decade (FAO 2010), the net increase does not imply that gross deforestation and forest conversion have been brought under control (Meyfroidt and Lambin 2011). Countries with increasing forest areas have increased their external footprint (net balance of imported and exported agricultural plus forestry products converted to area using national statistics on productivity) by an average of 50% of the reported domestic forest increase[3] (Meyfroidt and Lambin 2009; Meyfroidt et al. 2010; Minang et al. 2010). Planted tree cover replacing natural forest can occur in a gradual process of agroforest development (early stages of "forest domestication" *sensu* Michon et al. 2007), by direct replacement of natural forest, by plantation forestry or tree crop development, and/or after a phase interlinkage) and interrupted by of "degraded land" with low tree cover (Fig. 1a). The various components of the "tree cover transition" may not spatially move at the same rate, as a recent study in peri-urban trends in Tanzania showed (Ahrends et al. 2010), and the zone with "intermediate, low tree cover" stages can expand and contract as a consequence. Tree planting is, however, more likely at some distance from the forest edge (Santos-Martin et al. 2011), as (illegal) extraction is more profitable than growing trees and tending them.

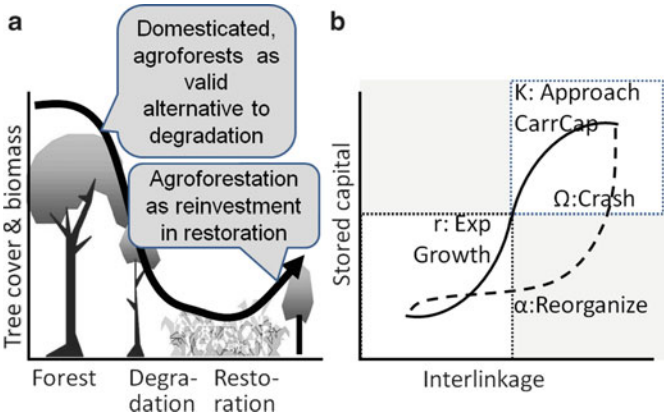

Fig. 1 (**a**) Tree cover transitions as temporal and spatial model with two primary roles for agroforestry (Van Noordwijk et al. 1995a); (**b**) Eight-shaped dynamics of stored capital and interlinkage of systems in their *r*, *K*, and *Ω*/*α* phases of growth, saturation, and crash/reorganization

Nonlinear System Dynamics and Punctuated Change

Changes in land use may follow a gradual incremental pattern, increasing or decreasing tree cover, or have an episodic, punctuated, transformational character (Fig. 1b). The eight-shaped looping of stored capital and component linkage as proposed by the Resilience Alliance (Folke et al. 2004; Chapin et al. 2009) suggests that there are three major stages: an exponential growth phase from a low and slow start (r-phase), a gradual and asymptotic approach to the "carrying capacity" for current technology and environment (K-phase), and a crash/reorganization (Ω/α-phase) stage that resets the clock. The postulated increase in interlinkage can be understood to operate across ecological, social, economic, and policy aspects. It is based on fine-tuning of relations around a new production system and increasing resource use efficiency with a diminishing-returns-type approach to the carrying capacity of the environment for the type of resource use.

Such eight-shaped looping may occur in systems at different scales. Relevant to our current discussion are three of such scales:

A. The (agro)forest patch and its processes of maturation and rejuvenation
B. The adoption of a certain land-use system in a landscape or regional economy
C. Societies in their development from frontier patterns of resource extraction to fully interlinked systems where social and environmental links are appreciated and reflected in functioning institutions

While we will focus on level B, the biodiversity aspects of A and policy implications of C reflect two other nonlinear systems of interaction.

At level A, a forest patch cycles through r-phases (pioneers, exponential growth) and K-phase (gradual approach toward carrying capacity and strong interlinkage) and interrupted by crash and reorganization Ω/α phases, while the forest as a whole may be in a steady state. Rubber's natural habitat is the species-rich Amazonian rainforests, mostly along rivers in forests that are frequently disturbed where *H. brasiliensis* is a pioneer species surviving into mature secondary forest stage. In parts of Asia, rubber after introduction naturalized into similar habitat and came to be cultivated as part of a diverse forest system (Gouyon et al. 1993; Salafsky 1994; Dove 2000). Patch-level, internal rejuvenation is also possible in rubber agroforests (Wibawa et al. 2005), replacing the field-level rotational cycle, with associated benefits for maintenance of tree diversity at plot scale as well as continued income and avoiding dependence on financial investment in a replanting cycle.

At level B, the adoption of new land-use systems normally has a slow start where local evidence that it works and is attractive needs to be built up before widespread use follows. Expressed against time, adoption curves are often S shaped, but in Fig. 1b, the "stored capital" or area allocated to a certain land use is plotted against the degree of linkage. The "linkage" dimension reflects the need for any land use, and thus also agroforestry, to match:

(a) Knowledge and technology to deal with the biophysical constraints of the production environment
(b) The surrounding ecology (including pest/disease, pollinator, dispersal relations, as well as lateral flows of soil, water, wind, or fire)
(c) The economic land/labor relationship and demands for domestic consumption and/or external markets
(d) Social systems that relate to land/labor relations, access to resources, and management of conflicts and jealousy
(e) Governance systems that control resource access and permit for market access, taxes, and subsidies
(f) Infrastructure that influences accessibility of markets and processing facilities

All of these can be involved in the positive feedback loops that start a period of exponential growth. Ecological (b) and socioeconomic factors (c, d, and e) can also involve in the negative feedback processes that lead to the gradual approach of a saturation level. It is unlikely that all these six types of relations (with human, natural, financial, social, political, and physical capitals) develop in one go. Any of the six categories can be a primary constraint to the use of trees in productive agroforestry systems (Roshetko et al. 2008; van Noordwijk et al. 2008a). In some cases, the land-use system "collapses" ecologically as pest and diseases catch up or due to market oversupply, but a more gradual replacement by better alternatives is also possible; there may be issues of definition and terminology whether the "something better" is a new variant of the same or a new land-use system.

At level C, the expansion of human use of natural habitat and emergence of associated governance, resource access, and tenure systems reflect the values of wider society. The objectives of a pioneer-to-mature society may emerge in a sequence such as:

(a) Resource extraction to support national income (and political elites) with limited local connectivity

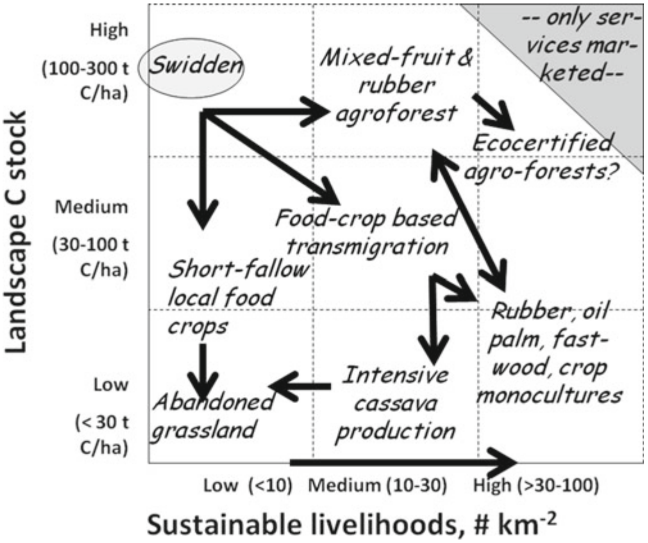

Fig. 2 Historical patterns of land-use change in lowland humid tropics of SE Asia with market-oriented agroforests leading the change away from subsistence local food production (Source: van Noordwijk et al. 2009)

(b) Economic growth or the initiation/expansion of value chains that benefit the wider economy (creating employment and capturable value downstream)
(c) Social welfare in the political center of power which may include concerns over flooding of cities by rural poor
(d) Social welfare in the political periphery of marginally productive landscape
(e) Environmental integrity and its impacts on water flows, biodiversity, and/or greenhouse gas emissions

The environmental policy category is the most recent concern, and its role relative to the social and economic ones is still contested. The balance between these objectives tends to change with time, with considerable change during the lifetime of trees. Punctuated change (Ω/α) may occur through "revolutions" or "reformation" episodes in autocratic systems or in a more regulated election cycle in democratic arrangements.

At the interface of issue scales A, B, and C, agroforests are currently understood to be an intermediate stage in intensification in a spatial as well as temporal sense. They occur somewhere along the home garden – natural forest spatial gradient around villages, depending on topography and the settlement pattern. Two extremes, found in different parts of Asia, are a) settlement and landscape access via valleys and b) settlement and transport via ridges. When landscape patterns are subject to intensification (Fig. 2), changes in landscape components are interlinked (Fig. 3). Agroforests may represent a transient temporal stage in landscape intensification, with the opportunity (or threat) of replacement by more specialized monocultural

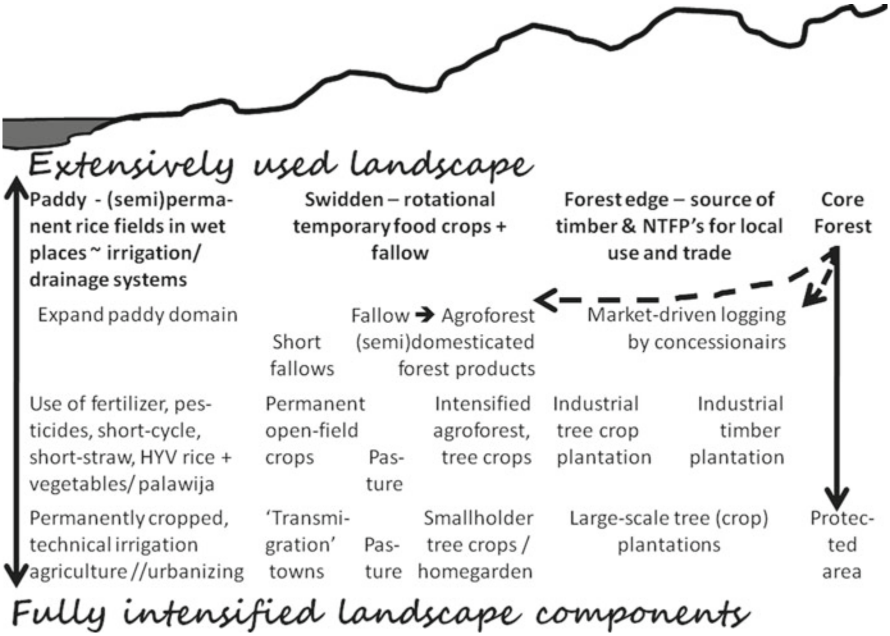

Fig. 3 Schematic transect of a landscape toposequence in (sub)humid Asia in four stages of intensification and the "intermediate" position of agroforests in spatial as well as temporal sense

tree crop systems in response to economic opportunity, unless innovations toward higher labor efficiency remain feasible and are utilized. Data on typical labor use per ha of different land-use systems, together with dependency ratio (fraction of nonworking members of the human population) and fraction of agricultural work of the labor force, can be used to calculate an equilibrium human population density for the main land uses (Murdiyarso et al. 2002). Strong correlations between landscape topography, human population density, and dominant land use (Hadi and Van Noordwijk 2005) suggest that agricultural intensification should be understood alongside demographic transitions and a switch to urban or service sector employment.

Questions for the Case Studies

In the rest of this chapter, we will contrast two case studies of dynamics in agroforestry landscapes: the current Ω/α phase of the rubber agroforest landscape of lowland Sumatra (case study in Bungo district, Jambi) following a century of r- and K-phase dynamics and the expansion of monocultural plantation/simple agroforest modes of rubber production in China and adjacent Laos. Our key questions on complex agroforest as "icon" for the way development+environment can be reconciled are:

1. How can the spatial and temporal patterns of change involving rise and/or fall of agroforests be understood at "driver" level from an actor perspective, including opportunities for increased labor efficiency and/or productivity growth, in its ecological, social, economic, and historical context?
2. What are consequences of these patterns for landscape multifunctionality? Are "intermediate intensity" agroforests inherently stable as a long-term contribution to landscape multifunctionality that includes effective biodiversity conservation?
3. What incentives would be needed to balance the productive and environmental aspects of such agroforests?
4. Are arguments for an "integrate" and "land sharing" approach to multifunctionality applicable and worthy of external support, or will a more segregated approach to environmental and productive functions be more efficient in the use of land?

After describing the two cases at driver (question 1) and consequences (question 2) level, we will briefly recapitulate segregate-or-integrate theory before discussing questions 3 and 4 for the rubber case.

The Sumatra Case Study

Pattern and Drivers of One Century of Rubber-Based Livelihoods in Bungo (Jambi, Indonesia)

Bungo district is located in the lowlands and foothills of the Bukit Barisan mountain range in central Sumatra and is administratively part of Jambi province. The government land-use designation of Bungo district consists of 10% protected natural forest in the foothills, 34% production forest (logged over), 50% agricultural lands, and 6% other land-use types (settlements, rivers, etc.).[5] The agricultural landscape includes (A) remnants of the traditional upland agriculture based on fallow rotations and upland rice as staple, (B) intensive rice paddy cultivation along rivers, (C) complex multistrata rubber agroforest on the peneplains, (D) home gardens, and (E) monocultural plantations of rubber and oil palm (*Elaeis guineensis* Jacq.). Land-use change and increases in human population density during the last century have been distinctly nonlinear (van Noordwijk 2005), with a first wave of migrants from elsewhere in Indonesia (mostly Java and northern Sumatra) arriving during 1905–1925 and a second wave starting around 1980.

The start of rubber agroforestry, a century ago, followed after Dutch conquest in 1906 which brought Jambi (and the neighboring sultanate of Damasraya that is now part of West Sumatra province) under the control of the colonial administration and opened up the area for plantation agriculture (Locher-Scholten 1994). Up to that time, swiddens for local food production had been combined with limited coffee and pepper production, traded via the Batang Hari River through Jambi town, located at the most seaward inhabitable place. Rapid adoption of the newly introduced *Hevea brasiliensis* from Brazil ("para rubber") by smallholders in the area, initially as part of the fallow in their swidden systems, transformed the landscape and beat attempts at establishing large-scale rubber plantations.[5] The area benefitted from the rubber boom of the 1920s, and farmers planted so many rubber trees that nonavailability of labor, not of land or trees, was the primary constraint to production. Rubber exports partly replaced rattan exports, and, after the rubber trees were established and intercropped, rice became scarcer, and the province became dependent on rice imports from elsewhere in Indonesia, which it could afford owing to the price of latex. Approximately 2 kg of rice was imported to the province per kg of dry rubber exported during the first two decades after rubber introduction, and this exchange left a financial surplus. In periods of high rubber prices, migrant labor from the Kerinci mountains and/or Java added to the labor force; when rubber prices declined (and Kerinci's coffee or cinnamon boomed) the labor force went elsewhere. Sustainagility required absence of social, cultural, or political restrictions to local migration. The ecophysiological flexibility of rubber, where the trees recover and gain in future productivity if not tapped, in contrast to other crops that need constant care to stay in productive condition, provided sustainagility to the farmer (Vincent et al. 2011a).

By the 1930s, Jambi became a "backwater," with most of the economy based on rubber. The Batang Hari River was the dominant mode of transport. A broad-sweep summary of the last century in Bungo (Table 1) suggests that shifts in national policy context had a profound impact on developments locally, as did the global ups and downs of natural rubber prices. Prices were high after World War I and became depressed in the late 1920s by oversupply and glut in demand but increased in World War II to the level that it sparked the development of a fossil-fuel-derived synthetic rubber as competitor. There have been price swings since that time related to global fossil-fuel prices through its relationship with global economic mood swings and through its effects on the processors' choice between natural and synthetic rubber.

Thus, the spatial and temporal patterns of the rise of rubber agroforests can be understood from the perspective of local actors, who replaced their upland rice for rubber but maintained the matrilineally inherited paddy rice (Otsuka et al. 2000) as basis of local food security, augmented with traded rice.

According to local custom, planting trees brought communal land under private control, and a small number of tappable rubber trees were enough to establish a claim (Suyanto and Otsuka 2001). The emphasis was thus on extensive rubber gardens, while the local rules in many villages established "fallow rotation reserves" (locally called *sesap-nenek* or "ancestors' bush") where tree planting was not allowed, so that after the rice was harvested, the land would return to the common pool (van Noordwijk et al. 2008b; Cramb et al. 2009). The private sector, mostly Chinese merchants from Jambi city, invested and supported rubber development by providing free seed, as the river ensured their captive market with all products passing through the town they controlled. This happened largely below the radar screen of the colonial administration, which supported a European plantation sector that largely failed to compete.

Table 1 Five broad categories of policy objectives reflected in key events affecting landscape "multifunctionality" in different periods of time in Bungo district (Jambi province, Sumatra, Indonesia)

	A	B	C	D	E
Historical period	Resource extraction	Economic growth	Center-based welfare	Decentralized welfare	Environmental integrity
1906 Jambi conquest by Dutch	Colonial power focused on generating economic surplus for home country		Elements of "ethical policy" slowly pay attention to education		
1910–1925 Initial rubber expansion		Export-oriented rubber industry transforms lives and landscapes		Rubber boom, area attracts migrants	All areas in reach of rivers get cleared for rubber
1925–1965 Political backwater		Out of the mainstream		Gradual decline	Riparian zones become "jungle rubber"
1970s National development: logging	Logging concessions	Trans-Sumatra Highway planned and implemented			Land use becomes oriented toward roads
1980s National development: transmigration	Logging concessions		Transmigration serves people from center		
1990s National development: oil palm	Logging industry transformed to pulp and paper industry for lower valued and smaller trees	Centrally controlled oil palm concessions and pulp/paper industry	1997 "Asian crisis" drives urban people back to rural livelihoods	National parks try integrated conservation and development (ICDP) with limited success	
2000s Local development: decentralization, environmentalism		Oil palm and pulp/paper industry protected		District government empowered, smallholder oil palm increases	Coal mining; all ex-logging concessions become fast-wood plantations

Source: Martini et al. (2010)[5]

The reliance on river transport in the formative years of the rubber industry in Jambi implied a path dependency of the current value chain: processing industry is geared toward handling low-quality "slab" rubber and pays low prices for all rubber assuming that it has low quality – which proves to be a self-fulfilling prophecy. In contrast, in West Kalimantan where road-based transport became important in early stages of rubber establishment, factories were set up for clean sheet rubber with an associated farm-gate-to-factory value chain. Changes toward price-to-quality relationship and reduced length of the farm-factory chain of intermediaries face a high resilience of status quo actors. Only in the past decade have efforts to create a more direct quality-price relationship started to change the value chain.[1]

The "jungle rubber" aspect (Gouyon et al. 1993; de Foresta et al. 2000; Michon 2005) of smallholder rubber became more apparent in the 1930–1960 period, when the area was a political backwater. Jambi was not a front-runner in the struggle for Indonesian independence and was administered as part of West Sumatra until that province fell out with national government in the late 1950s. In stark contrast to the rapid initial spread of rubber in farming communities that still were rather "remote," subsequent rubber germplasm was hardly adopted – even though a three- to fourfold increase in dry rubber yield per tree was achievable through clonal selection (Joshi et al. 2003; Penot[6]). In the 1990s, farmers were aware of a "yellow" and "red" type of rubber, derived from material introduced by the agricultural extension service in the 1940s, but they were not actively pursuing such germplasm known to be more productive. The substantial risk of failure of newly planted rubber, mainly due to damage by wild pigs, was quoted as the main reason (Joshi et al. 2003). The transition to planting material that has any appreciable cost and is planted at final density with low tolerance of loss proved to be more difficult (Williams et al. 2001) than the initial adoption of an exotic alternative to local latex-producing trees. When the use of fire in land clearing became controversial in the 1990s (Stolle et al. 2003), techniques based on large-sized planting material became popular, with some effort to obtain seedlings from grafted rubber plantations but with unclear genetic status of the material planted (Vincent et al. 2011b; Wibawa et al. 2005). The use of fire in land clearing is considered essential by farmers who want to plant an upland rice crop in the first year with the rubber (Ketterings et al. 1999), partly because it mobilizes organic soil phosphorus pools (Ketterings et al. 2002); it may lead to high within-field erosion and sediment transport, without much loss beyond field borders (Rodenburg et al. 2003).

Nonlinear Changes in Context: Rise and Decline

The big changes of the past three decades can be traced back to key changes in national policies: the policies surrounding logging concessions, development of the Trans-Sumatra Highway, and its impacts on economic geography, especially where the road cut across different river systems rather than follow the course of the river. Demographic change came with transmigration projects starting in the 1970s.

The new economic activities and labor force, mostly from Java, largely bypassed the local rubber-based economy. However, Miyamoto (2006a, b, 2007) recorded an increase in land-use intensity and rate of forest clearing before the Trans-Sumatra Highway was operational, as local farmers may have anticipated the increased availability of labor that would make larger rubber areas profitable through share-tapping agreements.

There is not a single example in Jambi where the Indonesian selective logging system (Sist et al. 1998) aimed at allowing regrowth of the forest for a second round of logging after 30 years has worked. Throughout Jambi, the increased accessibility of the logged-over forest by the network of logging trails connecting to public roads, the presence of a labor force brought in for the logging operations, and the policy vacuum at the end of a logging concession gave the appearance of a "free-for-all" phase of illegal logging, land claims, and conversion (Colfer 2005). Oil palm concessions were planned and licensed by the provincial government for virtually all logged-over forests, often including large tracts of smallholder-managed (and "owned") rubber agroforest. The direct link between local government and Jakarta-based elites was severed in the 1997–1998 beginning of the "*Reformasi*" period, giving more authority to local elites and entrepreneurs.

In the 1990s, establishment of large-scale oil palm plantations was protected from competition from independent smallholders by restrictions on establishment of independent mills with excess processing capacity. While commercial logging activities sanctioned by government concessions stopped in 2000, loss of natural forest cover continued. Ekadinata and Vincent (2011) analyzed land-cover change between 1973 and 2005 in Bungo district, an area of 4,550 km^2. During that period, natural forest cover declined from more than 75–30%, while monoculture plantations of rubber and oil palm increased from 3 to over 40%; rubber agroforests decreased from 15 to 11%, but most of the rubber agroforests present in 1973 had been converted to monocultures in 2005, while new rubber agroforests emerged elsewhere in areas under natural forest in 1973. Rubber agroforest appears to be a predominantly transient type of land use with high likelihood of conversion. Difficult access to the remaining forested land added more pressure to rubber agroforest conversion into more intensive agricultural systems.

Consequences: Agroforests as Last Haven for Lowland Forest Biodiversity in Jambi

With the intended and ongoing conversion of all "production forest" in the province of Jambi to fast-wood plantation for the pulp and paper industry, rubber agroforests have become a last haven for lowland forest biodiversity in the landscape, as protected areas in Sumatra mostly cover the hills and mountains or coastal peat swamp (Laumonier et al. 2010). Bungo district includes a portion of the Kerinci Seblat National Park (the largest park in Sumatra) at higher elevation and in the past provided ecological connectivity to the Bukit Dua Belas National Park (east of Bungo).

Table 2 Floral diversity in rubber agroforest in tree, sapling, and seedling stages compared to secondary forest in Bungo district (Jambi, Indonesia; eight replicates in Rantau Pandan and eight in the Muara Kuamang/Kuamang Kuning area)

Stratum	Parameter	Secondary forest $n=16$	Rubber agroforest (RAF) $n=16$
Tree	Number of species	9.6	6.0*
(dbh ≥10 cm)	Number of individual tree	12.4	12.7 ns
	Density (N ha^{-1})	621.9	634.4 ns
	Shannon-Wiener index	4.5	2.6**
Sapling	Number of species	11.2	10.6 ns
(dbh <10 cm,	Number of individual tree	18.2	18.0 ns
height >2 m)	Density (N ha^{-1})	3650.0	3600 ns
	Shannon-Wiener index	4.3	4.2*
Seedling	Number of species	15.4	15.7 ns
(height <2 m)	Number of individual tree	45.6	60.9 ns
	Shannon-Wiener index	4.3	4.0**

Source: Tata et al. (2008b)

Note: asterisk denotes significant difference of RAF to forest at $p=0.05$; ** at $p=0.01$ based on *t*-test (for diversity index) and based on Dunnet test for other parameters; *dbh* diameter at breast height (1.3 m); circular plot of 200 m^2 (for trees), with 50-m^2 subplots for saplings, 25-m^2 subplots for seedlings

The rubber agroforests that originally developed along the rivers in the beginning of the twentieth century became an ecological corridor that connected to the lowland protected areas, especially when roads attracted the focus of development to other parts of the landscape. Current pressure on conversion, however, means that only a limited number of "stepping stones" are left rather than a continuous corridor. Riparian zone connectivity between protected areas in the region through rubber agroforests (RAF) has never been recognized in conservation planning and did not get active policy support.

Initial transformation of forest to rubber agroforest resulted in a modest change in diversity and plant species composition, as active rejuvenation of forest species still took place (Lawrence 1996; Beukema and van Noordwijk 2004; Beukema et al. 2007; Tata et al. 2008b). The loss of forest cover significantly decreased species richness of vegetation in the (reproductive) tree stage. The structure of the seedling and sapling strata in forest and rubber agroforest, however, was not significantly different (Table 2). Selective culling of trees that stand in the way of rubber and have less value explains this pattern (Tata et al.[9]). The higher the intensity of RAF's management, the lower the species richness (Rasnovi[8]).

Rasnovi[8] reported 405 tree species of sapling stage encountered both in forest and RAF, while 241 species were found in forest only and 284 in RAF only, virtually all belonging to the native flora and indicative of the challenge of exhaustive enumeration of the forest diversity. About 71% of the saplings encountered in RAF belong to long-range zoochorous species, whereas in forest 64% of saplings have this dispersal mode. Autochory, that is, large seeds with limited dispersal range, accounted for 14.9 and 4.6% of species in forest and RAF, respectively (Tata et al.[9]).

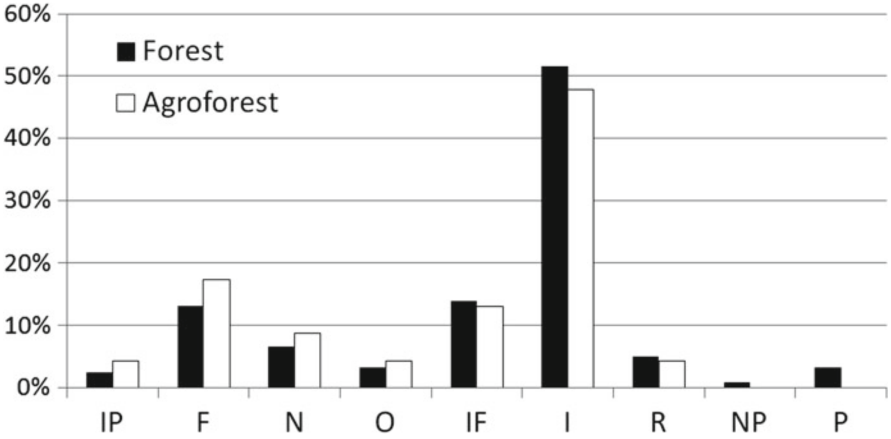

Fig. 4 Composition of bird guild types in rubber agroforest and forest in North Sumatra: *IP* insectivore-piscivore, *F* frugivores, *N* nectivore, *O* omnivore, *IF* insectivore-frugivore, *I* insectivore, *R* raptor, *NP* nocturnal predator, *P* piscivore (Source: Ayat et al. 2011[2])

Thus, RAF plays a role as refuge area of forest tree species for which the dominant mode of seed dispersal through birds and small mammals remains functional, but less so for the ecological group of trees with large seeds that tend to occur in later successional stages (Wunderle 1997); large seeds are ecologically functional in densely foliated forest patches where they allow saplings to reach a size that allows rapid response to gap (Chablis) formation. Among the trees that are allowed to reach reproductive stage in RAF, species with edible parts from a human perspective are positively selected, as are trees with use value as vegetable, spice, or medicinal use (Tata et al. 2008a); 64% of trees encountered in RAF had edible parts, compared to 29% of species encountered in the natural forest (Tata et al.[9]).

Diversity of the vegetation has a positive relationship with animal diversity, in particular birds and bats, which play important roles as dispersal agents, pollinators, and biological control agents. A recent study in North Sumatra showed that 14 out of 17 bird guilds found in forest comparator plots were also found in RAF.[2] The two commonest guild types of birds in both forest and RAF were insectivores and frugivores (fruit eating); frugivore birds were more frequent in RAF than in forest (Fig. 4), owing to a higher relative abundance of fruit trees in RAF.

Consequences: Local Appreciation of (Agro) Forest Diversity in Jambi

The main difference between forests and rubber agroforests, besides land-cover properties, is the tenurial system (de Foresta et al. 2000; Michon 2005). At the community level, forest is usually owned and managed communally, while rubber in the

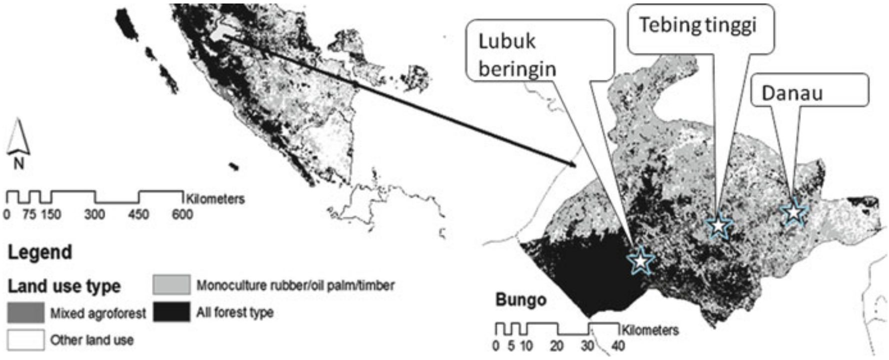

Fig. 5 Location of the three focal villages of the Landscape Mosaics Project in Bungo district

rubber agroforests is considered to be private property. At the government level, forests are under control of forest authorities, and only rubber agroforests that are located in agricultural zones are considered private property. Part of the current rubber agroforests are classified as production or watershed protection forest on the government maps, creating (potential) conflicts – but also opening space for negotiations such as the "village forest" in watershed protection forest that is managed as rubber agroforest with mutual consent (Akiefnawati et al. 2010). Within the local rules, rubber trees in rubber agroforests are privately owned, but products from other trees, such as durian (*Durio zibethinus* L.) or petai (*Parkia speciosa* Hassk.) and medicinal plants, can be collected by any villager. Decisions to intensify rubber agroforests thus reduce access to such forest resources in the landscape and involve a private gain but loss to the commons.

Some further insights into the role rubber agroforests play in provision of "forest services" were obtained as part of the Landscape Mosaics Project (Pfund et al. 2008, 2011). Three villages in Bungo district were selected based on an intensification gradient (Fig. 5): (1) Lubuk Beringin village (forest edge/low intensification), (2) Tebing Tinggi village (intermediate intensification), and (3) Danau village (most accessible, most intensified).

The perceived importance of the various forest (woody vegetation) types presents in a gradient of three villages, spanning the local forest margin to intensive use gradient (Fig. 6) across five countries (Laos, Indonesia, Madagascar, Tanzania, and Cameroon; Pfund et al. 2011). In the Jambi benchmark, the "forest margin" village Lubuk Beringin had three habitat types (Fig. 7), Tebing Tinggi had no natural forest left, and in Danau all secondary forest had been converted to agroforest. Some of the other sites included a "forest plantation" category not present in Bungo. The perceived importance to local livelihoods was quantified using a pebble-scoring technique, allocating 100 tokens across the functions (multidisciplinary landscape assessment method: Sheil and Liswanti 2006). The functions are here relabeled as three types of "goods" ("provisioning services": food, other items for local use, and marketable goods) and regulating and cultural services (Fig. 7).

Some of the other landscapes included an "other" category; the Bungo results did not. Figure 6 gives a breakdown of the "other goods" over four categories.

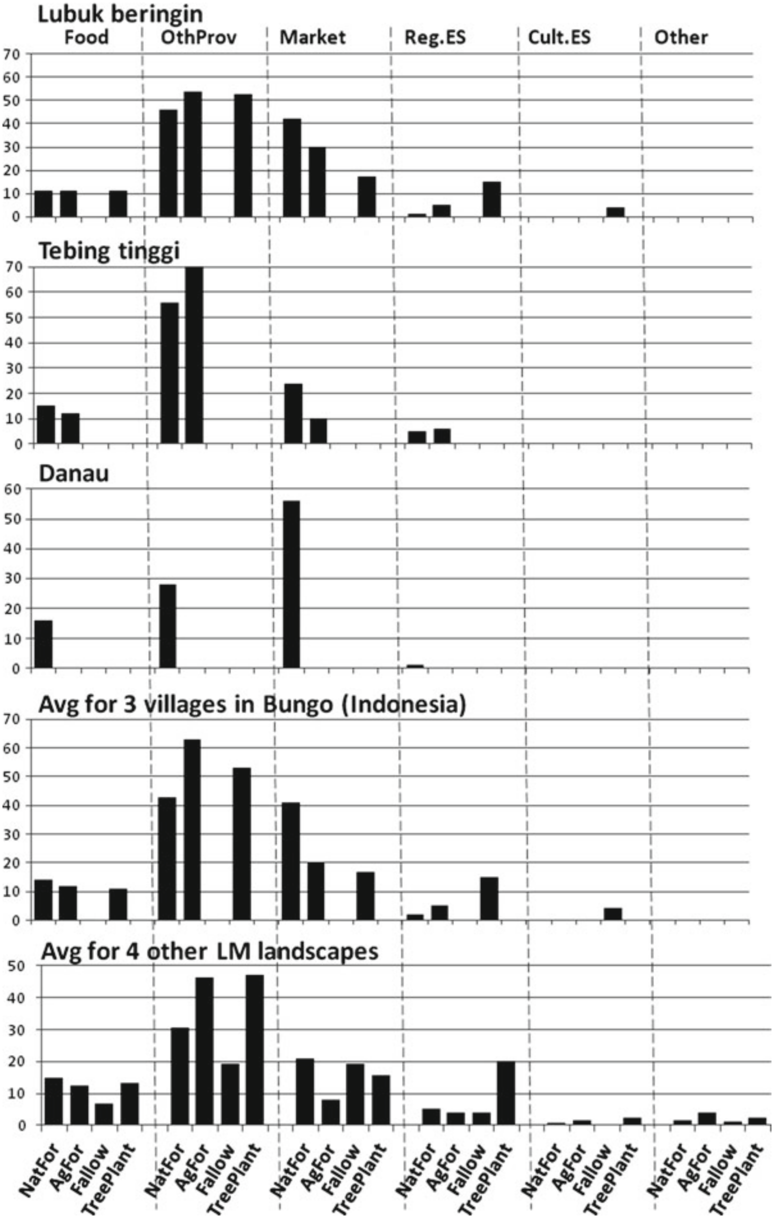

Fig. 6 The relative share of four habitat types, in as far as present in a landscape, in the total importance value (pebble-scoring result) assigned to four types of "nonfood goods" that can be obtained, mostly for home consumption and local use, in 3 focal villages of the Landscape Mosaics Project in the Bungo benchmark and as average for 12 other villages in 4 other countries (Laos, Madagascar, Tanzania, and Cameroon)

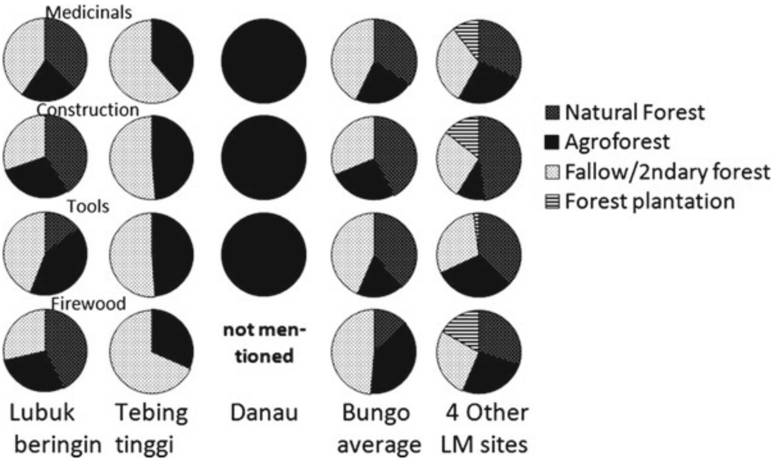

Fig. 7 Relative importance of food provisioning, other-good provisioning, marketable goods provisioning, and regulating and cultural services across up to four woody vegetation types ("natural" forest, agroforest, secondary forest, and forest plantation) in three focal villages of the Landscape Mosaics Project in Bungo, in Bungo as an average and across four other benchmarks (Laos, Madagascar, Tanzania, and Cameroon)

The results show that "goods" are substantially more appreciated than "services," with the given interview technique, in all five Landscape Mosaics sites (and in all 15 villages involved). Regulating services (mostly referring to water) got some mention; cultural services hardly received any. Within the "provisioning services," the role of food is relatively small (<20%), again with the Bungo (Indonesia) results aligned with the other four country studies; the "other goods" dominate (40–50%), and "marketable goods" (30–40%) are intermediate. The relative profiles of the various functions for each habitat type appear to vary more between the landscapes than they vary between habitats in a given place. For example, if firewood is important at all, any firewood is important irrespective of the nature of woody vegetation it comes from. Also, RAFs are at least as much appreciated as natural forests in a role as provider of nonmarketed nonfood products. The three test villages in Bungo differed in their landscape composition, human population density, as well as market orientation. In Danau, there was no natural forest or secondary forest left in the landscape at the time of the interview, so rubber agroforest had become the sole provider of "forest functions." Overall, however, this village is most focused on the marketable part of goods provisioning. Forest-based medicinal plants have been largely replaced by bought pharmaceuticals, leaving undomesticated fruits as a major reason that agroforests are appreciated locally (Lehébel-Péron et al. 2011; Therville et al. 2011).

Increasing market integration, assisted by a recent recovery of world market prices for rubber, has reduced the local relevance of diversity in semi-domesticated agroforest resources and has led to generally positive local perceptions of the opportunity for change toward monoculture intensified rubber and oil palm plantations

(Feintrenie et al. 2010; Feintrenie and Levang 2009, 2011). In some forest-edge villages, however, a positive reappreciation of the merits of rubber agroforests has taken place, and resistance to change into oil palm is expressed (Villamor and van Noordwijk 2011), partly in response to success in securing use rights in the "watershed protection forest" zone (Akiefnawati et al. 2010).

Case Study in Xishuangbanna, China

Pattern and Drivers of Half a Century of Rubber Plantation Economy

Rightly or wrongly, shifting cultivation is often held to be the principal driving force for deforestation in tropical Asia. Resource managers in these countries invariably see shifting cultivation as a single, simple system of farming in which the forest or scrub is slashed and burned to make swiddens. As argued by Rambo,[7] however, swidden agriculture is a composite farming system with high agro-biodiversity and livelihood flexibility, with a system built around patchy, phased removal of trees but not of the forest (Alcorn 1990). Swidden-fallow landscapes stay within the internationally accepted forest definition as long as the fallows reach a tree height of 5 m and a crown cover of 30% before opened for a next cycle, and thus shifting cultivation is not a driver of deforestation until a late stage in intensification and shortening of fallow periods.

Land use in the upper Mekong region has a direct ecological impact on lower Mekong locations. Economic development in the upper Mekong is not dependent on physical access via this river, and there is little direct reason to care about effects downstream, whether land use, climate change, or engineering projects are seen as the primary cause of change in river flow (Xu and Thomas 2010). Land-use change in the upper Mekong region has occurred where smallholder farmers switched from swidden agriculture to a plantation economy. While the number of hectares planted to these crops may still be relatively inconsequential, annual rates of change are significant. Recent research results suggest that most upland areas of Mekong will eventually see a major change in land use with the conversion from swidden agriculture to commercial tree crop plantation (Ziegler et al. 2009). As a result, biodiversity, as measured by the number of species found in the landscape (Xu et al. 2009), and carbon stocks both aboveground and belowground are declining, while watershed services deteriorate. In this context, the increase in rubber plantations received specific attention, as it alters the hydrologic system compared to native vegetation (Guardiola-Claramonte et al. 2010).

Bordering with Laos and Myanmar, Xishuangbanna prefecture is located in the upper Mekong, Yunnan province of southwest China. The prefecture covers only 0.2% of the land area of China, yet it contains 25% of all the plant species in the entire country (Cao and Zhang 1998); it also is a culturally diverse region. It is the home of many ethnic minority people including the valley-dwelling paddy-farming Dai people and upland shifting cultivators such as Hani (or Akha), Jinuo, Yao, Lahu, and Bulang. The Dai are Hinayana Buddhists but also worship nature in the form of "holy hills" and "temple yards." The Dai people have traditionally cultivated *Senna siamea* (Lam.) (Irwin & Barneby) (syn, *Cassia siamea* Lam.) for fuelwood for hundreds of years. Each Dai family would have a small plot of *S. siamea* near the village. They have also traditionally practiced homegarden agroforestry (Pei 1991). The Hani (called Akha in Thailand) are animists and place a strong emphasis on worshiping their ancestors, as exemplified in their strictly protected cemetery forests. They practice a composite swiddening system that includes jungle tea gardens in the forest, intensively terraced paddies, livestock grazing, and shifting cultivation in the uplands (Xu et al. 2009). Swiddens are called "taungya" by the Hani, which means "nonirrigated uplands" (compare Thai use of the term in Raintree and Warner 1986). Before 1949, Hani (or Akha), Lahu, and other upland ethnic groups paid taxes or tributes to the Prince in the Dai principality as well as exchanging forest products such as rattan, tea, and wildlife meat with lowland Dai people for betel nut (*Areca catechu* Linn.), metal, salt, etc. The lowland-upland networks also allowed lowland political centers to extend their governance over the uplands and helped upland communities to access markets and information. Customary rules maintained a ring of forest surrounding the hamlet as well as at the foothills of mountains, which served as an ecological and political buffer between the lowlands and uplands. Land property relations within and across ethnic groups were diverse, flexible and overlapping, and certainly fuzzy from the perspective of private, exclusive property (Sturgeon 2004). These socially constructed patterns of interdependence fostered a certain degree of autonomy and self-governance for indigenous people and allowed them to govern an ecologically diverse but integrated landscape for cultural and subsistence needs. The mosaic landscape is however considered by state and scientists as "unproductive"; the practices of shifting cultivation or rotational swidden-fallow agroforestry are considered "backward" land-use practices.

Between 1950 and 1985, forest cover in this region decreased dramatically from 63 to 34% (Zhang and Cao 1995). Today, forests remain primarily in nature reserves and state forests, while previously forested lands have been largely converted into rubber plantations. Rubber was not introduced to Xishuangbanna until 1940, when a Chinese settler returning from Thailand planted it in trials. After the 1949 Revolution, the new government of China saw rubber as an important strategic resource. To ensure the availability of natural rubber for national defense and industrial construction in the face of an international embargo, the Decision on Cultivating Rubber Trees was passed in 1951. This decision moved to establish rubber plantations in the tropical regions of China as rapidly as possible. The state organized a feasibility mission for establishing rubber plantations in 1953. Both Xishuangbanna in southern Yunnan and Hainan Island were identified as potential sites for rubber plantation.

In 1955, the first state rubber farm was established by researchers and staffed by Han Chinese from the inland province of Hunan and retired soldiers who formed the main labor force for the expansion of state farms. The first rubber planting by local farmers was in 1963, encouraged with technical support from state rubber farms – rubber spread quickly into most of the hilly areas of Xishuangbanna. The pace of rubber expansion has been particularly rapid since 1990s: the area under rubber increased from 87,226 ha in 1992 to 153,613 ha in 2002 and 349,965 ha in 2010, representing an increase of over 100% during the period from 2002 to 2010. Currently, rubber covers 18.3% of Xishuangbanna's landscape, and the expansion of its area continues (Xu and Grumbine[13]).

In line with the prevailing ideology in China, the state was keen to establish large-scale uniform rubber plantations in Xishuangbanna; monoculture rubber replaced large forest at foothills during 1960s and swidden-fallow mosaic landscapes in the uplands after 1990s. Rubber trees were either counted by the forest agency as forest cover or by the agricultural agency as agricultural production. Rubber plantation, as advanced productive forces, was considered as an approach to poverty alleviation or replacement of shifting cultivation. In this way, local farmers converted large areas of fallow forests (secondary forests) into smallholder rubber farms. Thus, a second wave of rubber planting followed in the 1980s, in tandem with the continued development of rural industry. This planting resulted in a mixed landscape including composite swidden together with a number of different crops and different management practices; generally, rubber replaced rice, or agroforestry systems included young rubber intercropped with pineapple (*Ananas comosus* (L.) Merr.), upland rice, or vegetables.

Consequences in China: Locally Driven Integration Versus State-Driven Segregation

While there is virtually no mixed agroforestry of rubber in Xishuangbanna, Chinese rubber production started with monoculture plantation operated at first by state industry and later followed by smallholders. Smallholders often manage rubber more intensively while the rubber price is high and less intensively while the price is low. By comparison with state rubber farms, they are also more flexible in terms of size, land tenure, and land-use practices such as the ability to intercrop with other annual crops depending on market fluctuations (Xu 2006).

Since the 1950s, the government of China has implemented numerous – sometimes conflicting – policies affecting agriculture and forestlands. Spatial segregation is the key approach to developing such policies. The common practice of segregation is called "state simplifications" described by Scott (1998) for constructing a "legible landscape." In effect, this is an attempt by the state to transform the local people and even the landscape with some common quantifiable standards to enable, as Scott (1998) puts it, a synoptic view. Rubber was a perfect crop for productive plantations for several reasons: it served the state interest to build China into a socialist country, made China self-sufficient in a period of international embargo, transformed agricultural-based production to an industrial mode of production, and produced a "legible landscape" for the state (Xu 2006). At its most literal sense, this "legibility" was a physical expression of organizing nature – even-aged rubber trees are planted in evenly spaced straight rows and managed by paid state labor. Furthermore, these crops were not only important products in their own right, but since they required some level of industrial processing, they furthered the state objective of creating and enhancing the role of a proletariat in rural industries.

The spatial segregation for large-field agriculture, monoculture plantations, and demarcation of natural forest (often as nature reserve) agreed well with the socialist model of collective operations. In comparison to culturally diverse smallholder farmers, the uniform collective was perceived to be superior. Following this logic, collectivization became the strategy that would free peasants from the constraints of a "peasant mentality," characterized by individualism, ignorance, poverty, and vulnerability to natural disasters. Since the mid-1980s, the government has also been putting pressure on the upland minorities to stop swidden agriculture in favor of crops such as rubber (Xu et al. 2009).

This combination of ideologies reconstructed natural landscapes all over China, including in Xishuangbanna. Shifting cultivators such as the Lahu, the Hani, and the Jinuo were thought to be more backward, representing a primitive mode of production. Based on this appraisal, ideologically driven planners concluded that state rubber farms needed to be staffed by people whom they saw as more "educated" and "advanced" peasants, that is, by Han Chinese farmers resettled to the border frontier of Xishuangbanna from inland China. Those "advanced" peasants were organized collectively throughout rubber plantations to become state workers representative of "advanced" productive forces in the socialist model. This reflected a general trend toward managed, "legible" landscape. As a result of this transformation, segregated landscape with clear boundaries has replaced integrated landscape (Xu 2006). Referring back to the three system levels in Fig. 1b, the policy level C clearly dominates in the context of China.

Segregate-or-Integrate Theory

Both the Sumatra and Xishuangbanna case studies are currently moving toward coarser-grained segregated landscape configurations in which there is little role for integrated agroforests that combine biodiversity conservation and profitability for farmers. Integration and segregation of functions in landscapes can be achieved in between the extremes of full allocation to a single function. Perpendicular to the single axis of deforestation/reforestation, we can compare complete segregation and complete integration of trees in a landscape as two extremes of a "spatial pattern" axis (Fig. 8). Agroforestation is associated with more integrated systems, while a coarse mosaic of "fields + forests" forms the alternative, at potentially the same total tree cover and associated properties such as carbon stock.

From a public policy perspective where multiple functions have value and a political platform in society, how can these options of more or less (natural) forest and more or less integration be rationalized? Formal analysis of intercropping experiments

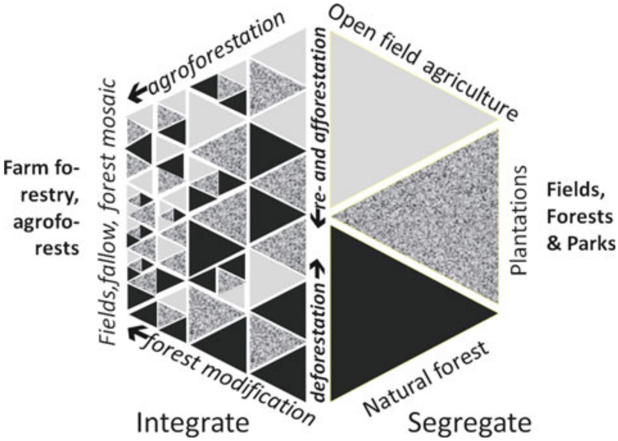

Fig. 8 Two basic approaches to multifunctionality (here represented by three *gray tones*): spatial segregation (*right*) and integration (*left*), in combination with variation in tree cover (*vertical axis*)

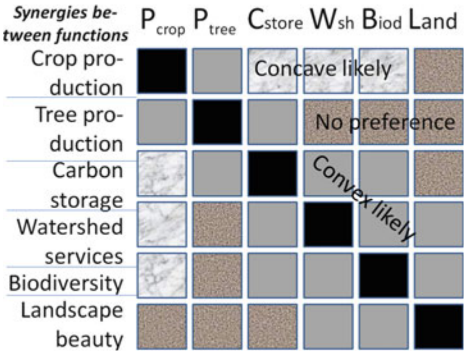

Fig. 9 Tentative summary of hypotheses on the potential for synergy and competition between landscape functions, indicating pairs where low compatibility or competition is likely to lead to concave trade-offs and pairs where convex synergy curves can be expected; formal reviews of literature exist for only a few of the pairs

introduced by De Wit (1960) has shown that "yield advantages" or "reduced land area equivalents" can only be expected for components that have a concave rather than convex trade-off relationship. The biophysical, niche-differentiation aspects of convex relations have been well studied for productivity of annual and perennial components of temperate and tropical agroecosystems and agroforestry (Cannell et al. 1996; Vandermeer et al. 1998; van Noordwijk et al. 2004a). van Noordwijk et al. (1995b, 1997, 2004b), and van Noordwijk and Ong (1999) applied similar analysis to the combination of biodiversity conservation and agricultural productivity in landscapes. Convex trade-off curves between "relative ecological functionality" and "relative agronomic functionality" lead to a potential efficiency advantage in "multifunctionality" solutions, while concave trade-off curves imply that segregation and simplification will pay off (Fig. 9).

Table 3 Relationship between land-use category and policy objectives under fully segregated (only diagonal cells are nonzero) and fully integrated (no cells are zero) extremes

	Policy objective				
Land-use category	A Resource extraction	B Economic growth	C Center-based welfare	D Decentralized welfare	E Environmental integrity
Segregated land-use plan					
f(A)	A	0	0	0	0
f(B)	0	B	0	0	0
f(C)	0	0	C	0	0
f(D)	0	0	0	D	0
f(E)	0	0	0	0	E
Integrated land-use plan					
1	f(1,a)	f(1,b)	f(1,c)	f(1,d)	f(1,e)
2	f(2,a)	f(2,b)	f(2,c)	f(2,d)	f(2,e)
3	f(3,a)	f(3,b)	f(3,c)	f(3,d)	f(3,e)
4	f(4,a)	f(4,b)	f(4,c)	f(4,d)	f(4,e)
5	f(5,a)	f(5,b)	f(5,c)	f(5,d)	f(5,e)
Total	$\Sigma f(i,a)$	$\Sigma f(i,b)$	$\Sigma f(i,c)$	$\Sigma f(i,d)$	$\Sigma f(i,e)$
Equivalence requirement	$\Sigma f(i,a) = A$	$\Sigma f(i,b) = B$	$\Sigma f(i,c) = C$	$\Sigma f(i,d) = D$	$\Sigma f(i,e) = E$
Multifunctionality advantage if there is asset of f(i) for which	$\Sigma f(i) < (f(A) + f(B) + f(C) + f(D) + f(E))$				

The Tinbergen (1952) rule that the number of policy objectives and number of policy instruments have to match follows from basic matrix algebra where the number of equations has to match the number of unknowns for a problem to be solvable. The "fully segregated" and "fully integrated" options are extremes of a wide range of partial integration solutions (Table 3). In the upper part of the table, a highly reduced matrix shows that each policy-relevant objective has its own part of the landscape. Synergy between objectives in such configuration is minimal, but policy makers can rapidly switch land-use allocations if objectives change in weight. In the lower half of the table, all land-use types potentially contribute to all objectives, and land-use planning has to find a solution that satisfies the minimum requirements for each function and maximizes the aggregate benefit beyond this minimum condition. Under certain parameter conditions, a multifunctional approach as in the lower part of the table can achieve more overall functionality on the same land area; the table provides a formal criterion for such outcome. Configurations in the lower half of the table can be strongly interlinked, in which case all functions may be buffered, but the flip side of this may be that the status quo is too resilient.

Another way of analyzing the relevance of the shape of bifunction trade-off curves (Fig. 10) is to consider the economic value that has to be assigned to the

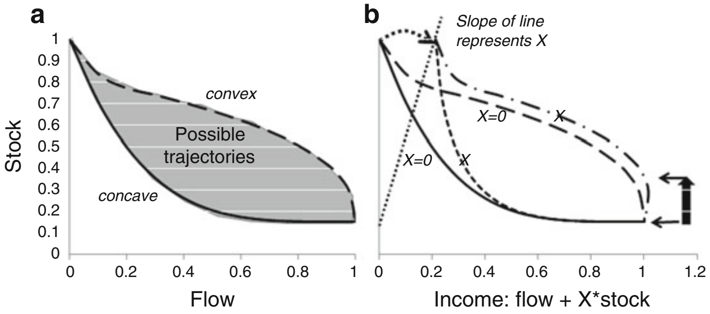

Fig. 10 (**a**) Concave and convex shapes of trade-off curves between flow (e.g., income) and stock (e.g., biodiversity or C-stock) of land-use systems; (**b**) total income based on the flows plus X times the stock, for concave and convex trade-off curves; *arrows* indicate income-maximizing solutions and the upward shift of stocks at income-maximizing land-use choices

secondary function relative to the primary function before optimization can lead to a choice for a mixed system. For concave curves, there is no such solution, and optimality implies a choice between the two functions; for convex curves, intermediate solutions exist for any nonzero value of the value ratio. Adding income value to landscape-level carbon and/or biodiversity stocks effectively means tilting the Y-axis of the biplot (Income = Flow + X*Stock) and may shift the point of maximum economic return to a higher carbon stock trajectory. Depending on the ratio between stock and derived income stream and the shape of the stock-flow trade-off curve, reward systems for environmental services related to carbon or biodiversity stocks can be expected to shift farmer decisions only where convex trade-off curves are involved.

What Incentives Could Keep Complex Agroforests in the Landscape?

Two competing perspectives are as follows: complex agroforests may have had their role in the past but have become obstacles to progress (Pfund et al. 2011), or they will remain an important part of the agricultural matrix and form a future paradigm for conservation (Vandermeer and Perfecto 2007). Local appreciation for parts of forest biodiversity and the way it persists in complex rubber agroforests in Sumatra is noticeable but not sufficient to keep rubber agroforests as an important component of the landscape. Concerns over the loss of integrated systems and their replacement by rubber monocultures are expressed in terms of both biodiversity loss and hydrological disturbance, with different groups of stakeholders concerned about the two issues.

Four approaches have been attempted to reverse the trends toward specialization and loss of ecosystem function "co-benefits":

A. Support for "ecological intensification"[4] by attempts to introduce more productive rubber clones in an agroforest context (Williams et al. 2001; Joshi et al. 2003), high-value timber trees (Tata et al.[10]; Tata et al. 2010a), and semidomesticated local fruit trees. The smallholder timber option is technically and economically feasible but still faces policy constraints in easing market access for legally produced timber.
B. Direct outcome-based payments for biodiversity conservation, although the initial responses of biodiversity conservation agencies have been disappointing; they focus on the last remaining parts of natural forest rather than agroforest landscapes (Kuncoro et al. 2006; Leimona et al. 2009); their attention may be more easily captured in landscapes that have rubber agroforests as well as orangutan populations (Tata et al. 2010b).
C. External co-investment (Arifin 2005b; Van Noordwijk and Leimona 2010) in maintenance of biodiversity-friendly modes of rubber production through forms of ecocertification and more direct farm-to-factory links for results of improved local rubber processing (Joshi et al. 2011).
D. Support for negotiations to develop "village forest" comanagement contracts between villages and forest authorities, applicable in the watershed protection forest category on slopes (Akiefnawati et al. 2010).

Overall, the efforts to keep appreciable amounts of rubber agroforests in the landscape are "rowing against the tide," and the growth of local and external appreciation for the biodiversity value that these agroforests contain may well come too late to retain more than a small fraction, in the least accessible places. By the time the overall economic level and wage rate of Sumatra will have caught up with the current level in peninsular Malaysia, oil palm and rubber farms will have a lower return to labor than urban and service sector jobs, and there may still be a small basis for recovery of diverse agroforests. In China, the monoculture rubber may have lower opportunity for ecological recovery as it does not contain saplings or poles of natural forest species and seed dispersal agents may have disappeared.

In China, rubber is regarded as forest and therefore included in state statistics as forest cover, which is supposed to be beneficial for watershed health. Establishing rubber plantations is considered to have a sound scientific basis, providing soil erosion control that is believed to be lacking in shifting cultivation – these supposed environmental benefits are a further source of legitimacy for rubber. The Chinese scientists working in Xishuangbanna have fallen into three camps since rubber plantations were introduced in 1955 (Edmonds 1994). There are those of the so-called dark-green camp who advocate turning the tropical prefecture into a nature reserve. The opposite "dark-red" view is that Xishuangbanna can be best utilized by turning the area into a tropical cash crop plantation base, particularly a rubber-tree-centered man-made agroecological community (Feng 1986). The third opinion or the "pale-green" view is that there should be some sort of mix between conservation and development (Pei 1991). The scientific research in Xishuangbanna was influenced by the political ideology and policy discourse particularly in the 1950s as well as during the Cultural Revolution (Xu 2006).

Discussion: Arguments for an "Integrate" and "Land Sharing" Approach to Multifunctionality

We can now focus on the final question framed in the introduction: in reflection on the two case studies, can integration of agricultural productivity and biodiversity conservation functions in the longer-term perspective be a valid alternative to a more segregated approach to environmental and productive land functions? Can it justify external support for maintaining complex rubber agroforests in the landscape?

The trade-off curves between plot-level tree diversity and profitability of tree crop production systems used to be concave in Jambi (Murdiyarso et al. 2002), supporting the conclusion that "integration" is an efficient choice at societal scale, if a society cares about its biodiversity loss. Increases in tree crop productivity, however, may stretch a concave trade-off curve into a more linear and ultimately convex shape, unless the total system productivity value is increased. Opportunities to derive more value from the "other trees" in diverse agroforests need to keep up with the increases in value of the primary tree cash crop. Active research support for "ecological intensification" may have been too little and too late to stem the tide, while the public policy support for biodiversity conservation has remained focused on the establishment of protected areas rather than the protection of biodiversity at large.

The biodiversity-rich agroforests of Sumatra developed as an ecologically more mature (K-phase) ecosystem, selected on the basis of labor use rather than land-use efficiency in a historical phase of declining rubber prices. The glamour of the earlier rubber boom had gone; the area no longer attracted migrants, but rubber remained the best option for local communities given the way the rubber value chain had emerged within the economic geographical pattern. Intensification of rubber toward rubber monocultures was technically feasible but not sufficiently attractive in a smallholder economy with its high discount rates and aversion of financial risk, linked to the risk of failure of planted rubber clones to survive. Initially, the introduction of oil palm in the landscape could only compete with smallholder rubber agroforestry where it received active government support in land-use allocations. High world market prices of rubber as well as palm oil and availability of government-supported credit have, however, triggered an Ω/α phase of shifting away from complex agroforests toward monocultural tree plantations. With lower interest rates and increasing pressure on land, the economic incentives shifted, while the loss of biodiversity and associated local goods and services was not expressed in equivalent values. Intensification in the 1920s had replaced part of local staple food (rice) production by a market exchange, but the diverse agroforests still played a role as safety nets and as providers of other goods and services for which the trade-based substitutes were not yet sufficiently attractive. In the 1990s, the land use followed a pathway toward segregation, with pressure on the "integrated" agroforests increasing in parallel with more active protection of national parks and specialized conservation areas (Ekadinata and Vincent 2011).

In terms of sustainagility, the initial preservation of a substantial share of the native tree flora in the sapling/pole stage of RAF gave farmers many options to acquire useful trees at little management cost. Only a small part of these early stages of domestication lead to organized on-farm production of semi-domesticated trees; the potential remained largely unutilized and is currently in a rapid phase of decline. One would hope that this loss occurs with free and prior informed consent (MacKay 2004) as is the current standard for all efforts to reverse the trend of ongoing losses of forests and trees from the landscape. In some villages, efforts to reverse this trend have started, but this is a minority of cases in the overall landscape as yet.

Conclusion

In conclusion, the way rubber was integrated as a productive element in smallholder mosaic landscapes in Sumatra at the start of the twentieth century is in stark contrast to the situation in China where rubber was introduced as a top-down state-driven monoculture plantation. The political economy provided context for the ecological role, similar to the current debate on oil palm where consequences of a mode of production are attributed to the tree species rather than to the way it is used. Rubber agroforests in Indonesia became an icon of environmental friendly integration, while in China the tree became associated with destruction of ecosystem services and reduction of biodiversity. While the situation in Xishuangbanna (China) has triggered public debate and a rethinking of the monoculture model of intensification in a segregated approach, the Indonesian agroforests are giving way to monocultural tree crop plantations after almost a century. In both countries, a mixed model of segregation (fully protected areas and areas of intensive agriculture) and integration (pursuing ecological intensification models in agroforest context) may be the best way to combine local livelihoods and downstream imperatives of conservation and service provision. In both countries, the current incentive structure is insufficient to support the “integration” part of this mixed solution, with government programs biased toward specific models of intensification. It might help if the market would start to differentiate between “light-green” natural rubber (as differentiated from synthetic rubber), grown in monocultural plantations, and “dark-green” rubber that is produced in biodiversity-friendly production systems. In both countries, the nature of the forest transition is influenced by government policies and current lack of market-based payment for ecosystem services or economic incentive for biodiversity conservation. Research efforts have so far focused on the monocultural systems, but there are many unexplored options for preserving forest resources in diversified agroforestry systems with species from the native flora that can support concave trade-off functions between profitability and biodiversity conservation. Without external attention and incentives, however, the route of least resistance leads to a planted monoculture and agroforests as local history of tropical land use.

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End Notes

[The authors apologize to authors quoted in these endnotes that editorial policy of this book does not allow their work to be cited.]

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Integrating Climate Change Adaptation and Mitigation Through Agroforestry and Ecosystem Conservation

Johanna Matocha, Götz Schroth, Terry Hills, and Dave Hole

Abstract Climate change adaptation and mitigation are usually the objects of separate projects, but in this review we argue that in agricultural contexts, there are often technical and financial advantages in pursuing them simultaneously. This is because (1) adaptation planning is often necessary for mitigation (i.e., carbon sequestration) planning, especially for assessing future climate risks to mitigation investments, (2) certain land-use interventions can have both adaptation and mitigation benefits, and (3) carbon finance can help in supporting adaptation which still tends to be underfunded. Agroforestry and ecosystem conservation are key approaches in the integration of climate change adaptation and mitigation objectives, often generating significant co-benefits for local ecosystems and biodiversity. Synergies between climate change adaptation and mitigation actions are particularly likely in projects involving income diversification with tree and forest products, reduction of the susceptibility of land-use systems to extreme weather events, improvement of soil fertility, fire management, wind breaks, and the conservation and restoration of forest and riparian

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corridors, wetlands, and mangroves. On the other hand, trade-offs between adaptation and mitigation are possible when fast-growing tree monocultures for mitigation conflict with local tree and forest uses, making livelihoods more vulnerable, when trees are planted in water-scarce areas conflicting with local water uses, and in some cases when "climate-smart" agroforestry practices conflict with the need for agricultural intensification to produce increasing amounts of food for a growing population. Such conflicts need to be avoided through careful, site-specific, and participatory project development. We conclude that adaptation considerations should be included in mitigation project planning and integrated adaptation and mitigation activities should be prioritized in carbon markets and policy formation.

Keywords AFOLU (agriculture, forestry, and other land use) • Ecosystem-based adaptation • Income diversification • Land-use planning • Resilience of livelihoods

Introduction

Overwhelming evidence is now available to show that human-driven climate change is occurring, and that its harmful effects will most directly affect those least developed nations that are vulnerable to declining food and water security (Parry et al. 2007). The effects of climate change have already begun to threaten food and water supplies, putting low-income farmers and others immediately dependent on natural resources most at risk (UNEP 2009). We may also be starting to see the effects of a warmer world in increased occurrence and intensity of flooding, droughts, and storms (Goswami et al. 2006; Parry et al. 2007). Given projections that extreme weather and changes in baseline values of variables such as temperature and rainfall will reduce crop productivity and food security, as well as result in ecosystem alteration and disruption (Parry et al. 2007; Schroth et al. 2009; Fagre et al. 2009; Williams and Jackson 2007), there is an urgent need to identify and implement adaptation measures to increase the resilience of livelihoods and ecosystems to climate change.

At the same time, climate change mitigation must be intensified to limit the extent of alterations to the Earth's climate, in the hope of keeping them within a range in which adaptation is still feasible. Current levels of greenhouse gas (GHG) emissions will very likely result in continued temperature increases, potentially triggering positive feedbacks in the Earth system that may overwhelm the capacity, especially of poor societies, to effectively adapt (Lenton et al. 2008). Thus, the more successful mitigation activities are, the more time there will be to develop and implement suitable adaptation initiatives and the less acute those initiatives will have to be (Parry et al. 2007).

Recent observational data show current GHG emission trends to be near the upper end of the worst-case scenario (A1F1) presented in the International Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (IPCC 2000), indicating that governments and the international community must take their commitments to both adaptation and mitigation far more seriously than they have done thus far (Anderson and Bows 2008). Indeed, it appears increasingly unlikely that mitigation efforts currently proposed will be effective in keeping global temperature increases at or below 2 °C and atmospheric carbon dioxide levels at or below 450–550 ppm, values that are often assumed to represent the thresholds to dangerous climate change (Ramanathan and Feng 2008), though they are based on political consensus rather than scientific evidence (Anderson and Bows 2008). It is therefore imperative to explore the potential to mainstream climate change adaptation and mitigation across the full spectrum of climate-sensitive development activities.

Given the pressing concern over food security in the next 20 years due to increased population and at least locally decreased food supply resulting from climate stresses (Lobell et al. 2008), agricultural systems must be a key focus of adaptation strategies to climate change. There are 450 million small farms in the world, which support over two billion people through subsistence, rain-fed agriculture (Cook 2009). In addition to being one of the sectors most vulnerable to climate change, agriculture is also a major contributor to its causes, producing approximately 14% of GHG emissions, including through agricultural expansion (IPCC 2007; Le Quéré et al. 2009). It is the largest producer (58%) of anthropogenic non-CO_2 emissions, emitting 84% of all N_2O and 47% of CH_4 (Beach et al. 2008). Seventy-four percent of all agricultural emissions originate in developing countries (FAO 2008), and these figures are expected to increase due to rising population and changing dietary preferences (Beach et al. 2008). These data show that agriculture not only is a key sector for climate change adaptation but also has great potential for contributing to climate change mitigation. It is therefore important to look for synergies and trade-offs between climate change adaptation and mitigation in agriculture and related land-use activities.

Recent work indicates that land use and land-use change have direct impacts on, for example, soil moisture availability, length of growing season, and local and regional precipitation patterns (Pyke and Andelman 2007; Mahmood et al. 2009), making agriculture and other land uses central to adaptation efforts in developing countries. At the same time, land-based carbon mitigation schemes, such as avoided deforestation, reforestation, and agricultural and agroforestry practices that sequester carbon in vegetation and soil, can make a significant contribution to global climate change mitigation while providing project financing and a potential source of income to resource-poor farmers (FAO 2009).

Though managed forests and agroforests typically contain less carbon than primary forests, agroforestry systems can, under certain conditions, increase landscape carbon stocks by providing sustainable alternatives to short-fallow slash-and-burn agriculture or unshaded tree crops. For example, one set of studies found that agroforestry systems contained carbon stocks of 50–75 Mg C ha^{-1}, while row crops contained <10 Mg C ha^{-1} (Verchot et al. 2007; Montagnini and Nair 2004), pointing to the significant potential for agroforestry to increase on-farm carbon stocks.

Albrecht and Kandji (2003) also found that agroforestry systems can have a wide range of carbon stocks ranging from 29 to 228 Mg C ha^{-1} with a median value of 95 Mg C ha^{-1}. Values quoted by Luedeling et al. (2011) for dryland Africa fall mostly in the lower part of this range, as would be expected. A prediction of the potential for carbon storage and sequestration in agroforestry systems for southern Mexico showed that reforestation, improved tropical fallows, and coffee plantations may, in 25 years, store approximately 130–181 Mg C ha^{-1} in aboveground biomass (Soto-Pinto et al. 2009). Shifting from pasture without trees to pastures with scattered trees in the same region also substantially increased carbon stocks (Soto-Pinto et al. 2009). According to Nair et al. (2010), annual rates of above- and belowground carbon storage in agroforestry systems range from 0.29 to 15.21 Mg ha^{-1} year^{-1}. Following a detailed analysis of the management factors influencing climate change mitigation and adaptation, Nair (2012) gives a SWOT (strengths, weaknesses, opportunities, and threats) analysis of the role of agroforestry systems in that regard.

Traditionally, climate change adaptation and mitigation are pursued by different groups in society through separate projects (Klein et al. 2005), with adaptation often focusing on engineering, land-use planning, and broader developmental approaches to reducing future risks of flooding, water scarcity, or other weather-related risks without specifically integrating mitigation objectives (Leary et al. 2008; Agnew and Woodhouse 2011). Climate change mitigation, on the other hand, usually emphasizes carbon efficiency in industrial processes, transport, housing, energy generation, etc., as well as, more recently, reforestation and forest conservation for C sequestration with little explicit reference to possible adaptation benefits, although Metz (2010) briefly mentions opportunities for mitigation-adaptation synergies and Klein et al. (2005) discuss the institutional complexities of achieving such synergies. In this review we argue that, especially in land use, there are strong opportunities for synergies, but also risks of trade-offs between climate change adaptation and mitigation. We therefore review possibilities for combined adaptation and mitigation activities, focusing on the interrelation of adaptation (e.g., disaster risk reduction and increased resilience for food and water security) and carbon sequestration in above- and belowground biomass and organic matter, with a focus on “Agriculture, Forestry and Other Land Use” (AFOLU) projects (Box 1). We focus on activities that have the added benefits of simultaneously conserving biodiversity and ecosystem services, characteristics that we consider essential for successful adaptation and sustainable development. We first review reasons for integrating climate change adaptation and mitigation, then analyze potential synergies and trade-offs between adaptation and mitigation for a range of situations, followed by recommendations and the identification of research needs. In considering these linkages, the breadth of responses that can be considered “adaptation” needs to be qualified. Depending on the specifics of the local climate exposures, sensitivity of the local people and economies to those exposures, and their adaptive capacity, adaptation responses may cover a wide range of activities that seek to enhance the technical capacity of people, strengthen capacities of institutions, incorporate climate change risk into various levels of decision making, or promote and disseminate knowledge and learning (UNDP 2010).

Box 1 Agriculture, Forestry and Other Land Use (AFOLU) Under the Clean Development Mechanism

The Clean Development Mechanism (CDM) is one of the flexibility mechanisms created under the Kyoto Protocol and allows industrialized countries to finance emissions-avoiding projects in developing countries and receive credit for such efforts. The CDM contributes to the reduction of GHG emissions, but also supports sustainable development in host countries through the mobilization of financial resources and the transfer of cleaner technologies. Under the CDM, Agriculture, Forestry, and Other Land Use (AFOLU) projects can contribute to the reduction of GHG emissions while providing benefits to rural communities in developing countries, potentially improving rural livelihoods by linking the poorest people with the global carbon market. In UNFCCC discussions, AFOLU has essentially the same meaning as land use, land-use change, and forestry (LULUCF) but integrates agriculture within LULUCF sectors (UNDP 2008). Current AFOLU project categories under the Voluntary Carbon Standard (VCS) include Afforestation, Reforestation and Revegetation (ARR), Agricultural Land Management (ALM), Improved Forest Management (IFM), Reducing Emissions from Deforestation and forest Degradation (REDD), and Peatland Rewetting and Conservation (PRC) (VCS 2011)

Why Integrate Climate Change Adaptation and Mitigation?

Both technical and financial reasons exist to look for synergies between climate change adaptation and mitigation:

- In some cases, successful adaptation is a precondition for successful mitigation. For example, where climate scenarios suggest that the climate will become hotter and drier and potentially more prone to wildfires, improved fire management (an adaptation intervention) reduces the risk from wildfire to projects that pursue climate change mitigation through forest conservation and reforestation (Schroth et al. 2009). The same argument would apply where adaptation measures attempt to reduce flooding risks in a wetter climate, thereby also benefiting reforestation projects at flood-prone sites. Also, future adaptation responses to climate change may influence the availability of sites for mitigation projects, for example, where agricultural land, roads, or settlements need to be relocated from increasingly flood-prone valleys or coastal areas to higher ground, affecting the availability of upland sites for reforestation. In a changing climate, adaptation planning is thus an essential input to the sustainable design of mitigation projects, especially where future climate conditions will affect viability and permanence of mitigation efforts.

Fig. 1 Mixed agroforests of coffee (*Coffea arabica*) and ornamental palms (*Chamedorea* sp.) in the Sierra Madre de Chiapas, Mexico, that provide diversified income, soil protection, and carbon storage (Photo: G. Schroth)

- In many cases, the same interventions generate both adaptation and mitigation benefits, so integration can be achieved with little or no additional cost. As explained above, both adaptation and mitigation projects require information on climate scenarios, land use, and community practices, providing an opportunity for joint planning of adaptation and mitigation projects. For example, the recent development of a climate change adaptation strategy for coffee-producing communities in the higher parts of the Sierra Madre de Chiapas in southern Mexico highlighted the importance of complex vegetation (both forest and coffee shade canopies) as a proven means to reduce the damage from hurricanes, whose intensity and severity is predicted to increase, while simultaneously sequestering carbon (Philpott et al. 2008; Schroth et al. 2009; Fig. 1). Similarly, the restoration of mangrove forests to reduce the exposure of coastal communities to storm surges has obvious climate change mitigation benefits and potential for carbon marketing. Adaptation actions involving the restoration and sustainable management of ecosystems as part of adaptation strategies have been termed "ecosystem-based adaptation" (EbA – Box 2).

Box 2 Ecosystem-Based Adaptation (EbA)

Ecosystem-based adaptation is the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people adapt to the adverse effects of climate change (Convention on Biological Diversity 2009). “As one of the possible elements of an overall adaptation strategy, ecosystem-based adaptation uses the sustainable management, conservation, and restoration of ecosystems to provide services that enable people to adapt to the impacts of climate change. It aims to maintain and increase the resilience and reduce the vulnerability of ecosystems and people in the face of the adverse effects of climate change.” (IUCN 2009)

- On the other hand, trade-offs between adaptation and mitigation are also possible – for example, where fast-growing tree monocultures reduce the availability of native forest resources that may be important for the resilience of local communities, or where greater vegetation cover through mitigation-based reforestation leads to reduced downstream water availability due to increased transpiration in an increasingly dry climate (Hayward 2005). An approach to climate change adaptation and mitigation that systematically assesses the interrelationships between both objectives will maximize synergies while avoiding or minimizing such trade-offs.
- Financial reasons also exist for considering climate change adaptation and mitigation in their mutual context. Presently, international funding commitments for climate change adaptation are growing (currently at around 20% of the climate funding pledge of over USD26 billion across 23 global funds; Climate Funds Update 2011), but are still widely considered to be insufficient to address the increasing vulnerabilities to climate change in poor countries, and the future of this adaptation funding is still unclear. In this situation, if adaptation co-benefits could be generated through climate change mitigation projects, the emerging carbon markets for land-based carbon projects could help bridge the funding gap while more sustainable solutions to the problem of adaptation funding are being pursued. This has been recognized, for example, by the authors of the Carbon, Community and Biodiversity Standard, who have systematically attempted to integrate adaptation measures as a best practice in mitigation projects (CCBA 2008).

Establishing a precise picture of synergies between adaptation and mitigation activities is a first step in the process of crafting policies and metrics that will enable more comprehensive and effective approaches to climate change and better assessment of the outcomes of these activities. Figure 2 shows how the integration of adaptation and mitigation strategies could be achieved at the level of project planning. In the following two sections, we briefly review synergies and trade-offs between climate change adaptation and mitigation for specific project types.

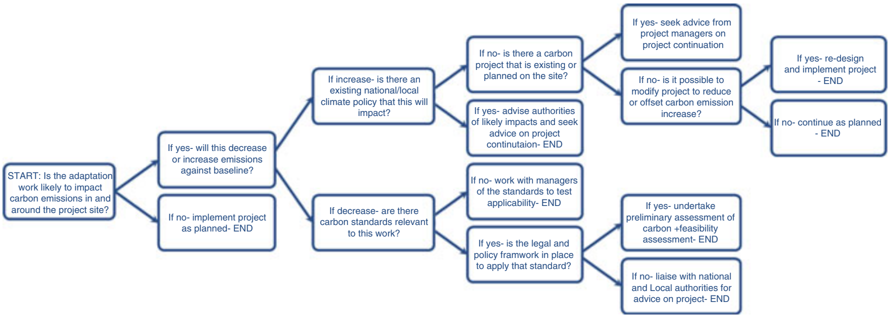

Fig. 2 Decision tree for the inclusion of climate change mitigation into the design of a climate change adaptation project

Synergies Between Climate Change Adaptation and Mitigation

Integrated adaptation and mitigation activities are intended to fortify the resilience of land-use systems to the adverse effects of climate change while at the same time reducing the negative and unsustainable impacts of human activity on the climate. Identifying and prioritizing these activities require a multifaceted analysis that takes into account the potential of a land-use system for carbon sequestration, the ability of an activity to increase the resilience of that system to climate change, and the capacity of local communities to implement and maintain a project, as well as the benefits they would derive from it. Verchot et al. (2007) coined the term "sustainagility" to highlight the dynamic element of adaptation within the assessment of a system's permanence and increased resilience. The following sections will discuss some types of interventions with potential for integrating ecosystem-based adaptation (see Box 2) and mitigation. Key messages are summarized in Table 1.

Income Diversification with Tree or Forest Products

Principle: Income diversification with tree or forest products can reduce the vulnerability of resource-poor farmers to climate and market shocks (adaptation) while increasing landscape carbon stocks (mitigation).

The diversification of livelihoods that spread risk over several crops or activities is continually listed as the most effective means of increasing resilience to climate change, especially for resource-poor farmers in the developing world (Douglas 2009; Eakin 2005; Lin et al. 2008; Schroth et al. 2009). While wealthier farmers with access to investment capital and possibly government subsidies may adapt to climate change through infrastructure improvements (e.g., irrigation) and crop insurance, resource-poor farmers may have to rely on diversification to reduce the impact of weather and climate uncertainty and prepare for gradual change in their

Table 1 Summary of practices offering synergies between climate change adaptation and mitigation

Practice	Adaptation benefits	Mitigation benefits	Key references
Income diversification with tree or forest products (e.g., through integrating trees in crop and pasture systems, reforestation of unproductive farm land)	Reduced impact of weather and climate uncertainty by spreading it over several crops or activities with different sensitivities; preparation for gradual change in land-use systems to match climate change	Increased carbon storage in biomass and soil	Douglas (2009), Eakin (2005), Kumar and Nair (2011), Lin et al. (2008), Montagnini and Nair (2004), Schroth et al. (2009)
Conservation agriculture and agroforestry (e.g., intercropping, cover cropping, live fences, shade trees)	Improved water retention and filtration; improved resilience of crops to drought; reduced hurricane susceptibility	Increased carbon storage in biomass and soil	Bradshaw et al. (2007), FAO (2008), Holt-Giménez (2002), Lin et al. (2008), Scherr and Sthapit (2009)
Practices to increase soil carbon storage (e.g., minimum tillage, use of compost and manure)	Reduced soil erosion and water pollution; increased soil water retention and biological soil function	Increased soil carbon storage	Nair et al. (2009, 2010), Nair (2012), Scherr and Sthapit (2009)
Reduced nitrogen fertilizer use (e.g., use of leguminous plants, targeted fertilizer application)	Reduced dependence on costly external inputs	Reduced greenhouse gas emissions from fertilizer production, transport, and soil (N_2O)	Lin et al. (2008), Nair et al. (2009), Scherr and Sthapit (2009)
Fire management	Reduced damage from wildfire	Increased carbon storage in biomass and soil	ProAct (2008), Scherr and Sthapit (2009), Schroth et al. (2009), Soto-Pinto et al. (2009)
Windbreaks	Crop protection from wind especially during drought; reduced wind erosion; income from tree products	Increased carbon storage in biomass and soil	Jindal et al. (2008), Klein et al. (2007), ProAct (2008)
Restoration and conservation of forest corridors including riparian forests	Protection against flooding and landslides; water and fisheries conservation; increased pollination and pest control; conservation of terrestrial and aquatic biodiversity	Increased carbon storage in biomass and soil	FAO (2008), Hannah et al. (2008), Heller and Zavaleta (2008), Pyke and Andelman (2007), Scherr and Sthapit (2009)
Mangrove conservation and restoration	Increased protection of coastal areas to erosion and storm surges; increased fish habitat; production of timber and non-timber products	Increased carbon storage in biomass and soil	Mukherjee et al. (2010), ProAct (2008)
Wetlands conservation	Regulation of water flows; water filtration	Carbon storage in peat and sediment	Battin et al. (2009), FAO (2008), Nyman (2011), ProAct (2008)

land-use systems (Schroth et al. 2009). If diversification is achieved by integrating trees into land-use systems and conserving production forests, it also benefits mitigation. Building of markets and supply chains and clarification of legal issues, for example, about tree ownership, are key issues in diversification, as are education, capacity building, and community involvement (Douglas 2009). Given the uncertainty associated with specific impacts that are likely to be experienced in a changing climate, diversification presents a way of spreading risk "on the ground" without requiring expensive modeling or infrastructure interventions. Agroforestry systems that include non-timber or timber trees in land-use systems are an important way of diversifying income. Examples of this include the smallholder forest gardens in Indonesia that integrate tree-based production of fruit, craftwood, timber, and other tree products with the production of field crops such as cassava (*Manihot esculenta*), maize (*Zea mays*), and rice (*Oryza sativa*; Roshetko et al. 2002). Under pressure from increasing ecosystem degradation, many cocoa (*Theobroma cacao*) farmers in West Africa now diversify into rubber (*Hevea brasiliensis*) which is more resilient than cocoa to poor soil and climate conditions (Ruf 2008). Where such systems are implemented as an alternative to degraded grassland or annual crops, there is also an increase in sequestered carbon.

The integration of trees with livestock production in silvopastoral systems can also provide a range of benefits. These systems can provide enhanced fodder and shelter for livestock, potentially improving their productivity in a hotter climate, and at the same time increase carbon stocks above those of conventional pastures (Ibrahim et al. 2004; Hänsela et al. 2009; Somarriba et al. 2012). Many of the land use and agricultural techniques already discussed can also incorporate livestock. The integration of livestock into mixed land uses will be increasingly important as the demand for animal protein grows and may be particularly attractive as a diversification option where the climate is becoming drier and less suitable for certain crops (Toni and Holanda 2008). One successful program combining mitigation and adaptation activities with benefits for both ecosystems and smallholders is the Regional Integrated Silvopastoral Ecosystem Management Project, which provided payments for ecosystem services (PES) to farmers in Colombia, Costa Rica, and Nicaragua during 2003–2007. In that case, PES helped to make the program attractive to land owners and provided a form of income diversification. The project also connected forest fragments (potentially benefitting biodiversity) and had a high rate of adoption after the end of the payments (Svadlenak-Gomez 2009).

Reducing the Susceptibility to Extreme Weather Events

Principle: Conservation agriculture and agroforestry can reduce the susceptibility to extreme weather events while increasing landscape carbon stocks.

Management practices such as intercropping, cover cropping, live fences, and shade trees can help to improve soil and water quality and reduce runoff and erosion (Lin et al. 2008). Farms using conservation practices have also been shown to be more resilient to extreme events. A study by Holt-Giménez (2002) on the role of agricultural practices in the aftermath of Hurricane Mitch in Nicaragua showed “agroecological” farms using soil conservation measures (contour plowing and planting, terracing, composting, etc.), integrated pest management, and agroforestry (live fences, vegetative strips, etc.) to have more topsoil and higher field moisture, more vegetation within the system, and lower economic losses compared to “conventional” farms that did not use such practices. A similar study by Tengo and Belfrage (2004) in Tanzania found that improved management through intercropping led to higher resistance to pest outbreaks and improved water conservation, increasing resilience to drought. Increased soil porosity from tree roots and shade provided by leaf cover, coupled with reduced runoff, can also enhance resilience to drought according to this study. Lin (2007) showed that shading results in lower evapotranspiration of coffee trees and mitigates microclimate extremes, which are expected to increase in a changing climate (Fig. 1).

Agricultural systems incorporating trees may also help protect against extreme events such as floods and storms with the incorporation of trees into grasslands providing greater slope stability in slip-prone lands (FAO 2008). Though there is debate about the degree of protection from landslides provided by forests and trees (FAO 2008; ProAct 2008), there is conclusive evidence that the majority of landslips and shallow slope failures occur on land cleared for crops, indicating that the shear resistance provided by tree roots can significantly decrease the risk of slippage caused by rainfall over extended periods. Such slippages not only harm agricultural productivity but also dump sediment into watercourses harming water quality and aquatic life and may be a direct danger to human settlements and infrastructure. Removal of tree cover accelerates runoff, thus increasing the risk of flooding in the rainy season and drought in the dry season. Although forests do not provide adequate protection against damage caused by high-magnitude storm events, they can help mitigate the severity of flooding and flood damage (Bradshaw et al. 2007). The forest floor and soil of riparian forest buffers trap sediment from upslope areas and can filter fertilizer and pesticides from runoff water. Forests in water catchments are thus particularly important for helping to provide clean drinking water to urban areas. Trees can also improve the water catch in cloud or fog situations, for example, in higher elevation cloud forest ecosystems (Postel and Thompson 2005). Agroforestry systems in strategic positions can approximate forests as regulators of sediment in water flow while providing marketable products (FAO 2008). Landscapes with year-round vegetative cover reduce runoff and can maintain most or all watershed functions, even when under (well-managed) productive use (Scherr and Sthapit 2009).

Improved Soil Quality

Principle: Best management practices for improved soil quality increase soil carbon stocks and aid in adaptation.

Management practices to increase organic matter in soil and improve soil nutrient availability provide an effective synergy of adaptation and mitigation strategies (Nair 2012). Increasing organic matter in soil increases water-holding capacity, nutrient availability, and carbon sequestration (Foley et al. 2005). Soil meanwhile constitutes an estimated 90% of agriculture's sequestration potential (FAO 2009), serving as the third largest carbon pool on the Earth's surface (Scherr and Sthapit 2009).

Practices such as minimum or zero tillage are shown to increase soil water retention, reduce erosion, improve carbon sequestration below ground, and often increase yields, as discussed in more detail by Nair (2012). Agroforestry systems both improve soil quality and are good candidates for soil carbon storage due to practices accompanying the management of agroforestry systems, such as returning harvested material to the soil (Montagnini and Nair 2004). The amounts of carbon sequestered in the soil under agroforestry systems can be substantial, adding to their aboveground carbon sequestration (Nair et al. 2009, 2010). Nair et al. (2010) reported C stocks ranging from 30 to 300 Mg ha^{-1} in the soil to 1 m depth.

Soil is concurrently an important source of nitrogen emissions, and these are influenced by management practices. Nitrous oxide (N_2O) has about 300 times the warming capacity of CO_2 and directly results from the use of inorganic fertilizer, emitting the equivalent of more than 2 billion t of CO_2 each year (Scherr and Sthapit 2009). To reduce emissions by minimizing the need for inorganic fertilizers, Scherr and Sthapit (2009) recommend using compost, green manure (where crops grown during fallows are plowed into the soil), nitrogen-fixing crops, cover crops and trees, and livestock manure. Planting crops and grasses that slow nitrification to a level that is still consistent with good crop growth, as in experiments with *Brachiaria* grass in Africa, would not only help reduce greenhouse gas emissions (N_2O) but also lower water pollution from nitrate, while enhancing productivity through more efficient use of fertilizer (CGIAR 2009). Such practices result in more closed nutrient cycles, thereby reducing farmers' dependence on external nutrient inputs and increasing their resilience in the face of fluctuating input prices (Lin et al. 2008; Nair et al. 2009).

Fire Management

Principle: Fire management is a precondition for successful mitigation and is a key adaptation measure in a hotter, drier climate.

Fire plays an important and natural, but potentially damaging, role in forest growth and management, with implications for both adaptation and mitigation. Fire is central in creating and maintaining ecological processes such as forest succession, as in the case of species that will not germinate unless they are exposed to fire (e.g., pines). However, fires set for agricultural or pasture management often get out of control and can release substantial quantities of carbon into the atmosphere, threaten the lives and livelihoods of communities, and destroy natural ecosystems. In Indonesia, the third largest emitter of GHG after the USA and China, forest fires are a major cause of deforestation; in 1997–1998, fire in that region contributed 2.1 billion t of CO_2 to worldwide emissions (Scherr and Sthapit 2009).

Where climate change increases the risk of crop failure and encourages the conversion of agricultural areas into pasture, fire use is likely to increase, with concomitant increase in the risk of wildfires. As an example, this scenario could occur in the near future in coffee-producing areas in Mesoamerica that are predicted to become marginal for coffee owing to increased drought, more frequent extreme events, and higher temperatures that reduce coffee quality (Schroth et al. 2009). Soto-Pinto et al. (2009) observed that in Chiapas, Mexico, the integration of timber trees into pasture land as part of a carbon project (Scolel'Te) created a strong incentive for not burning these pastures. Similarly, farmers practicing rubber agroforestry in the Tapajós region of Brazil have strong reasons to avoid the spreading of fire from their slash-and-burn plots (Schroth et al. 2003).

A study of the West Arnhem Fire Management Agreement in Australia, where the climate is predicted to become drier, found that the creation of fire breaks through early dry season prescribed fires reduced more dangerous wildfires by 15–20% across 28,000 km^2 and could reduce the yearly emissions associated with those wildfires by 100,000 Mg CO_2 (ProAct 2008). The same study also found that earlier dry season fires emit less GHG than later dry season fires because they are not as intense, burn less grassy fuel, do not burn the entire grass layer, stay in the grass layer without invading the canopy, and can be stopped more easily. Fire management implemented in that project had the added benefit of increasing aboriginal community participation, enhancing cultural practices around fire and providing payments to the Aboriginal Traditional Owners of Western Arnhem Land of $1 million per year over 17 years for the offset of 100,000 Mg CO_2 each year.

Windbreaks

Principle: Windbreaks sequester carbon and protect against erosion from wind and floods.

Shelterbelts, greenbelts, hedges, and living fences serve as windbreaks and shade the soil, binding it together with roots, trapping water, and restoring soil organic matter content. The amounts of carbon sequestered in these systems can be quite substantial with values in the range of 20–36 Mg C ha^{-1} in plant biomass and a potential 10% per hectare increase in soil organic carbon (Albrecht and Kandji 2003). All these techniques increase resilience to drought as well as improve soil health and prevent erosion through protecting fields from wind and surface water flow while often providing biodiversity benefits (Klein et al. 2007; ProAct 2008). The many benefits of windbreaks can be seen in a government adaptation project in Niayes region of Senegal promoting irrigated farming that also involved the planting of windbreaks along roads. The windbreaks increased agricultural productivity, reduced soil erosion and desiccation, and provided fuelwood for cooking, which had the added benefit of decreasing the need for women and girls to travel long distances in search of wood. The windbreaks also sequestered carbon (Klein et al. 2007). Another project in Sudan—the "Community-Based Rangeland Rehabilitation for Carbon Sequestration Project"—restored 700 ha of community rangeland by planting grasses and leguminous crops. The project also protected more than 300 farms from wind erosion by planting *Acacia senegal* and *Ziziphus mauritania* trees as windbreaks over 108 km.

The project aims to encourage community adoption of agroforestry through paying local communities for carbon offsets (Jindal et al. 2008).

Forest and Riverine Corridors

Principle: Forest and riverine corridors benefit adaptation by providing migration routes for animals and plants while storing carbon.

The restoration and conservation of forest corridors to improve forest connectivity is another mitigation activity that has adaptive benefits for both animals and people. Migration corridors can help species to shift their geographic distributions in response to a changing climate (Hannah et al. 2008; Heller and Zavaleta 2008) and can contribute to providing the genetic diversity necessary for adaptation as individuals move between populations, bringing alleles from one region that may not be present in another region (Guariguata et al. 2008). Forest corridors can also generate direct benefits to humans while at the same time sequestering carbon in tree biomass and soil. Examples include the protection against landslides and water conservation, as discussed previously, and may benefit agricultural systems by supporting pollination and pest control through protecting the habitats of the species that are involved in these processes (Scherr and Sthapit 2009).

The restoration and conservation of riverine corridors provides direct benefits to human adaptation by keeping water temperatures low in the face of temperature increases, thereby potentially protecting freshwater fisheries, while filtering nutrients from runoff and soil water (FAO 2008). Removal of riparian corridors, on the other hand, leads to higher daily and mean temperatures and results in faster nighttime cooling (Pyke and Andelman 2007) while reducing carbon storage. Riparian corridors also stabilize stream banks and decrease the sediment loads of streams, thereby reducing the negative effects of sediment deposition on spawning grounds of fish and on reservoir capacity, the latter being particularly critical in drying climates (FAO 2008).

Mangroves

Principle: Mangroves sequester carbon and protect coastal areas against increasing flooding risks.

Reforestation and avoided deforestation of mangroves offers another important synergy between adaptation and mitigation, with relevance to millions of people living and practicing agriculture in coastal areas and river deltas, in addition to the inhabitants of coastal towns and cities. Mangroves benefit these people through increased protection of coastal areas to erosion and storm surges. In addition, mangroves increase fisheries habitat, providing a direct source of food and income to local communities. Mangroves not only store carbon but may also serve as a complement and more cost-effective means of storm protection to built infrastructure.

For example, while storm damage to a sea wall would require costly repair, mangroves will naturally regenerate, although the level of protection and regeneration rate depends on area geomorphology, vegetative structure, and the frequency and intensity of storms (ProAct 2008).

There is evidence that many types of coastal forests can help dissipate wave energy and force, reducing flooding, and also help to capture debris that would otherwise do more damage (ProAct 2008). Recommended greenbelt width for protective mangroves varies from 100 m for tsunami protection in the Asia South Pacific to 200 m for protection of agricultural land (ProAct 2008), suggesting that carbon sequestration potential may be significant. However, given the lack of consensus on the capacity of mangroves to attenuate long-period waves such as storm surges and tsunamis (Mukherjee et al. 2010), they should not be seen as a substitute for early warning systems and planning for such events, but rather as part of a broader system of risk management (Baird 2006).

As with protection functions provided by other forms of forest, mangroves require time to mature before they offer their full protective benefit (ProAct 2008). Thus, avoided deforestation can be more effective as an adaptation strategy where existing mangrove structures are already meeting coastal protection objectives, as well as being more cost-effective than reforestation (UNEP RISOE 2010). In areas where people are heavily reliant on mangrove forests, the risk of mangrove loss can be minimized by increasing the capacity of communities to undertake alternative livelihood options (ProAct 2008).

Wetland Conservation and Restoration

Principle: Wetlands store carbon and improve water security by filtering pollution and managing water flow.

Wetlands in mountain areas supply water for agricultural land downstream while sequestering carbon. Natural peat wetlands in coastal and river areas serve as aquifers by absorbing and storing water in wet periods and releasing it slowly during low rainfall (FAO 2008). Wetlands discharge water through evapotranspiration, seepage, pipe flow from subsurface erosion, overland flow, and open channel flow (FAO 2008). In addition to managing water flow, wetland ecosystems, such as floodplains, salt marshes, mudflats, reefs, and wooded riparian zones can all serve as flood management protecting people, agricultural land, and infrastructure downstream (ProAct 2008).

Wetlands also filter pollutants such as arsenic, boron, mercury, nitrogen, and selenium out of water, making them possible candidates for water quality credits (Nyman 2011). Wetlands protect offshore fisheries from land-based pollution (FAO 2008), thereby potentially reducing the impacts of climate change on coastal fisheries. Wetlands are also gaining recognition for their carbon sequestration potential. Inland waters are estimated to transport and store approximately 2.7 Pg C year^{-1} (Battin et al. 2009). Wetlands store carbon with greater permanence than do oceans due to bottom-water anoxia in inland waters (Battin et al. 2009).

Trade-Offs Between Climate Change Adaptation and Mitigation

While there is a strong potential for synergies between adaptation and mitigation, in certain cases, there may also be trade-offs. The most common trade-offs are likely to occur where immediate infrastructure, water, and food security needs are satisfied at the expense of protecting ecosystems, thereby reducing their carbon stocks and jeopardizing the long-term flow of ecosystem services that would help to satisfy those needs over the longer term (Foley et al. 2005). Some examples of this situation follow.

Mitigation Activities: A Threat to Food Security?

The rising demand for cheap and abundant food, corresponding to the rapidly growing global population, has led to increased support for intensive agriculture. There is concern in some quarters that a shift away from intensive agriculture, through emphasizing reduced use of fertilizer and machinery and incorporating perennials to increase above and belowground carbon stocks, could threaten food security and farmers' livelihoods by reducing yields, which may already be under pressure from climate change (Smith 2009; Scherr and Sthapit 2009). Such concerns must be taken seriously and carbon sequestration or reduced emissions measures be introduced in agriculture only after careful evaluation of the consequences, rather than recommending "one size fits all" approaches.

The importance of highly participatory, site-specific approaches to promoting the inclusion of trees in agricultural systems or other "climate-smart" land-use practices cannot be overemphasized. Farmers are unlikely to adopt practices that they believe may compromise their crop yields or complicate their farming operations. For example, coffee farmers in the Sierra Madre de Chiapas, Mexico, who participated in a carbon payments scheme, rarely opted for the inclusion of additional trees in their already quite densely shaded coffee plots, which they rightly feared might have reduced coffee yields and increased disease pressures. However, many farmers had plots of annual crops or pasture, and so live fences to surround and subdivide these were perceived as the option for increasing the carbon stocks of their farms that was most compatible with their production objectives and was most commonly chosen (Schroth et al. 2011). Reforestation of sites that had been affected by wildfires or landslides was another option for increasing landscape carbon stocks without negatively affecting agricultural output (Schroth et al. 2009).

In addition, reforestation projects targeting presently underused land might conflict with future shifts in agricultural or pasture uses driven by climate change. Therefore, identification of land for reforestation and afforestation should consider future scenarios of land-use shifts, including through using agroforestry models that are more flexible to the integration of other land uses, such as crops and livestock, than are classical plantation forests. Again, participatory models that leave farmers a maximum of flexibility in how to achieve certain targets (e.g., an increment in farm carbon stocks) are among the best ways to increase adoption and permanence of proposed changes in agricultural practices (Schroth et al. 2011).

Tree Planting Versus Water Security

In regions with adequate water availability, afforestation and reforestation are often beneficial and can even increase water availability during the dry season by ensuring more gradual release of water from catchments. However, afforestation can also decrease water availability. Tree plantings use more water than other land uses, such as agriculture and pasture, and the removal of trees has been shown to increase downstream water yields (FAO 2008). One global study found reduced annual runoff levels of as much as 75% when grasslands were converted into *Eucalyptus* plantations (Jindal et al. 2008). Therefore, tree planting for climate change mitigation may have adverse adaptation effects in dry climates. Deciduous indigenous trees that shed their leaves in the dry season are often a more appropriate plantation choice in water-scarce catchments (Jindal et al. 2008).

In areas of low and decreasing rainfall, aboveground carbon stocks decrease when trees are removed to increase water yields from catchments, as has been the case in government campaigns to remove invasive trees from watersheds in South Africa. However, the net carbon release of such measures depends on the subsequent use of the tree biomass, with highest emissions occurring if trees are burned or left to decompose in the field, and less immediate and lower emissions if the timber is used for long-lived products (e.g., buildings) and eventually burned for generating energy and replacing fossil fuel. By reducing evapotranspiration, harvesting or removal of trees can increase groundwater levels. This is often desirable but may lead to increased salinization in areas where salt is present in the subsoil and is then able to move into the rooting zone of plants (Nuberg et al. 2009), hence the need to design site-specific land use solutions for both adaptation and mitigation projects.

Fast-Growing Tree Monocultures and Availability of Forest Resources

As discussed, the objective of maximizing tree growth in carbon sequestration projects should be balanced with the objectives of conserving and increasing the availability of native forest resources, such as wood, fodder, and various types of food, which may increase the resilience of local communities to climate change, as well as conserve local biodiversity. Therefore, the use of diverse stands of native trees is generally preferable to monocultures of exotic species (Brockerhoff et al. 2008).

Conclusions

Given the multiple mutual benefits between climate change adaptation and mitigation that this review has highlighted, we conclude that climate change adaptation should be integrated into mitigation projects wherever possible, while adaptation projects should preferably include mitigation components. The potential for the integration of mitigation objectives is particularly high in ecosystem-based adaptation approaches that have been highlighted in this chapter. In places where adaptation is needed and there is a risk of trade-offs with mitigation, adaptation should be prioritized as the more site-specific need, while mitigation projects have a global impact and are therefore geographically more flexible. In such instances, research into adaptive strategies that minimize damage to ecosystems and aid in mitigation should be prioritized.

Emission reductions achieved through integrated adaptation and mitigation activities should be promoted in the voluntary and compliance carbon markets, while adaptation projects should be designed with the objective of, as a minimum, no increase in carbon emissions. Emission reductions from sequestration through agricultural activity should be treated as equivalent to other offsets and should not be relegated to the lower tier of temporary certified emissions reductions (tCERs), as is currently the case with agricultural mitigation efforts. One way to address the concern about the permanence of carbon sequestration benefits obtained through agriculture for carbon markets is to include education campaigns, incentives such as long-term payments or tax rebates for carbon storage and "climate-smart" agricultural practices, and other adaptation-style strategies into mitigation projects. This is necessary to ensure that carbon sequestered in agricultural systems remains in place for periods long enough to have a significant climate benefit.

Many of the most promising techniques that combine adaptation and mitigation, such as those that combine trees in cropping systems or trees with animal production, are very knowledge intensive. This means that smallholders must over time learn a suite of new methods and gradually and successfully integrate them into their production systems. A significant level of support and knowledge transfer is required for this process to be attractive, successful, and of low risk to the participants, and subsidies, for example, through payments for carbon conservation or other environmental services, may be necessary to increase adoption rates of such practices. Overall, forestry and agroforestry projects involving the local community in management have lower-risk profiles than large plantations. As the investment in efforts to build climate-resilient development outcomes increases through dedicated (but "project-based") adaptation funding mechanisms, the opportunities for revenues from REDD+ projects to offer financing for community-level adaptation initiatives need to be explored.

In summary, given the severity of anticipated climate change, a rapid and truly integrative response is required on the part of the global community. The most efficient use of limited resources needs to be attained. Where efforts at climate change adaptation and mitigation can be combined so that resources do double-duty, this should be done. In other cases, government planners and project developers should avoid trade-offs where efforts in one sphere compromise the other. Opportunities for synergy between climate change adaptation and mitigation can be further developed by increasing the understanding of the complex interactions within natural and human-managed systems.

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High-Carbon-Stock Rural-Development Pathways in Asia and Africa: Improved Land Management for Climate Change Mitigation

Peter A. Minang, Meine van Noordwijk, and Brent M. Swallow

Abstract Low-carbon (emission) economic development pathways are needed to contain and gradually slow emissions of the greenhouse gases (GHGs) that cause global climate change. As developing countries contribute to GHG emissions largely through land management practices that degrade landscape carbon stocks, climate change strategies in developing countries must give specific attention to land management. Yet, current mechanisms for international investment or incentives in emission reductions from the land use sector, especially reduced emissions from deforestation and degradation (REDD+) and the clean development mechanism (CDM), have so far been slow to develop. Prospects remain good, however. Intensification of land use through tree-based production systems has emerged as a principal rural development pathway in much of Southeast Asia, with significant benefits for reducing GHG emissions, generating economic returns, providing ecosystem services, and adapting to climate change. In Africa, intensification of tree-based production systems has been much slower to develop despite great biophysical potential. This chapter develops the concept of a high-carbon-stock rural-development (HCSRD) pathway as an extension of the tree cover (forest) transition model and compares experiences of HCSRDP development in Asia and Africa. Those experiences show that achieving a HCSRD pathway requires coordinated

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attention to interactions and trade-offs among forestry, agriculture, and rural development. Innovative finance mechanisms, enabling policy and institutional environments, effective and efficient extension systems, and appropriate investment strategies can catalyze tree-based or agroforestry enterprises and optimize trade-offs between the multiple functions of landscapes.

Keywords Agricultural intensification • Tree-based agricultural systems • REDD+ • Low-carbon development pathways • Trade-offs

Introduction

There is a growing consensus that low-carbon-emission economic development (i.e., improvements in social well-being, with reduced intensity of carbon emission) is required for reliable long-term solutions to global climate change. With the rural economies of developing countries contributing about 30 % of global greenhouse gas (GHG) emissions through land use change in agriculture, forestry, and other land management activities (IPCC 2007), a sustainable land management approach to a low-carbon-emission economy has become imperative for developing countries. Reductions in carbon emissions can be achieved through reductions in emission intensity and maintenance of high carbon stocks in terrestrial ecosystems and agroecosystems.

The clean development mechanism (CDM) of the Kyoto Protocol sought to contribute to low-carbon economic development through the transfer of low-emission technology to developing countries funded through emission offsets within Annex 1 countries. Despite its importance, however, virtually no land-based emission credits have been generated through the CDM. In recent years, there has been widespread political support for reducing emissions from deforestation and forest degradation (REDD+) under the United Nations Framework Convention on Climate Change (UNFCCC), demonstrated by the agreement on REDD+ that was achieved during the Conference of Parties (COP) held in Cancun, Mexico, in December 2010 (UNFCCC 2010). Support for REDD+ is partially due to the expectation that emission reductions from land use change will be cheaper than other sectors (Stern 2006). Such a land-based approach through agriculture and forestry could be part of a larger green economy initiative that incorporates low-carbon economic development (UNEP 2011a, b)[1]. This chapter explores the role of trees in agricultural landscapes (agroforestry) and other tree-based systems in a low carbon economy. We refer to the role of agroforestry and tree-based systems in contributing to reducing carbon emissions and the full range of private and societal benefits in terms of livelihoods and environmental services as high-carbon-stock rural development. High-carbon-stock rural-development (HCSRD) pathways are dynamic processes that couple the development of tree-based systems, improved human well-being, and long-term improvements in environmental services. We contend that HCSRD pathways could be an effective way for developing countries to synergize development plans with nationally appropriate mitigation actions (NAMAs) and national adaptation plans that were called for by the Copenhagen Accord.

Worldwide, trees in agricultural landscapes hold great potential for climate change mitigation that at this time is not explicitly taken into account in any of the three UNFCCC mechanisms, namely, REDD+, CDM, and NAMA. About 46 % of agricultural land globally has at least 10 % tree cover: in Southeast Asia and Central America, 50 % of agricultural land has at least 30 % tree cover, while in sub-Saharan Africa, about 15 % of agricultural land has at least 30 % tree cover (Zomer et al. 2009)[2]. The place of agroforestry and related tree-based systems in potential UNFCCC emission reduction mechanisms depends on what definition of forest is adopted by a country – that is, whether the agroforestry system meets the forest canopy cover threshold chosen by the country (10–30 % choice range) and/or whether the land is classified as forest even if it is "temporarily unstocked" (van Noordwijk and Minang 2009). REDD+ only addresses forestry, CDM allows only afforestation and reforestation projects, while the design of NAMAs is left to discretion of individual countries, with no clear funding arrangement. This means that small-scale farmers and agriculture cannot directly benefit from emission reduction incentive schemes.

Uncertainty is rife on how far both REDD+ and CDM can contribute to sustainable development partly because they have been slow to take effect in large parts of both Africa and Asia. Furthermore, mitigation mechanisms within the UNFCCC have so far been kept completely separate from adaptation actions that seem to be the primary climate change concern for most developing countries (Klein et al. 2005; Najam et al. 2003). Besides contributing to development and emission reduction, we contend that HCSRD can be an approach that developing countries can pursue as part of their strategies for climate change mitigation and adaptation (Verchot et al. 2007). It is important to keep in mind that climate change mitigation and adaptation are not among the most basic concerns of governments in most developing countries and, in instances where it is assigned priority, little is done due to lack of capacity and resources (Mumma 2001; Najam 2005). However, we argue that, unless climate change is more directly linked to issues of greater concern, it is likely to remain a "luxury" perspective that keeps being assigned low priority.

Active participation in global climate change mitigation and adaptation (M&A) has been presented to and perceived by policymakers as a possible additional income stream or "environmental service rent" (Angelsen 2010) that may be competitive with low rents generated by the forest and agricultural sectors of the local economy. Returns to agriculture are often constrained by low food price policies that are aimed at appeasing urban masses (Bezemer and Headey 2008). The low opportunity costs of current emissions caused by land use changes in developing countries that yield low economic returns (Swallow et al. 2007; van Noordwijk et al. 2011)[3] have been interpreted as easy targets for global emission reduction when viewed through a perspective of economic efficiency in global economies. These low opportunity costs, however, translate into poor economic opportunity for the rural poor whose only options are to migrate to a city and start at the bottom rank of the urban pecking order. If environmental service rents can be captured by the state or its urban elites, they may appear attractive, but to be effective they have to be fully integrated in HCSRD pathways that offer rural poor real prospects for better lives. Ironically, the argument for developing countries becoming involved in climate change mitigation for economic gain tends to be resisted by the small but growing groups of people in developing countries who are actually concerned about global climate change and want real emission reductions rather than offsets. It is argued that carbon markets effectively create emission rights, with offset markets shifting those rights around. Skeptics of offset markets argue that developing countries may get paid "to be an atmosphere cleaner" but should demand a fairer role in the global order (Najam 2005).

Arguments for active engagement with climate change in developing countries are thus (Najam et al. 2003; Najam 2005; van Noordwijk and Leimona 2010):

(a) Climate change will affect territorial security, which is especially the case for small island states vulnerable to sea level rise.
(b) Climate change will affect food security in urban areas, as it interferes with a fragile food production system that is poorly buffered against climate fluctuations.
(c) Carbon-based environmental service rents may generate an income stream that is more profitable and sustainable than the current high emission/low return types of land use.
(d) International funding streams and investment are, to a limited extent, available to address issues of global environmental integrity and climate security, avoiding global risks to every country's fundamental concerns.

In the next section of this chapter, we articulate a model of high-carbon-stock rural development pathway through which agroforestry and tree-based systems could potentially enable developing countries to accommodate low carbon emissions, rural economic development, and food security in their policy priorities. Evidence from Southeast Asia and Africa shows that high-carbon-stock rural-development pathways are possible but by no means are automatic or easily obtained.

High-Carbon-Stocks Rural Development

The Intergovernmental Panel on Climate Change (IPCC) has established the global importance of land use, land use change, and other land use as sources of carbon emissions and sequestration. Land use changes often follow particular sequences or transitions, starting from primary forest or savannah woodlands, depending on the agroecological context. Land use transitions can take multiple pathways, with varied impact on forest cover (hence carbon), income, and human populations. Examples of such trajectories include intensification with deforestation, intensification with reforestation, abandonment with regrowth, abandonment, and irreversible degradation (Chomitz 2007)[4]. Different combinations of demographic, market, and policy pressures can underlie forest transitions of forest cover reduction, stabilization, and ultimate increase. Figure 1a shows the forest transition in which forests initially decline due to encroachments from farms and settlements and then stabilize and eventually

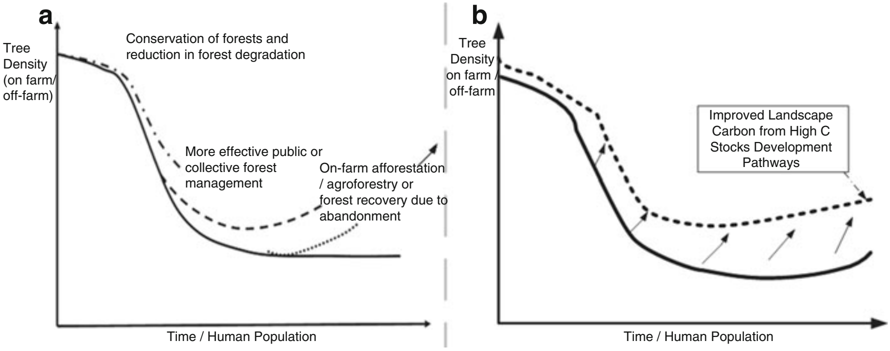


Fig. 1 Shows the overall aim of HCSRD on the tree cover transition. (**a**) shows the multiple pathways of land use transitions for high-carbon-stocks rural-development pathways (Source: Modified from Rudel et al. (2005), Chomitz (2007). (**b**) shows the overall objective in terms of shift in tree cover transition that should be targeted in the high-carbon-stocks rural-development process

increase due to mechanisms that enable regeneration (Grainger 1995; Mather and Needle 1998). When mechanisms for maintaining forests come to be the norm in the landscape, overall tree cover and carbon stocks increase (Fig. 1b). When land use transitions enable reductions in emission intensities or maintenance of high carbon stocks in terrestrial ecosystems, they contribute to low carbon pathways. When such transitions simultaneously contribute to low carbon pathways, increased incomes, food security, and environmental services, they contribute to low carbon economic development.

HCSRD can be seen as rural development through improved land management systems that ensure increased productivity, incomes, and environmental services – notably reduced carbon emissions. This can be achieved through the management of carbon in three related pools: (1) tree-based aboveground and belowground carbon in agricultural landscapes (e.g., trees along field boundaries, small woodlots, woody fallows, tree crops, and agroforestry systems); (2) soil and aboveground carbon in agricultural landscapes; and (3) tree carbon and soil carbon in standing forests. By managing each pool and all pools collectively, overall tree cover and carbon can increase over time as shown in Fig. 1b. HCSRD improves tree cover in landscapes through a rural-development process that generates positive benefits for the rural livelihood asset base, including positive direct benefits for food, income and carbon, and indirect benefits for biodiversity and hydrology. Therefore, HCSRD could be seen as complementary to landscape approaches to land management and sustainable intensification.

Key features of HCSRD can include:

Better management of soil carbon (Lal 2004) through:

- Reform and public investment in markets for inorganic fertilizer, combined with “smart” targeted subsidies for inorganic fertilizer (Palm et al. 2010)

- Integration of inorganic and organic sources of soil nutrients into agricultural production systems, including both perennial and annual crops (Vanlauwe et al. 2010)

Maintenance of carbon stocks in primary and secondary forests through:

- Community forestry for sustained harvesting of non-timber forest products (e.g., Blomley et al. 2008)
- Better control of fire risks and restoration of degraded forest lands (e.g., Pye-Smith 2010)[5]

Enhancement of tree-based carbon in agricultural lands (Albrecht and Kandji 2003):

- Improved soil fertility and belowground carbon storage in roots and soil
- Increased sequestration and aboveground carbon storage in trees within agricultural systems

Tree-based systems of value creation in rural landscapes:

- Tree-based commercial crops and agroforestry through provision of appropriate information, germplasm, and land tenure reform
- Development of value chains for trees and tree products and services including improved germplasm, inputs, harvesting techniques, processing, and marketing
- Taking advantage of relevant incentive systems to promote tree-based systems, their products and services, possibly taking advantage of REDD+, CDM, and NAMA mechanisms to enhance land-based emission reductions
- Specifically ensure that tree-based systems minimize the externalities of ecosystem services and/or enhance climate change adaptation and ecosystem services

In some circumstances, good management of soil carbon and avoided land degradation can reduce the need to expand cultivation into forests or wooded areas. Since the advent of REDD+, there has been renewed research interest in the drivers of deforestation. DeFries et al. (2010) argue that expansion of export-oriented agriculture has become the main driver of deforestation in much of the developing world, while Fisher (2010) argues that expansion of agricultural production for subsistence needs remains a primary driver for deforestation in Africa. Agriculture remains the largest employment sector in many developing countries, constituting a large share of exports in certain countries (World Bank 2008). Yet, these same developing countries need to continuously increase food production to ensure food security for their growing populations. Economic growth and greater prosperity tend to shift food consumption patterns toward dairy and meat products that often have larger carbon footprints than staple foods (Subak 1999).

Regarding soil carbon, a large difference between Africa and most of Asia is that production increases in Africa have mostly been generated from expansion at the extensive frontier of land use, while production increases in much of Asia have mostly been generated from more intensive use of already cleared land (World Bank 2008). Soil carbon has been maintained through both organic and inorganic fertilizer. Research by the Tropical Soil Biology and Fertility Programme (TSBF) and the

World Agroforestry Centre has shown the possible complementary effects of organic and inorganic sources of nutrients (Akinnifesi et al. 2011; Vanlauwe et al. 2010). More efficient fertilizer markets and more organic sources of soil nutrients (e.g., biological nitrogen fixation by tree legumes) are important. Here, trees are also an important source of soil fertility improvement and aboveground carbon.

Regarding carbon in intact standing forests, experience has shown that sustainable forest management can be achieved in ways that enhance local livelihoods while reducing deforestation pressures. Community forestry systems that are relatively effective in countries like Nepal and the Philippines are now showing promise in African countries like Tanzania and Cameroon (Larson and Ribot 2004). In some cases, forest management systems can be enriched through simple management techniques such as the *ngitili* system that is practiced in the Sukuma area of western Tanzania (Pye-Smith 2010). The *ngitili* system is a traditional management system in which an area of standing vegetation of grasses, trees, shrubs, and forbs is retained from the onset of the rainy season and managed for grazing and other purposes (Kamwenda 2002)[6]. Better management of secondary forests can generate income while maintaining carbon stocks and providing ecosystem services to surrounding farms.

The Potential for High-Carbon-Stocks Rural-Development Pathways

HCSRD aims at enabling effective and efficient achievement of the full potential of enhancing private and social livelihoods as well as environmental benefits from agroforestry and other tree-based systems. Long-term studies across the tropical forest margins show that intermediary land uses (agroforestry and tree-based production systems) enable moderate profits while sequestering or maintaining high carbon and sustaining relatively high levels of biodiversity (Palm et al. 2005). For example, Fig. 2 shows the trade-offs between carbon and profitability for multiple systems in the tropical forest margins in Cameroon, with agroforestry systems being moderately profitable and holding moderate levels of carbon compared to non-tree agricultural systems. There is evidence that these and other intermediary land uses have high potential for carbon sequestration (Verchot et al. 2007).

A number of factors are crucial to the success of any HCSRD pathway. We postulate that these factors include an effective and efficient extension service (including the provision of improved germplasm), an enabling policy and institutional environment (including unambiguous land and tree tenure, incentive schemes for environmental services), the development of markets and market infrastructure, investments in various tree-based enterprises (including processing and transformation of products), and functional systems for delivery of carbon services (monitoring, reporting, verification, etc.).

In the next sections, we review the dynamics of tree-based intensification in both Asia and Africa as a pointer to the potential for HCSRD pathways. Sub-Saharan Africa and Southeast Asia (SEA) were chosen for a number of reasons, including deforestation rates, human population density, and potential for increasing trees on agricultural land. Africa and Asia are losing much higher proportions of forest cover than other regions of

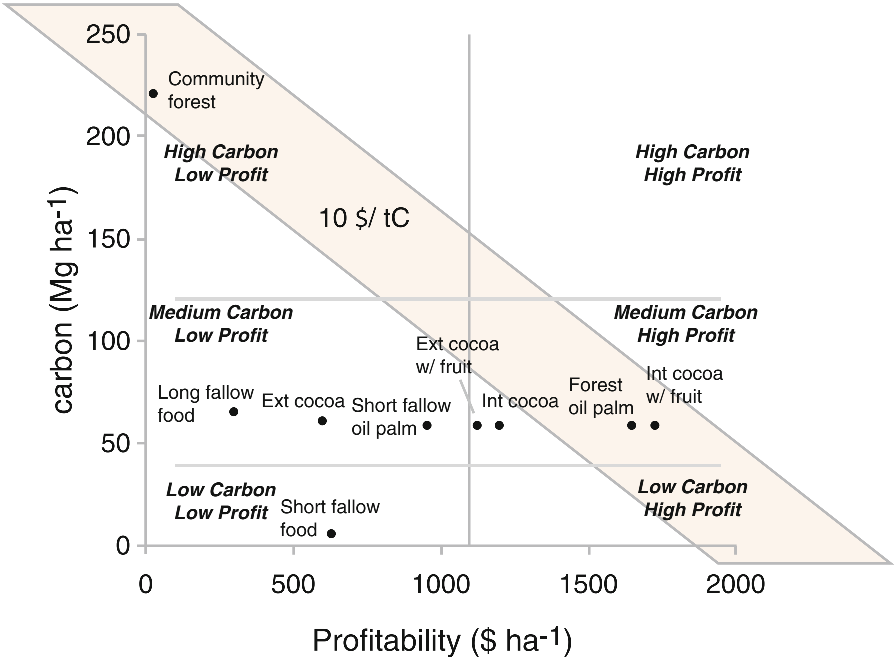


Fig. 2 Carbon storage and private profitability of different systems in the humid forests of Cameroon (Palm et al. 2005), the main negative diagonal represents an opportunity cost of carbon of 10$/tC when converting forest to the most profitable agroforestry system; conversions to systems in the lower left triangle yield less benefits per unit carbon loss (van Noordwijk et al. 2011)

the world (FAO 2010), while population densities on agricultural land are much higher in Asia (many areas having 25–250 persons/km^2) and sub-Saharan Africa (66–125 persons/km^2) than comparable regions in Latin America (often less than 65 persons/km^2) (Zomer et al. 2009). Lower population pressure implies less need for intensification of land use. Lastly, Africa and Asia have far larger areas of land with underdeveloped potential for tree-based systems compared to Latin and Central America (Zomer et al. 2009). The distribution and evolution of tree-based systems vary tremendously across the continents, with notable advances in SEA and slower progress in Africa. These different rates indicate varied potential for HCSRD. The case studies from Asia are based on studies from the Alternatives to Slash-and-Burn program (ASB), while the Africa case studies represent success stories reported from across the continent.

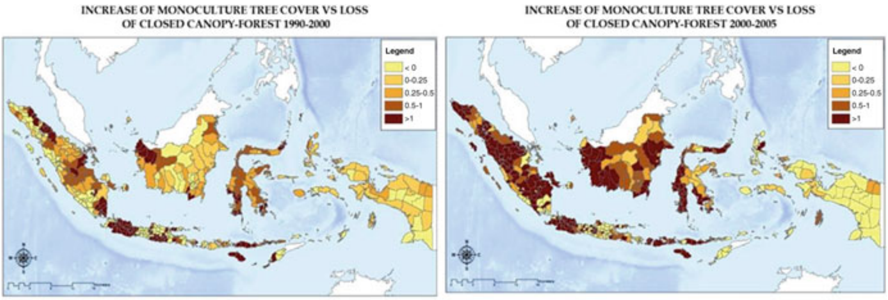
Tree-Based Agrarian Transformation in Southeast Asia (SEA)

Swidden systems have been the starting point for agriculture across the subhumid tropics, including most of SEA. "Swidden" or shifting cultivation refers to lands cleared of woody vegetation for temporary production of local staple crops for food

Fig. 3 Jungle rubber (*Hevea brasiliensis*) in Jambi, Indonesia. Currently being replaced by more commercial rubber and oil palm

or other uses, then left to fallow and allowed to regenerate. Padoch et al. (2007) estimated that 15–20 million people in Myanmar, Thailand, and Malaysia (Sarawak and Sabah) depended on swidden in the 1980s, cultivating an area of 5.5 and 6 million ha. There is growing consensus that swiddens have been evolving rapidly in many parts of SEA, though data on its extent and evolution are still inconsistent. Fallow periods of about 13 years between rice crops have been reduced to 3–5 year herbaceous fallows and permanent farms. Conversion from swidden fields to cash crop plantations and reforested land also occurs. For example, rubber plantations began to be established in the 1960s and by 1998 occupied more than 136,000 ha of land in SEA (Guo et al. 2002). More than half of the reported swidden cases are being replaced by some forms of permanent, annual agriculture (Schmidt-Vogt et al. 2009). Of over 90 cases reported in the reviewed literature, 52 were reported to be replaced by tree crops or tree-related enterprises with 17, 14, and 8 reporting replacements with rubber (*Hevea brasiliensis*) (see Fig. 3), fruit-tree cultivation (orchards), and oil palm (*Elaeis guineensis*), respectively.

In many ways, evolution of forest and agroforestry systems in northern Thailand over the last 20 years appears to be a good example of a HCSRD pathway. The proportion of farmland increased from 11 to 27 % in this period, largely through expansion of traditional agriculture within forests. Traditional agriculture is high carbon, mostly complex agroforests of jungle tea (*Camellia sinensis L.*) embedded



INCREASE OF MONOCULTURE TREE COVER VS LOSS OF CLOSED CANOPY-FOREST 1990-2000

INCREASE OF MONOCULTURE TREE COVER VS LOSS OF CLOSED CANOPY-FOREST 2000-2005

A: In the 1990's loss of natural cover increased the amount of 'low C-stock'/low economic value land; tree (crop) planting was 28% of the loss of natural forest area

B: After 2000 planting of tree (crop)s equals 90% of concurrent loss of natural forest; the amount of low C-stock/low economic value land decreases

Fig. 4 Spatial illustration of developments in tree-based systems in Indonesia in the 1990s and 2000s (Source: Ekadinata et al. 2011)

in hill evergreen forests (also known as "miang"). Though variations exist among ethnic groups, the trend has been toward gradual transformations of miang by substituting fruit trees and seed crops for many of the forest and tea tree species. There has also been active reforestation by government and communities, such as in the context of the Sam Mun Project, where the Forest Department was able to reforest 4,855 ha (out of 200,000 ha) in the area. A further 60,000 additional ha were regenerated by villagers through mutual agreement in a land use planning process in which communities were given mandate to control access, use fires, and other factors (Suraswadi et al. 2005).

Recent analysis of historical and ongoing swidden transformations in Indonesia by the ASB Partnership (van Noordwijk et al. 2008)[7] suggests that there has been strong agrarian transformation but also differentiation within the country, with major parts of Java and Sumatra moving out of shifting cultivation and into permanent cropping before 1990 and the province of Papua still mostly relying on swiddens. Swiddens usually occur in landscapes with high forest cover and low population density. An important shift in the dynamics of swidden systems occurs if trees in the fallow vegetation gain major economic importance. This has happened in the case of the development of rubber, oil palm, and mixed fruit-tree agroforests. In Sumatra, smallholder oil palm production is an emerging economic activity, while in Kalimantan, companies are making deals with local communities to establish oil palm monoculture systems.

Figure 4 shows that the nature of tree-based land use has changed in Indonesia between 1990–2000 and 2000–2005. An index of tree-based land use was created for each district of Indonesia, calculated as the ratio of increased monoculture tree cover to the area of loss of closed canopy forest. An index less than zero implies that monoculture tree cover reduced in area, an index between 0 and 1 indicates an increase in monoculture tree cover that was less than the loss of closed canopy forest, while an index greater than one indicates an increase in monoculture tree cover that exceeded the loss of closed canopy forest. Figure 4a shows that most districts in Indonesia experienced reductions in overall tree cover between 1990 and 2000, while Fig. 4b shows that most districts experienced increases in overall tree cover between 2000 and 2005 (Ekadinata et al. 2011)[8]. The nature of the tree transition clearly changed between the two time periods, with the latter period showing more evidence of HCSRD.

Tree-Based Agrarian Transformation in Africa

In Africa, like much of Southeast Asia, trends and directions of agrarian change are only indicative, with current evidence being largely drawn from case study narratives/analyses rather than coarse large-scale empirical studies. Nonetheless these analyses suggest that tree-based and managed agroforestry systems are beginning to emerge at some scale. In a recent analysis of developments in sustainable intensification in Africa four cases were reported of developments in agroforestry and soil conservation on over 3 million ha in Burkina Faso, Cameroon, Malawi, Niger, and Zambia (Pretty et al. 2011). Two distinct categories of developments in agroforestry systems were reported – agrarian change through the adoption of nitrogen-fixing trees, for example, *Tephrosia and Calliandra* in Malawi, Zambia, and Cameroon (Ajayi et al. 2007), and change through the introduction of fruit and timber trees in agroforestry systems in Tanzania and Kenya (Jama and Zeila 2005)[9]. Another impressive case is the transformation of the Sahel through increased tree planting in parkland systems in Niger and Burkina Faso. For example, in the Zinder and Maradi regions of Niger, there has been a 10- to 20-fold increase of shrub and tree cover over an area of over 5 million ha and more than 200 million trees protected and managed (Reij and Smaling 2008; Sendzimir et al. 2011). This has helped reclaim degraded lands, enhanced soil fertility, improved biodiversity, and generated income and livelihood benefits. The landscape transformation in Niger was enabled by a strong policy shift in tree tenure following reforms. Until the mid 1980s, trees were declared to be owned by the state and therefore people had little or no incentive to plant and care for them. Tenure reform strengthened farmers' rights to trees. Restoration of tree cover has also happened at a large scale in western Tanzania through the re-emergence of the ngitili system of pasture management (Pye-Smith 2010).

In West and Central Africa, cacao (*Theobroma cacao* L.) agroforestry systems continue to dominate the agricultural landscape, currently occupying about 5 million ha in the Guinea and Congo humid forest zones. Cacao cultivation continues to expand into the western region of Ghana and the Bas Sasandra region of Côte d'Ivoire – with projected growth in 2005 of 125,000 ha year^{-1} (Gockowski and Sonwa 2011). Oil palm is now emerging as a growing subsector and could soon overtake cacao. There is evidence that the main drivers of cacao plantation expansion in Cameroon are economic boom-and-bust cycles, international cocoa prices, and labor availability (Sunderlin et al. 2000). These cacao systems range from full-sun monospecific systems to complex cacao-timber-medicinal agroforestry systems – see Fig. 5. Full-sun systems are found mostly in the lower Guinea forest systems in Liberia, Ghana, Côte d'Ivoire, and Nigeria, while the more complex systems are mainly

Fig. 5 Multistrata cacao (*Theobroma cacao* L.) agroforestry systems in Cameroon

found in Cameroon and the Congo Basin countries. Complex systems have biodiversity values nearly equivalent to secondary forests (Gockowski and Sonwa 2011), with non-cocoa products accounting for 23 % of total revenue. Adding tree species to full-sun cacao systems would improve shade to between 30 and 40 % (low shade) and optimize yield. However, when tree cover is increased beyond 30–40 %, as in multi-story cacao systems that promote biodiversity, yield decreases, and so other benefits are needed to offset the cost of increased shade. For these systems to be economically viable to farmers, they must generate income comparable to full-sun systems. By sequestering carbon as well as optimizing production, a low-shade system stores new and additional carbon that would not be generated under a low-shade system. Financial incentives might be devised to account for the carbon and biodiversity benefits of higher shade systems. However, input, organizational, and marketing challenges abound to constrain such transitions.

Discussion and Conclusions

From the foregoing, it can be seen that agrarian transformations in both Southeast Asia and Africa have been different both in terms of nature and speed. There has been rapid adoption of more profitable and valuable tree-based systems in Asia (e.g., rubber, oil palm, orchards, and teak (*Tectona grandis* L.) plantations) as opposed to expansion in traditional cacao systems and management of trees in the parklands of Africa. These land use transitions have been largely influenced and woven into the broader economic trends and dynamics of each region. It can be said that better market access and connections to processing and industry in growing urban areas, dynamics in labor migration (rural–urban), and investment flows through remittances from urban areas have characterized the transformations that have occurred in Southeast Asia (Cramb et al. 2009; van Noordwijk et al. 2008). The slower pace of agrarian transformation in Africa has in several instances matched the boom-and-bust cycles of economic development (Sunderlin et al. 2000). Very weak extension systems, lack of inputs, poor physical and market infrastructure, lack of capital, and weak enabling policy environments have characterized this transformation in most of Africa, although there have been exceptions (Jama and Zeila 2005; Gockowski and Sonwa 2011). A glaring example of these differences can be seen in the rapid growth in Vietnam's coffee production compared to the stagnation (and failings in some cases) observed in Africa and other regions of the world (Greenfield 2009)[10].

Thus, rural development pathways that result in landscapes dominated by tree-based/agroforestry systems are about rural and economic development that yields corresponding co-benefits for sustainable development and climate change mitigation. High-carbon development pathways are about adding value (both economic and environmental) to land and the opposite of land degradation pathways that reduce those values. In Africa, there is potential to leverage carbon and climate adaptation finance to meet the financing gaps that impede the development of these systems. There is also a rights policy agenda around tree and carbon tenure that provides the opportunity to bring the kind of shift that was experienced in Niger to enable the transformation of landscapes into high carbon, high-economic value landscapes.

However, there are challenges that must be kept in mind when moving in this direction. The majority of these challenges relate to understanding and managing trade-offs in the development of high C development pathways. First, there is evidence that a focus on high value monoculture tree plantation systems could deliver high incomes but leave farmers exposed to high levels of risk from global price fluctuations (Greenfield 2009) and/or endanger farmer food security (Cramb et al. 2009). Due consideration needs to be given to multipurpose tree-based systems that can help spread risks and hence reduce vulnerabilities. Second, most high-carbon and high-profit tree systems take 3–5 years to recoup initial investments compared with food crop systems. Such long waiting periods can be prohibitive for small-scale farmers, thus representing the same kind of up-front financial requirements that have inhibited the development of clean development mechanism projects. Investments might also be required to support the development of alternative income-generating activities if and when high-carbon systems are adopted as part of a low-carbon development strategy within the land use sector. Specific financial incentives could help high-carbon options to succeed, advancing the multiple objectives of carbon storage, biodiversity conservation, and poverty alleviation.

Thirdly, there are concerns that rural households could lose access to the natural products from forest fallow fields during the intermediate stages where swidden systems shift to more permanent forest cover. Little is known about the environmental costs and benefits of changes in the traditional systems and landscapes and indeed what policy options might better optimize benefits. Further research could be very instructive for the future development of HCSRD strategies. There may be advantages to whole landscape approaches where forest reserves are managed through community forestry or co-management regimes, alongside other multiple land uses. The fourth challenge relates to the development of an enabling policy environment. Tree tenure policy and market infrastructure are extremely important to farmer incentives to plant and maintain tree-based systems. The Vietnam coffee example shows how an effective export-oriented policy model can overcome global instabilities in the coffee sector (Greenfield 2009), while the Niger example shows how a simple policy change can catalyze agrarian change through tree-based systems which have otherwise been documented to inhibit the same in Africa and Asia (Ruf 2011; Santos-Martin et al. 2011). Lastly, promoting public and private investments and investing in improvements in extension services for HCSRD would need urgent and sustained attention. Remittances from urban areas in Southeast Asia have proven to be a vital investment lifeline for the development of smallholder tree-based systems (van Noordwijk et al. 2008). Similarly, investments in viable extension services and the tree product value chain have driven Vietnam's coffee boom over the last two decades (Greenfield 2009). Only by addressing these challenges carefully can Africa and other developing regions begin the high-carbon-stock rural-development journey and eventually toward a low-carbon and green economy.

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Tree Domestication in Agroforestry: Progress in the Second Decade (2003–2012)

Roger R.B. Leakey, John C. Weber, Tony Page, Jonathan P. Cornelius, Festus K. Akinnifesi, James M. Roshetko, Zacharie Tchoundjeu, and Ramni Jamnadass

Abstract More than 420 research papers, involving more than 50 tree species, form the literature on agroforestry tree domestication since the 1992 conference that initiated the global programme. In the first decade, the global effort was strongly led by scientists working in humid West Africa; it was then expanded to the rest of Africa in the second decade, with additional growth in Latin America, Asia

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(mostly SE Asia) and Oceania. While the assessment of species potential and the development and dissemination of techniques for improved germplasm production were the principal activities in the first decade, the second decade was characterized by a growing research agenda that included characterization of genetic variation using morphological and molecular techniques, product commercialization, adoption and impact and protection of farmers' rights. In parallel with this expanding research agenda, there was also an increasing use of laboratory techniques to quantify genetic variation of the chemical and physical composition of marketable products (e.g. essential oils, food-thickening agents, pharmaceutical and nutriceutical compounds, fuelwood). Looking to the third decade, suggestions are made for further development and expansion of both the science to underpin agroforestry tree domestication and applied research in support of development programmes to enhance the livelihoods of poor smallholder farmers worldwide.

Keywords Commercialization • Genetic variation • Germplasm • Livelihoods • Propagation • Smallholders

Introduction

The 'International Year of Forests' (2011) is an appropriate time to reflect on progress since the 1992 Conference in Edinburgh, UK, on '*Tropical Trees: The Potential for Domestication and the Rebuilding of Forest Resources*' (Leakey and Newton 1994). That international conference was the first to specifically discuss the potential of tree domestication to improve the livelihoods of poor smallholders in the tropics by rebuilding the resource of tree species on which hunter-gatherers had relied. The concept of domesticating specific tropical tree species had been around for a few years before this time (e.g. Clement 1989; Holtzhausen et al. 1990). However, it was the Edinburgh conference that enunciated the vision of how the improvement and cultivation of these overlooked and underutilized 'Cinderella' species could play a critical role in rural development. That was the beginning of what has become a global multidisciplinary research initiative to use agroforestry for the alleviation of malnutrition and poverty in the tropics. This has now been seen as the start of a second wave of domestication to address the needs of societies in the developing world (Leakey 2012a, b).

The early concepts of tree domestication for agroforestry were rooted in traditional knowledge about the utility of forest species (e.g. Abbiw 1990) and in ethnobotany (e.g. Cunningham 2001), especially with regard to the nutritional value of indigenous fruits. From an initial focus on about six traditionally important tree species, the international literature of more than 420 research papers has grown to include more than 50 species. This information has been collated (Table 1) to illustrate the growth and evolution of agroforestry tree domestication.

Table 1 Summary of research topics published in the first two decades (*1* = 1992–2002 and *2* = 2002–2012) of agroforestry tree domestication worldwide

	Global		Africa		Humid West Africa		Sahel		Southern Africa		East Africa		Latin America		Asia		Oceania		Total		
Research topic	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1 + 2
Domestication concept	7	4	–	–	–	1	1	2	1	1	–	–	–	1	1	–	–	–	10	9	*19*
Domestication strategy	4	5	–	–	2	3	–	–	–	5	2	–	6	7	1	5	1	1	16	26	*42*
Propagation and germplasm	4	2	–	–	7	13	4	7	4	11	–	1	–	4	3	7	1	0.5	23	45.5	*68.5*
Species potential	–	–	–	2	14	5	6	7	8	1	2	3	3	5	1	–	3	9	37	32	*69*
Genetic characterization	–	1	–	–	8	7	3	14	4	5	–	–	–	13	–	–	1	4.5	16	44.5	*60.5*
Morphological molecular	–	1	–	4	2	2	–	8	–	3	1	2	3	3	–	–	–	–	6	23	*29*
Reproductive biology	–	–	–	–	3	1	–	2	–	–	–	2	–	–	1	–	–	–	4	5	*9*
Nutritional benefits	1	–	–	2	4	2	1	5	2	–	1	–	2	2	–	–	–	1	11	12	*23*
Product evaluation and development post-harvest	–	–	–	–	15	1	–	–	–	4	–	–	–	–	–	–	–	–	15	5	*20*
Participatory imple mentation on-farm	–	–	–	–	1	3	–	–	–	–	–	1	1	–	–	–	–	–	2	4	*6*
Agroforestry enrichment	2	2	–	–	–	–	1	–	1	3	–	8	–	4	1	–	–	–	5	17	*22*
Socio-economic issues	–	–	–	–	5	3	1	3	2	4	–	–	–	1	1	–	–	–	9	11	*20*
Commercial issues	3	–	–	1	2	2	2	–	2	4	–	–	2	–	1	2	–	1	12	10	*22*
Ecology	–	–	–	–	–	5	–	–	5	4	–	–	–	–	–	–	–	–	5	9	*14*
Adoption and impact	1	2	–	–	–	2	–	–	–	–	–	–	–	–	–	–	–	–	1	4	*5*
Policy	3	–	–	–	–	–	–	–	–	5	–	–	–	–	–	–	–	–	3	5	*8*
Total	25	17	–	9	63	44	19	53	29	50	6	17	17	40	10	14	6	17	172	252	424
Total per region	42		9		107		72		79		23		57		24		23		424		

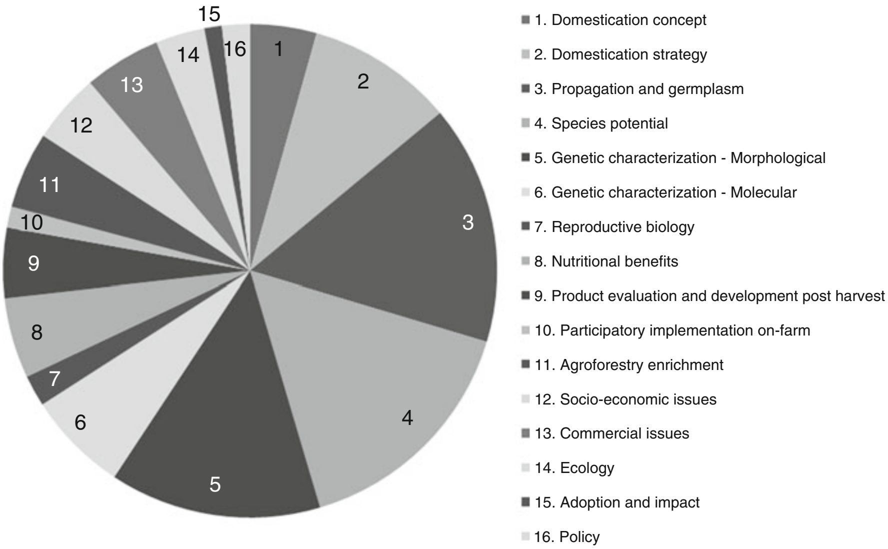

Fig. 1 The domestication of agroforestry tree species – by research topic (1992–2012) based on the number of published research papers

In this chapter we demonstrate how tree domestication has evolved temporally and spatially over the last two decades to become an important global programme. We then highlight some recent developments that enhance the capacity of agroforestry tree domestication to have meaningful impacts on the livelihoods of smallholder farmers around the tropics.

The First Decade (1992–2002)

The early history of agroforestry tree domestication has been reviewed in detail elsewhere (Leakey et al. 2005a; Akinnifesi et al. 2008) and is only summarized here. Agroforestry tree domestication research started in the humid zone of West and Central Africa on several fronts; however, the dominant areas of work were the assessment of species potential, the propagation techniques and the variation in fruit and nut morphology (Figs. 1 and 2). This set the pattern which was later followed in other regions, with or without the World Agroforestry Centre (ICRAF).

ICRAF's tree domestication programme began with a participatory species priority setting exercise with rural households (Franzel et al. 1996) which resulted in a subsequent initial focus on the indigenous fruit trees *Irvingia gabonensis* Baillon and *Dacryodes edulis* (G. Don) H.J. Lam in Cameroon and Nigeria. Parallel studies in the Congo, outside the ICRAF programme, examined the potential of post-harvest product processing (Mbofung et al. 2002; Kapseu et al. 2002). From the start, the interest of poor smallholder farmers in wild fruits and nuts directed the implementation

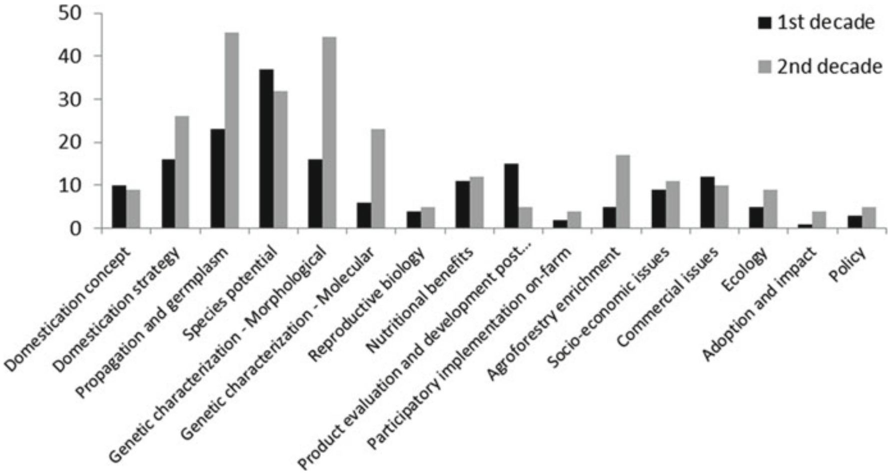

Fig. 2 The domestication of agroforestry tree species by research topic – comparison of 1992–2002 (first decade) with 2003–2112 (second decade) – based on the number of published research papers

of the programme. This led to the emergence of a tree domestication strategy that recognized the capacity of vegetative propagation to capture phenotypic variation amongst individual fruit and nut trees (Simons 1996: later refined by Leakey and Akinnifesi 2008) and the use of simple low-technology polythene propagators (Leakey et al. 1990). These propagators are particularly appropriate for use in remote locations because they do not require running water or electricity.

Based on this strategy, priority setting exercises were subsequently implemented in southern Africa and the Sahel (Franzel et al. 2008; Faye et al. 2011) and Amazonia (Weber et al. 2001). In these regions rural communities expressed interest in species for timber, fodder, medicines and fuelwood, in addition to local fruits and nuts. Much later, this model was also implemented in the Solomon Islands (Pauku et al. 2010).

In West and Central Africa, much of the work in the first decade (Table 1) was associated with the development of village nurseries (Tchoundjeu et al. 1998), the collection and dissemination of germplasm and the refinement of vegetative propagation techniques developed for tropical timber trees. These techniques then had to be augmented with better methods of marcotting so that sexually mature tissues with the existing capacity to flower and fruit could be propagated. The mature material creates cultivars which will start to yield within 2–3 years, while they are still small trees. This makes the cultivation of fruit trees much more attractive to farmers who want quick results from their investment of time and effort.

Before using vegetative propagation to develop cultivars, it is necessary to have some understanding of the extent and patterns of phenotypic variation in wild tree populations. Therefore, detailed studies were made of the tree-to-tree variation in morphological traits (fruit size, shape, colour, etc.) within and between villages (e.g. Atangana et al. 2001). This confirmed that the phenotypic variation in all the species studied was very extensive (three- to ten-fold) and continuous – i.e. not clustered into groups that could be considered to be genetic varieties. Importantly, most of this variability was found within individual villages. These results confirmed the appropriateness of village-level tree domestication, both from the point of view of giving individual farmers access to the full set of useful variation and that of minimizing the loss of genetic diversity often attributed to domestication activities.

Socio-economic studies of village communities found that farmers were taking an increasing interest in the cultivation of a mixture of indigenous and exotic fruit tree species (Schreckenberg et al. 2002), and that indigenous fruits were important at the household level for domestic consumption, as well as being a source of income based on local marketing. Parallel work in the Congo continued to provide a better understanding of product development, particularly nutritive value, oil extraction, post-harvest processing and the properties of *D. edulis* oil (Kapseu et al. 2002; Mbofung et al. 2002).

It also became clear from this early research that market price was not determined by fruit/nut size and morphology alone, but rather that the flavour and chemical composition of fruits and nuts contributed to consumer preference for the fruits of certain trees. This was confirmed by organoleptic studies (Kengni et al. 2001) and physico-chemical analyses (Leakey et al. 2005b). However, while market stallholders (retailers) recognized consumer preferences for the products of certain trees, wholesalers did not. Thus, farmers selling a wide range of unselected fruits in mixed batches were not the beneficiaries of consumers' willingness to pay higher prices for desirable fruits. This lack of discrimination by traders emphasizes the potential benefit for farmers to produce and market-specific varieties based on selected domesticated cultivars.

Work in humid West Africa in the first decade set the pattern that was subsequently adapted for species in other regions, including the Peruvian Amazon, southern Africa and the Sahel. By contrast, the participatory process in Southeast Asia identified priority topics to advance smallholder tree domestication research as well as a long list of priority species for the region's various biophysical, socio-economic and farming conditions. Priority topics for smallholder tree domestication were access to tree germplasm through its multiplication and dissemination; development of tree propagation, nursery techniques and silvicultural practices; expansion of species diversity and improved management in agroforestry systems; market integration; and improved agroforestry information and training (Roshetko and Evans 1999).[1] Subsequent research gave special attention to *Gliricidia sepium* (Jacq.) Kunth ex Walp. (Roshetko et al. 1999; Mangaoang and Roshetko 1999) and *Eucalyptus* species (Bertomeu and Sungkit 1999).

The Second Decade (2003–2012)

The basic concepts, techniques and strategies developed in the first decade have been endorsed in the second decade and used for a wider range of species, environments and sites (Table 1, Figs. 3 and 4). Additionally, they have been modified as

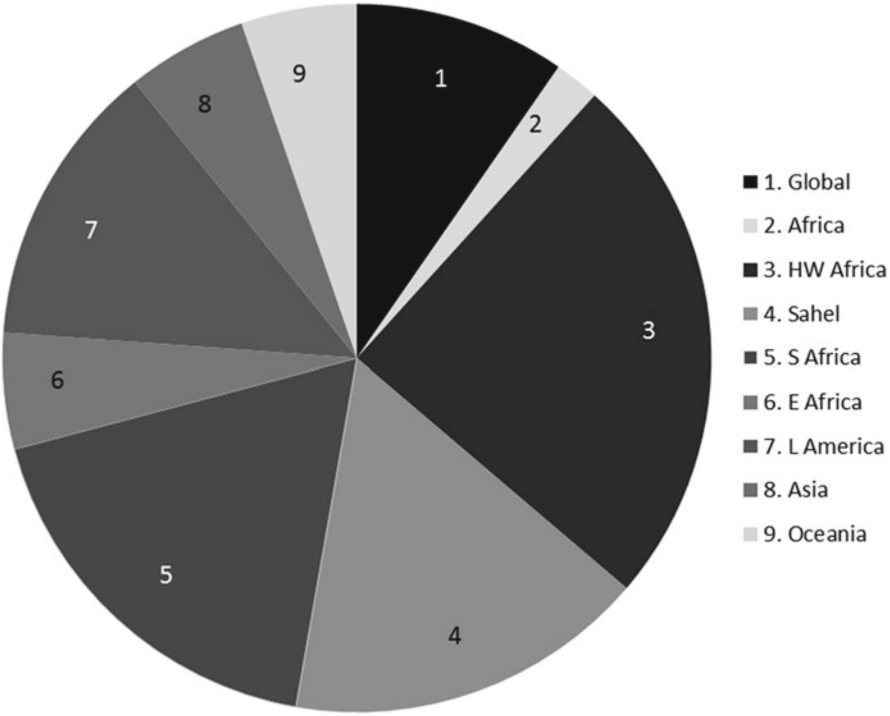

Fig. 3 The domestication of agroforestry tree species by region (1992–2012) – based on the number of published research papers

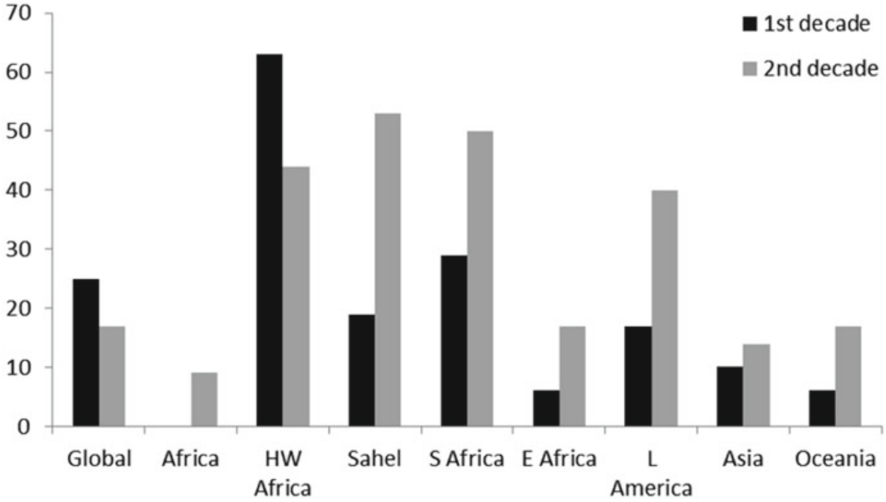

Fig. 4 The domestication of agroforestry tree species by region – comparison of 1992–2002 (first decade) with 2003–2012 (second decade) – based on the number of published research papers

required by local biophysical, ecological and social conditions and applied in the Sahel, the woody savannah of southern Africa, Amazonia and in some small Pacific islands of Oceania.

The Humid Lowlands of West and Central Africa

Indigenous fruits are important at the household level, as well as being an important source of income (Schreckenberg et al. 2006). In the humid tropics, indigenous trees have many potential on-farm niches, but the importance of shade for the cocoa (*Theobroma cacao* L.) and coffee (*Coffea* spp.) crops creates a great opportunity to increase the profitability of these cash-cropping systems by using indigenous trees that produce marketable products as the shade trees. Through domestication of these trees, this multistorey system becomes a productive agroforest. The cultivation of domesticated agroforestry trees converts these indigenous trees into new crops, and consequently, their marketable products become farm produce instead of being common property forest resources. To signify this important distinction, the description of these products as non-timber forest products (NTFPs) was changed to agroforestry tree products – AFTPs (Simons and Leakey 2004).

As part of the domestication process, the tree-to-tree variation in traits affecting yield and quality of fruits and nuts was quantified. From this it became clear that a large fruit is not necessarily a tasty fruit and may not have a large or useful nut. Thus, to select trees for cultivar development by vegetative propagation, the concept of an ideotype was modified so that the desirable combination of different traits to produce a cultivar targeting a particular market opportunity could be visualized (Leakey and Page 2006). Building on this ideotype, a range of different tree species have now been characterized for traits such as food-thickening agents (drawability and viscosity in *I. gabonensis* – Leakey et al. 2005b) and fatty acid profiles (stearic and oleic acids in *Allanblackia* spp. – Atangana et al. 2011).

Another outcome of the morphological characterization was a technique based on the frequency distribution of the data for any particular trait, which quantifies the stage of domestication that has been reached by the farmers' own selections for the most desirable trees. This revealed that, in some Cameroonian villages, out of the five stages of domestication (Leakey et al. 2004) *D. edulis* is at stage 2, while the same is true for *I. gabonensis* in Nigeria. It is therefore clear that farmers are interested in the domestication of their indigenous food species but lacked the knowledge to achieve this other than by the slow route of sexual recombination. Consequently, when ICRAF researchers and their local national research partners approached farmers about the initiation of a programme of participatory tree domestication, the farmers were enthusiastic (Tchoundjeu et al. 2006, 2010). This programme has now expanded from a few farmers in two pilot villages to over 10,000 farmers in more than 200 villages (Asaah et al. 2011).

Village-level participatory domestication is dependent on simple and robust techniques of vegetative propagation. The development and refinement of these techniques have been ongoing processes involving an increasing number of species.

This process is helped by the formulation of some basic principles which apply to most, if not all, species (Leakey 2004). These principles are particularly useful when domestication activities are centred on difficult-to-propagate species like those in the genus *Allanblackia*.

The initial focus on fruit and nut trees in this region has been expanded to include over-exploited medicinal species, especially *Prunus africana* (Hook. f) Kalkman*, Pausinystalia johimbe* (Schumann) Beille and *Annickia chlorantha* Oliv., whose barks are used to treat prostate enlargement, cardiac disease and malaria, respectively. Johimbe (*P. johimbe*) is also an aphrodisiac. The cultivation of these species as herbal medicines for local use is relatively simple, but their domestication for the production of internationally marketed drugs needs to involve industrial partners. This is further complicated by competition from synthetic drugs.

The Drylands of the Sahel

Rural communities in Burkina Faso, Mali, Niger and Senegal value more than 115 indigenous tree species for the livelihood benefits of their products and services (Faye et al. 2011). The 'parkland' is the most common agroforestry system in these countries and combines crops, trees and livestock. Farmers maintain several indigenous tree species in the parklands for food (e.g. *Adansonia digitata* L., *Parkia biglobosa* (Jacq.) Benth., *Vitellaria paradoxa* C.F. Gaertn., *Ziziphus mauritiana* Lam.); dry season fodder (e.g. *Balanites aegyptiaca* (L.) Del., *Faidherbia albida* (Del.) A. Chev., *Pterocarpus* spp.); wood for fuel, construction, household and farm implements (e.g. *B. aegyptiaca*, *Combretum glutinosum* Perrott. ex DC., *Guiera senegalensis* J.F. Gmel., *Prosopis africana* (Guill. & Perr.) Taub.); medicines; and environmental services such as shade, soil fertility improvement and soil/water and conservation. The sale of these products contributes 25–75% of annual household revenue in Mali (Faye et al. 2010), with some having international markets.

The provision of human and animal food is particularly important during the peak of the long dry season. Consequently, rural communities in the driest areas of the Sahel use significantly more species than those in wetter areas because this maximizes the chance that at least one species will provide products/services even in a dry year. Therefore, tree domestication programmes are focusing on the specific priorities of different regions and diversifying the number of species for each product and service.

To enhance dry season fodder production, fodder banks of exotic (e.g. *G. sepium* from Central America) and indigenous (e.g. *Pterocarpus erinaceus* Poiret) species were developed within thorny hedges for protection from livestock. These fodder banks have considerable economic importance with small bundles of shoots fetching good prices in local markets. The fodder trees have been propagated by both seed and vegetative propagation (Tchoundjeu 1996; Tchoundjeu et al. 1997). Likewise, both approaches have been used for fruit trees, especially those that are difficult to propagate by cuttings (e.g. *V. paradoxa*).

With international markets for indigenous fruits and nuts such as shea butter (*V. paradoxa*) and *B. aegyptiaca*, oil quality is important. In order to improve quality by genetic selection, studies have been made of phenotypic variation in fruit/seed traits across the Sahel. These have found significant variation both amongst and within provenances (Abasse et al. 2011; Ræbild et al. 2011). For example, fruit and/or kernel size is greater in more humid sites for *A. digitata* and *V. paradoxa* but in drier sites for *B. aegyptiaca*. This variation offers great potential for future selection and domestication. For example, fruits of baobab (*A. digitata*) are very rich in vitamin C, calcium and magnesium, while its leaves contain vitamins C and A. In addition, characterization studies of morphological variation in fruit and seed traits of *A. digitata* in Mali have found considerable potential for selection of trees with superior pulp mass and also with high pulp:seed ratios (De Smedt et al. 2011). Baobabs occur throughout dry Africa, so evidence that trees from Mali and Malawi differ in pulp percentages, seed size and shape illustrates even greater potential for selection in different countries across the continent (Sanchez et al. 2011). The potential gains from this selection will become apparent from ongoing provenance tests (Kalinganire et al. 2008). To further explore the extent of genetic variation in shea nut (*V. paradoxa*) and baobab (*A. digitata*), molecular techniques have been used (Jamnadass et al. 2009). In the latter, superior morphotypes were not genetically related varieties, suggesting that the development and use of a many clonal cultivars could maintain considerable genetic diversity.

As there are strong latitudinal and longitudinal gradients in mean annual rainfall in the Sahel, provenance/progeny tests are being used to compare the performance of germplasm collected from sites across these gradients. Results from tests of *B. aegyptiaca* and *Prosopis africana* indicated that provenances from drier sites had significantly better aboveground growth than provenances from more humid sites when tested at a relatively dry site (Weber et al. 2008; Weber and Sotelo Montes 2010). In addition, wood density of *Prosopis africana* and calorific value of the wood of both species also varied along the rainfall gradients (Sotelo Montes and Weber 2009; Sotelo Montes et al. 2011). Based on these tests, it is recommended that germplasm should be collected in the drier sites for future plantings in parklands, especially as this germplasm appears to be better adapted to dry conditions.

As part of a participatory tree domestication programme, rural communities in Burkina Faso, Mali and Niger are establishing provenance/progeny tests of several species for fruit, wood, fodder and medicines (e.g. *A. digitata*, *F. albida*, *G. senegalensis*, *P. biglobosa*, *Prosopis africana*, *V. paradoxa*) in their parklands to compare the performance of their local germplasm with germplasm collected in drier sites (J. C. Weber, personal communication, 2011). The tests will provide basic information about drought adaptation and variation in commercially important traits under farmer-managed conditions. In addition, it is expected that the introduced genes from the drier sites will increase the drought adaptation of the natural regeneration in the parkland species.

Studies are underway to determine if fuelwood properties of trees in natural populations vary with rainfall gradients. In Mali, for example, fuelwood properties were better for *B. aegyptiaca*, *C. glutinosum* and *Piliostigma reticulatum* (DC.) Hochst. in drier regions, worst for *Z. mauritiana* in the drier regions and good for *G. senegalensis* in both humid and dry regions in Mali (C. Sotelo Montes, personal communication, 2011). Since the climate is becoming hotter and drier in the Sahel than before, these studies could be used to identify the best regions, species and germplasm for fuelwood production in parklands as part of climate change adaptation planning (Nair 2012).

Woody Savannah of Southern Africa

The Miombo woodlands are rich in edible indigenous fruit trees, for example, *Sclerocarya birrea* (A. Rich.) Hochst., *Strychnos cocculoides* Baker, *Uapaca kirkiana* Muell. Arg., *Vangueria infausta* Burch., *Parinari curatellifolia* Planchon ex Benth., *Z. mauritiana* and *A. digitata,* many of which are traded in the region. However, land clearance for maize (*Zea mays* L.) and other staples has severely reduced their availability in Malawi, Zambia and Zimbabwe. In contrast, some of these fruit trees like *S. birrea* are commonly found as much appreciated scattered trees in parklands, as in northern Namibia. Due to the local knowledge about these traditionally and culturally important species, the domestication strategy that has been adopted is based on the premise that farmers have adequate knowledge of the natural variability in fruit and kernel traits to be able to locate and identify superior trees in the wild for themselves. Thus, farmers have been trained in techniques of germplasm collection, nursery management, propagation, tree cultivation and post-harvest processing. As the seeds of many of these species have short viability, their collection and germination have to be rapid.

Market research has indicated that traders want a consistent and regular supply of uniform fruits of good quality. Wild fruits do not meet these criteria. Domestication is the best way to achieve uniformity and superior quality. By selecting the best trees in wild populations and then multiplying them vegetatively, large numbers of genetically identical trees (cultivars) can be produced for cultivation in farming systems. As the use of cuttings has been found difficult in Miombo trees, the other options are grafting, budding and marcotting. These techniques are especially appropriate for fruit trees as they allow already mature trees to be propagated. Experiments have found that while marcotts are very effective, they seem to suffer from fruit bud abortion (Akinnifesi et al. 2009), and so experience suggests that grafting is the most appropriate option in *A. digitata, U. kirkiana, S. birrea* and *V. infausta*, while budding has been found to be best for *Z. mauritiana*. Both these techniques require a large supply of seedlings which are then used as the rootstock to which the desired mature scion or bud is attached. This necessitates seedlings with stems the same diameter as the mature scions. To achieve this, the seedlings of *U. kirkiana*, for example, normally have to be at least 2 years old, but this has been reduced to 10 months with intensive nursery management (Mhango et al. 2008). Experience and experiment have found that successful grafting is affected by the experience and skill of the grafter.

The selection of the mother trees can be based on farmer experience or on scientific assessment of the tree-to-tree variation within wild populations. The former is appropriate within village-based participatory domestication programmes, while the latter is beneficial to develop understanding of the range of traits that can be selected to maximize market appeal. This latter approach was implemented in South Africa and Namibia with *S. birrea*, which has numerous potential market opportunities for fruits, nuts, kernel oil and several alcoholic beverages (Leakey 2005). Other studies have been done with *U. kirkiana* and *S. cocculoides* in Malawi, Zambia and Zimbabwe (Akinnifesi et al. 2006). Enhanced acceptability and market demand are expected to serve as an incentive for farmers to domesticate their indigenous tree species.

The second way to boost and maintain the market demand is a focus on post-harvest quality and shelf life. Detailed studies have been made of the effects of fruit-handling procedures (blanching, drying, handling and storage) on fruit colour, bruising, durability, etc. in *U. kirkiana* (reviewed by Saka et al. 2008). These studies included assessments of nutritional quality of fruits, product processing, certification and on-farm economics.

In the case of *S. birrea,* a large multidisciplinary project has examined the potential winners and losers from the domestication and commercialization of this fruit tree in Namibia and South Africa. Commercialization activities in the region are both top-down for ‘Amarula’ liqueur and bottom-up by the ladies of the mineworkers union for fruit juice and kernel oil sold to commercial companies. While potentially the top-down approach might be expected to have negative impacts on the livelihoods of local people, this was not found to be the case, as Distillers Corporation buys fruits directly from community vendors. This finding has important policy implications regarding the development of appropriate models for production, marketing, protection of farmers’ rights and traditional knowledge and rural development (Wynberg et al. 2003). In Namibia, other interesting arrangements in the form of trade agreements between community producers and commercial companies both in the region and overseas have provided the prospect of protecting local communities from commercial exploitation (Lombard and Leakey 2010) and greatly expanding markets for products from indigenous species grown by smallholders.

The demand for seed of tree legumes used in soil fertility restoration and as fodder trees in Malawi has led to the development of Community Agroforestry Tree Seed Banks to produce and distribute improved germplasm to farmers (Nyoka et al. 2011). During 2006–2011, these have distributed nearly 50 t of tree seeds, so overcoming one of the biggest constraints to farmer adoption of agroforestry.

East Africa

There is an active tree planting culture amongst small-scale farmers in the East African highlands where a range of exotic and indigenous species are cultivated for fodder, poles, fuelwood, timber and fruits. However, most of the fruit trees are exotics like mango (*Mangifera indica* L.) and avocado (*Persea americana* Miller). This reflects the paucity of indigenous species with potential in the highlands – with the notable exception of *Prunus africana*, an important medicinal tree, which is restricted to Afromontane islands above 1,500 m throughout sub-Saharan Africa. This tree is heavily exploited for its bark, resulting in unsustainable harvesting practices. As the active ingredient in the bark is not known, domestication activities have been limited to improving the seed supply and the assessment of genetic diversity. Another species is *Warburgia ugandensis* Sprague, a multipurpose tree found in the lowland rainforest and upland dry evergreen forest of eastern Africa between 1,000 and 3,000 m. It is widely used by the local communities to cure diseases like measles and malaria. Stem and root barks are harvested for herbal remedies. Overharvesting of the bark and illegal felling of trees in protected natural forests, as well as encroachment of their natural habitat for farming and human settlements, threaten the species survival and conservation. Molecular analyses of both these species have determined that populations to the east and west of the Rift Valley are genetically distinct (Muchugi et al. 2006, 2008). This geographic variation has implications for strategies of germplasm collection and use and perhaps even for genetic characterization and selection with regard to the levels and quality of the medicinal compounds. It may also be relevant to drought responses arising from climate change.

Despite the large number of indigenous species grown by smallholders in the highlands of East Africa, few have been nominated for intensive domestication; consequently, domestication activities have been focused on the provision of seed to farmers. This addresses the major problem that tree seed currently used by farmers is characterized by widespread distribution of inferior seed with an almost complete absence of concern for genetic quality and adaptability of planting material.[2] Prime examples of programmes to reverse this trend are those of *Calliandra calothyrsus* Meissner for fodder and *Sesbania sesban* (L.) Merrill for soil fertility improvement. The development of an informal network for delivering *Calliandra* seed has allowed widespread adoption of dairy cattle and goat fodder production by East African smallholders and is now recognized as one of the best models of seed dissemination (Wambugu et al. 2011). Despite much success, seed/seedling production and distribution systems for good quality germplasm only reach a small proportion of smallholders. Efforts are being made to overcome the disconnection between seed sources, tree nurseries and farmers.

In contrast to the East African highlands, the semi-arid lowlands have a number of important indigenous species. Some such as *Acacia senegal* (L.) Willd., *Boswellia* spp. and *Commiphora* spp. produce high-value gums, while others (e.g. *A. digitata* and *Z. mauritiana*) are foods for local people and livestock (Simitu et al. 2008). Many of these dry zone species are also native to southern Africa and the Sahel.

Latin America

Some indigenous fruit trees of Latin America, such as *Bactris gasipaes* Kunth and *Chrysophyllum cainito* L., are recognized as being semi-domesticated (Parker et al. 2010). ICRAF's domestication research in the Peruvian Amazon focused on studies of genetic variation in four priority species (Weber et al. 2001): *B. gasipaes* for fruit and heart-of-palm, *Calycophyllum spruceanum* (Benth.) Hook. f. ex K. Schum. for construction wood and fuelwood, *Guazuma crinita* (Mart.) for construction wood and *Inga edulis* Mart. for fuelwood and food (fleshy aril of the fruit). Research methods included on-farm tests and molecular genetic approaches.

As a result of selection, domesticated populations typically have lower genetic variation in the selected traits (Cornelius et al. 2006) and perhaps in selectively neutral molecular markers (Hollingsworth et al. 2005; Dawson et al. 2008). Farmers commonly collect germplasm from only a few trees, especially fruit trees, when planting trees on farm (Weber et al. 1997), and this can lead to serious inbreeding problems in subsequent generations (O'Neill et al. 2001). A provenance/progeny test demonstrated that a low-intensity selection strategy can significantly increase tree growth without significantly reducing genetic variation in growth traits in the subsequent generation (Weber et al. 2009). It was recommended, therefore, that farmers select a larger proportion of trees for future planting, even though this will result in less genetic improvement compared with more intensive selection. In addition, since exchange of fruits/seeds amongst farmers from different watersheds can counteract the reduction in genetic diversity due to selection and genetic drift on farms (Adin et al. 2004), domestication programmes should incorporate germplasm exchange pathways within and amongst watersheds.

Understanding variation amongst provenances and gene flow patterns is important for tree domestication and conservation programmes. For example, provenance tests of *C. spruceanum* and *G. crinita* on farms demonstrated that the provenance from the local watershed generally grew better than most non-local provenances when tested in the local watershed (Weber and Sotelo Montes 2005, 2008). Therefore, it was recommended that farmers use the local provenance for on-farm planting unless there was evidence that non-local provenances were significantly better. Some replicates of these on-farm tests were later transformed into seed orchards for production and sale of improved, source-identified germplasm by rural communities. This created a new business opportunity for rural communities as producers of high-quality tree seed for reforestation programmes. In addition, if fruits/seeds are dispersed by rivers, as is the case for *C. spruceanum*, genetic diversity may be greater in populations below the confluence of major tributaries (Russell et al. 1999). For species like this, downstream populations therefore could be targeted for *in* or *circa situ* conservation.

Improving tree growth and wood properties depends on the magnitude of genetic variation in the traits, the heritability of each trait and the correlation between traits. Results from provenance and provenance/progeny tests of *C. spruceanum* and *G. crinita* indicate that (a) there is considerable genetic variation in tree growth and wood properties (density, strength, stiffness, shrinkage, colour); (b) wood traits have higher heritability than growth traits, especially in sites where trees grow rapidly; and (c) correlations differ amongst test sites and provenances (e.g. Sotelo Montes et al. 2006, 2008; Weber and Sotelo Montes 2008; Weber et al. 2011). Therefore, tree domestication programmes can simultaneously improve growth and wood properties of these species by selecting trees within provenances and test environments where the heritability of traits is high and the correlations between desirable traits are positive.

Asia

Most smallholder agroforestry systems in Southeast Asia are characterized by limited proactive management and planning, with species composition and genetic material most often a result of chance or opportunity. The quantity and quality of products are often below the systems' potential (Roshetko et al. 2007). Aptly, the prime focus of agroforestry tree domestication in Southeast Asia has focussed on the development of germplasm for smallholder and community organizations. These had been shown to play an important role in tree seed collection and dissemination but, like the local seed dealers, were not familiar with proper seed collection guidelines (Koffa and Roshetko 1999; Roshetko et al. 2008). Through farmer training and field tests, technically sound farmer-appropriate tree seed collection and farmer seed-orchard guidelines were developed.[3] This led to the establishment of farmer and community tree seed enterprises (Carandang et al. 2006; Catacutan et al. 2008). Capacity-building activities in smallholder nursery management and vegetative propagation skills resulted in the establishment of hundreds of local nurseries[4] and a set of farmer manuals.[5,6] Through a series of participatory on-farm trials, guidelines for farmer demonstration trials were validated (Roshetko et al. 2004b).

Research to improve smallholder timber production has centred in the Philippines, with some activities in Indonesia. Exotic species like *Gmelina arborea* Roxb. are widely planted[7] (Roshetko et al. 2004a); however, the choice of species is often determined by access to germplasm, knowledge/experience of the operator, market demand and the priorities of donors and government agencies (Carandang et al. 2006). In the Philippines, smallholder farmers have become major timber producers, with trees planted and grown on farms an important source of raw materials and income for themselves and the local timber industry. Government statistics show that since 1999 between 50 and 70% of domestic log production came from smallholder on-farm sources. The two most important factors driving this enterprise are a paucity of forests/trees and the existence of market demand for timber. However, poor management practices led to an oversupply of low quality timber and declining prices for farm-grown timber. Consequently, on-farm research has focused on identifying silviculture regimes that are adoptable by smallholder farmers (Bertomeu et al. 2011).[8]

Recently, there has been increased interest in indigenous timber species. Amongst the indigenous species, dipterocarps are important for both timber and non-timber products such as dammar resins and are grown by smallholder farmers in Indonesia, the Philippines and other countries in the region often in complex agroforests in association with cinnamon (*Cinnamomum* spp.), rubber (*Hevea brasiliensis* Muell. Arg.)

and many local fruit and nut tree species. However, seed supply, due to irregular flowering (masting) and short seed viability, poses a serious constraint to large-scale planting. This can, however, be circumvented by the use of vegetative propagation. So far, however, the opportunity to use these techniques to develop cultivars of these local trees has not been taken.

Oceania

A formal tree domestication programme in this region has been led by James Cook University (Agroforestry and Novel Crops Unit) with partners in the Solomon Islands, Papua New Guinea and Vanuatu since 2002. This is a region with many traditionally important nuts, such as *Canarium indicum* L., *Barringtonia procera* (Miers) Knuth, *Inocarpus fagifer* (Parkinson ex Zollinger) Fosberg and *Terminalia kaernbachii* Warburg, which have had great cultural and social significance for millennia. The region also had very significant resources of sandalwood (*Santalum* species), valued internationally for its scented heartwood, and other valuable export timbers such as *Endospermum medullosum* L. S. Smith, *Instia bijuga* (Colebr.) O. Kuntze, *Pterocarpus indicus* Willd. and *Terminalia catappa* L. Historic overexploitation of these sandalwood and timber resources has severely reduced the livelihood benefits derived from them, and, therefore, they are important candidates for domestication and genetic restoration.

In Oceania, the approach to the domestication of indigenous nuts has been strongly based on the experience of the team in Cameroon. Thus, feasibility (producer and consumer surveys – Nevenimo et al. 2008) and priority setting exercises (Pauku et al. 2010) were carried out as the first steps, prior to work to characterize the fruits and nuts morphologically. The characterization also included proximal and chemical analyses, demonstrating tree-to-tree variation in oil and protein content and yield as well as in antioxidant activity (mg ascorbate equivalents per gram), vitamin E (tocopherol content – α, β, γ, δ isomers) and anti-nutrients such as phenolic content (mg catechin equivalents per gram). Most interesting perhaps was the very considerable variation in the anti-inflammatory activity (prostaglandin E_2 assay) of kernels (Leakey et al. 2008) demonstrating the possibility of selecting trees for their medicinal properties.

B. procera and *I. fagifer* were easy to propagate by cuttings, but *C. indicum* was very difficult. However, when the stock plants were grown under the shade of a *Gliricidia* canopy, fertilized and well managed, the rooting percentage was greatly improved (from 10 to 80%). Mature shoots of *B. procera* were also easily propagated by marcotting (Pauku et al. 2010). Mature cuttings were also rooted, with success being enhanced when the harvested shoots were taken from marcotted branches, both before and after severance of the marcotts (Pauku 2005).

The industrial exploitation of sandalwood has depleted the wild resource of *Santalum austrocaledonicum* Vieillard across the region. An expedition to measure the remaining trees in Vanuatu located small remnant populations across seven islands. When solvent extractions of heartwood samples were analyzed for their content of four essential oils (α-santalol, β-santalol, (Z)-β-curcumen-12-ol and *cis*-nuciferol), significant tree-to-tree variation was found for each. Contrary to expectation, some trees exceeded the content of α- and β-santalol as prescribed in the International Standard for Sandalwood Oil conferring acceptability to the perfume industry (Page et al. 2010a). Interestingly, this variation was unrelated to heartwood colour, thereby breaking long-held beliefs by some in the industry. Near-infrared spectrometry technologies have been found to accurately predict α-santalol content of heartwood.[9] As sandalwood is a hemiparasite, it was not known to what extent the host species would influence oil quality or yield. However, no host:parasite relationships were found. Individual trees with elevated santalol levels were selected and secured as a grafted seed orchard. This orchard has served as a source of both seeds for establishing new agroforestry plantings and scion material for replicating the seed orchard on other islands. These developments offer smallholder producers an economic opportunity to replenish the natural resource and contribute to the industry in Vanuatu (Page et al. 2010b).

E. medullosum is a valuable timber species (whitewood/basswood) found in Vanuatu, Solomon Islands and Papua New Guinea. As with many valuable timber species throughout the world, the natural resources of *E. medullosum* have been depleted over long periods of commercial exploitation. Significant variation in growth and form characteristics was found within a provenance/progeny trial established in Vanuatu (Vutilolo et al. 2005). Continuing selection in this progeny trial and further efforts to develop both clonal cultivars and clonal seed orchards throughout the islands will give smallholder farmers greater access to this improved planting material. This in turn will increase productivity of smallholder plantings and relieve harvesting pressure on already depleted wild stands of the species.

Studies outside the main domestication programme have examined the diversity of existing cultivars of breadfruit (*Artocarpus altilis* (Parkinson) Fosberg), which were developed primarily by selection and vegetative propagation over generations in Oceania (Ragone 1997; Zerega et al. 2004). Initial diversity evaluations have been used to develop strategies for extending the breadfruit season through development and maintenance of a diverse range of cultivars with complementary fruiting seasons (Jones et al. 2010). In Vanuatu, germplasm was assessed for morphological diversity, and an ex situ strategy for conserving the germplasm was implemented with the view of increasing food security within its agriculturally dependent islands (Navarro et al. 2007). Indigenous methods for drying and preserving the carbohydrate-rich fruits are also being examined for their potential application in processing fruit for export.

It is evident from the above that the six regions of ICRAF have not implemented 'farmer-driven, market led' agroforestry tree domestication in the same way (Table 1). This is partly due to variation in the experience and skills of staff in the different regions, partly determined by the priority of different donors and partly because a participatory priority setting process was used, and the farmers themselves had different priorities for wood products versus food and medicinal products. In the latter case, the nature of the products selected and the species that produce them required different tree domestication strategies.

Recent Developments in Agroforestry Tree Improvement

Molecular Genetics

Modern molecular techniques have been used in 13 agroforestry tree species (*Allanblackia floribunda* Oliver, *A. digitata, B. gasipaes, B. procera, C. spruceanum*, *I. edulis*, *I. gabonensis, Prunus africana, S. birrea, Spondias purpurea* L., *W. ugandensis, V. paradoxa, Vitex fischeri* Gürke) to determine the structure of genetic variation in natural, managed and cultivated tree stands and to devise appropriate management strategies that benefit users (Jamnadass et al. 2009). The resulting knowledge is used in three ways:

- To determine whether cultivated stands are of local or introduced origin and, if so, assess whether planted material comes from single or multiple sources. This historical information is important for genetic conservation and to derive appropriate management strategies (e.g. sexual reproduction vs. clonal multiplication) which ensure that domesticated populations are both diverse and based on the most appropriate resources for future genetic improvement. The use of unrelated individuals is particularly important when developing clonal cultivars.
- To ensure that domesticated populations have sufficient genetic diversity to avoid future problems from inbreeding. Inbreeding results in depressed growth and/or poor reproductive success, both of which have important yield implications. The use of molecular markers assists the determination of effective population sizes, breeding systems and gene flow.
- To determine the proportion of a species genetic variation that is available at a local geographic scale. If this is high, then a decentralized approach to domestication is appropriate. On the other hand, if it is low, a more centralized approach with germplasm infusions from outside may be required. To date, most agroforestry trees appear to contain high levels of variation in local populations and to partition most of their total genetic diversity within rather than amongst stands – which permits the use of a decentralized participatory domestication strategy like that implemented in humid West Africa.

Some tree species have separate male and female trees which are indistinguishable until they are sexually mature and start flowering. This creates a problem in the clonal domestication of fruit trees as it is the females that are productive. Likewise, breeding programmes need to include plants of both sexes in an optimal sex ratio. The identification and use of sex-specific molecular markers suggest that the sex of young plants of *U. kirkiana* can be differentiated, and that the relevant genes are autosomal (Mwase et al. 2010). This result has important implications for tree domestication of dioecious species in the future. As the understanding of genetic variation based on these genomic studies increases, there are likely to be rapid advances in tree domestication, especially in the areas of nutritional quality, seasonality of production and resistance to pests and diseases and to abiotic stresses like drought, salinity and extreme temperatures.

The Use of New Technologies

The expanding research agenda and number of species being domesticated have led to the increasing use of sophisticated laboratory techniques to quantify genetic variation in the chemical and physical composition of marketable products and commercial partnerships (Leakey 1999). These techniques include the assessment of polysaccharide food-thickening agents (Leakey et al. 2005b), proximate analysis (protein, carbohydrate, oils, fibre, vitamins and minerals, etc.), assessment of nutritional and medicinal factors (Leakey et al. 2008), isolation of essential oils (Page et al. 2010a) and fatty acids (Atangana et al. 2011) and determination of wood density, strength, shrinkage, colour, calorific value (Sotelo Montes and Weber 2009: Sotelo Montes et al. 2011) and other important wood properties correlated with tree growth. This is a good example of how agroforestry is increasingly engaging with modern scientific technologies as it matures.

Community Engagement in Germplasm Production

Studies in Latin America (Cornelius et al. 2010), Asia (Carandang et al. 2006; He et al. 2011) and Africa (Dawson et al. 2009) have sought to determine the best forms of management and dissemination of genetic resources, using local and community infrastructure. There is clear potential for improved commercial community engagement in germplasm production.

Across Asia, successful national tree seedling supply systems integrate local, institutional (private sector and NGOs) and government nurseries. The latter two types generally provide better access to technology, germplasm and finance, while local nurseries effectively supply a wide variety of species and facilitate tree planting. They also play an important role in developing appropriate technology, providing feedback on farmers' technical needs and knowledge of indigenous species.[4] Unfortunately, central control over a national supply system can constrain the development of local germplasm enterprises (He et al. 2011; Roshetko et al. 2008). Additionally, such enterprises may have an over-reliance on external support, a paucity of leadership and limited business capacity (Catacutan et al. 2008) Helping these enterprises gain institutional and market capacity is relevant for both research and government agencies.

In the case of seed, the generalized current practice of selling seed per unit weight rather than based on reproductive potential (e.g. per 1,000 plants) in effect discriminates against small seed, prices of which are often orders of magnitude less than prices of large seed (i.e. when expressed per unit of reproductive potential) (Cornelius et al. 2010). Where pricing practices cannot be modified (e.g. in cases where the concept of reproductive potential finds market acceptance), the potential for commercial smallholder production will lie in large-seeded species and also in value-adding through seedling or clone production, ideally allied with development of new cultivars.

Recognition of the Rights of Small-Scale Producers

As already mentioned, the purpose of engaging directly with communities in participatory domestication is to empower them to help themselves. One crucial element is to ensure that the farmers who produce new cultivars are protected from unscrupulous entrepreneurs. Unfortunately, the international negotiations to develop new legal instruments to ensure this have not made adequate progress. To go some way towards proving protection, Lombard and Leakey (2010) have suggested three activities: developing a register of named varieties developed through participatory domestication together with clear ownership and genetic 'fingerprints', defining species descriptors based on published data for the purpose of identifying distinctiveness and establishing comparative field trials of selected cultivars and unselected clones to be protected in a small number of safe locations for purposes of quantifying and confirming yield and quality traits.

Negotiation of Access to Markets

Expanding farmers' market linkages is critical to the success of tree domestication innovations. In many cases, developing linkages and negotiating favourable access to markets – local, domestic or international – will depend on farmers adapting management regimes that yield reliable quantities of quality products (fruit, vegetables, timber) that meet market specifications. Improving their product quality will likewise strengthen their bargaining position, enabling farmers to move up the value chain increasing their margin. Part of this progression could be collaborating with traders to assume post-harvest processing to assure products of the desired quality (Holding-Anyonge and Roshetko 2003; Tukan et al. 2006). To help communities to secure long-term access to formal markets, PhytoTrade Africa has been involved in setting up these trade associations on behalf of local communities in southern Africa (Lombard and Leakey 2010).

Adoption and Impact: Towards Enhanced Farmer Livelihoods and Global Environmental Benefits

To date, one tree domestication project has been outstanding in its achievements. Interestingly, the 'Food for Progress' programme in west and northwest regions of Cameroon has placed agroforestry tree domestication at the heart of an integrated rural development project, which simultaneously reduces poverty, malnutrition, hunger and environmental degradation. This has been the catalyst for farmer adoption, and the socio-economic impacts have been impressive in only 12 years (Asaah et al. 2011). Success has in effect been the outcome of enthusiastic adoption of participatory tree domestication and the dissemination of knowledge and skills to neighbouring communities via rural resource centres (Fig. 5).

Fig. 5 A satellite village nursery in Batibo, Cameroon

To rebuild the forest resources of useful indigenous trees and their associated traditional knowledge, this programme has taken an innovative three-step approach to promoting adoption and impact (Asaah et al. 2011):

- To mitigate environmental degradation that constrains food production through the use of nitrogen-fixing trees to restore soil fertility and raise crop yields
- To create income generation opportunities through the establishment of village tree nurseries and then through the production of indigenous fruits and nuts in agroforestry systems for local and regional trade
- To encourage local processing and marketing of food crops and tree products in order to create employment and entrepreneurial opportunities for community members

This project therefore addresses the key socio-economic and biophysical problems facing smallholder farmers in Cameroon. Its success can be attributed to the relevance of its work to the farmers' needs and interests and the fact that the programme builds on traditional knowledge, local culture, local species and local markets. This initiative has hit the right set of buttons to appeal to farmers and rural communities. Impressively, this process also 'snowballs' as each community draws in neighbouring communities in a continuous progression of adoption and knowledge dissemination.

Some 30 life-changing positive impacts have been recorded. These range from income generation and better nutrition to the decision of young men to stay in the community rather than to migrate to town, because they can now see a future in the village (Asaah et al. 2011). Overall, therefore, this agroforestry programme is creating a pathway to rural development for the alleviation of hunger, malnutrition and poverty by delivering multifunctional agriculture (Leakey 2010, 2012a, b). The challenge is to scale this project up from ten thousand farmers to hundreds of millions of rural people, many of whom will have found employment and business opportunities in the rural economy outside farming.

Public/Private Partnerships: Localization and the Case of *Allanblackia* spp.

One very encouraging aspect of the agroforestry initiative for a multifunctional agriculture approach to Third World development is the recent involvement of a small number of multinational companies in the commercial development of AFTPs – especially their recognition of smallholder agroforestry as a better alternative than large-scale plantation monoculture. Some are also engaging in in-country processing rather than exporting raw materials to industrialized countries for product development. One relevant example of this public-private partnership in agroforestry crops is Unilever's initiative to develop a new margarine from the edible oils of *Allanblackia* trees in Tanzania, Ghana, Nigeria and Cameroon. The kernels of the large fruits of *Allanblackia* trees contain up to 50 nuts that are very rich (70–100%) in stearic and oleic fatty acids (Atangana et al. 2011). The company has committed to developing this new edible oil industry with smallholder communities in Africa (Jamnadass et al. 2010).

Towards the Third Decade

It is clear from the literature review that tree domestication activities are dynamic and expanding both geographically and in species number. The research agenda is also making increasing use of laboratory techniques to improve product quality (Figs. 1, 2, 3 and 4). It is also clear that there is an emerging sequence of steps (Fig. 2) at present dominated by direct genetic selection and propagation but leading to marketing, commerce and impacts from social and economic reform, steps which will become more dominant as the process gathers momentum.

Looking forwards to the next decade, further progress in agroforestry tree development research will probably come from:

- Improving the capture of ontogenetically mature phenotypes by identifying the principles for success in grafting and marcotting.
- Chemical analyses of a wide range of useful ingredients, including essential nutrients, medicinal compounds, perfumes, flavours and other sensory characteristics, found in AFTPs and their selection as traits for cultivar development to meet the needs of new markets.

- Post-harvest processing, storage and packaging of AFTPs to expand local, regional and global trade opportunities.
- Controlled pollination between cultivars with good morphological characteristics and those with high nutritive value and/or with out-of-season fruiting. This will require a more centralized approach to domestication research, but wherever possible this should be done in conjunction with rural resource centres working directly with farmers.
- Upscaling tree domestication, especially in Africa, focusing on species with impact on income generation and nutrition.
- Quantification of impact against baseline data based on well-defined criteria and indicators.
- Better understanding of the integration of domesticated agroforestry trees in different cropping systems for improved livelihoods and greater environmental benefits.
- Development of producer-trader linkages and agreements that expand farmer opportunities, promote transparency and reduce inefficiency for mutual benefit.
- Greater involvement of the private sector through public-private partnerships in the local processing and wider trading of AFTPs. The ideotype approach should be used to formulate trait combinations that meet a wider range of commercial markets.
- Enhanced recognition of the importance of AFTPs in agriculture by national and international policy makers and the adoption of appropriate policies.
- Formulation of intellectual property rights that protect the innovative activities of poor farmers and local communities in developing countries.

In conclusion, great progress has been made in the first two decades of agroforestry tree domestication since its conception. It is expected that the third decade will see further expansion in the size of the overall research effort, in the number of species, sites and research topics, as well as in the depth of the studies.

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Policy Support for Large-Scale Adoption of Agroforestry Practices: Experience from Africa and Asia

Oluyede C. Ajayi and Frank Place

Abstract Government policies play an important role in facilitating agroforestry promotion. Based on a set of five agroforestry practices that are adopted at a significant scale in different countries of Africa and Asia, we analyze the development path of the different practices and examine how they evolved into widely practiced systems, with the focus on the specific role that government policies had in facilitating such developments. The selected practices were regenerated parklands in Niger, cashew in Ghana, timber planting in India, smallholder fruit production in Kenya, and agroforests in Indonesia. Additionally, major roles of other key actors, such as the private sector, are examined in the light of the current state of knowledge on the policy implications on private sector investments in this field. The study reveals that both government and non-state actors played different roles to encourage the spread of agroforestry. In many cases, the spread of agroforestry was triggered when existing or new policies created market opportunities and increased the economic rationale for adopting given agroforestry systems. Widespread adoption of agroforestry is strongly influenced by the policy and institutional context within which agroforestry is disseminated. Agroforestry was found to be increasingly embedded into national development programs as evidence of its benefits became better known, although a significant number of policy measures disadvantage agroforestry. The study concludes that the dissemination of agroforestry at the farm level should be complemented with conducive policy, institutional and economic incentives. In addition, to ensure a sustained adoption of agroforestry over the long term, policy and dissemination questions will have to be researched with the same vigor that biophysical and farmer levels questions are being investigated.

Keywords Adoption • Impact • Agroforestry policy • Agricultural development • Sustainable livelihood

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Introduction

The current practice of agroforestry in developing countries is a mix of traditional systems and newly configured systems, including new management practices and the acceptance of nonnative species. As Zomer et al. (2009) have documented, about half (48%) of all global agricultural land has at least 10% tree cover. Mercer (2004) reported based on a comprehensive review that the level of adoption of agroforestry technologies in the tropics has generally lagged behind scientific and technological advances attained in such technologies, thereby reducing their potential impacts. Nevertheless, other publications have confirmed that some specific agroforestry practices, both traditional and new, have been adopted by hundreds of thousands of smallholders (Reij et al. 2009; AFSP 2010).

Although the parkland agroforestry systems of the Sahel are centuries old, a more recent phenomenon of their rejuvenation, through farmer-managed natural regeneration, has been documented to have occurred on nearly 5 million hectares (ha) by 2008 in Niger alone (Reij et al. 2009). A traditional agroforest systems in Indonesia, has been managed by hundreds of thousands of smallholders, though there are several threats to this system (Kusters et al. 2008). Smallholder farmers have long produced fruit trees in India, but a more recent development has been the ascendency of smallholder timber production, which followed upon decades of deforestation and eventually a ban on forest logging by the government (Zomer et al. 2007). Fruit tree growing is also a common feature of smallholder farms in Kenya, though relatively underreported and unknown to many.[1] More known are the valuable trees grown across wide areas of Africa, notably tree crops including coffee (*Coffea arabica*, *Coffea robusta)*, cacao (*Theobroma cacao* L.), tea *(Camellia sinensis)*, cashew (*Anacardium occidentale)*, and oil/resin trees such as shea (*Vitellaria paradoxa*). In addition to these systems which have been practiced for many decades, new ones are being promoted, with the most efforts being accorded to a range of systems for soil improvement or fertilizer tree systems, especially in southern African countries.

It is important to understand how such large-scale agroforestry systems developed given the recent interest in scaling up certain types of "new" agroforestry systems that were developed, especially to meet climate change adaptation and mitigation needs. For example, the 2009 conference of African Agricultural Ministers: "Calls upon Member States to increase investment support to initiatives aimed at strengthening knowledge, advancing technical capacity development, and up-scale sustainable land and water management practices including conservation agriculture, agro-forestry, watershed management".[2]

The prospect of scaling up any given agroforestry practice is filled with challenges. First of all, there are the germplasm needs – Where would seed or vegetative material for highly demanded species come from? And how would standards of quality and genetic diversity be maintained? How could the private sector play a significant role in supplying demand? Second, there are information constraints. Some agroforestry practices are now widely known and some may require more than a brief awareness-creation exercise. Third, will farmers make money from the agroforestry products? Do markets exist, is there good market information on tree products, and are there value-adding opportunities? A related question is: Will farmers be rewarded for the environmental services that their agroforestry practices may generate? And finally, do farmers have the necessary resources and property rights to have the basic incentive to adopt new land use practices?

Practically all of these challenges can be affected by policy, positively or negatively. This chapter reviews the role that policy played in relatively large-scale adoption of agroforestry. It draws upon existing literature and, as a result, the depth of information presented depends on what has been published. Thus, some of the case studies are richer than others. In the next section (see section "Methods Used for Case Study Analysis and Synthesis"), we discuss the methods we have applied to analyze various case studies from a policy perspective, followed by analyses and discussions of various case studies. The cases presented include a rather wide spectrum of recent agroforestry adoptions such as farmer-managed natural regeneration in Niger, smallholder timber in India, fruit growing in Kenya, conservation agriculture and fertilizer tree systems in southern African region, cashew in Ghana, and rubber and damar agroforests in Indonesia. The final section draws conclusions from a policy perspective and presents recommendations on methodological development and application in the area of policy analysis.

Methods Used for Case Study Analysis and Synthesis

In our discussions throughout this chapter, we have taken a broad perspective of policy. Rather than focus strictly on formal macroeconomic policies or markets and incentives exclusively, we have taken the position to view "policy" as any or all decisions taken by a political actor(s) concerning the selection of goals and the means of achieving them, i.e., the formal or informal "rules of the game" (UNEP 2010). To help understand how policies have contributed to certain developmental changes, Gregersen et al. (1992) suggested that it is important to obtain insights into issues such as the situation that existed before the change/s were observed; the changes in the local, regional, or national economy that have led to the achievement of the development objectives; information on the policies that have been effective in achieving desired development objectives; and policies or institutions that have been changed to ensure the realization of desired development objectives.

The discussion on policies includes those that are *explicit*, articulated, and announced clearly and others that are *implicit* that may not be as clearly stated or explained but can be equally powerful. We have therefore included in the discussions different policy types ranging from economic instruments (e.g., taxes, tradable permits, user fees, subsidies), direct expenditures (e.g., programs and projects, research and development, moral suasion), regulatory (legislative instruments, enforcement activities, competition and deregulation policy), and institutional (internal education, internal policies and procedures).

Given the wide range of agroforestry-based systems where varying levels of successes have been achieved in their widespread adoption by farmers in different locations across the globe, in this chapter, we use a case study approach by first identifying specific agroforestry systems to be included in the study and then review available literature and databases to provide more in-depth information about the system.

Choice of Case Studies

The first consideration was to choose agroforestry systems that have recorded widespread adoption in terms of the number of adopters and proven documented positive impacts of the system on households and communities. We also examined the availability and depth of information available for the various systems. Next, we considered including a mixture of agroforestry systems that focus on different products (timber, rubber, fruits, soil fertility, etc.). Finally, we considered having case studies that are drawn from different geographical regions in Africa and Asia. On this basis, six agroforestry case studies were identified for the study. These are farmer-managed natural regeneration of parklands (Niger Republic), cashew agroforestry (Ghana), multispecies agroforests (Indonesia), smallholder timber (India), smallholder fruits (Kenya), and conservation agriculture/fertilizer trees (Malawi and Zambia).

Review of Historical Development Trajectory and Drivers of Success for the Agroforestry System

For each selected case study, we reviewed available literature and data to highlight the historical and development trajectory of the system and understand the drivers of the widespread adoption of agroforestry systems and the role that policy and economic changes played in their development. In doing this, we specifically focused on three areas:

- Historical development of the agroforestry system – by tracing the history of the development of the system and posing the following questions: How did the system come about? What events triggered researchers and technology developers' interests in the system? What makes the system to continue to grow? What aroused farmers' interest and their investment in the system?
- The spread of the system and the players involved – by identifying key actors that were involved in the development of the system, the role played by each actor, and whether there has been a major change in the role played by the actors over time and reasons for the change.

- The roles that policy and economic changes played in the spread of the systems – by identifying specific events, trends, and changes in policy and economic scenarios that stimulated interest of researchers, farmers, and investors to invest in the development and widespread adoption of the agroforestry system. Also, distinct policy phases and policy changes that played crucial roles (positive or negative) in the widespread adoption of the system are discussed.

Case Studies

Farmer-Managed Natural Regeneration of Parklands in Niger

The parklands agroforestry systems have been the predominant land use system ever since farming has been practiced in the Sahel (Boffa 1999). There are variations in the systems in the region in terms of the dominant tree species found, which correspond somewhat to rainfall gradients but also to natural distribution of trees. Common species are *Faidherbia albida* (Faidherbia), *Adansonia digitata* (baobab), *Vitellaria paradoxa* (shea butter or karité), *Guiera senegalensis*, and *Combretum nigricans*. While the trees had been providing important benefits for centuries, in the late twentieth century, it became apparent that young trees were fewer in number compared with older trees and, overall, the tree cover had reduced over time (Boffa 1999). It turns out that this transformation was not often due to physiological constraints; rather, farmers had been removing young trees because of uncertainty of ownership and use rights to the trees. In Niger, a major exception to this began to take place in the 1980s when several NGOs in partnership with the Government of Niger (GON) encouraged and demonstrated the importance of farmer-managed natural regeneration agroforestry practice in the southern belt of the country (Fig. 1). Among the key NGOs that worked with local communities to develop the practice are “Serving in Mission” particularly in Maradi region (Reij et al. 2009) and the CARE International which worked particularly in Zinder region. In these sites, there was a substantial amount of tree vegetation and germplasm (e.g., stumps and root systems) in the soils, and they were resprouting or germinating. It turned out that what was required was management of natural regeneration – protecting the desired trees, thinning out the undesirable ones, and pruning the remaining ones to fit into farming systems in order to create a rejuvenated parkland. But these simple management interventions had not been done previously as there was no incentive to do so because farmers had no right over the trees, the ownership of which was vested in the forestry office. Although this now has taken place in some communities throughout the Sahel, the most widely practiced FMNR is in Niger, where at least 4.8 million ha have been regenerated (Reij et al. 2009).

Farmers’ interests in and benefits from parkland systems have been well documented, though not always well quantified, and are dependent on the types of trees found. Some tree products are highly valued even on the world market, such as shea

Fig. 1 Farmer-managed natural fallow regeneration in Sahel, West Africa (Photo credit: ICRAF Sahel Node)

kernels and butter, and many others are highly valued by domestic consumers, such as baobab leaves. In addition, there are other fruits, timber, firewood, fodder, and medicinal benefits. According to recent trade figures, regional shea butter exports are increasing exponentially, having multiplied fourfold between 2003 and 2007, while shea butter imports to the European Union in particular increased tenfold between 2000 and 2005. The market demand for shea butter of African origin has increased in recent years and is currently estimated at roughly 5,000–8,000 t (Mg) per year.[3] Trees also provide service benefits in the form of windbreaks and soil fertility and thus improve crop production. In terms of FMNR, a recent study by Haglund et al. (2011) in Niger found that the adoption of FMNR resulted in higher household income estimated at between 18 and 24% higher incomes relative to non-FMNR households. Larwanou and Adam (2008) calculated that with an average of 40 trees per hectare, a conservative estimate of the additional value from FMNR would be \$56 ha^{-1} $year^{-1}$(from improved soil fertility, fodder, fruit, firewood, and other produce).

Serving in Mission, the NGO that managed the Maradi Integrated Development Project catalyzed the initial scaling-up from their site through arranging visits by farmers in nearby community. Other NGOs picked up on the practice and included it within their portfolio of interventions. Although the cost to farmers of FMNR is negligible, formal project funds were used to help disseminate the technology. The roles of government extension or growing market opportunities for tree products have not been well studied, though the extent of adoption would suggest that such larger factors played some contributory role.

It is now clear that policy had an inhibiting, if not stifling, role in preventing a practice like FMNR from emerging in Niger. Two aspects were particularly problematic. The first was that there was ambiguity in the forest code about the ownership of land because any land could be declared as forest land depending on its tree cover and primary generation of products. This discouraged farmers from taking care of trees in their farms because higher tree cover could put their farms at the risk of being declared a “forest.” The second aspect concerned forest tenure regulations, which required approval and license fees for the felling or commercialization of certain parkland tree species, even if they were growing on farm land belonging to households (Elbow and Rochegude 1990). This tenure aspect is likely to have played a stronger role because the 15 protected species in Niger were all important parkland species. The result was that farmers would regularly remove young tree seedlings from their land before they were noticed by officials. The huge change that took place was not a formal policy change but rather its interpretation and implementation by the forest department including its field officers (Reij et al. 2009). They relaxed their policing role with respect to trees on agricultural land. Thus, in the latter half of the 1980s, farmers increasingly perceived private ownership over trees in their fields (Larwanou et al. 2006). This example shows that the slow pace of changes in formal legislation need not prevent government departments from undertaking progressive and forward-looking activities.

Cashew in Ghana

A native of Brazil, cashew was introduced to Africa as early as the seventeenth century. Potentially a highly profitable tree crop, cashew grows on very poor sandy soils, is drought-tolerant, and is commonly intercropped with cultivated food crops such as cassava (*Manihot esculenta* Crantz), thus providing a buffer against failure of rainfed annual crops in a context of climatic uncertainty (Mitchell 2004). From an ecological perspective, cashew has been shown to have high potential for the restoration of severely degraded lands. Cashew trees bear their first harvest at around 5 years, reaching peak productivity at about 15 years, and tailing off at around 40 years. While the true profitability of cashew production to rural producers has historically been variable, the trees provide a significant long-term resource in diversification of livelihoods, as well as significant environmental services such as windbreak and shade in a variety of cropping systems. Cashew can be described as a global “success story” – global export trade nearly trebled in the decade from 1998 to 2008, from 243,000 to over 707,000 t, with the value of shelled cashew exports nearly trebling from $724 million in 1998 to over $2 billion in 2008.[4] In recent decades, the dynamics of production and processing have evolved rapidly, with new and emerging opportunities for African producers and significant potential

Table 1 Export performance of cashew nuts (in shell) from Ghana during 1990–2006

Year	No. of exporters	Quantity (MT)	Value (US$)
1990	2	15.5	8,770.8
1991	1	30.0	17,400.0
1992	1	50.7	27,896.0
1993	–	–	–
1994	3	600.0	330,600.0
1995	1	289.0	203,705.0
1996	3	541.3	361,605.0
1997	5	3,571.6	1,844,210.4
1998	6	1,822.4	1,186,662.0
1999	5	5,571.6	3,797,623.4
2000	11	3,563.6	2,552,652.1
2001	5	418.91	88,936.7
2002	7	3,892.1	1,450,305.9
2003	8	6,338.0	2,598,635.1
2004	–	3,600.6	1,419,480
2005	–	654.9	261,799
2006	–	328.0	180,468

Source: Compiled from Cashew Processors and Exporters Association of Ghana (2007)

for restoration of existing plantations and smallholder stands of cashew in the coastal lowlands of both eastern and western Africa.

In Africa, Ghana is one of the countries where cashew has assumed tremendous economic importance. Other countries are Nigeria, Mozambique, and Tanzania. Available statistics indicate that the area under cashew cultivation in Ghana expanded from 35,547 ha in 2003 to 58,942 ha in 2006. Similarly, the production of raw cashew nuts increased from 7,212 t in 2003 to 16,422 MT in 2006. Prior to this large-scale development effort, isolated attempts were made by individuals, government, and NGOs to promote cashew in agroforestry programs. However, due to limitations in domestic capacity to process cashew, export of cashew has been generally low (Table 1).

Farmers are interested in cashew primarily because it is a source of household cash income. In some non–cacao growing regions of Ghana, cashew is expected to play the role of money spinner or the “new cocoa.” On the part of the government of Ghana, cashew was considered as one of the crops to broaden and diversify its export base. Estimates indicate that the cashew subsector can contribute to pro-poor economic growth by generating over 200,000 permanent and seasonal jobs, particularly for farm laborers and intermediaries (Cashew Development Project 2008). Furthermore, marketing, distribution, and processing of raw cashew nuts offer more than 5,000 permanent and seasonal jobs annually in Ghana’s cashew industry as of now (CDP 2009a). In 2008, exports of cashew nuts contributed to 6.1% of GDP and 18.2% of agricultural GDP of Ghana. (ACI 2010)

The history of the development of cashew involved research and development organizations. Ghana cashew research team, housed within the Cocoa Research Institute of Ghana, contributed to cashew production by identifying the key challenges of cashew production: poor quality of planting material and problem of low yield. For example, a survey conducted by the cashew research team in the Cocoa Research

Institute of Ghana (CRIG) in 1990 shows that from a total of 597 tagged trees, only 199 produced cashew yields of 7 kg and above.[5] They subsequently set out to develop improved planting materials, appropriate plant production and plant protection packages, and improved processing and development of by-products. As regards the specific influence of policies in cashew development in Ghana, three phases of development policy are identified:

Colonial and Postindependence Era: Although cashew was introduced in Ghana and West African countries by the Portuguese in the precolonial era, there was little effort to actively promote the crop until shortly after independence, when the government of Ghana embarked upon a vigorous project to establish cashew plantations at Dodowa, Omankope, and Bole in 1960. Through these projects, cashew trees were planted in towns and villages in the southern regions and were intended to make cashew a cash crop alongside the cocoa industry. But after the overthrow of the first republic, the development of cashew as a cash crop was abandoned by the then new regime.

Economic Recovery Era: This period spans from the early 1990s to early 2000s. As part of the economic recovery program in the 1990s in Ghana, cashew was considered as one of the crops to broaden and diversify its export base. The attention on cashew resulted in Ghana recording its first export of raw cashew nut in the early 1990s. In 1998, the Ministry of Food and Agriculture (MoFA) commissioned and funded a study to investigate the status of the cashew industry, particularly with regard to potential production areas and levels, as well as performance and problems hindering the development of the industry.

Cashew Development and Economic Promotion Project Era: This period began in 2003 with the establishment of a 6-year Cashew Development Project (CDP) through funding from the African Development Bank (AfDB). Integrated and coordinated approach to the development of cashew industry became possible with the initiation of CDP in 2003, covering ten districts in five regions of the country. In order to hasten the pace of growth of the cashew subsector, the ministry of food and agriculture, through CDP, put in place strategies to enhance extension delivery to cashew farmers and processors through provision of improved planting materials, development and distribution of training and extension materials on improved crop husbandry, provision of field and postharvest technologies to assist farmers improve the quantity and quality of their yields, a credit scheme to provide financial assistance to cashew farmers and groups, and establishment of cashew processing units.

In addition to CDP, another organization, the Cashew Processors and Exporters Association of Ghana (CAPEAG), was supported by CDP and Ghana Export Promotion Council in 2004 with the aim of developing a strong trade association that would assist in the formulation of policies toward the development of the cashew industry in Ghana. Interventions by the Ghana Export Promotion Council include establishing a Medium-Term Export Development Program for cashew (1987–1989), conducting a primary survey of cashew trees in Ghana, UNDP/Ghana Export Trade Promotion and Planning (1990–1994), and championing the selection of cashew as an export product for development alongside black pepper (*Piper nigrum*), mushroom (*Agaricus bisporus)*, and rubber (*Hevea brasiliensis*).[6]

Over the years, there has been a change in the dominance of the role played by different sectors in cashew development. First, the government played a dominant role especially after political independence, through its financial and programmatic commitment to cashew development. Then, NGOs featured more prominently until the early 2000s when a para-state agency (CDP) and private sector operators such as CAPEAG and Ghana Export Promotion Council assumed greater roles. Other nongovernment institutions that are involved in cashew development in Ghana include Technoserve, ADRA Ghana, and an Italian development organization *Ricerca Corporazione*.

Smallholder Poplar Timber in India

The smallholder poplar (*Populus* spp.) agroforestry system in northern India is well recognized as a major land use system, occupying about 280,000 ha of land or about 10% of all irrigated land in four northern states, Haryana, Punjab, Uttar Pradesh (UP), and Uttaranchal (Zomer et al. 2007). The common practice is to grow poplar trees on an 8-year rotation in lines mixed in with wheat (*Triticum aestivum*) and barley (*Hordeum vulgare)* fields. As of 2005, about 15,000 t (Mg) of timber are being converted into plywood and panel boards in the 600 factories located in Delhi and the four states mentioned above. This translates into about $700,000 per day for growers and about four times that amount in total value of finished products (Singh and Bhojvaid 2006).

Poplar was introduced in the region in 1969, when four clones of *P. deltoides* were received from Australia; the practice spread rapidly in the region ensuring attractive returns to the leaseholders.[7] Subsequently, the Uttar Pradesh (UP) Forest Department experimented with growing wheat, mustard (*Brassica nigra*), and sugarcane (*Saccharum officinarum* L.) as companion crops in association with the poplar in various configurations (Zomer et al. 2007). Poplars could be easily incorporated into wheat and barley fields for two main reasons. First, poplars do not have large canopies and therefore do not create much light competition for the crops; moreover, they drop their leaves in the winter so the winter crops can grow without any shade interference. Second, irrigation systems are commonplace in the region and therefore water scarcity for the crops and trees was not an issue. A World Bank–funded project during the 1980s helped to promote the spread of poplar agroforestry and other timber trees on farms and communal lands.

Rapid adoption of the poplar, thereafter, coincided with an alarming scarcity in regional wood supplies. Until the late 1970s, almost all of the wood-based industries in India depended on the state forest departments for raw material. That is, most wood came from forests, primarily forests in the Himalayas. A ban on timber cutting in state forests through the Forest Conservation Amendment Act of 1988 (and reinforced through a Supreme Court ruling in 1996), and the widening gap in demand and supply, meant that wood-based industries had no option but to go to farmers for their raw material needs. Price increases for wood followed, which provided further attraction for its adoption by farmers. The Western India Match Company (WIMCO) Limited is largely responsible for the introduction and widespread adoption of the poplar agroforestry system. In 1976, WIMCO initiated an extensive publicity campaign promoting the usefulness of poplar plantation in agriculture. They established a forestry extension center at Rudrapur, UP, to promote cultivation of poplar trees in the region. In 1983, WIMCO distributed 126,000 seedlings free of cost. In 1984, a WIMCO–NABARD (National Bank for Agriculture and Rural Development) poplar project, designed as a joint partnership between the industry and the banking sector, was implemented in selected districts of UP, Punjab, and Haryana (Zomer et al. 2007). The project offered a complete package of services to the tree growers, including:

- Improved planting material, grown for the program in the WIMCO nurseries and supplied at the site of planting
- Assistance in obtaining a bank loan for growing trees
- Free instructions on planting and management of trees provided along with the package cost for seedling charged by WIMCO
- Complete guidance for 8 years (till harvest of the trees)
- Free replacement of a limited number of seedlings in the initial 2 years and assured price and guaranteed purchase of trees at the end of 8 years

During the first phase (1984–1987), almost a million saplings were transplanted in the area. Initially, the government of UP accorded permission for poplar agroforestry on 13,600 ha of marginal/waste/barren land. However, the program was also taken up by farmers planting on fertile farmland. By 1991, during phase II of the program, approximately 3.2 million saplings were transplanted in 18 districts of UP. In 1992, the project area was further extended to encompass more districts. In 1994, WIMCO ended its collaborative contractual farming project. The company continues to provide planting material, technical support, and extension to farmers on a cost per tree basis.

Although the model of scaling up was largely one of a private sector nature, the government and the policies it enacted for the sector played important roles. First, the forest logging ban itself and the certainty with which all actors realized that this was to be long-lasting provided a huge opportunity for long-term private investment in tree growing. Where such a ban is not perceived to be enforceable or long-lasting, the private sector would not have taken such a risk with investment. Second, it facilitated credit for the undertaking through the National Bank for Agriculture and Rural Development. Credit for smallholder agriculture is a known constraint throughout the developing world inhibiting profitable investments in the sector. At the State level, the government approved the new land use for wider scaling up following a study of potential effects on groundwater supplies (Zomer et al. 2007). The government further allowed the felling and transport of the trees to proceed with minimal regulation. State governments in the region, who also have powers to regulate the cutting and transport of trees and tree products, have also allowed the free cutting and movement of poplar. It should be noted, however, that many states in India continue to restrict the felling and transport of certain species, even if grown on private land. So the successful case of poplar does not imply that the same model is immediately transferable to other trees and tree products. The state of Chhattisgarh has recently taken significant strides toward empowering farmers to plant and benefit from trees through the inclusion of trees on farms in its various agricultural support programs.

Smallholder Fruit Production in Kenya

Smallholder tree growing is perhaps more widespread in Kenya than in any other African country with the most common trees being timber and fruits. Although this case study is about fruits, it is important to note the significant planting of timber by farmers as well, as that has helped to instill a tree planting culture among the population and also was the linchpin behind a thriving nursery industry, from which fruits are sourced by farmers. National surveys have found that more than 80% of farmers grow fruits and half of all farmers are selling fruits. The most common ones are mango (*Mangifera indica* L.), avocado (*Persea americana*), and papaya (*Carica papaya*), but many others such as guava and passion fruit are emerging. In fact, more than half the farmers grew at least three different fruit species. Kenya exports of fruits were about $100 million in each of the past 3 years,[8] involving more than 30 types of fruit.[9] However, exports are just a fraction of commercial value of fruits. For example, only 1% of mangoes produced in Kenya are exported with a value of $14 million. Of the production that is consumed nationally, it is estimated that 50% is sold in national markets and the other 50% is consumed on farm (FAO 2005). Higher quality fruits are being grown by farmers, with an increase in grafting as well as an increase in varieties that are in demand by the market (e.g., avocado varieties appropriate for cosmetic use).

Farmers are interested in fruit production for home consumption as well as for generating income in the relatively lucrative fruit markets in Kenya. Data on the contribution of fruit to smallholder income are limited. Tschirley and Ayieko (2008) found that fruits and vegetables together accounted for 12% of agricultural income among Kenya smallholders in 2007. A study found that value of fruit production was between 6 and 8% of total crop production value from 2000 to 2007, but its contribution to income was higher because a higher proportion of fruits are sold as compared to other food crops.[10] There is very little current data on production costs and returns from fruit growing. Estimated revenues per hectare from Kenya which uses current prices and actual average yields from farms available from the Kenya Horticultural Crops Development Authority[10] show that papaya and passion fruit (*Passiflora edulis*) are particularly remunerative with revenues at over $4,000 per hectare. Citrus of varying varieties, avocado, and mango all are able to generate more than $2,000 per hectare with good management.

Fruit production among smallholders has been practiced for many decades, in some areas being hastened by land redistribution and registration some 50 years ago. Over the years, government, NGOs, and the private sector have all played roles in the expansion of the sector. More related to the fruit sector, the government established the Horticultural Crop Development Authority (HCDA) in 1967. Initially, the HCDA promoted development of production and marketing opportunities but more recently has evolved to a coordination, regulation, and advocacy role, recognizing the presence of strong sector stakeholders. There are clearly constraints facing the sector, such as on quality of germplasm, where government attention is needed.[11] But, largely, it was the government's decision not to intervene heavily in the fruit sector, whether on the production, marketing, or processing sides, and allow the private sector to develop, which was noted as a big factor in the sector's growth (Rowland 2007). Private sector institutions developed, such as the Fresh Produce Exporters Association of Kenya in 1975, to help develop export markets and to disseminate and implement trade standards. Very recently, large firms such as Coca-Cola, Pepsi, and Del Monte have all announced plans to invest in smallholder fruit marketing chains in Kenya.

There was not a major catalyst in recent times, but certain types of species and varieties did have their own factors behind their emergences. For example, market demand has influenced the types of mango varieties grown, resulting in some replacement of species. More recently, growth in export demand has led to uptake of passion fruit production. The strong tourism sector in Kenya has also played a role in developing the industry, firstly because of high fruit demand by tourists, but more importantly the high number of aircraft bringing tourists to Kenya offered cargo space for fruit exports.[12] Several projects and programs have had an influence such as the Green Belt Movement dating back 30 years and the then GTZ (now GIZ)-led Integration of Fruits in Smallholder Farming Systems project in the early 2000s. Many other projects, such as CARE and from the government, though focusing more on timber type trees, have also contributed to the uptake of fruits through the spawning of nurseries and seed systems and by increasingly responding to preferences of farmers.

The Kenya Forest Policy of 1968 recommended acceleration of rural tree planting activities by training of forestry extension professionals. Rural Afforestation and Extension Services Division (RAES) was started in 1971 to facilitate its implementation through training of farmers, establishment of tree nurseries countrywide, and deployment of extension staff to offer technical services to rural farmers.[13] Tree seedling output in government nurseries was over 100 million seedlings per annum by 1989 reflecting an equivalent area of between 53,000 and 84,000 ha (Odera 1989). Several NGOs in collaboration with government agencies and farmers have expanded tree-planting activities in the country. The importance of agroforestry and the nursery sector was further enhanced when the government imposed a ban on harvesting from public forests in 1999.

To promote tree planting on farms, the government has drawn up favorable policies that give emphasis to farm forestry through the Economic Recovery Strategy for wealth and employment creation paper (2003) and the Draft Forest Policy 2007 and Forest Act 2005. Among the key favorable actions include a proposal to entrench forest products trade liberalization, tax incentives for trees grown on farms reflected in the 2005–2006 budget, relief on regulations restricting harvesting and movement of trees and products, and the creation of outgrower schemes through appropriate funding mechanisms and promotion of value addition in forest products.

Fig. 2 A mature crop of maize in a *Faidherbia albida* field in Salima, Malawi (Photo credit: Oluyede Ajayi)

Conservation Agriculture and Fertilizer Tree Systems in Southern Africa

Based on nitrogen fixing and nutrient recycling principles, fertilizer tree systems[14] replenish soils and thereby increase crop production and household food security (Figs. 2 and 3). Over the years, different variants of fertilizer tree systems that have been developed include improved fallows, semipermanent tree/crop intercropping, and annual relay cropping systems (Kwesiga et al. 2003; Akinnifesi et al. 2008). Studies in Zambia show that at current per capita maize consumption in southern Africa, fertilizer tree fallows added 57–114 extra person-days of maize consumption per year, i.e., the system cuts the seasonal hunger period by this period per year (Ajayi et al. 2007). A recent meta-analysis conducted across several regions in Africa found that fertilizer trees doubled yields of maize relative to the control (maize without fertilizer) in the majority of sites where they have been tested (Sileshi et al. 2008).

In addition to improving soil fertility, the systems described above improve soil physical properties; enhance water filtration (Chirwa et al. 2007; Phiri et al. 2003); improve rainfall use efficiency, i.e., the quantity of a crop produced from each unit of available rainwater (Sileshi et al. 2011); store large quantities of carbon stocks in

Fig. 3 Maize grown with G*liricidia sepium* continuously in the tenth year in Chipata, Zambia (Photo credit: ICRAF Zambia)

plant biomass and in the soil (Kaonga 2005; Makumba et al. 2007); and can potentially mitigate global greenhouse gas emissions (Sileshi et al. 2007). From only 12 farmers who participated in the initial on-farm testing of fertilizer trees in Zambia in early 1990s, the number of planters increased steadily, especially from 2000 onward to over 66,000 farmers in the country in 2006. In Malawi, the number of farmers planting fertilizer trees is estimated at more than 146,000 at the end of 2010 season (AFSP 2010). As regards conservation agriculture (CA), about 60,000 farmers were practicing it in 2001–2002 season,[15] with the figure increasing to 180,000 farmers in 2010 season and projected to rise to 250,000 farmers (30% of farming population) by 2011.[16]

The key drivers of farmers' interest in fertilizer tree systems is the low cost and minimal cash transaction involved to establish the trees. The system helps resource-poor farmers to produce their own N nutrients through land and labor and largely eliminate the purchase of chemical fertilizers at high prices which is not affordable to most smallholder farmers. In addition to improved crop yields, fertilizer tree systems increased fuel wood availability, as approximately 10 t of wood was harvested from 1 ha of *Sesbania sesban* (Kwesiga and Coe 1994).

The development and promotion of fertilizer trees in the southern African countries went through three major phases:

Phase 1: The first phase which took place from the early 1960s shortly after political independence to early 1990s. It can be described as the "fertilizer

Table 2 Estimates of farmers reached with agroforestry technologies in Zambia

Training methods used to disseminate agroforestry	Male	Female	Total
Prong 1: direct training of farmer trainers and local change teams	7,373	8,773	16,146
Prong 2: training of collaborating partner institutions' staff, i.e., training of trainers	23,532	16,190	39,722
Prong 4: support to national extension system to promote agroforestry	7,446	3,165	10,611
Total	38,351	28,128	66,479

Source: Zambia ICRAF Agroforestry Project report for 2005, Chipata, Zambia
Note: The figure for farmers reached through Prong 3 (which involved farmer to farmer exchange) was not assessed

boom" period characterized by heavily subsidized fertilizer use in the maize production system. In addition to the direct price subsidy, the government also provided marketing and other non-price support to the distribution of fertilizer in villages including remote locations where transport costs would have made fertilizer prices to be highly exorbitant. The policy context during this phase made fertilizer trees to be considered impractical or less economically rational to use because nitrogen fertilizers were a cheaper option at that time (Sanchez 1999).

Phase 2: The second phase began in the early 1990s coinciding with the emergence of Structural Adjustment Programs (SAP) embarked upon in many African countries following fiscal burdens and economic challenges facing the countries. This phase can be described as the "fertilizer bust" era. As part of the solution to the economic crises, the overvalued local currencies which were sustained for several decades by strict exchange rate controls gradually gave way to a floated exchange rate in auction markets. The change in economic policy resulted in a *de facto* devaluation of the local currencies and led to increases in fuel and fertilizer costs. As is common elsewhere in sub-Saharan Africa (SSA), African agriculture has been the greatest victim of overvalued foreign exchange rate. However, the more dependent a country's national agricultural system is on imported farm inputs, the greater the negative effects of devaluation on the net benefits from agriculture.[17] In addition, the fiscal burden of maintaining government support for high-input fertilizer production system became more challenging in the face of the economic adjustment. This factor and growing awareness of the need to maintain land quality and natural resources of the soil increased the quest by farmers and researchers to seek new options to improve soil structure and soil fertility to complement fertilizers. As noted in studies conducted in West Africa, when inorganic fertilizer prices were not subsidized, the social profitability of fertilizer trees relative to inorganic fertilizers increases, leading to an increased interest by farmers and policy makers in such technologies (Adesina and Coulibaly 1998).

Phase 3: The third phase began in early 2000s and was characterized by scaling up of fertilizer trees through multi-institutional partnership and collaboration. Several dissemination projects were initiated at national and subnational levels to promote the systems. A number of factors contributed to the active promotion and scaling up of the systems during this phase:

(a) Increased public awareness on environmental stewardship especially in international forums and funding agencies. This awareness led to increased calls for adoption of "sustainable agricultural intensification," "environmentally friendly agriculture," "ecoagriculture," and "evergreen agriculture." Eco-friendly projects initiated in the region during the phase include Zambia Integrated Agroforestry Project (ZIAP), Conservation Farming Unit (CFU), Total Land Care (TLC) in Malawi, and Agroforestry Food Security Project (AFSP) in Malawi, among others. In addition to promotion of such programs, governments have also responded through regulation. An example is the case of Malawi, where regulations stipulate that tobacco farmers must have at least 10% of their land under tree cover to cater for the wood demand of the crop for curing and/or drying.

(b) Following increased concerns for food safety and food quality among the public, especially high- and middle-income group, the demand for organic farm products in international agricultural trade and the promotion of certified organic export production led to the establishment of eco-friendly organizations such as the Organic Producers' Association of Zambia (OPAZ) and the Malawi Environmental Endowment Trust Fund (MEET) in Malawi.

(c) Increased involvement of the nongovernment sector to promote fertilizer trees. Such partnership involved the private sector (Dunavant Cotton Company) and NGOs such as World Vision, AfriCare, Cooperative League of the USA (CLUSA), KEPA (a Finnish NGO), Catholic Development Commission (CADECOM) in Malawi, Catholic Relief Services (CRS), and farmers' organizations such as National Association of Small-Scale Farmers of Malawi (NASFAM). For example, the Dunavant Cotton Company, one of the original promoters of CA, collaborated with other research and development institutions to run a series of training programs on CA during each cropping season for their group distributors. These distributors are lead farmers through whom Dunavant distributes inputs, credit, and information on key management practices to cotton farmers.[18] The CFU and its partners participate in regular training sessions for Dunavant distributors, helping to disseminate conservation agriculture principles to these lead cotton farmers. Several Dunavant distributors also serve as demonstration farmers for CA.

(d) Emergence of reducing emissions from deforestation and forest degradation (REDD) and new market opportunities that recognize the role of trees to mitigate climate change. The recognition and emergent environmental markets provide various forms of new incentives that reward farmers for planting and maintaining trees in agricultural landscapes.

(e) There are new policies and programs initiated by governments in the region to promote tree planting by providing incentives to smallholder farmers. Such initiatives include "Tree Planting for Ecosystem Services" Project embarked upon by the Malawi Government which paid farmers up to K20,000 ($130) per hectare for trees planted to sequester carbon. There are new policies in Malawi to cede ownership to farmers for certain tree species that the government had hitherto laid exclusive ownership to (Tembo Chayenga, personal communications, 2010). The forestry policy is in the process of being reviewed to take cognizance of new opportunities that are emerging in agroforestry and for climate change (Dennis Kayambazinthu, personal communications, 2011).

Agroforests in Indonesia

Unlike the other case studies in this chapter, the case of agroforests in Indonesia is not about how policy affected a recently scaled-up agroforestry system but is rather how recent policy is affecting the continued existence and dynamics of a traditional practice. There are many types of agroforest in Indonesia, but the ones occupying significant land areas include rubber-based agroforests, damar-based agroforests, and tree crop (e.g., coffee) agroforests.[19] These systems have been practiced by smallholder farmers for many decades, going back to at least the early 1900s in some cases.

Rubber agroforests were started as a land use practice over large areas in the early 1900s from the farmers' own initiative. Rubber is a major export commodity supporting the Indonesian economy. More than one million households now depend on rubber as their main source of income, and much of this is grown under agroforestry conditions on nearly 3 million ha of land. Rubber was introduced into SEA in the late 1800s and had a very rapid effect on land use, being integrated with wide spacing into food crop systems (Wibawa et al. 2005). Smallholder rubber producers earn 90% of their incomes from farming (about 70% from rubber). They enjoy benefits from the other trees in the system, both for consumption and income. Rubber agroforestry systems that use selected clonal rubber planting material can achieve similar yields as the monoclonal smallholder plantations that have for several decades been promoted by global financial institutions, with approximately 46% lower investment costs and 69% higher returns to labor.[20]

A second major agroforest type is the damar (*Shorea* spp.) agroforest. Damar produces a valuable resin used in paints, varnishes, and some cosmetics. As normally practiced, it is a long-term system where annuals give way to perennials like black pepper and coffee which give way (after 20 years) to damar. The system grew significantly in late 1800s in response to demand for damar in industrial products. Kusters et al. (2008) found that the contribution of damar to household income decreased from 38 to 29% from 1995 to 2004. However, income from perennial tree crop components (e.g., coffee and pepper) increased so that overall contribution from tree enterprises remained the same. Price and market opportunities played a key role in this as pepper prices had risen over the period. Returns to labor are high for damar, although returns to land are lower compared to some monocropping alternatives. The issue facing these agroforests is whether in their current forms they are attractive enough for farmers to sustain them and secondly the role that policy has played in driving incentives for practicing agroforestry or other land uses. It is well known that there has been significant deforestation in Indonesia. Between 1990 and 2005, nearly 30 million hectares of forest was logged over or converted into other land uses, representing a total loss of about 23%.

The government has publicly stated its intention to reduce greenhouse gas (GHG) emissions with about half coming from land use/land use change. Deforestation rates have fallen in the most recent periods of time (FAO 2010), also suggesting greater commitment to forest protection. While forests were declining, so were multispecies agroforests. They declined from about 1.9 to 1.6 million ha from 1990 to 2005, or 16% (Ekadinata et al. 2011). The land use that has increased fastest over the same period was monocropped agriculture on large estates, with oil palm (*Elaeis guineensis*) being the major enterprise. Large estates have been planted to oil palm: between 1995 and 2008, the area under oil palm estates soared from 992,000 to 4,452,000 ha. Much of this is of course fuelled by the economics and the returns to different land use options known to farmers.

Government policy has been both supportive and obstructive to would be agroforest managers. In terms of support for agricultural enterprises, the government has supported the development of higher yielding varieties of tree crops. These could potentially be used to increase the returns to agroforests but in fact have been bred for and tested in monoculture production systems. Research has shown that with unimproved varieties of the main economic tree enterprise, the agroforestry systems cannot compete economically with monocultures using improved varieties.[21] However, a concerted effort by agroforestry researchers tested clonal rubber varieties in an agroforest context, with the positive results as noted above. Following this, there has been more positive interest by the government to make known such innovations to farmers.

Long-term right to land is another challenge to smallholder agroforest managers. Nearly 70% of land in Indonesia is owned by the Ministry of Forestry, and about 90 million people live on such land deriving livelihoods mainly from agriculture and forest-based resources. Over recent years, the government has fostered conversion of many of these lands to large monoculture estates (chiefly oil palm) through the granting of concessions with relatively strong private rights.[22, 23] At the same time, little had been done about the rights of smallholders who were *de jure* illegally settled on forest land and faced constant threats of eviction. This had the effect of reducing their incentives to protect and manage the longer term tree enterprises. However, through some champions within the Ministry of Forestry, in 1998, a ministerial decree designated an estimated 29,000 ha of *repong damar* as a Special Purpose Area (KDTI) within the State Forest Zone of Lampung Barat. Customary communities and farmers, represented by their customary authorities, could apply for perpetual land use rights, which eliminated the threat of eviction by the state, so long as certain conditions were met – notably that the damar agroforest was well managed. The decree also prohibited permanent coffee plantations, shifting cultivation, oil palm estates, and timber estates and required farmers to reforest using species suggested by the Provincial Forestry Office. As such, the environmental benefits of the damar agroforest system were recognized, including the buffering protection of the natural forests of the agroforests which were bordering the forests. Subsequent analysis found that indeed farmers operating under the KDTI decree were investing more in tree planting and management (Pender et al. 2008). Perhaps because of this successful pilot, the Ministry of Forestry has also paved the way for community control of forests through the declaration of Lubuk Beringin village as the first ever "hutan desa" in Indonesia in 2009 (which recognizes a "village forest" – one that can be managed by the village). Thus it can be seen that the government does recognize the importance of agroforests and the need to provide improved policy support for them. However, the measures taken to date are overwhelmed by policies that have led to large-scale development of monoculture land use systems by large private estates as well as smallholder farmers who benefit from the markets developed by such estates.

Synthesis of Key Lessons Learned

Despite the diversity of systems and locations where widespread adoption of agroforestry has taken place, a number of key general lessons can be drawn from the case studies:

- First, in addition to the technical characteristics of agroforestry systems, widespread adoption is affected by a matrix of factors including geo-spatial factors, and the institutional and policy context within which agroforestry is disseminated to farmers. Specific agroforestry systems and species should be targeted to their biophysical niches (to ensure that they perform well in the field) taking cognizance of the economic-political scenarios. This will ensure reasonable degree of rationality of farmer adoptability of the systems in the given scaling-up locations. Economic drivers are important in all cases: private returns to the agroforestry system must be evident for wide-scale and sustained adoption.
- Second, widespread dissemination and farmers' adoption of agroforestry in different geographical areas is strongly influenced by the policy and institutional context within which agroforestry is disseminated. Successful adoption of agroforestry will be enhanced if dissemination activities at the farm level are complemented by policy, institutional and economic incentives that are conducive to and

encourage farmers to adopt agroforestry. Economic factors and policies directly and indirectly send signals to farmers that may encourage or discourage them from long-term commitment to invest in agroforestry.

- Third, policies are often important in facilitating the growth of agroforestry and will continue to do so in the future. In many of the cases presented above, the spread of agroforestry was triggered when existing or new policies created market opportunities and increased the economic rationale for adopting given agroforestry systems. The examples above show that major policy decisions have worked for and against agroforestry depending on the context (e.g., logging bans in India vs. export crop promotion in Indonesia). It is also seen that policy goals in other sectors like expansion of fertilizer use in southern Africa can have a major role on the adoption of agroforestry.
- Fourth, evaluating the effect of the overall policy environment and trends toward agroforestry is not simple because many different policies can have an impact. Further, some can be favorable while others are not. The case of Kenya with fruit tree growing is an interesting example of where policy is rather neutral, the important result being that the government is not interfering with a sector that appears to be growing well with private sector in the lead.
- Fifth, policy will respond to evidence, though not always promptly. Agroforestry was found to be increasingly embedded into national development programs as evidence of its benefits became better known. However, as the case of Indonesia shows, policy makers may prefer to take a cautious approach, launching pilot policy reforms prior to major policy change. The adoption of policy measures are, nevertheless, often influenced by the political economy (e.g., the quest for export and foreign exchange diversification) and vested political interests surrounding a given policy measure.
- Sixth, to reach the goal of widespread adoption of agroforestry options on a *sustained* basis, over the long term, policy and dissemination questions will have to be researched with the same vigor that biophysical and farmer levels questions are being investigated. Much more research attention should focus on the role of policy, not only from a retrospective sense, but in a more proactive way during the different phases of farmer adoption of agroforestry systems. As part of the efforts to get the policy right, it is necessary to evaluate existing national and regional policies to determine whether they have inadvertently created direct and/or indirect (dis)incentives to the adoption of agroforestry. For example, several years ago, fertilizer tree systems were considered impractical or less economically rational to use in Nigeria because nitrogen fertilizers were a cheaper option at that time (Sanchez 1999). A review of the impact of institutions and policies to support the adoption of fertilizer tree systems in southern African region indicated that the low producer pricing policies adopted by several governments in the region heavily taxed smallholders in favor of urban consumers, thus reducing the financial ability of farmers to invest in these systems.[24]

Implications for Future

Improving Policy Research in Agroforestry

In conducting a literature search for this chapter, very few studies were found which reviewed policies or examined their effects on the adoption and impact of agroforestry. Future efforts should be focused on conducting more analysis of the different policies affecting or related to agroforestry that may be driving the adoption of agroforestry systems in various countries. Several analytical areas would be fruitful. The first would be to provide better evidence on the impact of policies through field research in a number of different countries. One aspect of this should be to conduct baseline and follow up evaluations of new or planned policy changes. Another aspect could dig more deeply into examples like our case studies to better understand overall success factors and the role that policy played. This perspective is lacking in depth in the literature surrounding many of the case studies. Second, a review of major policy documents would be beneficial to identify examples of good policy for agroforestry. Third, a better understanding is needed of the major policy processes at national level, the key players and institutions that contribute to the emergence of the policies, and their respective roles in the process.

Improving Policies for Agroforestry

Our review of six case studies has shown that many national governments have explicitly considered agroforestry as they have made policy changes. The recognition of the importance of agroforestry appears to be growing, especially with increased attention paid to climate change adaptation and mitigation. This may provide for further opportunities to improve the policy environment for agroforestry. If policy constraints in the area of land and tree tenure, germplasm supply, technology information dissemination, and markets for tree products could be resolved, increased use of agroforestry would provide climate change adaptation benefits to communities. Agroforestry could also provide mitigation benefits but their recognition and reward are challenged by a host of other constraints. Agroforestry is currently not recognized in REDD programs. There is need to expand mitigation opportunities to a full landscape perspective, such as AFOLU (agriculture, forests, and other land uses) and to recognize the value of agroforestry land uses in carbon sequestration. The awareness of the complementarity between the development of agroforestry and the protection of natural forests also needs to be increased. There are many knowledge gaps in moving this forward which research needs to fill. Examples include the implications of REDD on demand and supply of tree products and incentives for agroforestry, the potential carbon benefits and monitoring costs in agroforestry systems, determination as to who has rights to carbon sequestered or emissions reduced, the tradeoffs such land use change may pose on food productivity, provision of other environmental services (e.g., water flows), and fairness of marginalized groups. To answer such questions and indeed to provide more evidence on the types of policies that would better promote agroforestry, there is a greater need for collaboration among research and development organizations to design areas of inquiry and to draw lessons from the more fragmented efforts to date.

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Multifunctional Agriculture and Opportunities for Agroforestry: Implications of IAASTD

Roger R.B. Leakey

Abstract To explain the relationship between agroforestry and multifunctional agriculture, this chapter presents some of the key messages from the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) vis-à-vis the objectives of agroforestry. Multifunctional agriculture has been proposed as a paradigm for productive and sustainable agriculture, which is especially appropriate for poor smallholders in the tropics. Agroforestry, like multifunctional agriculture, has the objective of promoting economically, socially, and environmentally sustainable rural development. This chapter briefly summarizes some of the major global issues of land degradation, poverty, malnutrition, and hunger and examines how agroforestry can play a substantial role in the delivery of a better future. To illustrate these points, an integrated rural development project in Cameroon is presented as a good example of how agroforestry can rehabilitate degraded land, diversify farming systems with domesticated indigenous trees, and create business and employment opportunities in rural communities, which substantially improve the livelihoods of rural people.

Keywords Land rehabilitation • Livelihoods • Natural resources management • Poverty alleviation • Sustainable rural development

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Introduction

The International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) has reviewed the very complex sets of social and biophysical issues associated with the economic, social, and environmental sustainability of modern agriculture. The IAASTD reports examine the ability of agriculture to deliver high yields of good quality food at acceptable prices; the reduction of poverty, hunger, malnutrition (including obesity), and environmental degradation; the improvement of rural livelihoods; as well as the mitigation of climate change, against a background of increased economic growth. The reports, which were accepted by 61 governments at an intergovernmental plenary in Johannesburg, South Africa, on April 11, 2008, present the philosophy of "multifunctional agriculture," which recognizes the "inescapable interconnectedness of agriculture's different roles and functions" in rural development. The reports see the application of this philosophy as the means to make significant progress toward this list of highly complex and interacting development targets (McIntyre et al. 2008) and suggest that agriculture is at a "crossroads" and in need of redirection (Kiers et al. 2008). Leakey (2010) has suggested that agroforestry is an appropriate model and delivery mechanism of this new agricultural paradigm – one that is socially and environmentally sustainable, pro-poor, and promotes economic development and growth; this point has also been emphasized in several of the papers in the introductory section of this volume (e.g. Leakey et al. 2008).

Some of the major issues addressed by the IAASTD reports are:

- The scale of natural resource degradation (affecting 2.6 billion people and 2 billion ha of farmland), depletion of soil fertility (nitrogen, phosphorus, and potassium – NPK – deficiencies affecting 59, 85, and 90% of crop land, respectively), loss of biodiversity (valued at $1,542 billion/year), depletion of water resources (2,664 km^3/year), and agroecosystem function, against a background in which new land for agriculture is increasingly scarce. This situation that makes the rehabilitation of farmland an imperative has arisen from the overexploitation of natural capital rather than basing production on its effective management to generate "interest." Agricultural research and development has inadequately addressed the cycle of land degradation, which is responsible for a "yield gap" between the biological potential of Green Revolution crops and the yield that poor farmers typically manage to produce in the field.
- Over the last 60 years, agricultural intensification has resulted in:
  - Substantial gains in crop and livestock production. These are due to advances in breeding (e.g., genetic gain, stress resistance), husbandry (e.g., fertilizer, irrigation, mechanization), policy (e.g., Intellectual Property Rights, variety release processes), microfinance (e.g., credit, provision of inputs), education and communication (e.g., farmer-field schools), and market and trade (e.g., demand, incentives). World cereal production, for example, has more than doubled since 1961, with average yields per hectare also increasing around 150% (with the notable exception of sub-Saharan Africa).

  - Improved livelihoods of many farmers and the economic growth of developed countries. In real terms, food has become cheaper (although currently prices are increasing), and calorie and protein consumption has increased. On a global scale, the proportion of people living in countries with an average per capita intake of less than 2,200 kcal per day has dropped from 57% in the mid-1960s to 10% by the late 1990s.

- Advances in biotechnology, which are recognized as important tools for scientific progress, especially the role of genomics and marker-selected breeding, but there are concerns about the release of transgenic organisms before their impacts on the environment are better understood.
- The incidence of poverty (3.2 billion people with an income of less than US$2/day), malnutrition and nutrient deficiency (two billion people), and hunger (0.9 billion people) remain at unacceptable levels, despite the very significant improvements in agricultural production. In addition, one billion people are affected by obesity due to poor diet.
- Agricultural production and governance have focused on producing individual agricultural commodities rather than seeking synergies and optimum use of limited resources through technologies promoting integrated natural resources management.
- Modern public-funded agricultural knowledge, science, and technology (AKST) research and development has largely ignored the needs of poor smallholders and the improvement of traditional production systems based on "wild" resources which, traditionally, have played an important role in peoples' livelihoods.
- Agriculture is responsible for 15% of greenhouse gas emissions.
- There are numerous organizational and conceptual "disconnects" between agricultural disciplines and organizations, especially those responsible for environmental services and sustainable development.
- Since the mid-twentieth century, the globalization pathway has dominated agricultural research and development as well as international trade, at the expense of the "localization" benefits of many existing small-scale activities of farmers and traders that are aimed at meeting the needs of poor people at the community level. The formation of some recent public-private partnerships illustrates a mechanism for addressing the balance between globalization and localization.
- Agricultural professionals have often lacked the resources and skills base to adequately support the integration of agricultural, social, and environmental activities that would support the promotion of multifunctional agriculture.

There have been many research approaches to the addition of ecological principles to well-recognized areas of agronomy, livestock husbandry, and natural resources management – collectively described as Integrated Natural Resources Management (INRM). Through INRM, agricultural science has begun to address sustainability challenges with strategies that recognize the more socially relevant, pro-poor approaches to agriculture that relate to production, livelihoods, and ecosystem service functions. However, there is a need to further revitalize farming systems, rehabilitate natural capital, and increase income generation opportunities in ways that meet the needs of local people. This requires further development and upscaling of socially and environmentally sustainable agricultural practices that achieve simultaneous impacts at different points in the cycle of land degradation and social deprivation (Leakey 2010).

Toward Multifunctional Agriculture

To build on the positive outcomes of the last 60 years of agricultural intensification, it is important to find ways of restoring soil health by enhancing fertility and diversifying the farming system to promote more resilient risk management. The achievement of this would reduce dependency on purchased inputs and increase the biodiversity necessary for improved agroecosystem function at the plot and landscape level (see Fig. 1). The inclusion of trees within these systems would increase the number of niches in the agroecosystem in ways which make them less damaging to the environment, provide environmental services, and help to counter climate change. Due to the diversity of moist and dry tropical forests and woodlands, there are many species available to play these important ecological roles in a developing agroecological succession (Leakey 1996). If this diversification includes indigenous species with market potential that meet the everyday needs of local people, this would importantly also strengthen and support local culture while generating much needed income.

Fortunately, there are examples from around the world of low-input, socially relevant, pro-poor approaches to rural development that relate to production, livelihoods, and ecosystem service functions. Some of these approaches are based on an understanding of agroecology and soil science, but, currently, few of them provide a complete package. Many of these low-input, resource-conserving technologies are based on integrated management systems such as reduced- or no-tillage, conservation agriculture, ecoagriculture, agroforestry, permaculture, and organic agriculture. Of these, agroforestry seems to be particularly relevant to the delivery of multifunctional agriculture. Like the other systems, it can address the issues of soil fertility management, the rehabilitation of degraded farming systems, loss of biodiversity above and below ground, carbon sequestration, and soil and watershed protection. However, in addition, agroforestry can also provide five crucial outputs that are not provided by the other systems, namely, (1) useful and marketable tree products for income generation, fuel, food and nutritional security/health, and the enhancement of local livelihoods; (2) complex mature and functioning agroecosystems akin to natural woodlands and forests; (3) linkages with culture through the food and other products of traditional importance to local people (Leakey 2010); (4) farms serving as carbon sinks rather than contributing to climate change as carbon sources; and (5) an enhanced agricultural matrix in fragmented landscapes which promotes movement of forest species among the forest fragments (Perfecto and Vandermeer 2010). These processes are all part of creating healthy landscapes and “sustainagility” (van Noordwijk et al. 2012). The above characteristics of agroforestry are very similar to

Fig. 1 A landscape in South Vietnam illustrating diversified and multifunctional agriculture based on tree crops

those of multifunctional agriculture as described by IAASTD (McIntyre et al. 2008). Likewise, they both share the objective of simultaneously promoting the social, economic, and environmental benefits of agriculture[1] for land users.

Typically, farmers in developing countries, who do not have access to other sources of income or social support, still have to provide food, medicines, and all their other day-to-day needs from their natural resources, just as they did in the past as subsistence farmers. But now, as a result of deforestation on the one hand and modern farming systems on the other, local communities do not have access to all the species that used to provide the products needed for everyday survival. However, there are many indigenous tree species producing nutritious fruits, nuts, and leaves (Leakey 1999a; Saka et al. 2008) that have the potential to be crops producing marketable food, fodder, and nonfood products (Leakey et al. 2005). Thus, through the integration of trees in farming systems, it is possible to produce a wide range of food and nonfood products. In this way, it is possible to create highly productive farming systems, rich in biodiversity (Leakey 1999b), yielding both staple foods and marketable tree products, while also providing the ecological services traditionally obtained by long periods of unproductive fallow. There is, however, another environmental benefit from the integration of trees in farming systems. Large perennial trees have a high volume of standing biomass, and through litter fall and root turnover, they also enrich the soil with carbon (Minang et al. 2012). This long-term and effective sequestration of carbon gives farming systems which include trees the capacity to reduce CO_2 emissions to the atmosphere and so to play an important role in the mitigation of climate change (Nair 2012). Studies suggest that the conversion of degraded farmland to mature agroforest could increase carbon per hectare from 2.2 to 150 Mg over a potential area of 900 million ha worldwide (World Agroforestry Centre 2007).

After two decades of research and development, about 50 tree species are being domesticated as new crops for integration in agroforestry systems (Leakey et al. 2012) as an incentive mechanism for farmers to improve their own livelihoods. Tree domestication is increasingly engaged in modern scientific technologies to assess and analyze the opportunities to bring improved agroforestry tree products (AFTPs) into new markets based on compounds extracted from tree products. Some of these tree species are currently the subject of participatory domestication programs using local knowledge to improve the yield and quality of their products (Leakey et al. 2003; Tchoundjeu et al. 2006) in ways that empower local communities, promote food self-sufficiency, generate income and employment, and nutritionally enrich the diets of rural people in tropical countries. This is now a global initiative which brings together agricultural science and technology with traditional knowledge in an integrated package capable of helping to meet sustainability and development goals (Leakey 2012). Through these projects, there is growing evidence that agroforestry can help rural communities in the tropics to be self-sufficient and to support their families on an area of less than 5 ha, as well as to lift themselves out of poverty, malnutrition, and hunger (Schreckenberg et al. 2006; Degrande et al. 2006; Asaah et al. 2011). However, to be fully sustainable, it will be important to develop Intellectual Property Rights instruments to protect the innovations developed by the smallholder farmers.

Agroforestry is widely practiced, especially in the tropics, with more than 1 billion ha having 10% or more tree cover worldwide (Zomer et al. 2009). Agroforestry practices are numerous and used by 1.2 billion people, while the tree products are also important for the livelihoods of millions of other people, for example, in urban areas in developing countries. Many of the benefits from agroforestry products arise from local and regional marketing. Nevertheless, with more than 38% of the global crop area severely degraded, and so many people suffering from poverty, malnutrition, and hunger, there is a need to expand the use of agroforestry practices in support of multifunctional agriculture. One of the ways that agroforestry can mitigate these problems would be to improve crop husbandry and close the yield gap.

Filling the Yield Gap: A Special Role for Agroforestry

To be productive for more than a few years, high-yielding staple food crops on land cleared of much of its natural vegetation typically require large inputs of fertilizers, pesticides, and often irrigation, especially in the tropics. The dependence of this type of agriculture on fossil fuels and fossil water is unsustainable. In many parts of the world, poor farmers have cleared the forest vegetation to make way for crops but do not have sufficient access to these agrochemicals, principally due to their high cost relative to farmer income, but partly also as a result of availability. As a consequence, the farmers are trapped by their inability to purchase fertilizers and other inputs. Thus, other ways have to be found to maintain and restore soil fertility and sustain crop production.

The yield gap can be filled through good land husbandry to rebuild natural soil fertility and health and diversification into perennial cash crops that meet social and market needs. Poor smallholders (70% of the 3.2 billion people living on less than US$2 per day) have to be self-sufficient for food, micronutrients, medicines, and all their other day-to-day needs. But, modern farming systems lack all the traditionally important species that used to provide all the products needed for everyday survival. Making matters worse, in the event of failing to provide these household needs, government-funded social-security systems to fall back on do not exist. Part of the solution to rural development and sustainable living is therefore for farming to provide the livelihood needs of the local communities. Fortunately, indigenous and culturally important species do still have local markets. If these traditional species can be domesticated as new and genetically improved crops, there is enormous opportunity to diversify and intensify agriculture with productive trees selected to meet the needs of the community for food and nutritional security, as well as to supplement diets with the micronutrients that boost immunity to diseases. Then, if the markets can be expanded by matching the product value chain to the needs of traders for more uniform and higher quality products with improved shelf life, there is the further prospect of opening up a pathway out of poverty based on either employment or business opportunities. As the trade in indigenous tree products is typically the prerogative of women (Kiptot and Franzel 2012), these opportunities are excellent for promoting gender equity in rural and urban communities. This combination of social and economic advancement with the environmental restoration possible from diversifying agriculture with perennial tree crops points the way forward to closing the yield gap.

Using the example of maize (*Zea mays* L.) production in eastern and southern Africa, the following three-step approach has been suggested as a way to address the yield gap (Leakey 2010). It is based on the use of agroforestry fallows, tree domestication, and the marketing of AFTPs as a way to deliver multifunctional agriculture:

Step 1: Adopt agroforestry technologies such as 2-year improved fallows or relay cropping with nitrogen-fixing shrubs that improve food security by raising maize yields fourfold from around 1 Mg ha^{-1} (Buresh and Cooper 1999; Kwesiga et al. 1999). Likewise, stands of *Faidherbia albida* (Del.) A. Chev. trees play a similar role in the so-called Evergreen Agriculture (Garrity 2012; Swaminathan 2012). This allows the farmers to reduce the area of their holdings planted with maize and so make space for other crops, perhaps cash crops which would generate income. An additional benefit arising from improved fallows with leguminous shrubs like *Sesbania sesban* (L.) Merr. and *Desmodium* spp. is the reduction of parasitic weeds like *Striga hermonthica* Benth. and the reduced incidence of insect pests like the stem borers of maize (Cook et al. 2007).

Step 2: Adopt the participatory domestication of indigenous trees producing marketable products so that new, locally important, and nutrient-rich cash crops are rapidly developed as a source of income and products of day-to-day domestic importance and help empower women and maintain culture and traditions (Cooper et al. 1996; Sanchez and Leakey 1997). Sale of these products would allow the purchase of fertilizers and so, potentially, the increase of maize yields up to 10 Mg ha^{-1}. Consequently, the area under maize could be reduced further to allow more cash cropping. Filling the yield gap will also maximize returns on past investments in food crop breeding.

Step 3: Promote entrepreneurism and develop value-adding and processing technologies for the new tree crop products, so increasing availability of the products throughout the year, expanding trade, and creating employment opportunities – outputs which should help to reduce the incidence of poverty.

Case Study of Agroforestry Delivering Multifunctional Agriculture in Rural Communities

The "*Food for Progress*" program in Cameroon – a winner of the prestigious Equator Prize[2] – is an example of an agroforestry project based on the above three steps and delivering economic social and environmental benefits (Tchoundjeu et al. 2010; Asaah et al. 2011). It involves more than 10,000 farmers and over 200 communities in the west and northwest regions of Cameroon, as well as entrepreneurs in local towns. The project is centered on five rural resource centers which are providing a wide range of training to farmers engaged in agroforestry and the domestication of indigenous fruits and nuts. This capacity building also empowers local farmers to help themselves through an understanding of group dynamics; the use of microfinance (short and small-scale loans); community project management; skills in trade, marketing, and business; and the management of local infrastructure development (e.g., installing water pipes and village standpipes, digging wells, building bridges, and storage sheds for crops). The community-level training in agroforestry includes topics such as the restoration of soil fertility by the use of nitrogen-fixing trees and shrubs, tree propagation and nursery management, and tree domestication using simple low-technology horticultural techniques. This has led to the growth of more than 120 satellite tree nurseries in surrounding communities supported by Relay Organizations (NGOs, CBOs [community-based organizations], etc.) that provide further training and mentoring in the villages. Improved fallows with nitrogen-fixing trees and shrubs for soil fertility enhancement have doubled or tripled staple crop yields.

One of the constraints to better food processing is the availability of local equipment. To overcome this, local metal workers have been supported to develop appropriate equipment for drying, chopping, and grinding a range of foodstuffs, including tree products not previously processed. This has created employment for metal workers and allowed local entrepreneurs to extend the shelf life and the quality of the produce they sell in local markets. These products are selling at higher than usual prices and in a few cases are being sent abroad.

For the farmers, income generation from the sale of plants from village nurseries has risen dramatically as the project gathers momentum with plant sales at the

Rural Resources Centers in Cameroon generating a total of USD 145, 16,000, and 28,350 after 2, 5, and 10 years, respectively. Meanwhile in town, the fabrication of about 150 discharge mills and 50 dryers has generated income in excess of US$120,000 (Asaah et al. 2011; Leakey and Asaah in press), while the women who have set up businesses for grinding crops like cassava (*Manihot esculenta* Crantz) have also increased their income substantially. The largest of these groups was run by ten women who employed eight workers and processed about sixty-six 180 kg bags of dried cassava flour per day throughout the year. Profits from bags selling at US$40–$54 per bag, depending on the season, were said to be more than US$2.5 per bag.

The most important and exciting thing about this project has been the wide range of positive livelihood impacts that the farmers are saying have truly transformed their lives. These require further quantification and verification but include substantially increased income, new employment opportunities, retention of youths in the villages due to career opportunities, improved nutrition, improved health from potable water and better diets, and the ability to spend money on children's schooling, home improvements, wells, etc. Additionally, women indicated reduced drudgery in their lives from not having to collect water from rivers and farm produce from remote farms, as well as from mechanical processing of food crops. All these things mean that they had more time to look after their families and engage in farming or other income generating activities.

These impacts strongly suggest that by promoting self-sufficiency through the empowerment of individuals and community groups through the provision of new skills in agroforestry, tree domestication, food production and processing, community development, and microfinance, it is possible for communities to climb the entrepreneurial ladder out of poverty, malnutrition, and hunger. This case study illustrates the use of agroforestry to deliver multifunctional agriculture in ways that break the cycles of land degradation and social deprivation that have kept nearly half the world's population in poverty (Leakey 2010) and so to steer a path toward social, economic, and environmental sustainability. What is needed now is to disseminate this approach to millions of other poor people in Africa and other tropical countries. There are many ways of doing this, but one very interesting and hugely important one is already in progress in West Africa. It involves Unilever, a multinational company that has recognized the need to use participatory domestication and community agroforestry for the development of several species of *Allanblackia* trees as a new oil crop (Jamnadass et al. 2010).

Opportunities for Enhanced Adoption of Agroforestry

The IAASTD proposal, approved by 61 countries, that agricultural development should be redirected toward multifunctional approaches to agricultural production presents a great opportunity for agroforestry if it becomes recognized as a highly desirable delivery mechanism for the new paradigm (Leakey 2010). To achieve this potential, there is a need to:

- Develop policies to promote agroforestry as a key delivery mechanism for multifunctional agriculture.
- Use multifunctional agriculture to improve public knowledge and understanding of the importance of agroforestry.
- Scale up agroforestry R&D to levels that could have significant economic, social, and environmental impacts. Given that there are 1.8 million needy farmers involved in some sort of agroforestry activity on over 1.0 billion ha of land, any meaningful initiative should have a good chance of rapid adoption.

Attaining political will to implement this upscaling of sustainable rural development will require a better understanding of what agroforestry is and what it can do. An improved public image should lead to political action. Linking agroforestry clearly to multifunctional agriculture should produce mutual benefits and improve the lot of billions of poor and disadvantaged people, as has been illustrated on a small scale in Cameroon (Tchoundjeu et al. 2010; Asaah et al. 2011).

Conclusion

Multifunctional agriculture based on agroforestry meets many of the needs of poor people, but the redirection of agricultural knowledge, science, and technology in support of it will require a paradigm shift with greater emphasis on:

- Integrated approaches to land use management involving participatory approaches to planning and implementation
- Less exploitative approach to natural resources, especially soils and water, and a lower dependence on inorganic inputs and fossil energy
- Good husbandry to support agroecosystem health, restoration of degraded land, and the reduction of the "yield gap"
- Increased involvement of local user groups in actions to improve natural resources management
- Diversification of agriculture for improved soil amelioration, pest and disease control, and new marketable products
- The domestication of new nutritious and marketable crops from local species, especially trees, to diversify diets and the local economy
- Enhancement of rural livelihoods by meeting the needs of local people and supporting culture and tradition
- Better integration of agricultural sectors, government departments and institutions, communities, and stakeholders to overcome "disconnects" in policy and practice
- Public-private partnerships involving diverse stakeholder groups at the local level to support sustainable production, and in-country processing and value adding

End Notes

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Part III
Regional Perspectives

The Future of Temperate Agroforestry in the United States

Shibu Jose, Michael A. Gold, and Harold E. Garrett

Abstract Agroforestry has been practiced in the United States since the 1930s in the form of windbreaks; however, science-based agroforestry research and practice gained attention only in the1970s. Even then, the progress of agroforestry and its acceptance by practitioners, farmers, and policy makers were hindered by the paucity of hard evidence to support the practice. The scientific foundation that has been laid, over the past decade in particular, has elevated agroforestry's role as an integral component of a multifunctional working landscape in the United States. Recent trends in the agriculture sector necessitate farm diversification as an essential strategy for economic competitiveness in a global market. The realization that agroforestry systems are well suited for diversifying farm income while providing environmental services and ecosystem benefits has increased receptivity on the part of some landowners. Agroforestry systems offer great promise for the production of biomass for biofuel, specialty and organic crops, pasture-based dairy, and beef, among others. Agroforestry also offers proven strategies for carbon sequestration, soil enrichment, biodiversity conservation, and air and water quality improvement not only for the landowners or farmers but for society at large. The USDA Agroforestry Strategic Framework released in 2011 identifies agroforestry as an important component of a much-needed national strategy to "enhance America's agricultural landscapes, watersheds, and rural communities." Minor shifts in national agricultural policy can serve to catalyze the growth of agroforestry further. In an era of environmental sustainability and green business, the realization that agroforestry is an environmentally sound, ecologically sustainable, and economically viable alternative to traditional farming will propel its adoption to newer heights in the coming decades.

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Introduction

In order to understand the future of agroforestry in the United States, one must first understand its past. Even though windbreaks took on great prominence following the "dust bowl" years (Droze 1977), and landowners have known the value of their woodlands for livestock management for decades (DenUyl and Day 1934; Chandler 1940), the use of science-based agroforestry technology in the United States is of very recent origin. J. Russell Smith created early interest in the US agroforestry in his classic work *Tree Crops: A permanent Agriculture* (1950). While the book primarily emphasized "tree-based" agriculture as a source of food for livestock, attention was drawn to the potential ecosystem services that could result from the integration of trees with agricultural crops. Smith argued that "an agricultural economy based almost entirely upon annual crops such as corn and wheat is wasteful, destructive of soil fertility and illogical." However, it was not until the mid-1960s and -1970s that agroforestry had its beginning as a science in the United States. It was at this time that dedicated research began in the southeast to study the potential benefits of integrating pine (*Pinus* spp.) with pastures (Silvopasture: Hart et al. 1970) and in the Midwest to study the interactions between black walnut (*Juglans nigra* L.) and conventional row crops (Alley Cropping: Garrett and Jones 1976). From these beginnings, agroforestry in the United States has grown into an integrated science that also includes the practices of riparian and upland buffers, windbreaks, and forest farming (Garrett 2009).

With the increased understanding of the strengths and weaknesses of agroforestry practices has come an increased receptivity on the part of landowners to explore its use to address farm-related, environmental issues (Udawatta et al. 2002), conservation and wildlife needs 1), and economic gain (Alavalapati and Mercer 2004). While many agroforestry proponents believe that the US agroforestry is best adapted to provide ecosystem services (e.g., carbon sequestration; soil, air, and water quality; biodiversity conservation), agroforestry practices can also result in great economic value when tree species that produce a marketable annual crop are matched with the appropriate companion crop. In particular, combining tree crops such as pecan (*Carya illinoinensis* (Wangenheim) K. Koch) or chestnut (*Castanea mollissima* Blume) with specialty crops (e.g., botanicals, ornamentals, small fruits) or biomass for energy crops (herbaceous or woody species) can provide a competitive and sustainable source of income while yielding multiple conservation benefits. The scope of this chapter is to discuss some of these potential benefits and future applications of agroforestry in the United States. Beginning with a brief overview of the five recognized temperate agroforestry practices in the United States and followed by specific examples for integrating production agriculture and forestry to create more productive and ecologically beneficial land-use strategies, the chapter challenges the reader to think creatively—a tree becomes a great deal more than just a tree when properly used.

Agroforestry Practices in the United States

In the United States and Canada, agroforestry is defined as intensive land-use management that optimizes the benefits (physical, biological, ecological, economic, and social) from biophysical interactions created when trees and/or shrubs are deliberately combined with crops and/or livestock (Gold and Garrett 2009). The five agroforestry practices commonly found in the United States (Table 1) are described below.

Table 1 Five categories of agroforestry practices in the United States and potential area available for each practice

Practice	Predominant region(s)	Use(s)	Associated technologies	Potential area[a] (million ha)
Riparian and upland buffers	All regions	Ameliorate non-point-source pollution, abate soil erosion and nutrient loading, protect watersheds	Streambank bioengineering	1.69
		Modify microenvironments and protect aquatic habitats	Constructed wetlands	
		Create wildlife corridor		
Windbreaks	Great plains	Protect and enhance production of crops and animals, control soil erosion, distribute snowfall	Living snow fences	8.95
		Trap snow		
Alley cropping	Midwest	Increases and diversifies farm crops and income, creates wildlife habitat	Plantation management	17.9
Silvopasture	All regions	Economic diversification, improve animal health, fire protection, timber management	Pine straw harvest	77.7
Forest farming	All regions	Income diversification	Forest management	37.35

[a] Potential area as given in Udawatta and Jose (2011)

Fig. 1 A riparian buffer at the Bear Creek watershed in Iowa. It includes mixed hardwood trees, shrub species, and a native prairie mix of about 15 different grass and forb species. The picture was taken when the buffer was 13 years old (Photo credit: Iowa State University NREM Buffer Team)

Riparian and Upland Buffers

Riparian and upland buffers are strips of permanent vegetation, consisting of trees, shrubs, grasses, and forbs that are planted and managed together. Riparian buffers are placed between agricultural land (usually crop land or pastureland) and water bodies (rivers, streams, creeks, lakes, wetlands) to reduce runoff and nonpoint source pollution (NPSP), stabilize stream banks, improve aquatic and terrestrial habitats, and provide harvestable products (Fig. 1). Upland buffers are placed along the contour within agricultural crop lands to reduce runoff and non-point-source pollution, improve internal drainage, enhance infiltration, create wildlife habitat and connective travel corridors, and provide harvestable products (Schultz et al. 2009) (Fig. 2).

Windbreaks

Trees or shrubs are planted as barriers to reduce wind speed. Windbreak practices include shelterbelts, timberbelts, and living snow fences. Windbreaks are planted and managed as part of a crop or livestock operation. Field windbreaks are used to protect a variety of wind-sensitive row, forage, tree, and vine crops, to control wind

Fig. 2 An upland buffer with trees and grasses at the Greenley Memorial Research Center of the University of Missouri (Photo credit: Ranjith Udawatta, The Center for Agroforestry, University of Missouri)

erosion, and to provide other benefits such as improved bee pollination of crops and wildlife habitat. Livestock windbreaks help reduce animal stress and mortality, feed and water consumption, and odor. Timberbelts are managed windbreaks designed to increase the value of the forestry component (Brandle et al. 2009).

Living snow fences or snowbelts are strategically placed living barriers that have been specifically designed and planted to reduce blowing and drifting snow to improve public safety and emergency services, decrease road maintenance costs, and reduce livestock and wildlife mortality.

Alley Cropping

This practice combines trees planted in single or multiple rows with agricultural or horticultural crops cultivated in the alleyways between the tree rows (Fig. 3). High-value hardwoods such as oak (*Quercus* spp.), walnut (*Juglans* spp.), chestnut (*Castanea* spp.), and pecan (*Carya illinoinensis* (Wangenh.) K. Koch) are favored species in alley cropping practices, and many can provide high-value lumber or

Fig. 3 A pine-cotton alley cropping in Northwest Florida (Photo credit: Shibu Jose, The Center for Agroforestry, University of Missouri)

veneer logs. Crops grown in the alleys, and nuts from walnut, chestnut, and pecan trees, provide annual income from the land while the longer-term wood crop matures. When specialty crops such as herbs, fruits, vegetables, nursery stock, or flowers are grown in the alleys, the microclimate created by the trees enhances the economic production of these sensitive high-value crops in stressed environments (Garrett et al. 2009).

Silvopasture

This practice combines trees with forage (pasture) and livestock production (Fig. 4). Silvopasture can be established by adding trees to existing pasture or by thinning an existing forest stand and adding (or improving) a forage component. The trees are often managed for high-value products (e.g., sawlogs, veneer, posts, and poles), and at the same time, they provide shelter for livestock, protecting them from temperature stresses and reducing food and water consumption. Forage and livestock provide short-term income while at the same time a high-value tree crop is being grown, providing a greater overall economic return from the land (Sharrow et al. 2009).

Fig. 4 A silvopastoral system with hardwood trees at the Wurdack Farm of the University of Missouri (Photo credit: Dusty Walter, The Center for Agroforestry, University of Missouri)

Forest Farming

High-value specialty crops are cultivated under the protection of a forest overstory that has been modified and managed to provide the appropriate microclimate conditions. Shade-tolerant specialty crops like ginseng (*Panax quinquefolium* L.), log-grown shiitake mushrooms *(Lentinula edodes* (Berkeley) Pegler), decorative ferns, and spring ephemerals grown in the understory are sold for nutritional supplement, food, decorative/handicraft, and landscaping products. Overstory trees are managed for high-value timber or veneer logs (Chamberlain et al. 2009).

Agroforestry for Biomass and Biofuel Production

One of the commodities agroforestry is well suited to producing is biomass for bioenergy. The Energy Independence and Security Act Renewable Fuels Standard Version 2 (RFS2)[1] mandates that annual biofuels use nearly triple from the current 45–136 billion L by 2022, with nearly 80 billion L coming from advanced biofuels. Billions of dollars are being invested annually by major private companies, venture capitalists, and the federal government in the development of new technology to convert woody and nonwoody species into advanced, drop-in biofuels such as butanol, jet fuel, and green diesel. Major US companies are seeking to purchase large volumes of advanced biofuels. However, the development of a sustainable feedstock system with minimal impacts on existing food and fiber sectors has been a bottleneck in which the technology cannot be deployed until the feedstock production is in place. In the past 5 years, there have been massive investments in both corn (*Zea mays* L.) ethanol and soybean (*Glycine max* (L) Merr.) biodiesel facilities throughout the Midwestern United States. In 2007 and again in 2010, due to the surge in demand for biofuels and increased oil prices, commodity prices for corn and soybeans spiked to near record levels. The fear of losing productive agricultural land to short rotation woody crops and other bioenergy crops such as switchgrass (*Panicum virgatum* L.) is real but can be negated by adopting integrated approaches such as alley cropping or other relevant agroforestry systems in which food and bioenergy production could be combined.

Incorporating the agroforestry model for biomass production into the traditional agriculture model, however, is challenging. While overcoming the logistical, financial, and cultural obstacles will be an uphill task, it may be an attractive option for many farmers on marginal crop lands. For example, marginal floodplain land is ideal for biomass production using an agroforestry model. Such land could be placed into an alley cropping or riparian buffer system that would integrate rows of short rotation, high yielding woody crops such as willow (*Salix* spp.) and poplar (*Populus* spp.) with alleys of perennial and/or annual grasses (Table 2). Marginal floodplain land is ideal for this type of land use because the land is oftentimes poorly suited for annual agricultural production and better suited for perennial plants (Groninger 2005; Thelemann et al. 2010). In addition, many of these areas are currently out of production because of participation in federal programs such as Conservation Reserve Program (CRP), and biomass could be produced in these areas to meet the goals of the EISA RFS2 without taking additional agricultural land out of production (Volk et al. 2004). Furthermore, these lands are abundant (e.g., nearly 47 million ha of frequently flooded highly erodible land along the Mississippi River alone) and easily identifiable on the landscape, and agroforestry systems for biomass production could be concentrated so that they would not interfere with traditional agricultural operations.

While agroforestry holds great promise for integrating food production with biomass for fuel, little attention has been placed on this subject (Henderson and Jose 2010). Of all the common North American agroforestry practices (Garrett 2009), windbreaks, riparian buffers, and alley cropping appear to be the most promising for maximizing biomass production in the United States, without sacrificing food production. Although none of these practices incorporating biomass production is currently widespread, small-scale examples exist throughout the United States.

Field windbreak systems require linear rows of trees evenly spaced, typically anywhere from 150 to 300 m apart, across a landscape. Normally, one to three rows of fast-growing trees are established within each windbreak. In order for a windbreak to be effective in both biomass production and increased crop yields, a minimum of

Table 2 Production of annual and perennial biomass species within the US North Central region

Species	Annual yield (Mg ha^{-1})	Rotation	Location	Citation
Agricultural crop				
Maize (*Zea mays*) grain	7–9	Annual	Illinois	Tollenaar and Lee (2002)
Sorghum (*Sorghum bicolor*) grain	4.5	Annual	United States	USDA-NASS (2010)
Sorghum biomass	8–16	Annual	Missouri	Stevens and Holou (2010); Houx, personal communication (2011)
Sorghum biomass	16	Annual	Iowa	Hallam et al. (2001)
Alfalfa (*Medicago sativa*)	10	Annual	Iowa	Hallam et al. (2001)
Tree species				
Black locust (*Robinia pseudoacacia*)	13	5 years	Kansas	Geyer (1989)
Cottonwood (*Populus deltoides*)	11.8	5 years	Kansas	Geyer (1989)
Populus deltoides x P. trichocarpa	15.1–22.7	4 years	Wisconsin	McLaughlin et al. (1987)
(*Populus*) clones NE-41	14.5	3 years	Vermont	Laing (1985)
Honey locust (*Gleditsia triacanthos*)	6.1	Annual	Kansas	Geyer (2006)
Silver maple (*Acer saccharinum*)	9.7–12.8	2–5 years	Kansas	Geyer (1989)
Silver maple	9.0	3 years	Vermont	Laing (19 85)
Willow (*Salix alba*)	12.5	1 year	New York	Adegbidi et al. (2001)
Salix alba	21.7	3 years	New York	Adegbidi et al. (2001)
Grass				
Miscanthus (*Miscanthus x giganteus*)	40	Annual	Illinois	Pyter et al. (2007)
Miscanthus (*Miscanthus x giganteus*)	32.3	Annual	Missouri	Houx, personal communication (2011)
Switchgrass (*Panicum virgatum*)	12	Annual	Iowa	Vogel et al. (2002)
Switchgrass	9–12	Annual	Indiana	Wright and Turhollow (2010)
Giant cane (*Arundo donax*)	30–40	Annual	Arkansas	Burner, personal communication (2011)
Big bluestem (*Andropogon gerardii*)	8.5	Annual	Iowa	Hallam et al. (2001)
Eastern gamagrass (*Tripsacum dactyloides*)	14.6	Annual	Missouri	Roberts and Kallenbach (1999)

Source: Modified from Holzmueller and Jose (2012) two tree rows would be necessary. Windbreak effectiveness is a function of tree height, and increased crop yields per hectare would decrease, and perhaps disappear, if the entire windbreak was harvested for biomass. Therefore, as one row is harvested for biomass, the second row would be left in place until the previously harvested row would be tall enough to be effective. Longer rotations would be necessary to ensure adequate tree height; however, this might actually increase perennial biomass production as most short rotations of woody biomass occur before the culmination of the mean annual growth (Riemenschneider et al. 2001; Goerndt and Mize 2008).

Riparian buffers are a common feature of the landscape in the US North Central Region in particular. Because agricultural runoff has been identified as a key contributor to non-point-source water pollution, including the hypoxia in the Gulf of Mexico, riparian buffers are a heavily subsidized, agroforestry practice by federal cost-share programs such as the CRP, Environmental Quality Incentives Program (EQIP), Wetlands Reserve Program (WRP), Conservation Stewardship Program (CSP), and Wildlife Habitat Incentive Program (WHIP). Landowners receive financial incentives to take land within highly erodible or riparian areas and plant perennial vegetation (riparian buffers) that reduce non-point-source pollution and increase wildlife habitat. Although land within these programs is oftentimes used to grow perennial biofuel species, harvesting of these crops is not allowed under CRP until after the contract ends. For the other programs, harvesting may be allowed as long as the function of the buffer for water quality or other purposes is not lost. While in the past, farmers have been hesitant to take fertile agricultural land adjacent to waterways out of production without financial incentive, increased market values for biomass could potentially increase voluntary participation for establishing riparian buffers that would not have the harvest restriction of current government-sponsored programs. Although establishment of additional riparian buffers would take land out of grain production, these areas would likely yield the greatest amounts of perennial biomass given the fertile soils of riparian areas (Tufekcioglu et al. 2003; Goerndt and Mize 2008; Thelemann et al. 2010).

Properly designed and applied alley cropping can “overyield” compared to its component species in monocultures (Jose et al. 2004). Although somewhat common in tropical regions, alley cropping has had limited adoption in the United States. Most of existing examples have used primarily high timber value species such as black walnut, and these tree species are unlikely to be used for biomass production (Garrett et al. 2009). While there are several studies that have investigated short-term yields of annual crop and tree biomass species in alley cropped systems in the US North Central Region (Miller and Pallardy 2001; Delate et al. 2005; Reynolds et al. 2007), review of the existing literature did not reveal any published crop/biomass production estimates over a long-term period (series of multiple rotations for annual crops and biomass species) for these systems.

The limited research that has been conducted on temperate alley cropping systems does suggest grain yield decrease in these systems as the trees mature (Gillespie et al. 2000; Garrett et al. 2009). However, switching from a summer crop (e.g., corn) to a spring crop (e.g., winter wheat; *Triticum aestivum* L.) can increase phenological complementarily and high grain yields in alley cropping systems (Chirko et al. 1996). Given the high price of maize in recent years, this may be a challenging proposition for many landowners in the Midwestern United States. Substitution of maize with cool season grasses or legumes may also help maintain biomass yields once the trees are older. Typically, cool season grasses and legume species utilizing C_3 photosynthesis are more shade tolerant than C_4 species. In a study of several cool season grasses including orchardgrass (*Dactylis glomerata* L.), tall fescue (*Festuca arundinacea* Shreb.), and clover (*Trifolium* spp.) in Missouri, Lin et al. (1999) reported minimal yield reductions under 50 % shade. While mixing fast-growing woody crops such as willow, poplar, and pines with perennial grasses could be an attractive alternative to traditional row cropping on marginal land, further research needs to be conducted across a broad range of site conditions to see if greater annual biomass production per hectare can be achieved. Several trials are in place throughout the United States, but results are preliminary at this stage. Adoption of such biomass feedstock production systems in the United States will depend primarily on the production economics in comparison to traditional row crops.

Agroforestry for Specialty and Organic Crop Production

Specialty Crops

The Specialty Crop Competitiveness Act of 2004 and the Food, Conservation, and Energy Act of 2008 define specialty crops as “fruits and vegetables, tree nuts, dried fruits, horticulture, and nursery crops (including floriculture).” Eligible plants must be intensively cultivated and used by people for food, medicinal purposes, and/or aesthetic gratification to be considered specialty crops.[2] Specialty crop growers nationwide face fierce competition and low prices. Making a living from traditional commodity production is also difficult for the small- and medium-sized family farm. In many regions, there are large acreages of farmland available for specialty crop production. Profitable and value-added enterprises provide alternatives for the family farm. Profitability allows future generations to remain on or return to the farm and can strengthen rural communities. Agroforestry practices enable landowners to generate income from the production of a wide range of conventional and specialty products while simultaneously protecting and conserving soil, water, and other natural resources (Gold et al. 2004, 2009; Aguilar et al. 2010). For example, within riparian buffers, there are potentially profitable market-based opportunities, including linear production acreage of woody florals, elderberry, and perennial biomass.

Many observers have examined the potential of dual-purpose market-driven conservation systems in North America, including Chamberlain and Hammett (1999), Kays (1999), Josiah et al. (2004), and Gold et al. (2009). Products produced through agroforestry practices, including specialty or nontimber forest products, are produced from trees, within forests, or in myriad combinations with trees or shrubs, crops, and/or animals (Garrett 2009). Many of these products have proven economic value but have been overlooked by, or are unknown to, agricultural and forest landowners. Examples of developing specialty crop industries using an agroforestry system include eastern black walnut, Chinese chestnut, pecan, American elderberry *(Sambucus canadensis* L.), American hazelnut (*Corylus americana* Walter), and pawpaw (*Asimina triloba* (L.) Dunal). Farmers are planting these emerging specialty crops in the Midwest and throughout the United States in response to increasing market opportunities. In the majority of cases, these farmers are taking substantial risks due to the lack of sound horticultural and market information. Farmers who purchase emerging specialty crop nursery stock may be planting unimproved varieties or material not adapted or tested for their site. Detailed financial decision-making information is lacking for most specialty crops. Knowledge networks and supporting industry infrastructure are also lacking.

To successfully launch specialty crop industries, a comprehensive, multifaceted, and long-term approach is required. It will be necessary to develop, test, and deploy the best cultivars. Orchard production and best management practices must be developed for each specialty crop. Market-, consumer-, and value-added research must be conducted. Consumer awareness and demand (“market pull strategy”) must be increased. Financial decision models must be created to convince both prospective growers and agricultural lenders that a given specialty crop is truly an economically profitable enterprise. Finally, to launch the industry, beginning and advanced grower training workshops must be offered including models of business development such as new-generation cooperatives and other information needs.

While specialty crop production using agroforestry has great potential in the United States, their widespread adoption requires multiple, integrated approaches. These include a culture of entrepreneurship, readily available market information through the USDA Agriculture Marketing Service, and private sector investments providing “nurture capital” to create an infrastructure for investing in local food systems (e.g., Slow Money[3]; Rudolf Steiner Foundation Social Finance[4]). In addition, the growth of specialty crop industries will require the development of knowledge networks similar to those already in place for larger and more mature agriculture industries (e.g., state pecan growers associations, the California Walnut Board). Knowledge networks will combine high-tech, long-term, targeted research support from the federal government including funding sources and ideas drawn from the USDA Specialty Crop Research Initiative and Know Your Farmer Know Your Food[5] and bottom-up grassroot “high touch” one-on-one outreach programming that includes landowner innovation and support through USDA’s Sustainable Agriculture Research and Education program and Land Grant University Extension services. New industries will need to consider creating active partnerships such as new-generation cooperatives, the development of value-added products to ensure long-term industry growth, and ongoing consumer education to grow the market in the long term.

Organic Crops

According to the Organic Trade Association[6], the Agriculture Marketing Service (AMS), and the Economic Research Service (ERS), there has been enormous growth in the market for locally grown and organic food products in both fresh and value-added form within the United State (Green and Dimitri 2009).[7] Organic and locally grown foods are perceived by consumers as healthier and safer for both people and the environment. Organic food market retail sales growth has grown 20 % annually since 1990. There was a sixfold increase in retail sales of organic food products from 1997 to 2008. Both within the United States and globally, concerns about industrial agriculture practices, food quality, and links to human health have fostered interest in new, alternative, local, and more sustainable agricultural practices which offer great opportunities to include agroforestry as an organic farming option. The pace of conversion of cropland from conventional to organic has failed to keep up with growth in sales. The United States imported $1.5 billion in organic products in 2006. This trend provides a burgeoning opportunity for US farmers to enter this market and is reflected in a major increase in the number of certified organic operations and land devoted to organic production in recent years (Eades and Brown 2006).

Consumers are also strongly interested in consuming products that are locally grown (Kirby et al. 2007; Brown 2003; Loureiro and Hine 2002). Farm diversification through agroforestry can help farmers produce fruits, nuts, and vegetables from small and large farms alike. Brown (2003) indicated that marketing local products should stress quality and freshness and the consumers are willing to pay a premium price to support local farmers: 16 % of the study respondents would pay a 5 % premium, and 5 % of respondents would pay a 10 % premium for local foods. Similarly, Schneider and Francis (2005) found that consumers were willing to pay a 10 % price premium for locally grown foods. A nationwide survey conducted by the Leopold Center (Pirog and Larson 2007) indicates that American consumers are skeptical about the safety of the global food system, and many believe that local foods are safer and better for their health than foods from abroad. Respondents placed high importance on food safety, freshness, and pesticide use with 85 % stating that local foods were somewhat safe or safe compared to 53 % who perceived foods grown elsewhere in the world as somewhat safe or safe. Consumers concerned about the origin of products they buy and how they were produced are willing to pay a premium for locally grown or sustainably produced products (Yue and Tong 2009). Aguilar et al. (2009, 2010) showed that consumers are 15–20 times more likely to choose locally grown Missouri chestnuts compared to imported nuts. Additionally, the odds of consumers choosing organically grown chestnuts are 5.2 times higher than for conventionally grown chestnuts.

Nationwide, farmers markets have increased from 1,755 in 1994 to 6,132 in 2010, growing over 26 % from 2009 to 2010.[8] Numerous surveys report that consumers shop at farmers markets primarily because of product quality and the fact that the food is locally grown (SAN 2003). All five recognized temperate agroforestry practices, intensively managed to incorporate a diverse number of crops, can be designed to produce locally grown and/or organic crops in both fresh and value-added form for these growing markets. It has been proven that agroforestry can increase soil organic matter, improve nutrient cycling and plant-water relations, and increase the density and diversity of beneficial insects compared to monoculture cropping systems (Bugg et al. 1991; Smith et al. 1996; Stamps and Linit 1997; Brandle et al. 2004; Jose 2009). These attributes will help agroforestry gain popularity as an organic farming option.

Agroforestry for Ecosystem Services

Widespread concerns over environmental issues including nonpoint source pollution, loss of wildlife habitat, and climate change have resulted in a wide array of mitigation efforts. Riparian and upland buffers and windbreaks are agroforestry practices widely known for their positive environmental impacts; however, all five recognized agroforestry practices, when properly implemented, directly address each of these major environmental issues. Godsey et al. (2009) and Alavalapati and Mercer (2004) describe the values of nonmarket goods and services that can be realized through increased use of agroforestry practices. The US Farm Bill incentive programs have provided cost share for landowners to establish agroforestry practices on their land. USDA Economic Research Service conservatively estimates CRP benefits of $1.3 billion per year, excluding carbon sequestration, ecosystem protection, and other less easily quantified benefits.[9] Farm Service Agency (FSA) estimates that, compared with 1982 erosion rates, the CRP has reduced erosion by more than 412 Tg per year on 14 million ha of program land. Through April 2006, CRP had also restored 1 million ha of buffers and planted 1.1 million ha of trees. Also, the USDA Natural Resources Conservation Service (NRCS) documented conservation benefits include the sequestration of more than 48 Tg of carbon annually, more than 1.3 million ha of wildlife habitat established, and a reduction in the application of nitrogen (by 681,000 Mg) and phosphorus (by 104,000 Mgs) (Cowan 2010). Markets for carbon credits are well established in Europe while still under development in the United States. All of these provide landowners with substantial opportunities to incorporate agroforestry as part of their farm management. A discussion on some of these ecosystem services to demonstrate agroforestry's potential follows.

Carbon Sequestration

Of all the acknowledged ecosystem service benefits of agroforestry, C sequestration has received the least attention in the United States. Carbon sequestration involves the removal and storage of carbon from the atmosphere in carbon sinks (such as oceans, vegetation, or soils) through physical or biological processes. The incorporation of trees or shrubs in agroforestry systems can increase the amount of C sequestered compared to a monoculture field of crop plants or pasture (Sharrow and Ismail 2004; Kirby and Potvin 2007). In addition to the significant amount of C stored in aboveground biomass, agroforestry systems can also store C belowground. Carbon sequestered in agroforestry systems could be sold in carbon credit markets where such opportunities exist. The largest amount and most permanent form of carbon may be sequestered by increasing the rotation age of trees and/or shrubs and by manufacturing durable products from them upon harvesting.

The potential of agroforestry systems to sequester C varies depending upon the type of the system, species composition, age of component species, geographic location, environmental factors, and management practices. A large number of studies have appeared in recent years that report C sequestration potential of agroforestry systems from the tropics. While such studies are scarce in the United States, a recent attempt by Udawatta and Jose (2011) has provided a review and synthesis of the available literature; they estimated that the potential for C sequestration under agroforestry systems in the United States is 548.4 Tg year^{-1}.

Based on their analysis, Udawatta and Jose (2011) concluded that silvopastoral systems, the most common form of agroforestry in North America (Clason and Sharrow 2000; Nair et al. 2008; Sharrow et al. 2009), had the greatest potential to sequester C in the United States. Using a sequestration potential of 6.1 Mg C ha^{-1} year^{-1} on 10 % marginal pasture land (23.7 million ha) and 54 million ha of forests, they estimated total C sequestration potential for silvopastoral lands in the United States as 474 Tg C year^{-1}. Similarly, Udawatta and Jose (2011) estimated that alley cropping could be practiced on 10 % of the 179 million ha cropland (USDA NRCS 2007; USDA NASS 2008) in the United States, which could sequester 60.9 Tg C year^{-1}. Based on several published studies (e.g., Boggs and Weaver 1994; Harner and Stanfoord 2003; Naiman et al. 2005), they estimated that the average aboveground C sequestration potential was 2.46 Mg C ha^{-1} year^{-1} for riparian buffers. This estimate was lower than the maximum reported by Hazlett et al. (2005) for a riparian buffer in Canada (269 Mg ha^{-1}) but higher than that reported by Schroeder (1994) for another temperate riparian buffer (63 Mg C ha^{-1} aboveground storage with a 30-year cutting cycle). The total river and stream length in the United States is approximately 5.65 million km (3.533 million miles).[10] Lakes and estuaries occupy 16.8 and 22.7 million ha, respectively. If a 30-m-wide riparian buffer is established along both sides of 5 % of total river length, it would occupy 1.69 million ha. Using a conservative estimate of 2.6 Mg C ha^{-1} year^{-1} accrual rate for above, below, and soil C sequestration by riparian buffers, the potential C sequestration by riparian buffers along rivers in the United States could be as high as 4.7 Tg C year^{-1}. Like other agroforestry practices, windbreaks also offer promise for C sequestration (Schoeneberger 2009). In addition to C sequestered by trees, windbreaks provide additional C sequestration due to improved crop and livestock production and energy savings (Kort and Turnock 1999). Udawatta and Jose (2011) estimated that the total C sequestration potential for windbreaks was 8.79 Tg C year^{-1}.

Overall, the C sequestered by agroforestry could help offset the current US emission rate of 1,600 Tg C year^{-1} from burning fossil fuel (coal, oil, and gas) by 34 %. These estimates indicate the important role of agroforestry as a promising CO_2 mitigation strategy in the United States and possibly in other parts of North America.

Agroforestry for Water Quality Enhancement

More than three decades after the implementation of the Clean Water Act in the 1970s, non-point-source pollution from agricultural watersheds continues to impact the nations' water bodies (Udawatta et al. 2011). Despite adoption of conservation practices, managed fertilizer application, and crop rotations, large losses of nutrients still occur in runoff (Udawatta et al. 2006). Agricultural surface runoff can result in excess sediment, nutrient, and pesticide delivery to receiving water bodies and is a major contributor to eutrophication in the Gulf of Mexico. According to the latest report of the USEPA (2010), 50, 66, and 42 % of rivers, lakes, and reservoirs, respectively, are impaired. The loss of productivity due to loss of arable land in the United States is nearly $37.6 billion per year (Pimental 2006).

In addition to farm chemicals, livestock manure also constitutes a major NPSP in the United States. In supplying livestock products, farms in the United States generate more than 350 million t of manure that must be disposed of in some manner (Ribaudo et al. 2003). Jones et al. (1996) estimated that 95 % of cattle waste, 90 % of poultry waste, and 85 % of pig waste are returned to land. On average, poultry manure contains 14–31, 18–25, and 16–19 kg Mg^{-1} N, P_2O_5, and K_2O, respectively (Vest et al. 2004). Dairy manure contains 6.56 g kg^{-1} P, 39.99 g kg^{-1} N, and 2.1×10^6 CFU g^{-1} fecal coliform (Stout et al. 2005). In addition, manure contains bacteria and other microorganisms that can be harmful to humans if they are introduced into waterways or groundwater (Edwards et al. 2000). Poultry litter also contains the hormone 17β-estradiol which may disrupt the health and reproduction of fish and other animals (Nichols et al. 1998). Applying too much manure at the wrong time or improper handling of manure can release nutrients, bacteria, and other undesirable pollutants into the air, groundwater, and surface water. These losses are further exacerbated if manure is applied in fall or winter months (when plant uptake is minimal to none), as it is usually done in order to free up storage volume. When manure is applied to meet plant N requirement, it often exceeds plant P requirements (National Research Council 1993). Soils with excess P levels are vulnerable to releasing environmentally significant levels of P (Nair et al. 2004; Allen et al. 2006) and have been linked to accelerated eutrophication of fresh water bodies (Siddique and Robinson 2003) and an increase in the hypoxic zone in the Gulf of Mexico (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2008). Since less manure is needed to meet the crops' P needs, more land is required to spread manure under P standards than under N standards.

A well-designed riparian or upland buffer is recognized as one of the most cost-effective approaches to mitigate NPSP (Schultz et al. 2009). Enhanced infiltration, trapping efficiency due to flow resistance, root safety net, water use by the buffer vegetation, and denitrification are major mitigation processes by which particulate and dissolved nutrients and herbicides transported in surface and subsurface flow are intercepted (Schultz et al. 2009; Udawatta et al. 2002, 2011). There are several physical, chemical, and biological mechanisms involved in the process of bioremediation within vegetative buffers. Organic pesticides can be intercepted by the roots and residue of the vegetation via sorption and physical filtration (Pestemer et al. 1984; Hoffman et al. 1995). Bacteria growing in the root zone may have the capacity to metabolize herbicides through various biochemical mechanisms including enzymatic oxidation and hydrolysis (Ambus 1993; Mandelbaum et al. 1993, 1995; Struthers et al. 1998). Direct plant uptake may also help to eliminate nutrients and agrochemicals (Burken and Schnoor 1997). Furthermore, the improvement of soil characteristics by vegetation (e.g., increased OM content, improved porosity, and microbial diversity) may enhance the rhizosphere's capacity for sorption and abiotic transformation of pollutants (Seobi et al. 2005; Udawatta et al. 2009).

Proper plant species selection also plays a significant role in buffer effectiveness for mitigating NPSP transport. Plant species selection strongly influences physical, chemical, and biological soil properties that are involved in buffer bioremediation processes (Seobi et al. 2005; Udawatta et al. 2005; 2009). Trees with more vertical roots than horizontal would compete less for resources with crops (Udawatta et al. 2005). The incorporation of warm-season grasses into a buffer encourages sheet flow creating more surface interaction between the grass and the runoff reducing transport of both dissolved and sediment-bound NPSP in surface runoff (Blanco-Canqui et al. 2002; Lin et al. 2007a). For example, Lee et al. (2003) showed that a 7-m-wide switchgrass buffer in Iowa removed 95 % of the sediment, 80 % of the total-N, 62 % of the NO_3–N, 78 % of the total-P, and 58 % of the PO_4–P. These authors also demonstrated in a field study conducted under natural rainfall conditions that a switchgrass + woody buffer (7 m + 9.2 m woody zone) removed 97 % of the sediment, 94 % of the total-N, 85 % of the NO_3–N, 91 % of the total-P, and 80 % of the PO_4–P in the runoff. In a rainfall simulation and a growth chamber study on claypan soils in Missouri, Lin et al. (2005, 2007a, b) reported that 4-m-wide vegetative buffer strips with native warm-season grasses removed 75–80 % of the atrazine, metolachlor, and glyphosate in surface runoff and 63–90 % of the atrazine degradation products in the rhizosphere of warm-season grass species, compared to 24 % degradation in the control. While synthesizing the information from long-term upland buffer studies in Missouri, Udawatta et al. (2011) reported that agroforestry buffers (trees + grasses) always resulted in greater reduction of sediment, total-N, and total-P compared to grass buffers in both row crop and grazed pasture systems (Table 3).

Overall, agroforestry buffers, if properly designed in strategic locations throughout sensitive watersheds, can enhance water quality. For example, the hypoxia issue in the Gulf of Mexico could be alleviated with proper installation of agroforestry buffers and associated conservation practices such as conservation tillage, crop rotation, and nutrient management throughout the Mississippi River Basin.

Table 3 Percentage reduction of sediment, total nitrogen, and total phosphorus losses on grazing and row crop management practices with agroforestry and grass buffers compared to the respective control treatment

	Managements and treatments			
	Grazing management		Row crop management	
Parameter	Agroforestry	Grass buffer	Agroforestry	Contour grass
	%			
Sediment	48	23	30	28
Total nitrogen	75	68	11	13
Total phosphorus	70	67	26	22

Source: Udawatta et al. (2011)

Agroforestry for Improved Air Quality

In recent years, interest in adapting windbreak designs as a potential approach to dealing with livestock odor has received considerable attention (Tyndall and Colletti 2007). The majority of odor-causing chemicals and compounds are carried on aerosols (particulates matter, PM). This very special use of a windbreak has also been called a vegetative environmental buffer (VEB). A VEB can filter airstreams of particulates by removing dust, gas, and microbial constituents. While financial considerations have motivated producers to use confined animal feeding operations (CAFO) as the preferred approach to livestock production, especially in swine and poultry industries in the United States, concerns associated with potential environmental and health effects of odor emissions have also been rising. For example, in an effort to reduce odor emissions from swine CAFOs, 44 of the 50 states in the United States have enacted air emission policies directly or indirectly to reduce odors from these operations (Vander 2001).

The use of agroforestry VEBs for odor abatement is a new management practice, and the science in support of using VEBs for this purpose is limited. Although the literature on VEBs is scarce, VEBs have been shown to impact odor plume dispersion (Lin et al. 2006, 2009). While reports in the literature strongly suggest that significant quantities of compounds known to correlate highly with malodors can be removed through the use of VEB technology (e.g., 47 and 50 % reduction in ammonia (NH_3)and dust emissions, respectively), the overall effect on reducing odor, based upon the literature, appears to be low (6 %)(Malone et al. 2006). The effectiveness of a VEB is known to be related to its physical location, species composition, density, and geometric configuration. Odor reduction by VEB occurs via physical interception, dilution, and chemical adsorption (Tyndall and Colletti 2007). The VEB canopy encourages the interception of odor carriers, such as dust and organic particulates. In addition, VEB reduces wind speed and facilitates the deposition of PM and bioaerosols (Tyndall and Colletti 2007). The vertical turbulence created by VEB could dilute the odor by forcing the mixing of odor with clean air. The VEBs may also have a sociological impact in which they reduce people's awareness of the CAFOs, thereby subconsciously reducing the smell. In their detailed review on this topic with particular reference to swine odor, Tyndall and Colletti (2007) suggested that when planted in strategic designs, VEBs could effectively mitigate odor in a socioeconomically responsible way. We believe that properly engineered VEBs can be an effective tool for odor abatement when used alone or in combination with other technologies, but improvements in design are required to optimize the benefits.

Agroforestry for Biodiversity Conservation

Ecosystems and species important in sustaining human life and the health of our planet are disappearing at an alarming rate. Consequently, the need for immediate action to design effective strategies to conserve biodiversity is receiving considerable attention worldwide. Scientists and policy makers are becoming increasingly aware of the role agroforestry plays in conserving biological diversity in both tropical and temperate regions of the world (Jose 2009). The mechanisms by which agroforestry systems contribute to biodiversity have been examined by various authors (e.g., Schroth et al. 2004; McNeely 2004; Harvey et al. 2006; Jose 2009). In general, agroforestry plays five major roles in conserving biodiversity: (1) provides habitat for species that can tolerate a certain level of disturbance; (2) helps preserve germplasm of sensitive species; (3) helps reduce the rates of conversion of natural habitat by providing a more productive, sustainable alternative to traditional agricultural systems that may involve clearing wildlife habitats; (4) provides connectivity by creating corridors between habitat remnants which may support the integrity of these remnants and the conservation of area-sensitive floral and faunal species; and (5) helps conserve biological diversity by providing other ecosystem services such as erosion control and water recharge, thereby preventing the degradation and loss of surrounding habitat. Designing and managing an agroforestry system with conservation objectives would require working within the overall landscape context and adopting less intensive cultural practices to achieve the maximum benefits.

While the literature on the role of agroforestry in conserving biodiversity is growing rapidly in the tropics, such reports are limited from the temperate parts of the world. In the United States, variations in tree-crop combinations and spatial arrangements in agroforestry have been shown to affect insect population density and species diversity. Studies with pecan have looked at the influence of ground cover types on arthropod densities in agroforestry systems (Bugg et al. 1991; Smith et al. 1996; Stamps and Linit 1997). Bugg et al. (1991) observed that cover crops (e.g., annual legumes and grasses) sustained lady beetles (Coleoptera: Coccinellidae) and other arthropods. Brandle et al. (2004) reported greater density and diversity of insect populations in windbreaks. They attributed this to the heterogeneity of the edges that provided varied microhabitats for life-cycle activities and a variety of hosts, prey, pollen, and nectar sources.

Agroforestry practices also provide improved wildlife habitat by increasing structural and compositional plant diversity on the landscape. Windbreak and riparian buffers offer the only woody habitat for wildlife in many agriculture dominated landscapes (Johnson and Beck 1988). In a comparison of corn monoculture to riparian buffer plantings of clover (*Trifolium repens* L.) and orchardgrass (*Dactylis glomerata* L.) with three different tree species in Indiana, Gillespie et al. (1995) observed that the riparian buffers had higher bird density and diversity than corn monoculture. In a recent study in Iowa, Berges et al. (2010) reported a dramatic increase in bird species diversity in a riparian buffer compared to row crop fields and pastures.

As suggested by McNeely (2004) and McNeely and Schroth (2006), the interrelationship between forest ecosystems, agroforestry, and biodiversity can be made more dynamic through adaptive management strategies that incorporate results from research and monitoring in order to feed information back into the management system. Active participation by local landowners and communities is also critical in this context. Agroforestry's role in creating habitats and maintaining and conserving diversity across landscapes is increasingly being recognized in the United States and, as such, will help increase adoption in many parts of the country.

Agroforestry Policies

The United States currently lacks a consistent national policy on agroforestry. And, as was reported by Garrett and Buck (1997), agroforestry development has primarily been guided by an array of agricultural, forestry, environmental, and rural development policies and programs at respective levels of government. Unfortunately, this has resulted in a limited allocation of resources and incentives to individuals, agencies, and organizations interested in agroforestry. And, it has failed to take advantage of the unique opportunities offered by agroforestry to address biophysical and socioeconomic limitations that are often associated with conventional agricultural and forestry enterprises. The lack of policy is, in part, attributed to a lack of understanding of agroforestry benefits on the part of policy makers due to the difficulties and time required to develop and dispense the science of a new technology such as agroforestry—a limitation that is rapidly disappearing in the United States. While consistent policy on agroforestry has been slow to evolve, the need has been discussed by many (Henderson 1991; Garrett et al. 1994; AFTA 1995; USDA 2011).

Agroforestry policy had its beginning in the United States with the Forest Stewardship Act of 1990, a component of the Food, Agriculture, Conservation, and Trade Act (i.e., 1990 Farm Bill). This legislation called for the US Forest Service to establish a Center for Semiarid Agroforestry whose scope was broadened to include the entire country in 1994 and the center was renamed the National Agroforestry Center (NAC). Moreover, to expand national agency support for agroforestry, in 1995, the USDA NRCS partnered with the Forest Service to provide a technology transfer dimension to the NAC. The center and the Association for Temperate Agroforestry (AFTA), established in 1991, have evolved as the key players in informing and guiding public policy makers on US agroforestry policy needs.

While only limited success has been achieved, gains have been and continue to be made. Although little mention is made of agroforestry, per se, in the most recent US Farm Bill (The Food, Conservation and Energy Act of 2008, FCEA), several USDA programs authorized by this legislation support agroforestry practices. The EQIP, which is designed to address critical resource needs on agricultural land and is especially well suited for agroforestry practices, has provided funding to landowners for establishing riparian buffers, alley cropping, and silvopasture practices. The USDA conservation programs such as the WHIP, Conservation Reserve Enhancement Program (CREP), CRP, and the CSP have also funded agroforestry practices. The CSP, in particular, has targeted practices such as alley cropping, windbreaks, riparian buffers, and silvopasture for wildlife and water quality enhancement benefits. And, recently, "multi-story cropping, sustainable management of nontimber forest plants," a forest farming dimension, was authorized under the CSP.

All of these programs provide private landowners with multiyear contracts with provisions for reimbursing some percentage of establishment costs and have practice incentives and annual rental payments that vary with programs. Other readily recognizable USDA programs such as Sustainable Agriculture Research and Education (SARE), Organic Agriculture Research and Extension Initiative (OREI), and the Specialty Crop Research Initiative (SCRI) all have important roles that they could and should play in agroforestry, but, similar to the previously identified programs, they are either grossly underfunded and too narrow in conception or are too restrictive in execution to have a significant effect on agroforestry.

While agroforestry can and does provide many benefits, it is especially well adapted to address environmental problems, and for that reason alone, incentive-based conservation programs should place a high priority on agroforestry practices. A USDA policy is needed that gives natural-resource-based, sponsored programs (including agroforestry) a value in keeping with their importance and that discriminates against no farmer or crop. While it is appropriate that the majority of USDA funding be used in support of important conventional crop commodities (e.g., wheat, corn, soybeans, cotton), it is inappropriate that our vision for the future of agriculture not include provisions, established by policy, that support (socially, administratively, and financially) the use of agroforestry and other technologies to address conservation and agricultural sustainable development objectives. After all, agricultural-derived contaminants, such as sediment, nutrients, and pesticides, constitute the largest diffuse source of water quality degradation in the United States. Agroforestry bioassimilative strategies have been developed and proven to successfully address the negative impacts of agricultural practices, often at costs considerably less than the dominant alternative strategies (e.g., field terracing) and specific policy in support of using agroforestry to address environmental concerns, is justified and needed.

In addition to the need for funding, it is imperative that obvious disincentives to the practice of agroforestry (e.g., USDA's Direct and Counter-Cyclical Payment; DCP) restrictions on establishing fruit or nut trees on base acreage, programs specifying minimum acceptable tree-planting densities that can effectively exclude many agroforestry practices, provisions that restrict tree management and harvesting of nontimber products, etc. be reevaluated in light of what is known today about the cumulative environmental and economic benefits of agroforestry that far exceed those anticipated earlier by planners and policy makers. There is a need for a national policy that allows and promotes the use of agroforestry under all appropriate USDA conservation programs. This will require a new USDA vision that recognizes and advocates landscape diversification for social, biological, and economic benefits.

The USDA Agroforestry Strategic Framework, Fiscal Year 2011–2016,[11] is designed to create a new USDA vision that recognizes the multiple benefits of agroforestry and supports its implementation. In the Secretary of Agriculture's introductory message, he identifies it as "a roadmap for advancing the science, practice, and application of agroforestry as a means of enhancing America's agricultural landscapes, watersheds and rural communities." Within this framework is found the promise that the USDA "will integrate agroforestry into agency programs and policies to maximize and highlight economic, social, environmental, and conservation benefits" (USDA 2011).

In 1994, a team of agroforestry specialists was asked to prepare the agroforestry component of the Resource Conservation Act Appraisal for the Soil Conservation Service (now the NRCS). That appraisal was entitled, "Agroforestry: An Integrated Land-Use Management System for Production and Farmland Conservation" (Garrett et al. 1994). Within this document, it was acknowledged that agroforestry could not achieve its potential in the United States without the SCS/NRCS assuming ownership and providing leadership. Further, it suggested that development must be guided by USDA-established policy. The recent establishment of the USDA Agroforestry Strategic Framework, Fiscal Year 2011–2016 framework (USDA 2011a, b), is the first step toward the creation of a meaningful, national USDA policy on agroforestry. It "provides new direction on how USDA agencies, partners, and landowners together can significantly expand agroforestry to balance agricultural production with natural resource conservation." That significant instrument is to be followed by a USDA policy statement that will "guide USDA efforts to enhance production of food, feed, fiber and renewable energy; enhance the sustainability and prosperity of rural communities; and protect, conserve, and restore natural resources" through the further development and implementation of agroforestry technologies.

Conclusions

While agroforestry has not yet achieved the success in the United States that it is destined to achieve, there is a heightened awareness of its benefits and an increased willingness on the part of landowners to adopt it. It has been demonstrated to provide landowners a way to plan for the future while meeting the needs of the present (economic, environmental, and social). It enhances resource stewardship and land conservation, while keeping the family farm economically viable. Thus, in the short span of four decades, agroforestry in the United States has transitioned from a little used name and practice to a science-based technology, and it has advanced from a fragmented effort on the part of a few to an area of focus on the part of many through the recent establishment of the USDA Agroforestry Strategic Framework, Fiscal Year 2011–2016. This framework “identifies agroforestry as an important component of a much needed national strategy to enhance America’s agricultural landscapes, watersheds, and rural communities” and “provides new direction on how USDA agencies, partners, and landowners together can significantly expand agroforestry to balance agricultural production with natural resource conservation.” The future for agroforestry in the United States thus seems to be very promising. From improving our environment to revitalizing rural America, agroforestry offers an attractive option to more conventional management approaches, many of which have resulted in undesirable environmental and economic consequences.

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Agroforestry Research and Development in Canada: The Way Forward

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Abstract The purpose of this chapter is to describe the history and current status of agroforestry research and practices across Canada and provide recommendations as "the way forward." Each of the five regions (the Atlantic Region, Quebec, Ontario, the Prairies, and British Columbia) has unique climates, soils, landforms, and natural resource management systems. The influence of these factors has resulted in different agroforestry practices and approaches to their application in each region. For example, the riparian buffer systems are promoted for the Atlantic Region; tree-based intercropping and windbreak systems in Quebec, Ontario, and in the Prairies; and silvopastoral systems in British Columbia. European settlement, beginning in the late 1700s, initiated the conversion of much of eastern Canada from native forest into agricultural land. As farming practices modernized across the country, new environmental problems (e.g., soil erosion and loss of wildlife habitat) and new socioeconomic issues

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(e.g., loss of income diversity) emerged. Recently, Canadian citizens have become increasingly concerned with potential ecological impacts of agricultural production, and the policy has moved toward fostering stewardship initiatives that address not only environmental goods and services but also climate change issues with a special emphasis on carbon sequestration. Agroforestry is perceived to be able to provide benefits in these areas; however, the problems and their potential solutions are different in different regions. Each region faces a unique set of challenges and constraints related to lack of knowledge, high initial capital and labor costs, farm operational issues, resource tenure, lack of niche markets, and lack of incentives.

Keywords Forest farming • Intercropping • Riparian buffers • Silvopasture • Windbreak

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Introduction

Canada is the second largest country in the world with an area of 10 million km^2. A broad swath of its southern regions from the Atlantic to the Pacific oceans consists of fertile soils and climates conducive to the growth of both agricultural crops and trees. However, significant agricultural and forest production occur in all regions. Prior to European settlement, First Nations actively utilized a variety of agroforestry systems, incorporating trees and food into production systems; these have been described in Williams et al. (1997) among others. With European settlement in the late 1700s, large tracts of native forest, especially in eastern Canada, were removed for agricultural production. Agriculture dominates much of southern Canada to this day.

As agricultural production in Canada modernized over the past 150 years, standard global problems associated with modernization became obvious. Examples include increased soil erosion by wind and water, declining crop productivity on marginal lands, loss of habitat for native animals and plants, and enhanced nutrient loading into streams draining agricultural areas with subsequent effects on water quality. In addition, a host of socioeconomic challenges have emerged in tandem with loss of income diversity, and changes in rural community structure. These problems are not unique to specific regions in Canada but may be more prevalent in particular areas depending upon the nature and combination of regional soils and climates. Our early agricultural ancestors, while adamant about clearing land for agricultural practices, were also cognizant of the important roles that trees play in sustaining farm systems. Although they may not have practiced "agroforestry," they appreciated the products and services that could be derived from trees. In this chapter, we examine temperate agroforestry systems that have emerged from these early practices and that may now represent one possible solution to the problems currently faced by the agricultural sector.

In Canada, we embrace the classification of agroforestry systems of the Association for Temperate Agroforestry (http://www.aftaweb.org/): integrated riparian systems (tree, shrub, and grass buffers on stream banks), intercropping/alley cropping systems (cultivation of crops between rows of trees), windbreaks and shelterbelts (linear plantings of trees within or around field perimeters), forest farming systems (food and other products from managed native and planted woodlands), and silvopastoral systems (intentional combination of trees, forages, and livestock). In addition, bioenergy agroforestry systems are discussed, and current research in many parts of Canada is exploring how it may or may not be compatible with mainstream agroforestry practices. Where appropriate, all of these tree-based systems are discussed for each of the five regional areas in Canada: the Atlantic Region, Quebec, Ontario, the Prairies, and British Columbia. Historical perspectives and current issues germane to the future development of agroforestry research and development strategies are also provided.

The Atlantic Region

History of Forestry and Agriculture

In Canada's Atlantic Region, comprising the provinces of Newfoundland and Labrador, New Brunswick, Prince Edward Island, and Nova Scotia, a large percentage of the land area is forested and government owned ("crown land"). The forestry industry has historically been an important income generator (timber, pulp, and paper). Much of the privately owned forest land and most agricultural producers have woodlots which generate significant income through the sale of wood as a source of fuel and pulp fiber.

Status of Agroforestry

Management of farm woodlots, which is focused on conservation and sustainable growth, has been encouraged through various provincial programs over the past 30 years. Although the purposeful integration of trees and shrubs into the landscape through the adoption of agroforestry practices has been less prevalent, interest in agroforestry has grown in the region in the past 5 years, as a result of demonstration work by government and nongovernment organizations, as well as emerging environmental issues such as climate change and renewable energy. Hedgerows for wind-erosion protection have been encouraged on agricultural landscapes for many years through various government incentive programs (Chris Pharo, personal communication, October 2011). Additionally, windbreaks have a special value in blueberry (*Vaccinium corymbosum*) production systems. For example, lowbush blueberries constitute an important crop on acidic soil that was previously under forest. Poor pollination is a major concern in large blueberry fields that do not provide habitat for native bees and other pollinators (Javorek et al. 2002). Installation of beehives and leafcutter bee shelters has not addressed this problem; however, mixed plantings of trees and shrubs have proven to be successful (Javorek et al. 2002). The tree rows also provide shelter from the wind and a microclimate within which native pollinators can do their work efficiently and effectively. The establishment and maintenance of riparian buffers is one of the focal areas in agroforestry in some parts of the Atlantic Region, where intensive potato (*Solanum tuberosum*) production, especially on sloping soils, has raised concerns about contamination of watercourses by sediments, nutrients, herbicides, and pesticides. Environmental programming by federal and provincial governments has included provisions to plant native woody materials in riparian buffers, but, as the region is naturally forested, it is likely that natural regeneration of native trees and shrubs will occur in many buffer areas. Some forest farming of mushrooms and ginseng (*Panax* spp.) has been attempted in this region, but it is not widely practiced. However, there are several non-timber forest products that generate significant income in this region, including maple syrup, wild mushrooms, and coniferous boughs for Christmas wreaths.

Challenges, Constraints, and the Way Forward

There is currently a lack of technical support and expertise in the Atlantic Region to advise landowners about the concepts and principles of agroforestry and how to incorporate these into their farming systems. The development of agroforestry expertise in this region should include formal agroforestry training at the college/university level. The Faculty of Forestry at the University of Moncton (Edmundston campus) in New Brunswick has developed a master's program in agroforestry, which was discontinued after several years, due to a lack of student enrolment. This perhaps indicates that agroforestry education would be better implemented as a component of a broader environmental resource management education. Agroforestry knowledge would also be greatly advanced with the initiation of research projects and the development of showcase projects. The development of agroforestry knowledge and professional expertise would be an important step in the increased awareness and adoption of agroforestry practices in the region.

As with many other regions, there is a separation of agriculture and forestry, both as academic disciplines, and at an institutional level. This makes it difficult to provide integrated support for landowners who are looking for knowledge and advice on the use of trees on their agricultural land, or for the integration of environmental or other programming that addresses landscape-level environmental issues (e.g., watershed management). Improved integration of these two disciplines in programming or extension services would be a benefit in the Atlantic Region because of the proximity of forest land to agricultural land throughout the region and because many landowners operate on both types of land base.

Regionally generated production and economic data on agroforestry practices are needed, especially where agroforestry practices have the potential to generate wood, biomass, or other products. Economic gain is one of the most influential factors in determining the rate of adoption of agroforestry practices, yet agroforestry research conducted in other regions of Canada, the United States, or other countries is often of limited value due to differences in climate and soil. The existence of agroforestry systems on which these analyses can be based is also essential. It would also be relevant to consider the economics of environmental goods and services (EG&S) provided by agroforestry practices. From the example of lowbush blueberry production, the pollinator habitat provided by windbreaks has potential economic benefits for the producers. As another example, the province of Prince Edward Island implemented a province-wide EG&S program, by which landowners benefited economically for good environmental stewardship practices, including the establishment of native tree and shrub species in riparian buffers. Other issues of relevance include evaluation of the potential of windbreaks and forest farming in the region, as well as the role of agroforestry in the region in climate change discussions.

Because the Atlantic Region has a population of only 2.3 million, the local/regional domestic market for agroforestry products is relatively small. Producers of agroforestry products may therefore need to compete on larger, more competitive national or international markets. When valuable agroforestry products are developed, they should be of export grade in order to take advantage of these larger markets. There is a growing interest in generating renewable energy on the farm as the price of fossil fuel continues to increase or fluctuate. Several applied research projects are currently underway to evaluate hybrid willow's ability to sequester excess nutrients to protect groundwater as well as provide a source of renewable energy on farms. This may provide an opportunity for willow production as a field crop, similar to what is currently undertaken in parts of Europe. However, trees or shrubs used in riparian or other agroforestry buffers could be harvested so that they provide biomass in addition to their other environmental benefits. Finally, the strong research and development capacity, including several teaching and research institutions, that is available in the region, indicates a clear possibility for strengthening agroforestry research and development in the region.

Québec

History of Forestry and Agriculture

Before European colonization, some 450 years ago, the landscape of southern Québec was dominated by northern temperate mixedwood forests comprising species such as black cherry (*Prunus serotina* Ehrh.) and red oak (*Quercus rubra* L.). The establishing rural communities were based heavily on agriculture, resulting in a gradual removal of trees from the landscape. In the twentieth century, however, the advent of modern agricultural practices such as tile drainage substantially increased crop yields on nutrient-rich clay deposits, which, in turn, led to a gradual abandonment of less productive agricultural land. In many cases, old-field succession restored wooded areas, but these new forests differ greatly from precolonial stands in their structure and species abundance (Brisson and Bouchard 2003). Over the past century, intensive agricultural practices in southern Québec have resulted in a loss of biodiversity, a loss of fertile topsoil, the eutrophication of waterways, and high levels of nitrate concentrations in groundwater. Reintroducing trees could restore the landscape's aesthetic appeal, mitigate some of these environmental impacts, and provide quality hardwood products. Regional forestry agencies in southern Québec have made considerable efforts to restock lands with native hardwood species, such as restoration silviculture in open areas (Paquette et al. 2008), in early successional shrub communities (Fournier et al. 2007), and in degraded (i.e., species-poor) forest stands (Truax et al. 2000; Paquette et al. 2006). These actions have brought various stakeholders to explore the feasibility of also producing hardwood timber within the agricultural milieu.

Currently, windbreaks and shelterbelts represent the most accepted and widespread agroforestry systems in Québec. A third practice gaining interest among Québec stakeholders is planting trees along riparian banks to help stabilize banks and decrease nutrient export to waterways (Fortier et al. 2010). Since 2004, federal and provincial funding agencies have supported research on a fourth type of agroforestry system in Québec, tree-based intercropping (TBI or alley cropping), which consists of widely spaced tree rows with annual crops in the alleys. The remainder of this section will focus on salient findings from these studies and discuss how to create incentives for the widespread implementation of agroforestry systems in Québec.

Agronomic and Silvicultural Considerations

Large-scale monocropping systems have long been the agricultural paradigm in Québec. Tree-based intercropping (TBI) systems are undoubtedly more complex than current monocropping systems and call upon agricultural landowners to develop new practices that are adapted to their current crop production systems. Tree-row spacing and tree crown architecture must allow large equipment to circulate within the alleys. Tree rows must be oriented so as to minimize interference with drainage tiles. Tree species selection should favor those that maintain a strong apical dominance and that produce little tension wood, as trees planted in widely spaced rows are more vulnerable to wind and other weather extremes. Pruning schedules and alley crop rotations must strive to minimize competition for light and soil resources and maximize positive interactions between trees and alley crops. A mix of tree species within and/or between rows, with different growth rates and phenological characteristics, could further minimize competition and maximize positive interactions with alley crops.

Yields and Economic Returns

In recent years (2000 to 2004), three pilot study sites were established at St-Rémi, St-Édouard, and St-Paulin to investigate the economic and environmental benefits of different TBI systems in southern Québec. The TBI systems consisted of fast-growing hybrid poplars (*Populus* spp.) alternating with rows of high-value hardwood species (*Juglans nigra* L., *Fraxinus americana* L., *Fraxinus pennsylvanica* Marsh., *Quercus rubra* L., and *Prunus serotina* Ehrh.). Included were control plots without trees (i.e., monocropping) and control plots without crops (i.e., harrowed). This experimental design allows for the calculation of the land equivalent ratio (LER) to assess the costs and benefits of growing two or more crops together relative to growing each crop in monoculture (Kantor 1999).

At the St-Édouard site, it was found that the average yields of winter wheat in 3-year-old TBI plots were similar to those in monocropping plots, whereas hybrid poplar yields were significantly higher in TBI than in harrowed plots (Table 1). At the St-Rémi site, substantially lower soybean yields were observed in TBI plots at high stem density (i.e., 417 or 313 stems ha^{-1}, according to alley width) than in

Table 1 Annual yields of hybrid poplar and alley crop products grown in tree-based intercropping (TBI) systems in southern Québec

				Annual yields (Mg DM ha^{-1})				
				Alley crop		Hybrid poplar		
Location	Tree age (years)	Stem density (stems ha^{-1})	Alley crop	TBI	Monocrop	TBI	Harrowed	LER
St-Édouard	3	250	Winter wheat	2.4 a	2.2 a	0.7 a	0.6 b	2.2
St-Rémi	6	417	Soybean	1.2 b	2.1 a	3.9 a	3.3 b	1.5
	6	313	Soybean	1.9 b	2.7 a	2.4 a	1.7 b	2.0
	7	139	Soybean	1.4 a	1.5 a	2.6 a	1.8 b	2.1
	7	104	Soybean	1.7 a	1.7 a	1.8 a	1.1 b	2.3

Winter wheat and soybean = total grain yield; hybrid poplar = leafless aboveground biomass. Alley crop yields are compared to those in monocropping plots (i.e., without trees); poplar yields are compared to those in harrowed plots with similar tree row spacings (i.e., without crops or fertilization). Different lower case letters (a, b) in paired columns indicate significant differences ($p < 0.05$), according to *t* tests. *LER* land equivalent ratio (Rivest et al. 2009a, b)

monocropping plots. Competition for light appeared to be a major determinant of soybean (*Glycine max*) yield (Rivest et al. 2009a). The following spring, however, tree rows were thinned (139–104 stems ha^{-1}) and remaining stems were pruned. This resulted in higher and more regular light transmission throughout the alley, and soybean yields equivalent to those of monocrop plots. At both the St-Édouard and St-Rémi sites, the LER varied between 1.5 and 2.3, meaning that equivalent yields of alley crops and poplars using monocultures of each crop would require between 1.5 and 2.3 times more land. These LER values, however, are expected to decrease with time as trees progressively interfere with the alley crops (Dupraz 1999).

Given the recent interest in growing biofuel crops that do not encroach on land currently producing food, it was hypothesized that growing canola (*Brassica campestris* L.) within TBI systems would provide incentives to return abandoned farmland into crop production. Fertilizer trials using three newly developed canola cultivars as the intercrops were conducted at the St-Édouard site in the fourth and fifth years after plot establishment. In both study years, fertilizer N application caused seed oil yields to increase while seed oil concentrations decreased (Beaudette et al. 2010). Over both years, seed oil yields in TBI plots ranged from 0.7 to 2.2 Mg ha^{-1} and were neither numerically nor statistically different compared to monocrop plots. As the highest seed oil yields obtained in this study compare favorably with those of other trials in North America, it would appear that TBI systems incorporating first-generation biofuel crops provide an opportunity for generating profits from marginal agricultural land in Québec.

Climate Change Mitigation

The TBI systems may indirectly mitigate agricultural greenhouse gas (GHG) emissions. Trees that utilize residual fertilizer nitrogen (N) applied to alley crops will eventually return this N to the soil via leaf litterfall. This, in turn, should result in a more efficient cycling of N, thereby decreasing fertilizer N demand and, by implication, reducing soil N_2O emissions. TBI systems may also directly reduce soil N_2O emissions by reducing denitrification rates. At the St-Édouard site, N_2O emissions were found to be three times higher in monocropped plots than in TBI plots (Beaudette et al. 2010). The average soil moisture content over the growing season was significantly lower in TBI than in monocropping, thereby supporting the hypothesis that tree rows are more water demanding than alley crops, increasing soil oxidation potential and reducing denitrification rates.

Ecosys is a complex mathematical model capable of predicting C and nutrient cycling as well as landscape-level gas fluxes through space and time (Grant 2011). The model uses site inputs for weather, plant and soil properties, as well as information on plant and soil management events. Thus, data on soil C sequestration and biomass production gathered at three pilot study sites in southern Québec were combined with similar data from the Guelph Agroforestry Research Station (GARS) in Ontario to calibrate data for the *ecosys* model over a 20-year TBI chronosequence. The purpose of this study was to compare the accumulation of C in plant biomass and soils of TBI and monocrop systems, in addition to predicting carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions. For the monocrops, the model was run from 1987 to 2008 with a 3-year (maize (*Zea mays*)–soybean–winter wheat (*Triticum aestivum*)) rotation with planting, harvesting, and fertilizing practices that followed those in the field experiment. For the TBI treatment, the model was run over the same period with the same rotation, but with poplar, black walnut, and Douglas-fir trees seeded in spring of 1987. Table 2 summarizes the C balance of a simulated 18–20-year-old TBI vs. monocropping system.

The model results indicated that TBI raised total net primary productivity (NPP) by 11% in 2006 and 5% in 2007 but reduced total NPP by 3% in 2008. However, TBI reduced NPP and hence harvest of soybean by 22% in 2006, of winter wheat by 13% in 2007, and of maize by 17% in 2008. Increases in total NPP and reductions in harvest under TBI in 2006 and 2007 raised net biome productivity (NBP) by 60–80 $\mathrm{g\,C\,m^{-2}\,year^{-1}}$. However, the reduction in total NPP and removal of tree trimmings under TBI in 2008 reduced NBP slightly. TBI raised total NBP modeled over the 3-year rotation from −53 $\mathrm{g\,C\,m^{-2}}$ (a net C source) to +87 $\mathrm{g\,C\,m^{-2}}$ (a net C sink). Because the model is based on fundamental processes driving C, nutrient, and water cycles in terrestrial ecosystems, it will enable researchers to focus on TBI practices that optimize C sequestration and mitigate GHG emissions under current and future climates.

Soil Quality Improvement

Lacombe et al. (2009) assessed soil quality of TBI systems in terms of microbial diversity and stability. Based on phospholipid fatty acid profiles, the study confirmed a statistically greater spatial heterogeneity (i.e., higher β-diversity) of soil microbial

Table 2 Modeled annual C budgets of an 18–20-year-old tree-based intercrop (TBI) and a monocrop (MONO)

	18-year-old			19-year-old			20-year-old		
	TBI		MONO	TBI		MONO	TBI		MONO
	Trees	Soybean	Soybean	Trees	W. wheat	W. wheat	Trees	Maize	Maize
C budget	g C m^{-2} y^{-1}								
GPP	313	786	933	292	906	1,042	249	953	1,164
R_a	170	341	401	165	326	371	141	372	456
NPP	143	445	532	127	580	671	108	581	708
R_h	403		407	471		473	393		395
R_s	583		542	593		549	497		461
R_e	914		808	962		844	906		851
NEP	185		125	236		198	296		313
DIC, DOC	17		13	6		5	12		15
Harvest	0	97	124	0	156	179	52	290	349
NBP	71		–12	74		14	–58		–51

GPP gross primary productivity, R_a autotrophic respiration, *NPP* net primary productivity, R_h heterotrophic respiration, R_s soil respiration, R_e ecosystem respiration, *NEP* net ecosystem productivity, *DIC/DOC* losses as dissolved inorganic and organic C, *NBP* net biome productivity

community composition in the TBI system. Soil samples were then treated to increase concentrations of a heavy metal (Cu) contaminant. Regression analysis confirmed that microbial communities of TBI systems were more tolerant to Cu stress than those of monocropping systems. Most annual crops, as well as some tree species such as poplars (*Populus* spp.) and sugar maple (*Acer saccharum* Marsh.), benefit greatly from symbiotic associations with arbuscular mycorrhizal fungi (AMF) that help increase soil nutrient uptake, especially phosphorus (P), as well as the plant's resistance to pathogens and to drought. While many AMF species are generalists in their choice of plant host (Smith and Read 2008), it is increasingly understood that different AMF taxa represent different functional attributes (Munkvold et al. 2004). High diversity of AMF species available to crops resulted in a high number of potential benefits to be derived from plant-AMF associations. Results from a study by Chifflot et al. (2009) suggested that TBI systems enhance the taxonomic diversity of AMF species in soils. All AMF species are obligate symbionts, meaning that hyphal growth cannot persist in the absence of a host and that AMFs must then survive as spores. De novo colonization of plant roots is apt to proceed more efficiently, however, when there is a large biomass of living hyphae to colonize new roots rather than only spores. Successive harvesting and tillage in monocropping systems will substantially lower AMF hyphal densities and cause a dilution of AMF spores (Kabir 2005). Lacombe et al. (2009) showed that TBI systems maintained significantly more AMF hyphal biomass under alley crops than in adjacent monocropping systems. This suggests that the perennial tree root component of TBI systems may act as a nursery for AMF inocula, thereby facilitating de novo colonization of annual alley crops.

Soil quality assessed in terms of nutrient cycling efficiency at the St-Rémi and St-Édouard sites confirmed that poplar tree roots in these relatively young TBI systems played an important "safety-net" role of capturing nutrients leaching below the rooting zone of alley crops (Bergeron et al. 2011). The capture of subsoil nutrients by tree roots prevents groundwater pollution and allows these nutrients to be efficiently recycled within leaf litterfall. Rivest et al. (2010) found significantly higher soil microbial biomass, mineral N concentrations, nitrification rates, and N response efficiency of poplars in TBI than in control (i.e., harrowing) plots at St.-Rémi.

Acceptance of TBI Systems

Although TBI systems are not yet widely implemented in Québec, 7 years of field trials indicate that their widespread adoption could improve current agricultural and silvicultural systems as well as provide various social, economic, and environmental services to rural communities and to society as a whole. The TBI systems address the most important environmental problems that these communities face (i.e., groundwater pollution, degradation of soil quality, and loss of biodiversity), while providing a means of producing high-quality timber. If applied on a large scale, TBI systems could substantially reduce agricultural GHG emissions and increase atmospheric C sequestration in soils and woody biomass. It is important that landowners be informed of these economic and environmental benefits of TBI systems. Many NGOs in Quebec, through their extension programs, are working along with landowners in the adoption of TBI systems. Research grants from the *Conseil de recherches en sciences naturelles et en génie* and from the *Fonds de recherche du Québec – Nature et technologies* have resulted in the establishment of several pilot TBI study sites in Québec.

Furthermore, agroforestry is now represented by an independent, nonprofit committee at the *Centre de référence en agriculture et agroalimentaire du Québec*. The momentum created by pilot projects on windbreaks, shelterbelts, wooded riparian buffer strips, and TBI systems in Québec has been matched by some degree of "institutionalization" of agroforestry. For example, Agriculture and Agri-Food Canada (AAFC) recently issued a comprehensive report on the state of agroforestry throughout the province (de Baets et al. 2007). New positions have been created by AAC for personnel mandated specifically to promote agroforestry. Likewise, the Canadian Forest Service has been active in promoting discussion groups and seminars and in conducting surveys to better understand the legal and political framework required to promote agroforestry in Québec. Through its *Programme de développement régional et rural*, the Québec government's *Ministère des affaires municipales, des régions et de l'occupation du territoire* has begun supporting agroforestry development projects, notably pilot TBI systems in the Gaspésie region. In 2011, the provincial *Ministère de l'agriculture, des pêcheries et de l'alimentation du Québec* launched a pilot program on the "multifunctionality of agriculture" specifically targeting agroforestry and TBI as production systems for which the implementation could eventually get subsidized.

Despite these positive initiatives, there remains much to be done to facilitate the transition from conventional monocropping toward the widespread implementation of TBI systems in Québec. Here, we have noted five fundamental policy and framework changes that would provide incentives for landowners to adopt agroforestry systems. As they are common and applicable to other Canadian regions, these policy and framework changes are discussed in the "Synthesis" section at the end. Clearly, government policies and subsidies alone will not bring about drastic changes in Québec's current land management practices. The widespread acceptance of TBI and other innovative agroforestry systems will require social change as well. Governments can only provide the framework by which ethical and skilled individuals may become active agents of change through their own personal undertakings and examples.

Ontario

Introduction

In agriculturally prominent Ontario, concerns exist on the ecological sustainability of current agricultural practices, stewardship of the agricultural environment, and the economics of both traditional and environmentally friendly farming systems. As TBI systems have been widely researched in Ontario in relation to their environmental services, this section will mainly deal with such aspects. The major areas of research included C sequestration, N_2O reduction potentials, nutrient leaching reduction and improved water quality, enhancement of bird diversity and earthworm activity, and woody biomass production for bioenergy. These studies were supported primarily by the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) and by Agriculture and Agri-Food Canada (AAFC).

Carbon Sequestration

The TBI systems are considered to be C sinks because the integration of trees results in greater CO_2 sequestration and thus enhances C storage in permanent tree components. These systems are expected to store more C than conventional cropping systems through two mechanisms: (1) increased C storage in the biomass of planted trees (Peichl et al. 2006) and (2) slower decomposition of lignin-rich litter provided by the TBI systems and consequent stabilization of soil organic carbon (SOC) (Montagnini and Nair 2004). In southern Ontario, Thevathasan and Gordon (2004) reported of 2,400 kg ha^{-1} year^{-1} in a TBI system with hybrid poplar compared with

400–600 kg ha^{-1} year^{-1} in a maize (*Zea mays* L.) monocropped field. This four- to six-fold increase in C in the TBI system over a period of 7–8 years resulted in an approximately 1% increase in SOC (0–15 cm depth) close to the tree row; this effect extended into the alley for approximately 4 m. Thus, there was 30–35% increase in SOC close to the tree rows over the given period (Thevathasan and Gordon 2004; Thevathasan et al. 2004; Oelbermann et al. 2006). Based on these results, Thevathasan and Gordon (2004) and Evers et al. (2010) projected that the TBI systems that could potentially be adopted in an estimated 4 million ha of agricultural land of classes 1 through 4 in Ontario could lead to a significant effect on C sequestration and GHG emission reduction. Furthermore, increases in SOC in the cropping area may reduce soil erosion and help to maintain soil fertility and stability.

Reduction of Nutrient Leaching and E. coli Loading

One of the soil-related advantages of agroforestry systems is based on the "safety-net" hypothesis, which states that the incorporation of trees into agricultural systems will allow for a more efficient use of resources, since the rooting system of the trees captures nutrients that are not captured by the crop component of the system (Van Noordwijk and Lusiana 1999). Dougherty et al. (2009) tested the validity of this hypothesis in temperate intercropping systems. Tile drain effluents collected from two adjacent agricultural systems (TBI and monocrop) in a paired mini-watershed experiment were subject to application of biotracer *E. coli* NAR (nalidixic acid resistance); both sites were analyzed for concentrations of the biotracer and NO_3–N. Both sites had received total inorganic N application at the rate of 130 kg N ha^{-1} in 2006. The results showed that nitrate levels were significantly higher in the monocrop effluent (164.67 kg ha^{-1}) compared with 88.59 kg ha^{-1} for TBI, representing a 46% reduction in nitrate-N leaching. The total colony-forming units found in the monocrop and TBI effluents were 34,025 and 28,401, respectively. These results suggest that the trees in intercropping systems could mitigate the movement of *E. coli* to the groundwater (Dougherty et al. 2009).

Nitrous Oxide Reduction Potentials in TBI Systems

Evers et al. (2010) examined the potential role of intercropping systems in reducing N_2O emissions from agricultural lands in a study in Ontario by analyzing N_2O flux in both TBI and monocropping systems. Gas samples were taken from June 2007 to August 2008 using the chamber method and divided into seasons according to planting and harvesting times; N_2O fluxes (kg ha^{-1} day^{-1}) were 1.07 and 0.75 in the monoculture and TBI system, respectively, with no significant difference in emissions between the two systems over all seasons. The results, however, were not statistically different. Further research is needed to investigate this more convincingly.

Woody Biomass for Bioenergy Production Within a TBI System

Results from experiments conducted at the GARS over the past 24 years suggest that two distinct zones exist across a 15-m-wide alley with temperate mixed species. The first, a competitive zone, is the area within 2 m of tree rows. The second, a complementary zone, is the remaining area in the center of the alley, which is ~11 m wide (Fig. 1). The competitive zone is characterized by direct competition for nutrients, moisture, and light. The complementary zone is characterized by favorable growing conditions such as enhanced nutrient cycling, N mineralization, soil organic C addition, and earthworm activity. In addition, the complementary zone has lower soil temperature and higher moisture availability, the latter as a result of less evapotranspiration and less C assimilation (Thevathasan and Gordon 2004; Reynolds et al. 2007; Clinch et al. 2009).

Given the current interest in biomass for bioenergy, studies have been initiated to evaluate the use of willow (*Salix* spp.) as an alternative crop that could be successfully grown in the alleys of a mature (21-year-old) TBI system. This (trees within trees) is a new concept in temperate agroforestry; willow is considered a "crop" due to its short harvest cycle of 3 years. Existence of complementary growth-promoting interactions in the middle of cropping alleys due to the presence of mature trees along the tree rows has been clearly demonstrated in past studies (Thevathasan and Gordon 2004; Reynolds et al. 2007; Clinch et al. 2009), which may have enhanced willow biomass yield in the agroforestry site compared with the monocropping site.

Biodiversity (Avian, Insect, Earthworm, and Mycorrhizae Dynamics) in TBI Systems

Avian usage has been investigated at the GARS comparing TBI with cornfield and old fields. The results showed that more species foraged in the intercropped plots (ten species) compared to the cornfield (two species) and old-field site (eight species). The study revealed that intercropping provided opportunities for birds to nest and forage that were not available in the monocropped cornfield. The diversity of the breeding population in the intercropped field approached that found in the nearby old-field site, demonstrating the value of the intercropped site to local and migrating bird populations. Arthropod abundance, representation by functional group, and hymenopteran family richness and diversity were all compared between the intercropped and the adjacent monoculture sites at the GARS (Howell 2001). The results suggest that taxa such as the Opiliones, Dermaptera, and Carabidae, which are associated with organic litter and areas that provide shelter during the day, were significantly higher in the intercropped system than in the monoculture system (Fig. 2). The abundance of Hymenoptera, and several of its families, was also significantly higher in the intercropped site than in the monocropped site, although no differences were observed in terms of overall family richness and

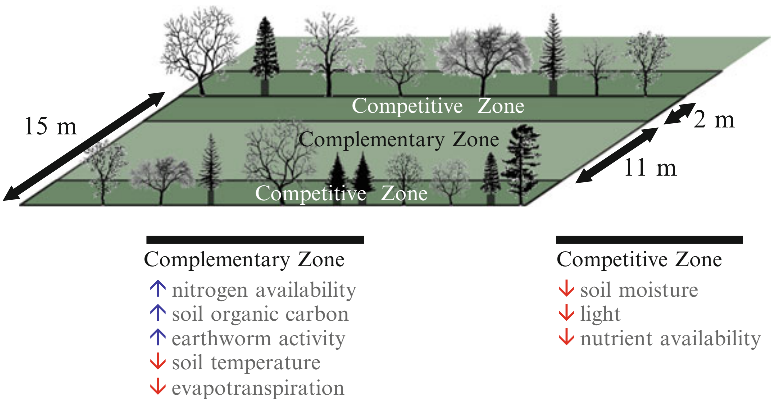

Fig. 1 Schematic diagram showing the competitive and the complementary zones in the tree-based intercropping field at the GARS, Guelph, Ontario, Canada

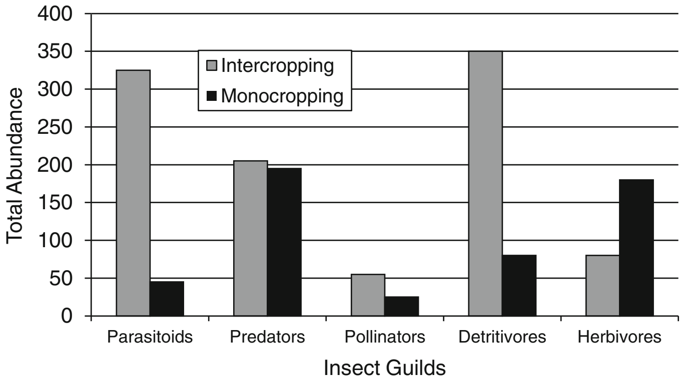

Fig. 2 Comparison of total arthropod abundance in June malaise samples from agroforestry and monoculture sites, University of Guelph, Guelph, Ontario, Canada

diversity. It could be concluded that trees with crops such as corn may improve pest management by providing habitat to augment populations of natural enemies.

A study of earthworm population dynamics in a temperate intercropping system was conducted at the GARS in 1997 and 1998. Tree species (hybrid poplar) played an important role in determining the spatial and temporal distribution of earthworms within the intercropping system. Significant differences ($p < 0.05$) in earthworm density and biomass were observed between sampling periods and tree species. For example, poplar and ash (*Fraxinus americanus* L.) tree rows had the greater earthworm densities, possibly due to either greater litter contributions or more rapid decomposition of leaf litter. Earthworm numbers decreased during the summer period, but these values were still significantly greater ($p < 0.05$) than those from a conventionally cropped field.

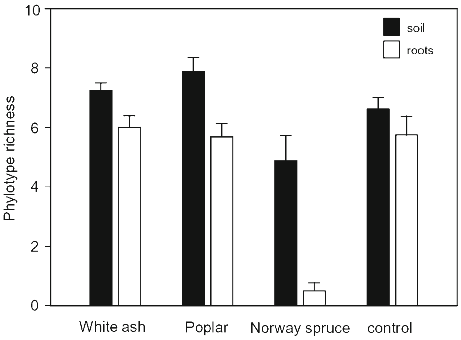

Fig. 3 Arbuscular mycorrhizal fungal (*AMF*) phylotype richness in the tree rows of the University of Guelph tree-based intercropping (*TBI*) site (*Fraxinus americana* (white ash), *Picea abies* (Norway spruce), *Populus sp.* (poplar – hybrid))

Spatial analysis of the arbuscular mycorrhizal fungi (AMF) community at the GARS TBI site revealed significant variation in the AMF community composition (Bainard et al. 2011). There were differences in the mycorrhizal status and associated AMF communities among the tree species in the TBI site. White ash is colonized by AMF, Norway spruce is colonized by ectomycorrhizal fungi, and poplar is colonized by both AMF and ectomycorrhizal fungi. White ash and poplar had the highest AMF richness and similar AMF communities in their roots and in soil collected from their tree rows (Fig. 3). These results are interesting considering that tree species that form a tripartite association with AMF and ectomycorrhizal fungi generally have low levels of AMF colonization as they mature (Bainard et al. 2011). The TBI site contains little or no ectomycorrhizal inoculum, which could have promoted greater AMF colonization in trees.

Ontario Summary

The success of intercropping depends mainly on the ability of the system components to maximize resource utilization while at the same time maintaining "complementary" interactions between them. When this occurs, productivity per unit land area is often enhanced, resulting in higher economic returns. When components of an intercropping system are different (e.g., woody and non-woody), the demand for limited resources is staggered in space and time so that resource capture and productivity per unit land area may be maximized. On a biological level, intercropping increases micro and macrofaunal diversity and activity, both above- and belowground. The increased range of faunal activity gives a clear indication of ecosystem integrity within an intercropping system relative to that associated with conventional agricultural practices. From an ecological perspective, intercropping systems trap larger amounts of energy at different trophic levels, demonstrating higher energy utilization efficiency. In relation to C sequestration and greenhouse gas (e.g., N_2O) emission reductions, TBI systems have the potential to greatly contribute to climate change mitigation. The tangible benefits that are derived from the above-described eco-biological processes, along with combined yields obtained from the trees and crops, place this land-use practice above conventional agricultural systems in terms of long-term overall productivity. However, the economics of TBI systems in Ontario need to be examined in more detail. Initial establishment costs and the loss of revenue due to removing cropland from production often deter Ontario farmers from adopting these types of systems. Therefore, investigation into policy measures and/or tax incentives and cost-share programs should be initiated in order to obtain successful adoption rates in Ontario, in particular, and the rest of the country, in general.

The Prairie Region

History and Status of Agroforestry

In the Prairie Provinces of Manitoba, Saskatchewan, and Alberta, regional differences in climate and soil result in a wide variety of agricultural practices. The ranching of beef cattle is common in the foothills of the Rocky Mountains, south-central grasslands, and the northern wooded parklands. In the central plains, wheat, barley (*Hordeum vulgare*), and canola cropping predominate, while corn, sunflower (*Helianthus annuus*), and soybean are the common crops grown in southeastern Manitoba and southwestern Alberta (PFRA 2000). Irrigated potatoes and a significant horticulture industry that produces vegetables and some small fruits are also found in these areas. Although the entire Prairie Region was originally grazed by bison, which supported the aboriginal peoples of the plains, little or no agriculture used to be practiced. Widespread agricultural settlement occurred rather rapidly following the building of railroads in the early 1880s. Agroforestry activities in the region began soon afterward. Many settlers acutely felt the need for shelter on the treeless southern plains, while the need was less in the more wooded regions in the north and east. When tree planting began in the 1890s, much of the activity was in the southern prairies while, further north, settlers were clearing trees from their lands.

Settlers who arrived from the Ukraine and the steppes of Russia brought with them a thorough understanding of the need for trees to protect crops and soils, and some prairie shelterbelt networks date back to those initiatives in the early 1900s. In the 1930s, the combination of drought, depression, and soil erosion led the Government of Canada to pass the Prairie Farm Rehabilitation Act (PFRA 2000), through which field shelterbelt planting was greatly increased, including several designated locations for high-density field shelterbelt networks. In 1950, the Government of Alberta created its own provincial shelterbelt nursery to meet the need for adapted tree and shrub seedlings throughout the province.

Some settlers brought the agroforestry concepts with them, while in other areas where erosion had been severe, individuals stepped forward to lead their communities in establishing shelterbelts. Often, shelterbelt planting for erosion control was done at the height of a drought, while complacency and good crops in wetter years resulted in lower rates of tree planting. In the 1960s and 1980s, recurrence of drought again led to concern about soil erosion in some parts of the prairies, and large-scale field shelterbelt planting programs were implemented. Over the years, improved local organization at a municipal or a watershed scale has resulted in increased stability in local programs of tree planting and care. Increased recognition of the multifunctionality of shelterbelts since the 1980s also increased the involvement in tree-planting programs by other environmental nongovernment organizations.

Since the 1990s, the adoption of agroforestry measures on the prairies has changed, due to changing technical and socioeconomic circumstances. In large part, there has been an increase in the awareness by Canadians about environmental challenges. Concern about soil erosion has increased with added concerns about biodiversity, climate change, and water quality. Technological changes have greatly affected how agricultural land is managed. The widespread use of glyphosate and the development of minimum-tillage seeding technology have resulted in increased adoption of continuous cropping (PFRA 2000). At the same time, farm demographics have changed, so that farms have become larger and more farming is done on rented land (PFRA 2000), on which neither renters nor owners are motivated to plant trees in new windbreaks. However, some adoption of new buffer types has occurred. A rapid increase in intensive livestock operations for swine production in all three provinces has been accompanied by multirow windbreaks being planted around them to reduce odor and to buffer them from surrounding residences or urban areas. As a result of the development of local markets for fruits and vegetables, and the increase of demand for specialty products, such as those with organic certification, some innovative ecological windbreaks have been designed for some of these enterprises, windbreaks that are composed primarily of native species of mixed trees and shrubs.

The Government of Canada, through Agriculture and Agri-Food Canada (AAFC), continues to conduct agroforestry research and development on the prairies. Departmental changes resulted in the formation in a new Agri-Environment Services Branch (AESB) in 2009 within AAFC, which has among its lines of business, the promotion of appropriate agroforestry measures throughout Canada, partly through an expanded role of AESB's Agroforestry Development Centre (ADC). The inclusion of agroforestry in an overall program of environmental stewardship is justified by the amount of detailed information about the environmental and economic benefits that is available, which depends on continued research. The substantial economic benefits of agroforestry on the prairies to landowners and to society that were demonstrated by Kulshreshtha and Kort (2009) show agroforestry to be an important Beneficial Management Practice (BMP) that should be a component of any environmental programming.

Agroforestry is also being addressed by provincial governments, universities, and other organizations throughout the Prairie Region. In Saskatchewan, after more than 5 years of poplar research, the University of Saskatchewan, in 2006, established the Centre for Northern Agroforestry and Afforestation in the College of Agriculture and Bioresources. Because of this initiative, the university has been graduating M.Sc. and Ph.D. students in various aspects of agroforestry and afforestation as well as offering agroforestry courses. Also, the Saskatchewan Research Council collaborates with AAFC, the University of Saskatchewan, and other partners to develop agroforestry options in the province. In Alberta, the provincial government, in cooperation with AAFC and industry, supports the Agroforestry and Woodlot Extension Service, which conducts technology transfer to landowner and other groups, collaborates in applied research, and develops research/demonstration plantings and projects related to agroforestry. The University of Alberta also has faculty members engaged in agroforestry research and teaching. In Manitoba, the provincial agriculture department provides agroforestry expertise to landowners and watershed-based conservation districts.

Agroforestry research for the Prairie Region has been led for over 70 years by the ADC, including studies on the use of trees for the control of wind, snow distribution, soil erosion, and other purposes. Kort et al. (2011) reported that significant water from snow was conserved by shelterbelts because of the reduction of sublimation from blowing snow. This conserved moisture would be especially important, given increased drought predicted by some climate change models. Agroforestry-related studies in biodiversity and the protection and microclimate modification for crops near windbreaks have also been done by the ADC and its collaborators.

Climate change mitigation and adaptation has been the focus for a number of studies. An important study that reported the biomass in various species of trees and shrubs in mature shelterbelts showed how much carbon was fixed in the aboveground wood (Kort and Turnock 1999). The use of windbreaks to reduce energy required for home heating was studied in a 1981–1983 project, while recent projects have been undertaken that consider harvestable woody biomass on the agricultural landscape. One important conclusion was that coppice harvesting could be done of existing native willows in riparian zones, as a sustainable way to rejuvenate them, while deriving valuable bioenergy with minimal inputs (Schroeder et al. 2009; Savoie et al. 2010).

Tree assessment and improvement has always been an important part of the ADC's research, particularly with regard to adaptation and performance under prairie conditions. This began in 1947 with the initiation of a poplar improvement program. Since that time, poplar improvement work has continued at the ADC with the development of at least five well-adapted poplar clones. Adaptation of agroforestry species to climatic and soil conditions is a continuing concern, especially under climate change scenarios. Steppuhn et al. (2008) showed that the hybrid poplar clone, Assiniboine, was significantly more tolerant of saline conditions than the clones Walker, CanAm, and Manitou, while poplar clonal differences in water relations and responses to drought were studied by Kort and Blake (2007). There has also been considerable research into the genetics and physiological adaptation of poplar (Bekkaoui et al. 2003; Soolanayakanahally et al., 2009; Talbot et al. 2011). Other species that have been studied, with test plantings throughout the Prairie Region, include green ash (*Fraxinus pennsylvanica* Marsh.), bur oak (*Quercus macrocarpa* Michx.), Scots pine (*Pinus sylvestris* L.), and others (Schroeder 1994). Sea buckthorn (*Hippophae rhamnoides* L.) has been studied particularly for the use of its fruit and leaves as nutraceuticals (Barl et al. 2003).

Other agroforestry practices, uses, and designs have also been researched by the ADC and its collaborators. Because of the large area of parkland (i.e., mixed aspen and grassland) in the Prairie Region, Kort et al. (2008) studied the principles and potential of silvopasture in relation to Saskatchewan. Shelterbelts around swine barns have been adopted in many cases, and multirow, mixed-species shelterbelts have been designed as forest belts (wide, multirow field shelterbelts) or as ecobuffers (narrow multirow, densely spaced shelterbelts consisting of mostly native species). The use of aerial and satellite imagery to monitor and quantify agroforestry has been under investigation because the prairie agricultural area is so extensive that it would be otherwise difficult to know the state and trends of trees and shrubs, given the changes in agricultural technology and demographics. Wiseman et al. (2009) showed that object-oriented software held promise for the semiautomated monitoring of agroforestry practices on the prairie landscape.

The University of Saskatchewan's Centre for Northern Agroforestry and Afforestation has a mandate to strengthen, coordinate, and facilitate research on the development of woody crops for agricultural systems. The center's focus has been in several areas. In 2002, a study was initiated to determine the best stock types for planting of hybrid poplar, and after 3 years of growth, rooted cuttings (both bareroot and plugs) outperformed unrooted cuttings where survival rates were >67% and <17% for rooted and unrooted cutting, respectively, after the second year (Block et al. 2009). There was no response to fertilization of 100 kg N ha^{-1} or pruning for the stock types after 3 years of growth (Block et al. 2009). However, some modeling efforts have indicated that fertilization early in the stand rotation could increase fiber yields for hybrid poplar grown on agricultural soils (Welham et al. 2007). Kabba et al. (2007) showed that competition by weeds, particularly dandelion (*Taraxacum officinale*) and quackgrass (*Agropyron repens*), greatly reduced hybrid poplar growth not only in growth chamber studies but also in field studies in Saskatchewan (Kabba et al. 2011). Steckler (2007) found that harvesting on a 20-year rotation would impact nitrogen and phosphorus cycles and hence the long-term productivity of the stand. Growth of hybrid poplar plantations after 14 years has estimated yields of about 11 m^3 ha^{-1} year^{-1} for trees spaced at 2.4 m × 2.4 m (unpublished data), suggesting a viable fiber industry is possible in the Prairies. New models for tree growth and biomass yields have also been developed for hybrid poplar using the 3PG model (Amichev et al. 2010). Research has also been directed at using hybrid poplar in phytoremediation of hydrocarbon-contaminated sites (Gunderson et al. 2008) and determining the role of ectomycorrhizal colonization of hybrid poplar roots on the remediation of diesel-contaminated soil (Gunderson et al. 2007). Recently, the center has been focused on the production of willow as a biomass energy crop. Over 30 clones have been planted throughout Saskatchewan to determine clone suitability to soils and climatic conditions and to measure biomass yields. Early results indicate that some clones are capable of producing up to 10 $\mathrm{t\,ha^{-1}\ year^{-1}}$ and C model predictions suggest that, if grown on marginal land in the province, willow plantations could sequester 5.7–7.5 $\mathrm{Mg\ C\,ha^{-1}\ year^{-1}}$ (Amichev et al. 2012). The center is also actively involved in teaching agroforestry courses and in outreach.

Challenges, Constraints, and the Way Forward

On-the-ground conservation activities are increasingly undertaken by watershed-based conservation groups composed of landowners and other stakeholders. In Manitoba, for example, conservation districts have been formed that cover the agricultural area of the province, and they each operate according to an annually updated Integrated Resource Management Plan. They receive relatively stable, long-term funding, based on local tax levies and contributions from the provincial government. As these organizations develop and become more stable, it is likely that conservation programs from provincial, federal, and other sources will be delivered by them. This likely represents an opportunity for agroforestry since the management plans of these organizations should include all aspects of resource management at a landscape scale.

Water quality and climate change are two major environmental issues for agriculture. Agroforestry plantings that address these issues, such as riparian buffers and buffers that can be harvested for biomass or that sequester C effectively, are likely to receive increasing attention, including research, promotion, and program support to organizations and individuals. Protection of water quality is the major focus of many watershed-based conservation districts, and these are likely to focus on riparian management. The agricultural products from prairie farms continue to be mostly for export. There is also a change toward larger farms and more corporate farms on rented lands (PFRA 2000). However, the domestic market provides opportunities for more specialized, often smaller, farm enterprises. Corporate farms may, on one hand, be less interested in tree planting or other environmental practices that are not seen as profit-generating activities, and farming on rented land may also present obstacles to long-term conservation practices with trees. On the other hand, public concern about environmental issues may encourage corporate farms to make sound environmental management of the landscape an essential part of the core business. Government debts and annual deficits at the federal and provincial levels may limit government ability to provide incentives for some environmental practices or may result in programs that are limited to environmental measures where the danger is perceived to be the most acute – for example, riparian zone protection. Agroforestry practices that will be adopted most in the future, therefore, may be those that address the greatest environmental concern or those that are of the greatest economic interest to producers.

British Columbia

History of Agroforestry Development

British Columbia's aboriginal peoples have a long, intergenerational history of integrated management of overstory and understory resources through the legacy of their traditional ecological knowledge. This body of knowledge and ecological awareness incorporates a wealth of information relating to sustainable, integrated management such as selective harvest, harvest diversification, and habitat modification. Current agroforestry applications within the province have evolved from efforts to integrate resource practices on public lands and, more recently, as a means of economic diversification and approach to environmental stewardship. For example, compatible management for wild-harvested non-timber forest resources (NTFR) and timber has historically been the provincial focus rather than integrated forest farming by design. Riparian buffers and buffers to mitigate dust and odor in agriculture are gaining prominence due to environmental stewardship objectives of the agricultural sector. The history of windbreak development parallels that of the Canadian Prairies.

Several factors have converged to increase awareness of agroforestry practices in British Columbia: the success in using sheep grazing for silvicultural purposes since 1984, economic diversification efforts in coastal woodlots starting in the mid-1990s, and the mountain pine beetle (*Dendroctonus ponderosae* Hopkins) epidemic in the BC interior. This has also given rise to greater organized research, pilot projects, and demonstration initiatives. Development of agroforestry in British Columbia is driven by partnerships between producer and industry associations, First Nations (indigenous people of Canada), academic institutions, non-governmental organizations (NGOs), and municipal, provincial, and federal government agencies.

Silvopasture Development

Little research directly addresses silvopasture systems in British Columbia, and most guidelines have been adapted from forest grazing and silviculture trials. Development has focused on understanding three critical interactions: tree-forage and livestock-tree interactions in establishing or young forests (herbaceous establishment phase) and tree-forage interactions in mature forests (arboreal phase). Interest in silvopasture as a complementary or supplementary land-use approach is growing, particularly as land managers seek new tools and approaches to address problems inherent in current resource management practices. For example, the mountain pine beetle (*Dendroctonus ponderosae*) epidemic and subsequent large-scale tree mortality has resulted in extensive salvage harvesting, and a disruption in the spatial and temporal timber harvesting and reforestation cycles. Compatible management of timber and range becomes less effective as extensive tree plantations mature and exclude understory production without providing forage alternatives, which are reflected in exacerbated forage shortfalls. Silvopasture demonstration pilots are in the process of being initiated to understand the spatial and temporal disruptions in forage supply by integrating forage and timber values in a working forest. Further environmental benefits being explored include the ability of silvopasture to sequester C, alter livestock distribution, and protect riparian areas.

Forest Farming

An important complement to integration of trees into agricultural landscapes is the integration and management of other crops into forested landscapes. Forest farming systems may be developed from full-canopy forests managed for understory development, or they may be managed from a young age to provide understory crops in conjunction with timber. Less frequent is the introduction of stands of trees into agricultural lands, given the predominance of forested landscapes within the province. However, as alley cropping systems mature and canopies close, landowners may convert the alley cropping system into a forest farming system. As such, forest farming approaches may incorporate in situ NTFRs or manage shade-tolerant crops introduced into assorted treed systems. A variety of individual enterprises and community initiatives around the province incorporate forest farming elements into their business models. One example is the developing cottage industries focused on paper birch (*Betula papyrifera* Marsh.) and bigleaf maple (*Acer macrophyllum* Pursh) tapping, harvesting sap from the trees to make birch or maple syrup, as a component of integrated forest or farm management.

Integrated Riparian Management as an Agroforestry Practice

Integrated riparian management (IRM) or riparian forest buffers in agricultural settings is still in its infancy as a recognized land-use system. Most agricultural production occurs on only 4–6% of the total British Columbia's land base, mainly located in valley bottoms. These lands are surrounded or intersected by a range of watercourses, lakes, and wetlands, which sustain much of British Columbia's fisheries sector. Additionally, most of the agricultural production occurs where 60% of the provincial population resides, resulting in elevated land prices that have pushed producers to maximize use of all available production areas. As such, encroachment and destruction inclusive of all land-use activities have resulted in substantial deterioration of riparian areas.

Most conservation activities have focused on design, restoration, and riparian ecosystem functioning by research institutions, industry, and/or agencies along with similar promotion from NGOs and First Nations communities. Little attention has been paid to the design of systems that may also provide a direct economic benefit to landowners. The riparian stewardship approach in agricultural areas has been supported through initiatives from Ducks Unlimited, British Columbia Cattlemen's Association through their Farmland-Riparian Interface Stewardship Program, and other local or regional initiatives. One method to address habitat loss concerns has been the development of stewardship initiatives through the Federal/Provincial Agricultural Policy Framework and Growing Forward Bi-lateral Agreements Environmental Farm Plan (EFP) Program that offers cost-share incentives to improve riparian areas on farmland (BCAGRI 2010). In addition, an attempt to bring a unified approach to riparian interface issues, a Riparian Management Framework for Agriculture, is in development that incorporates the principle of IRM into its management options with delivery through the EFP Program. To date, agencies, conservation groups, and environmental NGOs are reluctant to entertain this model of integrated management in riparian areas due to concerns over habitat marginalization, accountability, and governance. To help inform the ongoing debate, the Agroforestry Industry Development Initiative (2003–2008) funded three IRM projects to demonstrate the viability of such a management regime and to balance environmental and socioeconomic outcomes on agricultural lands. The three projects encompass the use of high-value hardwoods within a riparian buffer, the enhancement of hawthorn in riparian areas for the production for natural health products, and the use of native riparian shrub species for the floral market in conjunction with habitat restoration along a channelized watercourse. Additional work is needed to better understand the environmental benefits of an integrated approach, impacts to riparian integrity, and function related to biodiversity at site and watershed scales.

Windbreaks, Timberbelts, and Buffers

Adoption of windbreaks and timberbelts has primarily occurred in the northeast corner of the province (Peace Region), through Agriculture and Agri-Food Canada's Prairie Windbreak Program. A few instances of windbreaks and timberbelts occur in other areas of the province, such as the Cariboo and Fraser Valley regions. Buffers are also being used for other purposes such as around greenhouses to intercept light, around intensive livestock and poultry facilities to mitigate dust and odors, and in agricultural-urban interface areas.

Alley Cropping Development

One of the earlier users of alley cropping in British Columbia was the tree fruit industry in the late 1800s and early to mid-1900s. Alley cropping was used in the Okanagan, Thompson, and Kootenay regions not only as a means to diversify production and recover start-up costs but also as a means for improving soil conditions for future production (Bealby 1912). The row trees were most commonly apple trees, and crops produced in the alleys included tomatoes, root crops, potatoes, and fruits.

While Garrett et al. (2009) noted the opportunity for the inclusion of alley cropping in American orchards, in British Columbia, this practice became less prominent in the second half of the twentieth century. Green manure is sometimes produced in orchard alleys and, in some cases, grazing is used as a tool to manage growth in alleys, but these are viewed more as management devices and less as products or outputs of the system. While significant investigations of alley cropping with high-value hardwoods have occurred in eastern Canada, little work has occurred in British Columbia. Recently, three alley cropping demonstrations have been initiated, encompassing production of crops for the natural health products market, and the production of wood fiber, field crops, and landscape and floral crops. A partnership between Agriculture and Agri-Food Canada and the British Columbia Ministry of Agriculture is undertaking a joint installation of a replicated alley crop site with three species of high-value hardwoods interspersed with forage crops as part of an effort to investigate issues including production under high-efficiency irrigation, development of production recommendations, and the effects of alley cropping on system services including microclimate modification (L. Liggins, personal communication 2012).

Challenges, Constraints, and the Way Forward

There are several key conditions and developmental factors shaping the "way forward" for agroforestry in the province:

- Growing awareness of environmental stewardship, as well as policies and programs focusing on sustainable agriculture, is resulting in increased interest in the potential roles that agroforestry systems can play in agricultural sustainability.
- For a given land unit in British Columbia, varying resources may be managed by different agencies or users, yielding a complex regulatory and management framework within which models facilitating adoption need to be developed.
- There is a need for partnership and collaboration among the NTFR sector, aboriginal peoples, and government agencies, as concerns exist about sustainable production practices, product safety, aboriginal intellectual and cultural rights, and lack of a comprehensive policy framework regarding these products.
- A mountain pine beetle epidemic has affected ~726 million m^3 of mature lodgepole pine (*Pinus contorta* ex Louden var. *latifolia* Engelm ex S Watson) timber in British Columbia. Producers and resource managers are seeking alternatives to complement and supplement conventional production systems and diversify local economies.

- The Agroforestry Industry Development Initiative has been built based on practitioner input from the sector (Sylvis 2003; Powell 2009). Gaps or barriers were identified as a lack of regional production and economic information, regulatory complexity, labor availability, and lack of developed markets and marketing know-how. Powell (2009) suggested the need for further development in partnerships, demonstration, enhancing the business case, improving market connections, awareness, extension, and policy/regulation initiatives.

Synthesis

In summary, the sections above discussed the historical perspectives and current status of the agroforestry systems across five Canadian regions: the Atlantic, Quebec, Ontario, Prairies, and British Columbia. They also discussed the challenges and potentials for practicing agroforestry systems in these Canadian regions; these are summarized in Table 3. Although each province has its own unique preference to different agroforestry systems, the challenges/constraints and potentials are almost similar across the provinces.

Growing emphasis in government policies on the economic, social, and environmental sustainability of current agricultural systems is resulting in increased awareness of the potential role that agroforestry can play toward agricultural sustainability. In addition, the ongoing research and development programs in different Canadian regions identify agroforestry as one possible solution to the problems faced by the current agricultural systems. A synthesis of the experience across the different regions brings out five policy and framework issues that would provide incentives for landowners to adopt agroforestry systems in all regions:

- Forestry and agriculture are regulated by independent government ministries, both at the federal and provincial levels. Accordingly, the recognized land base for each of these activities is mutually exclusive. Current government incentives for environmental practices are provided independently to farming or forestry operations. Specialized agroforestry systems such as TBI systems, riparian buffers, windbreaks, and timberbelts require that different legislative bodies consult themselves and reform the way in which incentives are offered to landowners.
- Research and training in forestry and agriculture are currently segregated into separate colleges and university faculties. The TBI systems require that complementary expertise be merged to provide training to a new class of highly qualified personnel required to transfer technology and skills to landowners.
- Implementing a TBI system involves a high capital cost that many landowners cannot meet. Governments need to provide incentives to support the initial investment of planting trees and acquiring the necessary equipment.
- Given the long time lag needed for trees to become harvestable, it would be advantageous to establish a Futures Market for the woody component of TBI systems so that landowners may get early returns on their investments.

- In the context of climate change, the creation of a cap and trade C market could generate extra returns to landowners who implement TBI systems, providing a supplementary economic incentive.

Recently, a national agroforestry strategic framework has been established in the United States (USDA 2011). While these goals are unique to the United States, the principles upon which they rest are well suited for Canada as well. The Canadian government, through Agriculture and Agri-Food Canada, the national agriculture ministry, has recently taken the lead to initiate and establish a national network of agroforestry practitioners, ideals, and practices, in both research and development through the Agriculture Greenhouse Gas Program (AGGP), Canada's contribution to the Global Research Alliance. Provincial support for agroforestry varies across Canada but is emerging as it becomes obvious that agroforestry has a role to play in the continued development of sustainable agricultural practices. Local conservation districts and authorities, watershed groups, or other farm-based conservation organizations exist in every Canadian province and play a key role in the adoption of agroforestry practices.

Irrespective of the above-indicated positive initiatives both at the federal and provincial levels, there are also numerous other challenges ahead, including (1) evolution of agroforestry practices in light of changing socioeconomic and environmental conditions, (2) evaluation of ecological goods and services provided by different types of agroforestry systems, (3) evaluation of potential impacts (both benefits and concerns) of agroforestry systems at the landscape scale, (4) continued investigation of the relationship between agroforestry practices and water quality in agricultural watersheds, and (5) carbon programming, including detailed studies and accounts of biophysical carbon budgets in agroforestry systems and their relationship to emerging taxation and credit schemes. Most importantly, we need to build upon emerging collaborations that have developed among various levels of government, universities, and national NGOs. Development of a specific Canadian Agroforestry Network would be beneficial to identifying regional perspectives and questions on agroforestry research and development. For example, what genetic research is needed on regional trees and shrubs; what local market niches could be developed; what concerns exist about invasive species, biodiversity, and the relationship to tree-based systems; and what role might private industry play? There is also a need for continued studies and analyses of the economics, risks, and life-cycle components of all agroforestry systems currently found on the Canadian landscape. Significant progress has been achieved in agroforestry research and development over the last quarter century in Canada. Much remains to be done, especially with respect to advancing the ease of adoption. This is both a multistakeholder challenge and opportunity, which is being championed by producers, academics, governments, First Nations, and NGOs across Canada.

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Table 3 Summary comparison of land-use history, current status of agroforestry practices, challenges/constraints, and future potentials of agroforestry industry in five regions of Canada

	Atlantic Provinces[a]	Québec
Geographic region (including coordinates)	• The region includes the provinces of Newfoundland and Labrador, Nova Scotia, New Brunswick, and Prince Edward Island. The region shares borders with Quebec and the state of Maine • Total land area is 53.9 million ha, with 21 million ha in productive forests • Total agricultural area: 1.1–0.5 million ha in annual crops • Climate is strongly influenced by the Atlantic Ocean. Winter temperatures average −5 °C and summers 14 °C, although much variability exists within the region due to microclimates • Population: 2.3 million	• Area: 154.2 million ha • Québec shares borders with Ontario to the west, United States to the south, and New Brunswick to the east (61°36′N 77°2′W – 45°43′N 70°25′) • Crown land: 92% of Québec • Forest: 76.1 million ha • Water: 17.7 million ha • Agriculture: 3.5 million ha and 30,500 farms • Population: eight million • Climate: humid continental in southern and western Québec; subarctic in central Québec; arctic in northern Québec • Vegetation zones: tundra, taiga, boreal forest, mixed forest, and deciduous forest
Land-use history	• Aboriginal peoples: long, intergenerational history of inhabitation, land, and resource management • First area in Canada to be settled by Europeans drawn by abundant fishery and timber resources • Currently, local economy remains resource based with agriculture, forestry, fishing, mining, and tourism as primary industries	• Before the French colonization, Algonquian, Iroquois, and Inuit tribes were peoples inhabiting Québec • European settlement: exploration, fur trade, timber • The colonization is heavily based on agriculture, especially in the St. Lawrence Valley, where about 80% of the total current population is living • Today: forestry, agriculture, mining, hydroelectricity, wind farms, recreation, urbanization, conservation, and protected areas

Ontario	Prairie Provinces[a]	British Columbia
• Area: 107.6 million ha • Located in east-central Canada (54° 31′N 92° 14′W – 44° 18′N 76° 28′W) Crown land: 86.9% of Ontario • Forest: 71.3 million ha • Water: 19.3 million ha, of which 10.7 million ha is great lakes • Agric/field: 5.5 million ha • Population: over 12.1 million • Climate: three main climatic region – southern, central/eastern, and northern • Conceptually divides into two: northern and southern Ontario • A majority of Ontario population (94%) and its agricultural land is located in the southern part. In contrast, northern Ontario consists of 97.6% of Ontario forests and sparsely populated	• Total area – 196 million ha, with 67 million ha in productive forests • Total agricultural area: 54.8–29.3 million ha in annual crops. The area is roughly triangular with corners at 56.5°N, 120°W; 49°N, 114°W; 49°N, 95.5°W • Population: six million • The region includes the provinces of Manitoba, Saskatchewan, and Alberta and shares borders with Ontario to the east and British Columbia to the west • From the southwest of the region, natural vegetation transitions in a northeasterly direction from shortgrass prairie to medium and tall grasses, then to aspen parklands, boreal forest, and finally tundra in northern Manitoba	• Area: 95 million ha • Westernmost province (59°46′N 134°49′W – 49°19′N 115°0′) • Crown land: 94% of British Columbia • 60 million ha forested • 1.8 million ha lakes and rivers • 34.9 million ha grazing land (forested and nonforested) • Agricultural land reserve: lands capable of agricultural production 4.7 million ha • Population: 4.45 million • Volcanism and glaciations resulting in mountains, river valleys, plateaus, and plains • Climate: cool, moist, and mountainous to continental, marine, Mediterranean-like, semiarid, alpine, and subarctic[b, c]
• Aboriginal peoples: long, intergenerational history of inhabitation, land, and resource management • European settlement: exploration, timber, minerals • Early history as a province: British Colony 1867, Provincial designation 1872 • Today: forestry, agriculture, agroforestry, mining, fishing, recreation, urbanization, conservation, and protected areas – Total # of farms:~57,000 – Total farm area: 5,390,000 ha	• Most of the current agricultural land was native prairie before the 1880s. Aboriginal people hunted bison and subsisted on other naturally available foods • Railway construction in the early 1880s brought large-scale agricultural settlement, tillage, and the disappearance of the bison • Agricultural settlers came mainly from central and eastern Canada, the United States, and Europe, including Russia and Ukraine • Annual crops are mainly cereals and oilseeds, with pasture and forage crops produced where annual crops are unsuitable	• Aboriginal peoples: long, intergenerational history of inhabitation, land, and resource management • European settlement: exploration, fur trade, gold rushes • Early history as a province: British Colony 1858, Provincial designation 1871. Fur trade, gold rushes, ranching, forestry, cultivated agriculture, and fishing • Today: ranching, forestry, mining, oil and gas, -agriculture, fishing, recreation,urbanization, conservation, and protected areas

(continued)

Table 3 (continued)

	Atlantic Provinces[a]	Québec
Status of agroforestry (major practices and their roles; give speculative estimates of area under each)	• Windbreaks and shelterbelts – 2,000 km estimated • Riparian buffers – 200 km estimated • An emerging discipline. Growing interest in the role agroforestry may play in contributing to the sustainability of farms in the region	• Windbreaks and shelterbelts are the most widespread systems (10,000 km) • Tree-based intercropping and tree riparian buffers are emerging systems. Many pilots and demonstration sites, and major research projects established and being developed • Understory crops (e.g., ginseng and goldenseal) in maple stands: growing interest but current production still remains relatively low and not well documented
Challenges and constraints	• More applied research is required to quantify the ecological goods and services provided by agroforestry practices • More technical expertise is required to promote the adoption of agroforestry practices on farms	• Lack of institutional recognition within agricultural and forestry policies and programs • Lack of appropriate subsidizing programs covering agroforestry practices • Training of high-qualified personnel • Adoption of an economic and market development approach

Ontario	Prairie Provinces[a]	British Columbia
• Farm woodlot: 587,045 ha, $19.7 million annual value and $60 million in-kind use of forest products on farm (fuel wood, posts, food, building materials, decorative) • Christmas trees: 12,141 ha, $8.3 annual value • Nuts: 810 ha, $200,000 annual value • Forest ginseng: 400–800 ha • Maple products: 2,600 farms, 1.3 million taps, $15 million annual value, plus tourism and spin-off values to local communities • Windbreaks: 76,269 (#) • Timberbelts (sawlogs from fencerows): 10 ha • Hardwood plantation and tree-based intercropping: area is not documented[d]	• Windbreaks and shelterbelts: estimated 700 million trees and shrubs planted since 1901, including field, farmyard, and roadside windbreaks. Estimate 0.2 million km currently on the landscape • Riparian woody buffers: recent initiatives and incentives, but adoption has been on a small scale. Existing natural woody riparian buffers are extensive in the northern and eastern prairies • Forest grazing in aspen forest is common but not intensively managed silvopasture due to low value of wood • Alley cropping sites are few – limited to high-value crops (market gardens, U-pick fruits, organic production, nurseries) • Forest farming is not practiced but wildcrafting of mushrooms and other NTFPs does occur	• Emerging sector • Demonstrations, pilots, and applied research projects established and being developed • Practitioner interest in and adoption of all practices • Approaches evolving from integration of resource management practices on public lands, and as a means of economic diversification and approach to environmental stewardship on both public and private lands • Driven by partnerships among producer and industry associations, First Nations, academic institutions, nongovernmental organizations (NGOs), and municipal, provincial, and federal government agencies
• Economics of tree-based systems is not well examined • No adequate policy measures to recognize the environmental goods and services (e.g., no tax incentives or cost-share programs) • Lack of developed -awareness/ training program for farmers and inadequate marketing network	• While general concern for the environment increases, larger farm size and more farming of rented land may reduce interest in agroforestry • Climate change may affect the performance of current plant materials • Major focus on water quality and climate change requires more agroforestry research on systems that address those issues	• Mountain pine beetle epidemic – landscape-scale impacts • Complex regulatory and management framework • Lack of regional production and economic information • Labor availability • Developing new market channels and know-how

(continued)

Table 3 (continued)

	Atlantic Provinces[a]	Québec
Future potential	• Emerging renewable energy sector could have positive implications for agroforestry both in terms of displacing fossil fuels on farms as well as generating new income streams	• Establishment of a Futures Market for wood • Creation of a cap and trade C market • Creation of incentive programs recognizing the public value of ecological goods and services provided by agroforestry systems

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[a] Population and agricultural and forestry land-use statistics for the Atlantic Provinces and the Prairies Provinces were obtained from the Statistics Canada website: http://www.statcan.gc.ca/start-debut-eng.html

[b] Quick Facts About British Columbia (2010) Edition http://www.bcstats.gov.bc.ca/data/bcfacts.asp. Accessed 8 Sept 2011

[c] Agricultural Land Commission http://www.alc.gov.bc.ca/index.htm. Accessed 9 Sept 2011

[d] Agroforestry Statistics http://www.omafra.gov.on.ca/english/crops/facts/info_statistics.htm. Accessed 9 Sept 2011

Ontario	Prairie Provinces[a]	British Columbia
Adoption of agroforestry systems for: • Production of high-quality biomass for bioenergy • Greenhouse gas mitigation (e.g., N_2O) • Environmental goods and services	• Better organization and stability of local conservation organizations provide for improved flow of information and services to landowners • International efforts to combat climate change (the Global Research Alliance) provides -opportunities to increase agroforestry knowledge • Interest in woody biomass for bioenergy or for carbon -sequestration may increase if economics become attractive • The large prairie land area make it feasible to adopt agroforestry on a large scale if the economics are attractive for producers	• Growing awareness of environmental stewardship. Adoption of agroforestry approaches which complement other stewardship initiatives • Adoption of agroforestry approaches which supplement conventional production and help diversify local economies • Partnership and collaboration among government agencies, First Nations, industry, producers, academics, NGOs, and resource sector stakeholders • Focal areas for developmental activities (sector feedback, Powell 2009): partnerships, demonstration, developing the business case, improving market connections, awareness and extension, and policy/regulation initiatives

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Past, Present and Future of Agroforestry Systems in Europe

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Abstract Many traditional land-use systems in Europe involved agroforestry in the pre-industrial era, but, over the years, increased mechanization led to the development of increasingly specialized crop, animal and wood production systems. As a consequence, the area under agroforestry declined in many regions of Europe, and agroforestry systems became confined to situations where understorey primary production is restricted due to cold temperatures (Boreal and Alpine areas) or drought (Mediterranean areas) and to plots that are hard to reach or too small for cultivation with modern machinery, as in Spain, Italy and the lower altitude mountain regions

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in southern and central Germany. On the whole, agroforestry continued to be practised only where it enabled farmers to obtain economic returns from lands that were otherwise relatively unproductive and mostly limited to silvopastoral practices. Since the mid-1990s, however, European policies have encouraged land management systems that combine production, environmental services (biodiversity, carbon sequestration, nutrient cycling and water quality) and social benefits, and this has created a new interest in agroforestry systems. Today, the major agroforestry practices in Europe include silvopasture and silvoarable. However, the benefits and opportunities offered by agroforestry can only be realized with substantial investments and coordinated efforts in research, education, knowledge transfer and appropriate national policies across Europe.

Keywords Environmental services • Silvoarable • Silvopasture • Policy

History of Agroforestry Systems in Europe

Land cultivation and the management of domestic animals started and rapidly spread across Europe in the Neolithic period (Pinhasi et al. 2005). During this period, the production of agricultural products in Europe was often based on forested land. This dependence was based on the use of the enhanced soil fertility immediately after forest clearing and the increased light availability for crops after tree thinning (Pinhasi et al. 2005). Further, manure from animals raised in woodlands was used to transfer nutrients to agricultural land and increase crop production (Castro 2009). In France, a recent study has concluded that using trees as fodder for ruminants was already practised in Neolithic times (Thiébault 2005); the author suggests that certain species such as ash (*Fraxinus* spp.) and deciduous oaks (*Quercus* spp.) were selected and their fodder gathered to feed animals during the seasons with lower pasture availability. Bergmeier et al. (2010) report that silvopastoral systems (the combination of trees with livestock) started 7,500 years ago in southeastern and central Europe, 6,000 years ago in Britain, north-western Germany and Denmark and 4,000 years ago in the Baltic and the Scandinavian countries. Agroforestry

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Table 1 Agroforestry practices in Europe

Agroforestry practice	Brief description
Silvoarable agroforestry	Widely spaced trees intercropped with annual or perennial crops. It comprises alley cropping, scattered trees and line belts
Forest farming	Forested areas used for production or harvest of natural standing specialty crops for medicinal, ornamental or culinary uses
Riparian buffer strips	Strips of perennial vegetation (tree/shrub/grass) natural or planted between croplands/pastures and water sources such as streams, lakes, wetlands and ponds to protect water quality
Improved fallow	Fast-growing, preferably leguminous woody species planted during the fallow phase of shifting cultivation; the woody species improve soil fertility and may yield economic products
Multipurpose trees	Fruit and other trees randomly or systematically planted in cropland or pasture for the purpose of providing fruit, fuelwood, fodder and timber, amongst other services, on farms and rangelands
Silvopasture	Combining trees with forage and animal production. It comprises forest or woodland grazing and open forest trees

Source: Modified from AFTA, Association for Temperate Agroforestry (AFTA 1997); Alavalapati and Nair (2001); Nair (1994), Alavapati et al. (2004); Mosquera-Losada et al. (2009a, b)

systems (AFS) have been recorded from about 4,500 years ago in the south-west of the Iberian Peninsula (Stevenson and Harrison 1992). The presence of livestock in olive (*Olea europaea* L.) and orange (*Citrus sinensis* (L.) Osbeck) groves was common in Roman times, and references to intercropping crops in olive and fig (*Ficus carica* L.) groves are found in the Bible (Nair 1993).

The interaction between forestry and farming on the same plot of land was either based on the simultaneous combination of woody plants and (a) pasture or a crop (or crops) or (b) on the rotation in time of the woody and the crop components of the system. The modification in the microclimatic conditions generally produced by agroforestry (milder radiation, temperature and dryness) meant that these integrated systems were more suitable for the southern part of Europe. This may be one of the reasons why the number of extant agroforestry systems is more prominent in the Mediterranean biogeographic region of Europe than in more northerly regions (Tables 1 and 2) (Papanastasis et al. 2009; Pardini et al. 2009). The long summer drought period found in the Mediterranean area results in little tree growth and unreliable crop production, so pastoralism has always been the predominant land use. Animals managed in a traditional way on these lands graze stubble and the rough vegetation of forests and agrarian land. Stocking rates can be adjusted to match seasonal forage availability, and this is easier with smaller ruminants such as sheep or goats than with cattle due to the small size of the former (Pardini 2009). Moreover, cows eat pasture by pulling up the plant and sometimes the roots with their tong. On the contrary, goats and sheep cut the grass due to their specific mouth morphology (Mosquera-Losada et al. 1999). Therefore, goats or sheep are preferred to cows that cause bare patches on ground that are more difficult to regenerate in the Mediterranean than in more humid environments. Consequently, in Mediterranean systems, pastoralism is actually the main link between the agricultural and forestry

Table 2 Conifer tree species in stands where agroforestry practices were cited and percentage of each tree species in the European Union

Tree genera and species		European biogeographic regions							
		Med	Atl	Alp	Pan	Con	Art	Mac	Total area (%)
Abies	*A. alba* Mill.	X		X					1.6
	A. borisii-regis Mattf.	X							<0.2
	A. cephalonica Loud.	X							0.2
Cupressus	*C. sempervirens* L.	X						X	<0.2
Juniperus	*J. sabina* L.	X							<0.2
	J. communis L.	X							<0.2
	J. thurifera L.	X							<0.2
Larix	*L. decidua* Mill.			X					0.8
	L. kaempferi (Lam.) Carr.	X							<0.2
Picea	*P. abies* (L.) H. Karst.			X					21
Pinus	*P. brutia* Ten.	X						X	<0.2
	P. halepensis Mill.	X							1.2
	P. leucodermis Ant.	X							<0.2
	P. nigra J.F. Arnold	X		X	X				1.8
	P. pinaster Aiton	X							2.5
	P. pinea L.	X							0.2
	P. radiata D. Don		X						<0.2
	P. sylvestris L.	X	X	X		X	X		31
	P. uncinata Raymond ex DC. In Lam & DC.	X							0.4
Pseudotsuga	*P. menziesii* (Mirb.) Franco		X						<0.2

Source: Köble and Seufert (2011)

Med Mediterranean, *Atl* Atlantic, *Alp* Alpine, *Pan* Pannonian, *Con* Continental, *Art* Artic, *Mac* Macaronesian resources (Papanastasis et al. 2009). The modification of microclimatic conditions by the tree, such as the higher temperatures found under trees than in open areas in the coldest areas of Europe, may be one of the reasons why the combination of trees and pasture is currently used in alpine areas, both in mountains and in northern European countries (Rigueiro-Rodríguez et al. 2010b). It should also be noted, however, that some important AFS, such as pig farms using oak forests in Germany, originate from animal rearing based on tree resources in the medieval times (Luick 2009).

The need to use forests as a source of nutrients to maintain soil fertility on agricultural land was reduced in the 1930s with the manufacture of mineral fertilizers and their subsequent use across Europe (Isherwood 2000). This was also associated with increased mechanization on arable land, a reduced need for labour and a general increase in the quality of life for farmers (Angus et al. 2009). During the twentieth century, the increase in population and associated need for food generally led to an increase in the arable area (Angus et al. 2009). In many areas, the presence of widely spaced trees in cropland was seen as a hindrance because of the reduced crop area and increased difficulty for mechanization. The EU Common Agricultural Policy (CAP) until the early 1990s placed no emphasis on the environmental benefits of integrated tree and agricultural systems and farmers maximized their agricultural subsidies by maximizing the cropped area on their farms (Graves et al. 2009). The reduction in the practice of agroforestry was also a consequence of re-parcelling and land consolidation programmes carried out in most of the regions during the twentieth century. These measures effectively eliminated thousands of kilometres of tree and bush lines in Europe (Miguel et al. 2000). However, the reduction of forested area was less important in Mediterranean countries, where the use of fertilizers in rain-fed cropland is less profitable. An EU research project dealing with AFS concluded that loss of many traditional agroforestry systems in Europe had unfortunate consequences: loss of the knowledge base amongst farmers, simplification and standardization of landscapes, increased environmental problems such as soil erosion and water pollution, significant carbon release, reduction of biodiversity, loss of habitat for natural enemies of crop pests and the loss of a source of alternative income for farmers (Dupraz et al. 2005).

Since the 1992 reform of the CAP, the EU governments have increasingly valued the multiple services provided by forest and agricultural lands and provided incentives to increase the amount of woodland on agricultural land. Indeed, there has been a 7 % increase in the area under forest (trees) in the EU since 1990 (FAO 2011). In some instances, this has led to a reduction in agroforestry areas due to land abandonment (Garbarino et al. 2011). European policies have focused on objectives such as biodiversity conservation, improved water quality, increased carbon sequestration and soil, water and nutrient conservation, which are valued by European citizens (Eurobarometer 2008) – the very same issues that could be addressed by the promotion of AFS. Further, AFS can reduce fire risk in forest areas and promote carbon sequestration compared with exclusive arable monocultures (Nair et al. 2009, 2010; Mosquera-Losada et al. 2011b).

Current Status of Agroforestry Systems in Europe

Most of the agroforestry systems practised globally – silvoarable, forest farming, riparian buffer strips, improved fallow, multipurpose trees and silvopasture (Nair 1994; AFTA 1997; Alavalapati and Nair 2001; Alavalapati et al. 2004) – can also be found in Europe (Mosquera-Losada et al. 2009a, b) and are detailed in Table 1.

The Tree Component

Current agroforestry practices in Europe are based on a relatively narrow range of dominant tree species (Tables 2 and 3). Most of them are broad-leaved (74 %) and are found in Mediterranean environments (71 %). Indeed, oaks are the predominant tree species in current European agroforestry systems (17 species) and are particularly common in the Mediterranean. In Spain, *Quercus ilex* L. and *Q. suber* L. are the most widely found; in Greece, *Q. humilis* Mill., *Q. frainetto* Ten., *Q. coccifera* L. and *Q. trojana* Webb; and, in Italy, *Q. cerris* L., *Q. humilis* Mill. and *Q. suber* L. (Dupraz et al. 2005; Pardini 2009; Papanastasis et al. 2009). The coniferous agroforestry tree species are commonly found in the high altitudes of the Mediterranean mountains, where almost all systems are silvopastoral with coniferous species such as pines (*Pinus nigra* Arn. and *P. sylvestris* L.), junipers (*Juniperus communis* L. and *J. sabina* L.) and firs (*Abies cephalonica* Loud. and *A.* x *borisii-regis* Mattf.). Pines such as *P. halepensis* Mill. and *P. brutia* Ten. on the coast of Greece*, P. pinaster* Aiton on the coast of Italy and *P. pinea* L. and *Cupressus sempervirens* L. on the inlands of Italy are also broadly used in silvopastoral systems in the lowland Mediterranean area (Papanastasis 2004; Papanastasis et al. 2009; Pardini et al. 2009).

Agroforestry Practices in Europe

Dehesa (in Spain) or montados (as they are called in Portugal) are the most important broad-leaved agroforestry systems in Europe (Fig. 1). They occupy an estimated 3.1 million ha in the southwestern part of the Iberian Peninsula (Moreno and Pulido 2009). The most common species of oaks in this system are *Q. ilex* and *Q. suber* and to a lesser extent, deciduous oaks like *Q. faginea* Lam. and *Q. pyrenaica* Willd.; these species are appreciated because of the value of their acorns as food resource for animals grazing underneath. The structure, function, management and persistence of the dehesa system have been reviewed thoroughly by Moreno and Pulido (2009).

By contrast, reindeer husbandry systems based on forest understorey resources in Finland, Norway and Sweden extend to 41.4 million ha and occupy 33 %, 34 % and 40 % of the total area of these countries, respectively (Jernsletten and Klokov 2002). Reindeer feed on the lichens growing in the understorey in northern forests,

Table 3 Broad-leaved tree species in stands where agroforestry practices were cited and percentage of each tree species in the European Union

Tree genera and species		European biogeographic regions							
		Med	Atl	Alp	Pan	Con	Art	Mac	Total area (%)
Acer	*A. campestre* L.	X							<0.2
	A. negundo L.				X				<0.2
	A. pseudoplatanus L.			X	X				<0.2
Alnus	*A. cordata* (Loisel.) Duby		X						<0.2
Betula pubescens	*B. pubescens* Ehrh.	X	X						5.0
Castanea	*C. sativa* Mill.	X	X						1.1
Celtis	*C. australis* L.	X							<0.2
	*C. occidentalis*L.				X				<0.2
Ceratonia	*C. siliqua* L.	X						X	<0.2
Corylus	*C. avellana* L.	X	X		X				<0.2
Cydonia	*C. oblonga* Mill.								<0.2
Eucalyptus	*E. globulus* Labill.		X						<0.2
	Eucalyptus spp.								0.9
Fagus	*F. sylvatica* L.	X	X	X					7.1
Ficus	*F. carica* L.	X						X	<0.2
Fraxinus	*F. excelsior* L.	X	X			X			0.6
Juglans	*J. regia* L.		X	X					<0.2
	J. nigra x J. regia		X						<0.2
Malus	*M. communis* f. mitis (Wallr.) Gams in Hegi	X							<0.2
Morus	*M. alba* L.	X							<0.2

(continued)

Table 3 (continued)

Tree genera and species		European biogeographic regions							
		Med	Atl	Alp	Pan	Con	Art	Mac	Total area (%)
Quercus	*Q. calliprinos* Webb	X							<0.2
	Q. canariensis Willd.	X							<0.2
	Q. cerris L.	X							1.0
	Q. coccifera L.	X						X	0.2
	Q. faginea Lam.	X	X						0.2
	Q. frainetto Ten.	X							0.7
	Q. humilis Mill.	X							1.8
	Q. ilex L.	X							2.2
	Q. macrolepis Kotschy	X						X	<0.2
	Q. lusitanica Lam.	X							<0.2
	Q. petraea (Matt.) Liebl	X			X	X			2.2
	Q. pyrenaica Willd.	X							0.7
	Q. robur L.		X						3.0
	Q. rotundifolia Lam.	X							0.2
	Q. suber L.	X							0.9
	Q. trojana Webb	X							<0.2
	Q. rubra L.		X						<0.2
Olea	*O. europaea* L.	X						X	<0.2
Pyrus	*P. amygdaliformis* Vill.	X							<0.2
	P. communis L.	X							<0.2
Populus	*P. alba*L.				X				<0.2
	Populus spp. (clones de chopos híbridos)	X	X						<0.2
	P. nigra L.				X				<0.2
	Populusnigra L. subsp. *thevestina* (Dode) Maire	X							<0.2

Prunus	*P. dulcis* Mill.	X						X	<0.2
	P. armeniaca L.	X							<0.2
	P. avium L.	X	X		X				<0.2
	P. domestica L.	X							<0.2
	P. persica (L.) Batsch	X							<0.2
	P. serotina Ehrh.				X				<0.2
Robinia	*R. pseudacacia* L.	X			X			X	0.5
Sorbus	*S. aria* (L.) Crantz			X	X				<0.2
	S. aucuparia L.			X	X				<0.2
	S. torminalis (L.) Crantz				X				<0.2
Tilia	*Tilia* spp.				X				0.2
Ulmus	*U. minor* Mill.	X							<0.2
	U. glabra Huds.			X					<0.2

Source: Köble and Seufert (2011)

Med Mediterranean, *Atl* Atlantic, *Alp* Alpine, *Pan* Pannonian, *Con* Continental, *Art* Artic, *Mac* Macaronesian

Fig. 1 A typical dehesa with ~80-year-old scattered holm oaks (*Quercus ilex* L.), in a stand density of ~40 trees ha^{-1}, and a native understorey of annual pasture in northern Extremadura, Spain. Pasture is permanently grazed by native breed of cows (Retinta) and bulls (Blanco cacereño) (Photo credit: Gerardo Moreno)

mainly under *Pinus sylvestris* and *Picea abie*s (L.) H. Karst. (Jernsletten and Klokov 2002). Agroforestry systems based on *Pinus sylvestris* occur in most European agroclimatic regions, mainly because of the widespread distribution of the species – 31 % of 30 European Union countries' (Finland, Sweden, Norway, Denmark, the Netherlands, Luxembourg, Belgian, Ireland, the United Kingdom, Estonia, Latvia, Lithuania, Belarus, Poland, Moldova, Romania, Bulgaria, Czech Republic, Slovakia, Hungary, Austria, Croatia, Slovenia, Germany, Italy, France, Spain, Portugal, Greece, Switzerland) forested area is under *P. sylvestris,* followed by 21 % under *Picea abies* (Köble and Seufert 2011).

Papanastasis et al. (2009) described 40 prominent silvoarable and silvopastoral systems in Greece. The most common systems include walnut (*Juglans regia* L.), almond (*Prunus dulcis* (Mill.) Webb), mulberry (*Morus alba* L.) and poplars (*Populus nigra* L. subsp. *thevestina* (Dode) Maire), olive (*Olea europaea*), carob (*Ceratonia siliqua* L.) and fig (*Ficus carica* L.) with associated crops such as maize (*Zea mays* L.) and other cereals, tobacco (*Nicotiana tabacum* L.), vines, vegetables and various forage crops (mainly lucerne (*Medicago sativa* L.)). Those systems that involve cereal crops often become agrosilvopastoral as livestock graze the stubble after grain harvest (Yiakoulaki et al. 2005; Correal et al. 2009).

In the UK, the most promising new AFS are those where trees have a particularly high value, for example, orchard intercropping systems, or the presence of trees provides animal welfare and marketing benefits, for example, "woodland eggs" from free-range hens roaming under trees.[1] Woodland grazing systems are also being encouraged within existing forests to increase understorey diversity and the regeneration of some tree species. Parkland systems, involving widely spaced broad-leaved trees in grazed pasture, are also widely valued for their landscape, biodiversity and cultural value (Isted 2006). Other systems where the trees, and crops and animals are less closely mixed include shelterbelts to provide wind protection to animals and crops, tree belts to capture ammonia from intensive pig and poultry units, and riparian planting (Hislop and Claridge 2000; McAdam 2006). The widespread traditional practice of surrounding fields with hedges including trees also results in an "agroforestry landscape." Lastly, the increased planting of perennial crops (other than just grass) in the UK (e.g. *Miscanthus*, short rotation coppice, vines and even tea) also provides farmers with more opportunities than a simple divide amongst annual arable crops, grasslands and perennial woodland systems (Lawson et al. 2011).

In Germany, the best-known extant agroforestry systems are "open orchards" (Reeg 2011). However, alley cropping agroforestry practices with fast-growing tree species such as poplar (*Populus* spp.), willow (*Salix* spp.) and black locust (*Robinia pseudoacacia* L.) treated as short rotation coppices (SRC) are currently recommended for biomass production, as they improve the use of resources and biodiversity levels compared to traditional agrarian practices (Grünewald et al. 2007; Quinkenstein et al. 2009). In recent years, many scientific as well as practical efforts have been made to promote "modern agroforestry" for its ecological benefits and to obtain higher-value wood products (e.g. veneer), especially in the southern part of Germany (Bender et al. 2009; Reeg et al. 2009). In the past, line belts were also very important in northern Europe, but since the end of the 1960s, they have been reduced by 40–80 % (Herzog 2000). Shelterbelts, windbreaks and forest belts are currently used in Hungary to protect crops and livestock from adverse factors such as strong winds (Takács and Frank 2009).

Silvopastoral practices, which include forest or woodland grazing (Fig. 2) and open forest areas, are the most important AFS in Europe; these include the before-mentioned dehesas and reindeer husbandry in coniferous forests (Mosquera-Losada et al. 2009a, b). Forest farming, which includes the production of natural or cultivated special crops for medicinal, ornamental or culinary uses, is an important type of AFS when the significant economic returns are taken into account. However, most of the harvesting practices of these non-timber products (mushrooms, medicinal plants, truffles, berries, etc.) are not controlled. European black truffle (*T. nigrum* Bull.) production systems are exclusively found in holm oak (*Quercus ilex*), downy oak (*Quercus humilis*) and hazel (*Corylus avellana* L.) forests of Spain, Greece and Italy and have been recently described by Reyna-Domenech and García-Barreda (2009). Riparian buffer strips (strips of perennial vegetation (tree/shrub/grass) between croplands/pastures and water sources to protect water quality) can be found in most of the countries of Europe, whereas improved fallow (fast-growing, preferably

Fig. 2 A silvopasture practice at Lugo, Spain. Radiate pine (*Pinus radiata*) planted in 1970 at 3.5 m × 3.5 m spacing (photo 2005) at a density of 800 trees ha^{-1}. Horse authocthonous breed: Cabalo Galego de Monte. The understorey is mainly gorse (*Ulex europaeus*) (Photo credit: José Javier Santiago-Freijanes)

leguminous woody species planted during the fallow phase of shifting cultivation) is less common (Mosquera-Losada et al. 2009a, b). Multipurpose trees are nowadays mainly managed for the production of fruits such as *Quercus* spp. acorns or chestnut (*Castanea sativa* Mill.), which are of great use to feed pigs (Moreno and Pulido 2009; Mosquera-Losada et al. 2009a, b; Papanastasis et al. 2009).

Production Benefits

The principal objectives of agroforestry practices vary across Europe. In Mediterranean countries, the focus was on improving production up to the 1970s and then slowly incorporated environmental benefits (Pardini 2009; Rigueiro-Rodríguez et al. 2009). Profitability depends on the outputs that agroforestry systems provide and the value given by society to all of their products in a given period of time (Campos et al. 2010). For example, up until the 1960s, *Q. suber* (cork) dehesas were less valued than *Q. ilex* dehesas because cork was not marketed and the nutritive value of cork acorns is lower than those of *Q. ilex* (Rodríguez-Estévez et al. 2007). However, since around the 1980s, the importance of cork products has raised the economic value of *Q. suber* over *Q. ilex* dehesas. In some cases, like in silvopastoral system shaped by ash trees or other riparian trees planted in lines or scattered through, the timber harvest from the trees acts as an insurance for the owner as it can generate additional income (Castro 2009). Also, in the chestnut orchards or coppice systems, mushroom production increases the income from the system. The increased productivity associated with Mediterranean agroforestry is usually focused on the tree component providing animal feed (fruits and leaves) during drought or timber, firewood, charcoal and cork (from *Q. suber*). The marketability and profitability of some of these products is increased by using niche labelling (e.g. organic) or through associated activities such as rural tourism, especially farm tourism and on-farm game hunting (Pinto-Correia and Mascarenhas 1999; San Miguel-Ayanz 2006; Pardini 2009; Campos et al. 2010). Currently, many marginal farms survive by generating income from services related to environmental conservation which are funded and promoted by the EU and national policies (especially biodiversity conservation, soil protection via erosion control and forest fire prevention). The land-use focus has shifted to a multifunctionality of land uses. This increased focus on nature and landscape conservation also creates new opportunities for income generation from these systems (Palma et al. 2007; Castro 2009).

The long rotation period for trees in AFS means that estimates of the financial value of such systems must usually be based on models (Graves et al. 2005, 2011). Such models require simulation of the interactions of tree and understorey yields (van der Werf et al. 2007). In a silvopastoral system model, ash (*Fraxinus excelsior* L.) growing in lowland UK (Fig. 3) gave an increment of 15 % of the net present value when compared with treeless pastures (Sibbald 1996). The use of an AFS instead of either a conventional forestry system or a livestock grazing increased profitability around 53 % and 17 %, respectively, in a model for *Pinus radiata* D. Don stands (Fernández-Núñez et al. 2007). McAdam et al. (1999a) and Thomas and Willis (2000) found that under a range of changes in commodity prices (food and timber) and agricultural subsidy support, silvopasture (ash at 400 stems per ha) had a net benefit over agriculture (sheep grazing) ranging from 34 % (food prices constant, 1 % increase in timber price, 25 % reduction in grazing over 10 years) to 181 % (food prices down 2 %, timber prices up 2 %).

From 2001 to 2005, the Silvoarable Agroforestry for Europe (SAFE) project (Graves et al. 2007) developed a system to evaluate the biophysical and economic performance of arable, forestry and silvoarable systems in Spain, France and the Netherlands. Results showed that growing trees and crops in silvoarable systems was more productive than growing them separately (Borrell et al. 2005; Graves et al. 2007; Palma et al. 2007). Conditions that are favourable for high profitability appeared to include the use of relatively high tree densities to make full use of available resources, the use of deciduous trees and autumn-planted crops to make complementary use of light and high soil water availability to ensure that extra biomass production could be sustained. The financial predictions indicated that silvoarable systems (Fig. 4) were most attractive where both components of the system were profitable as monocultures, since an unprofitable, or relatively unprofitable component, also reduced the profitability of the mixed system.

Fig. 3 A pasture of mainly perennial ryegrass (*Lolium perenne*) under ash trees (*Fraxinus excelsior*) planted in 1989 (photo 2005) at a spacing 5 m×5 m and stand density of 400 trees ha^{-1} in AFBI Loughgall, N. Ireland. Sheep breed: Wicklow cheviot X (Photo credit: Rodrigo Olave)

Fig. 4 A silvoarable practice at Les Eduts, France. Walnut tree (*Juglans nigra*) planted in 1978 (photo 2007) at a density of 70 trees ha^{-1} (spacing 14 m×10 m); the arable crop is wheat (*Triticum aestivum*) (Photo credit: Fabien Liagre)

Profitability was maximized with the use of high-value trees such as walnut or short rotation trees such as poplar. It was also predicted that holm oak and stone pine (*Pinus pinea*) silvoarable systems would cause only small reductions in crop yields, relative to those in arable systems. Since these trees (oaks) are of ecological and landscape importance, for example, in areas of open woodlands (dehesas), rather than of timber production importance, additional support in the form of an agri-environment payment could be justified as for those systems with high productive trees like walnut and poplar in France. By contrast, agroforestry systems were relatively unattractive in the Netherlands, based on assumptions of a low value for timber and the particularly high returns obtained from arable land.

Environmental Benefits

Environmental benefits of AFS comprise their positive impact on biodiversity, nutrient cycling (McAdam 2000; McAdam and McEvoy 2009; Rois-Díaz et al. 2006; Moreno and Pulido 2009; Rigueiro-Rodríguez et al. 2010b; Dupraz et al. 2005), water quality and carbon sequestration (Dupraz et al. 2005; Mosquera-Losada et al. 2011b).

Biodiversity

Biodiversity is conserved and generally enhanced in AFS, compared to conventional agricultural systems (Tuupanen et al. 1997; Rigueiro-Rodríguez et al. 2010b), and in some cases, biodiversity levels are greater than in both agricultural and woodland systems (McAdam et al. 1999b). Biodiversity is modified as a result of establishing an agroforestry system, which creates an ecosystem where biodiversity depends on the initial soil conditions (Mosquera-Losada et al. 2009a, b), tree species (conifer vs. broad-leaved) and the planting density (Rigueiro-Rodríguez et al. 2010a). At a plot scale, the presence of a tree creates heterogeneity in ecological factors such as radiation, humidity and temperature, and this creates different microhabitats for plant and animal species (Rigueiro-Rodríguez et al. 2010b).

Dehesas are considered one of the most biodiverse ecosystems in Europe (Moreno and Pulido 2009), and the implementation of proper agroforestry practices could maintain this biodiversity (Díaz et al. 1997). In these systems, the rotation of arable and pasture crops under the trees promotes annual species to grow, and this helps explain this high diversity. This heterogeneity is not found in exclusive agronomic systems where uniformity is encouraged or traditional forest systems where there is a full canopy cover. The presence of different animal species in silvopastoral systems or silvoarable systems that use the stubble to feed animals causes disturbances, which usually increase biodiversity (Buttler et al. 2009).

Afforestation with fast-growing coniferous tree species instead of broad-leaves planted at a high density on former agricultural land causes a clear reduction in cover and number of pasture species. Biodiversity reduction is mainly explained by the rapid light reduction and the development of a thick layer of needles caused by the natural pruning process of the tree branches due to the lack of light (Rigueiro-Rodríguez et al. 2010a). Short rotation coppice taken as a component of an agroforestry system might increase animal diversity when compared with arable land by enhancing the structural richness, especially in cleared agricultural landscapes (Schulz et al. 2009).

The importance of agroforestry for biodiversity conservation is also associated with the landscapes and the practices linked to their management. For example, transhumance, the seasonal movement of animals from lowlands to highlands and vice versa, is a traditional practice in Mediterranean Europe and is very important for biodiversity (Bunce et al. 2009). It acts as an ecological connection between lowlands and highlands, but it also connects open and wooded areas placed at short distances along the corridors or paths along which animals are shepherded. In Italy, any remaining transhumance is now performed using trucks to transport the animals, and it is still in use so as to maintain the natural diversity and floristic attraction of pastures in places where tourism is important, such as in the Alps (Staglianò et al. 2000). In Greece, special silvopastoral habitats are created along these corridors characterized by pruned oak trees; the branches of these trees are used for feeding animals or building temporary huts for sheltering shepherds and their families (Ispikoudis et al. 2004; Papanastasis et al. 2009).

Nowadays, the destruction of some bird habitats due to the reduction of forests could be overcome to a certain extent if scattered trees were established between those smaller forests and planted at a minimal distance that allows those forests to be connected to one another. This is particularly important in those countries with a small forest area such as in the central Atlantic biogeographic region of Europe. In the United Kingdom, agroforestry harbours greater bird diversity than forested areas (Toal and McAdam 1995; Burgess 1999). Bergmeier et al. (2010) state that silvopastures are a “habitat of importance” for at least 37 European bird species, while for another 18 species, a high proportion of their European populations use this habitat too. A high number of the threatened and red-listed vascular plant species in central Europe are associated with silvopastoral areas (Bergmeier et al. 2010). While most of these species can be found in thermophilous woodland habitats in southern Europe, they are mainly found in silvopastoral habitats of northern Europe (Bergmeier et al. 2010). In the United Kingdom, arthropod biodiversity including beetles, spiders and snails was higher in silvopastoral and silvoarable systems than in open grassland (Peng et al. 1993; Cuthbertson and McAdam 1996; Dennis et al. 1996; McAdam et al. 1997).

Agroforestry systems are also linked to the use of marginal lands to which indigenous livestock breeds are adapted and where very productive and resource-demanding breeds are not so profitable. This is highly relevant as Europe holds around half of the world’s livestock breeds, and half of them are endangered (Mosquera-Losada et al. 2005).

Nutrient Cycling and Water Quality

Temperate AFS generally result in greater nutrient cycling than pure agricultural crops because the leached nutrients from the crop rhizosphere layer can be captured by the deeper roots of trees once the crops are not able to take them up due to excess of inputs or the lack of crop growth (Lehmann 2001; Reisner et al. 2007; Bambo et al. 2009; Rigueiro-Rodríguez et al. 2009; Dupraz et al. 2005). In addition, these nutrients are made available again for crops once tree leaves fall down on the soil as leaf litter. This explains why soil fertility is higher below than at a distance from trees in agroforestry (Moreno and Pulido 2009). Moreno et al. (2007) described how nitrogen (N), phosphorus (P), cation exchange capacity and exchangeable calcium (Ca^{2+}) and potassium (K^+) levels were increased near the trees in a dehesa system. The importance of this better nutrient use and recycling is clear: nutrients are not lost from the system thus avoiding reduction of soil fertility and potential contamination of watercourses.

Nitrate leaching into water bodies can cause eutrophication problems in rivers and seas, and it is regulated in Europe by the Nitrates Directive (Council Directive 91/676/EEC). Computer models have suggested that agroforestry (compared to agriculture) can reduce nitrate leaching in the Atlantic region of Europe, whereas the effect in rain-fed Mediterranean areas is limited (Palma et al. 2007). Moreover, nitrate leaching was reduced in sandy soils when a mixture of sweet cherry (*Prunus avium* L.) and pasture was developed in an irrigated sandy soil in a Mediterranean environment (López-Díaz et al. 2011). Silvoarable systems in a wheat (*Triticum aestivum* L.) intercropping experiment were also found to reduce nitrate leaching in the UK (Nichols et al. 2000). In Switzerland, agroforestry experiments established on fertile arable land showed that nitrate leaching could be reduced by 46 % over that from an arable crop alone (Kaeser et al. 2011). However, no nitrate reduction was found in newly established plantations (Mosquera-Losada et al. 2010) where trees were too young and had not developed enough to explore deeper soil layers. Agroforestry has also been shown to decrease soil erosion losses and the associated loss of P (Correal et al. 2009). In soils with low P-soil retention, silvopastoral (Nair et al. 2007) and alley cropping (Allen et al. 2006) practices were found to reduce phosphorus losses in sandy soils of Florida, USA.

Carbon Sequestration

Compared to treeless systems, agroforestry is able to sequester more carbon due to the tree component which is able to store it in wood and reach deeper soil layers and higher aerial height than arable crops, as found in silvopastoral and alley cropping agroforestry practices (Howlett et al. 2011; Mosquera-Losada et al. 2011b). Cultivation of perennial woody plants to produce biomass in alley cropping contributes significantly to carbon sequestration within the soil because it supports the formation of soil humus. Moreover, the produced biomass can be used to replace fossil energy resources that further increase the utility of alley cropping in mitigating the effects of climate change (Quinkenstein et al. 2009).

The importance of AFS in the total world carbon balance system is twofold: first, the already established AFS have a large reserve of carbon that should be maintained by the preservation of these systems, and, in some dry environments (Mediterranean), shrub colonization will be promoted, fire risk will be increased and large amounts of carbon will be released to the atmosphere (Moreno and Pulido 2009); second, the establishment of AFS on cropland as a way of land-use change will increase the carbon sequestered by terrestrial ecosystems and, therefore, will help fulfil the Kyoto requirements to mitigate climate change (Nair et al. 2010). The capacity of an AFS to sequester carbon should be related to the increase of soil carbon sequestered, as this component has the largest proportion of carbon within the terrestrial systems. Carbon sequestration in agroforestry will be promoted, not only by the roots colonizing deeper soil layers but also by the litter fall and deposition of senescent materials on the soil, which will act also as a carbon resource (Fernández-Núñez et al. 2010). The dynamics of soil carbon, as affected by microenvironmental conditions created by scattered trees, which in turn depends on the light interception by each specific tree species and by the growth rate of the tree, should be further studied (Mosquera-Losada et al. 2011b). In general, silvoarable practices are able to sequester less carbon in the upper soil layers when compared with silvopastoral or alley cropping practices with perennial crops in the same edaphoclimatic conditions due to accelerated decomposition of soil organic matter following soil tillage done as a soil management practice for crop production (Nair 2012).

Future Prospects of Agroforestry Systems in Europe

Indications from Recent Research Initiatives

The potential of agroforestry systems to deliver economic, environmental and social benefits in Europe has been demonstrated by national research programmes (e.g. McAdam et al. 1999a, b; Sibbald et al. 2001; Burgess et al. 2003, 2005; Mosquera-Losada et al. 2010) and EU research projects (Dupraz et al. 2005). There are also informal networks of scientists and growers across Europe, for example, the Farm Woodland Forum in the UK[2] (http://www.agroforestry.ac.uk), and the French Agroforestry Association[3] (http://www.agroforesterie.fr/). In Spain, the Spanish Grassland Society and the Spanish Forestry Society both have agroforestry working groups. A European Agroforestry Federation based in France has recently been created to coordinate national initiatives and influence European policies. In Greece, an agroforestry network was established in 2006. In Germany, a project called "agroforestry"[4] launched in 2005 and lasting 3 years was the first recent effort at applying the concepts of agroforestry as an approach to land use as an alternative to the spatially segregated practices of forestry and agriculture (Bender et al. 2009).

As has been demonstrated, AFS are generally more productive than treeless land-use systems (Dupraz et al. 2005; Rigueiro-Rodríguez et al. 2009). However, the importance of this fact depends on edaphoclimatic conditions and the proper choice of the species and planting configuration of the tree species as well as the understorey component. Once the tree is established, aspects related to pruning and thinning should be taken into account in order to promote understorey production and concentrate growth on individual trees (instead of volume per hectare) to deliver high-quality wood. On the other hand, there is also a need to study agroforestry system implementation in dense forest stands, as this could be a way of reducing forest fire risk in southern Europe and of avoiding costly clearing operations throughout Europe and at the same time generating additional income (wool, milk, mushrooms, etc.).

All these aspects should be evaluated for different types of trees and edaphoclimatic environments for new forms of agroforestry. Research in agroforestry system establishment should also take into account the tree growth when fast- or medium-growing species are considered and the effect they have on the light reaching the understorey and its productivity. They should be modelled and should serve as a basis for different tree and understorey price scenarios, similar to the economic model based on biophysical models for silvoarable systems developed by Dupraz et al. (2005). Compatibility between the understorey and tree components should be evaluated in different environments. It has been shown that understorey legumes enhance initial tree growth, while it is reduced by the traditional sown grasses (López-Díaz et al. 2008). Also, shrubs promote initial tree growth when compared with herbaceous species, but once tree roots colonize deep soil layers, shrubs reduce tree growth when compared with herbaceous understorey development (Mosquera-Losada et al. 2011a). Nevertheless, the role of shrub understorey on silvopastoral systems varies widely amongst species, and shrubs can have contrasted effects on pasture understorey and tree overstorey productivities (Rivest et al. 2011; Rolo and Moreno 2011). Aspects related to tree regeneration and tree health seem to be of high importance in established traditional agroforestry systems such as dehesas and montados. Models to describe the impact of a range of variables on such systems should also include both environmental benefits including contamination reduction, carbon sequestration and biodiversity, and social benefits like rural tourism, landscape improvement and hunting.

Policy and Institutional Support

The research carried out during the past decades in different countries of Europe helped to include the establishment of AFS as part of direct payments in the last rural development directive (EAFRD 2005). This is a highly relevant development considering the loss in economic viability of some traditional agroforestry systems in recent decades. The degree of implementation of the Rural Development Directive (EAFRD 2005) is, however, not extensive and homogeneous throughout Europe, and at present, there is no regional or national policy to improve silvoarable systems and make them economically viable (Eichorn et al. 2006).

In most regions of Spain, there are no specific programmes to implement the EU's Agroforestry Regulation (EAFRD 2005), but funds can be accessed (e.g. in the Galicia region) for woodland grazing, harvesting the understorey under the trees to reduce fire risk and fencing. In the Andalusia region of Spain, Robles et al. (2009) developed an innovative programme to use grazing animals to maintain firebreaks and reduce the fire risk in public forests. The programme that started in 2005 with five contracts involving 1,930 grazing animals and 520 ha currently (2011) involves 59 contracts, 34,005 grazing animals and 2,200 ha (Mirazo 2011). In Spain, several regions plan to support planting of new agroforestry plots, but the success of the programme is still marginal. Planting would focus on promoting (1) silvopastoral systems in native forest and afforested lands as a strategy for reducing fire hazard (mountainous regions) and water competition (Mediterranean regions), (2) conservation and multifunctional use of traditional silvopastoral systems to preserve their high biodiversity and (3) integration of quality timber trees with crops and pastures in intensively managed fields (Atlantic region and irrigated lands in Mediterranean regions) to reduce pollution caused by agrochemicals and enhance C sequestration on farmlands. Forest and firebreak grazing has also been used in France as a tool to reduce forest fire risk (Rubino 1996).

In Germany, there is currently no specific support for agroforestry, and many German farmers have no knowledge or experience of such integrated land-use systems. Furthermore, there is a lack of institutions to inform and advise farmers in this regard (Reeg 2011). However, the need to increase renewable energy production (particularly in the light of recent decisions against nuclear power) means that new ways must be sought to increase land productivity, such as short rotation coppice in combination with grassland or other crops. Such systems can result in ecological benefits (Dimitrou et al. 2009) or negative environmental externalities, especially with respect to water issues (Raftoyannis et al. 2011).

In Italy, the regional plans for implementation of the rural development regulation (1257/1999) have led to some interest in agroforestry systems. For example, in the Tuscany Region, the 2000–2006 rural development plan supported the conversion of cropped fields with over 30 % slope to pasture, planting of timber trees and energy biomass plantations on formerly cropped fields and establishment of windbreaks and hedges around fields. The new plan for 2007–2013 for Tuscany increased the level of support which now includes conversion of cropped fields with slopes more than 20 % to pasture, the establishment of timber trees in pasture or cropped fields and establishment of riparian buffers and truffle forests. These regional examples are in line with the rest of the country and demonstrate increased interest in environmental themes and the presence of legislative support to tree reintroduction in pastures and cropped fields, especially in steep areas.

In the UK, in the 2007–2013 rural development plans, the four regional governments (England, Scotland, Wales and Northern Ireland) did not provide specific support for the establishment of agroforestry systems, although there is support for forestry systems with widely spaced trees and for parkland systems. The new UK government elected in 2010 has recently set targets for increased tree planting, uptake of stewardship schemes, and expansion of linear features (DEFRA 2011), which should provide opportunities for agroforestry. In Northern Ireland, with certain stipulations, silvopasture establishment is fully eligible as an agricultural subsidy for paying farmers by the EU called Single Farm Payment.

There is still a consistent separation of forestry and agriculture (including intensive animal rearing) in most European countries. Although silvopastoral and silvoarable systems were experimentally established in several European countries in order to demonstrate their technical and economic feasibility to farmers, institutional and policy support for agroforestry is weak or non-existent in most countries. For example, in Italy, there are no national research programmes on the topics of agroforestry or agro-silvopastoral systems. In Germany, as there is currently a strong focus on enhancing woody biomass production, the future development of agroforestry will strongly be linked to the application of high productive short rotation forestry in alley cropping systems. In Greece, several efforts have been made in the last few years to attract the interest of land management authorities and farmers in the ecological and economic importance of the traditional agroforestry systems and stress the need for their conservation. These included seminars to foresters and agronomists, research projects to collect scientific information, inventories and dissemination networks. In 2006, the Greek Agroforestry Network was established to coordinate these activities. Nevertheless, Greece has not yet implemented article 44 of the EU regulation 1698/2005 about the financial support for agroforestry practices in Europe. In the UK, the Farm Woodland Forum continues to represent the interests of scientists and practitioners involved in agroforestry development. On the island of Ireland, where there are separate national controlling state bodies for agriculture and forestry, a Cross Border Agroforestry Development Group has been formed to establish demonstration sites on both sides of the border.

The most important European project dealing with agroforestry (SAFE project) concluded that at a European scale, 90 million ha are potentially suitable for silvoarable agroforestry and 65 million ha would benefit from silvoarable plantations to contribute to mitigation of some key environmental problems such as soil erosion or nitrate leaching. Even if 20 % of the farmers in these areas adopt agroforestry on 20 % of their farm, it would result in 2.6 million ha of silvoarable agroforestry in Europe (Reisner et al. 2007). The quality timber that would be available from this activity would help reduce the need of imported high-quality tropical timber as well as tropical deforestation, which is another important goal of the Kyoto protocol. However, within the latest European Rural Development document (EU 2009), it is expected that the established measures of AFS will only cover 60,000 ha of agricultural lands owned by 3,000 farmers. One of the main results of the SAFE programme was to underline the great interest of European farmers in silvoarable systems. A survey to evaluate the possibility of adoption of agroforestry practices by the farmers in individual country participants concluded that tree planting was no longer considered as an obstacle and almost 50 % of farmers were ready to set up a silvoarable plot on their own farm (Liagre et al. 2005). The evidence from this project has resulted in a new research and development programme being set up to promote agroforestry projects. The French National Association was created in 2007 and France counts now almost 4,000 ha of modern agroforestry (Liagre 2009).

In terms of tourism and other services offered by farms, a new kind of agro-silvopastoral system that integrates conventional agriculture and delivers a wider range of valuable services can considerably enhance tourism. These new integrated systems would benefit from the complexity based on their diversity of resources, which include agriculture, forestry and livestock rearing on pastures (Pardini et al. 2008a, b).

Development of policies to promote these systems as well as their implementation in the different regions of Europe should also be considered. Trends in modern social needs have increased people's awareness of environmental values. The Millennium Ecosystem Assessment[5] pointed out the consequences of ecosystem change for human well-being and proposes a value for each service/ecosystem. Hence, some of these systems could incorporate agroforestry practices as providers of services for human welfare, as proposed in the Millennium Ecosystem Assessment. These agroforestry practices are already being implemented in Portugal and are currently under development in other countries. A demonstration of (1) environmental benefits of agroforestry, (2) the types of agroforestry systems and practices that maximize benefits and (3) edaphoclimatic and socioeconomic conditions under which the goals are achievable is needed to assure the long-term support of European Common Agrarian Policy (CAP) funds to agroforestry implementation in Europe.

Education at different levels, to farmers, technicians, policymakers and university students, should also be established. Over the last few years, there have been various training courses in the different countries, including international courses (ERASMUS Program (EuRopean Community Action Scheme for the Mobility of University Students),[6] but, more efforts should be made to overcome the traditional separation between forestry, agricultural sciences and land management.

Even though European policies have encouraged land management systems that combine production, environmental services (biodiversity, carbon sequestration, nutrient cycling and water quality) and social benefits, and this has created a new interest in agroforestry systems, a strong effort should be made to increase the presence of agroforestry practices in the European continent. The benefits and opportunities offered by agroforestry can only be realized with substantial investments and coordinated efforts in research, education, knowledge transfer and appropriate national policies across Europe.

End Notes

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Agroforestry for Mine-Land Reclamation in Germany: Capitalizing on Carbon Sequestration and Bioenergy Production

Ansgar Quinkenstein, Dirk Freese, Christian Böhm, Penka Tsonkova, and Reinhard F. Hüttl

Abstract Surface mining operations generate significant and large-scale landscape disturbances. As a consequence, effective reclamation management is required to ensure the establishment of a sustainably productive, ecologically valuable, and economically attractive post-mining landscape. In the post-surface-mining landscape of Lower Lusatia (northeast Germany), a new land-use option during reclamation is the establishment of alley cropping systems (ACSs) producing food and woody biomass for obtaining bioenergy. The established multi-row tree strips are typically managed as short rotation coppices (SRC), for which black locust (*Robinia pseudoacacia* L.) is the most frequently used tree species. The alley cropping systems are promising land-use systems for mine-site reclamation because they provide a multitude of ecological and economic benefits; furthermore, within these plantations, significant amounts of carbon (C) can be accumulated in the biomass and the soil. The results of field studies on C sequestration in *R. pseudoacacia* stands on reclaimed mine sites within the Lusatian region indicate an average shoot dry matter (DM) production of *R. pseudoacacia* between 3 and 10 Mg DM ha^{-1} year^{-1} depending on the plantation age and rotation period. The DM yields for foliage biomass ranged

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between 12 and 32 % of the shoot biomass for 2- and 4-year-old trees. Estimates of the C storage within the soil are up to 7 Mg C ha^{-1} year^{-1} within 0–60 cm depth. In summary, the results support the hypothesis that ACS of *R. pseudoacacia* may be in many respects a beneficial land-use system for marginal, post-mining landscapes, with a significant C sequestration potential above- and belowground.

Keywords Alley cropping • Ecosystem services • Land reclamation • *Robinia pseudoacacia* • Short rotation coppice

Introduction

Surface mining activities that cause landscape destruction are one of the most severe anthropogenic disturbances of terrestrial and aquatic ecosystems. These operations constitute one of the most visible and significant landscape destruction on a large scale, and they can lead to serious conflicts of interest between the extractive industry and the public need for sustainable management of reclamation and restoration after mining. Cao (2007) pointed out that mining is the oldest and the most important "land-use activity" after agriculture but has caused considerable negative impacts on the environment. Chatterjee et al. (2009) estimated that the land area affected by surface mining for coal in the United States is about 1.25 million ha, which constitutes about half of the total "disturbed" land area. In China, the current total disturbed land due to various mining activities amounts to 4.0 million ha with an increase of 33,000–47,000 ha per year, but there are no data specifically for coal mining (Cao 2007). In Germany, approximately 350,000 ha of land have been claimed for lignite mining over the last 100 years. The proportion of the land that is reclaimed after mining in Germany, Spain, Canada, and the USA is between 50 and 70 %, but the average rate of land reclamation in China is merely around 12 % (Sheoran et al. 2010). It can be assumed that in developing countries the proportion of reclamation is still significantly lower (Morrey 1999). The worldwide output of lignite coal amounted to 940 million t in 2005, of which about 64 % was produced in European countries. The area occupied by surface mines, as open-pit mines and area mines, is large and each mine often extends to several square kilometers.

The reclamation and/or restoration of mining sites is both technically and economically challenging and in most cases very time-consuming (Botin 2009; Bradshaw and Chadwick 1980). There is no clear difference between reclamation and restoration. The former can be described as a process of improving disturbed landscapes (soil, biota, water) to achieve land capability with a minimum equivalence to the predisturbance level of quality or for a specified alternative end land use. Reclamation is often used where some new features of land use will be involved. On completion of the reclamation process, a new post-mining landscape with partly original features emerges (Botin 2009; Bradshaw and Chadwick 1980). Restoration is defined in terms of ecosystem reestablishment covering the aim of achieving the composition, structure, and function of the predisturbed landscape. This process contains activities designed to return injured natural resources and services provided to baseline conditions or to accelerate the natural recovery process. However, the main aim of restoration/reclamation is the reestablishment of long-term land sustainability choosing between different options of land use. In practice, the application of reclamation in combination with restoration is quite common in developed countries whereby the area ratio of them depends on site conditions (e.g., quality of the overburden substrates, water availability, and specified land end use).

Reclamation may provide the potential for ecological adjustment or improvements compared to the pre-mining situation and for practical reuse of mined land. The rationale and methods for reclamation of surface mines can vary considerably between different locations (landscape, climate, soils, quality of overburden, etc.). Besides natural differences, there are also significant differences between developed and developing countries in relation to socioeconomic conditions and legislation (Cao 2007) when land reclamation is going to be performed. Developed countries usually have stringent and effective regulations, e.g., in the USA the Surface Mining Control and Reclamation Act (SMCRA) and in Germany the Federal Mining Law (in German: “Bundesberggesetz, BBergG”). In Germany, all activities of mining companies are strictly regulated by legislation and regulatory frameworks which are the regional planning law, the mining law, and specific environmental laws. The overall mining operation is thus completely controlled, ranging from planning over extraction to the final reclamation, whereby the mine owners are economically in charge of all these steps and the time lapse between the mining and reclamation is minimal. In practice, the reclamation starts 1–2 years after excavation of lignite and dumping the overburden. The core aim of reclamation is to identify the potential of post-mining land and to choose appropriate technologies and measures to realize this potential for economic, recreational, and aesthetic land use (Morrey 1999). Reclaimed sites have a wide range of potential uses including agriculture, forestry, recreation, nature conservation, and surface water storage, as well as infrastructure creation and resettlement opportunities.

Post-mining landscapes are not comparable with the original landscape because they do not completely represent the same landscape functionality, composition, and structure. But that implies the chance to develop new post-mining landscapes containing functions and elements of the prior and new structures and processes of development in the new system. Depending on the national mining regulations, which can markedly differ between countries, the development of post-mining landscapes is carried out on different levels of quality. In general, high standards of reclamation and restoration aim at the establishment of former and novel land-use systems, including agriculture, forestry, surface water, and areas for nature protection and conservation. One major challenge is the period of time needed to achieve the target values of quality (e.g., soil quality standards) in post-mining development, which could take several years up to decades. The effective time period depends on the initial state of the area before restoration and on management practices of reclamation over the long term. Assuming carbon (C) sequestration as a target parameter of soil development, one of the best adopted managements of reclamation is agroforestry (Nair et al. 2009).

Along with the realization of the importance of bringing industrial wasteland back into cultivation, the importance of growing biomass for energy purposes has been increasing during the recent past, in the Lusatian mining district in Brandenburg (Germany) The state government of Brandenburg strives for the goal of 20 % of the primary energy consumption supplied by regenerative energy carriers in 2020 whereby biomass shall contribute a share of about 40 % in renewable energy resources by that time (BMWE 2007). Black locust has been found to be a well-suited and promising tree species for cultivation on reclamation land such as can be found in the Lusatian mining areas (Grünewald et al. 2007, 2009). This chapter provides an overview of the results of selected growth experiments with *R. pseudoacacia* on mine sites in the region. The focus is on C sequestration within alley cropping system (ACS) with *R. pseudoacacia* managed as a short rotation coppice (SRC) species. Relevant scientific literature is reviewed and complemented with results from ongoing field studies. Before presenting detailed information from experiments with *R. pseudoacacia*, however, a general description of the mining industry and the mining site is given as well as the general principles of C sequestration and biomass production at post-mining sites.

Surface Mining Sites in Germany: The Lusatian Lignite Mining District

The Lusatian mining district is located in northeast Germany in a region bordering Poland (Fig. 1). The region has been heavily influenced by ongoing opencast lignite mining activities for over 100 years. During this time, more than 82,000 ha of land have been turned into dumps (SdK 2007), whereby much more land is indirectly affected by the continuous pumping of groundwater (Hüttl 1998). Within the region, five open lignite pits will continue to operate until 2040. In 2010 alone, about 400×10^6 m^3 of overburden material was excavated to extract around 57 Tg of lignite (SdK 2011). After processing, the resulting dumps have to be reclaimed. Usually this is done by transforming the land into forest or agricultural lands. The reclamation aims to establish at the very minimum a comparable land-use structure to that which existed in the landscape before mining activities started. However, in many places, reclamation efforts are impeded by unfavorable site and growth conditions mainly due to frequently occurring drought periods, low soil pH values, and overall low nutrient contents of the soil material.

For a better understanding of mining and post-mining landscapes, the technology applied in Lusatia, Germany, is shown in Fig. 2. The conveyor belt technology in the Lusatian lignite mining district enables large-scale excavation of lignite seams. This technology mixes the upper quaternary and lower tertiary sediments inducing the oxidation of pyrite from the tertiary marine-brackish sediments and leading to strong acidification and high salinity (Hüttl and Weber 2001). In Lusatia, the lignite seam has an average thickness of 12 m and is covered by overburden material of approximately 90 m thickness. The active mine moves in one direction leaving an area of

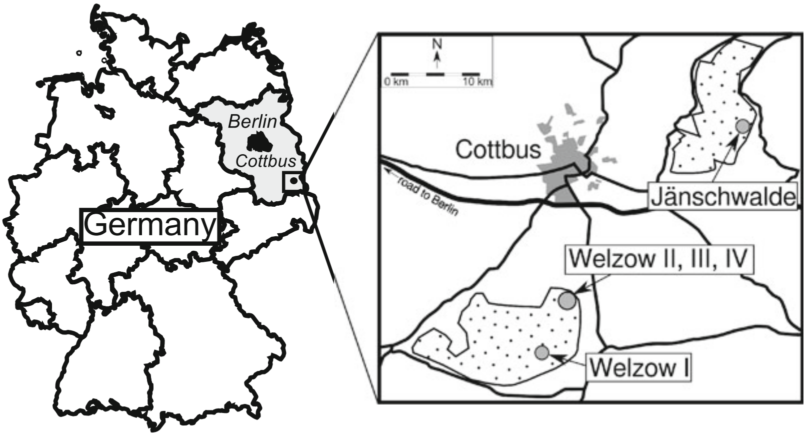

Fig. 1 Map of the sampling area in the region of Lower Lusatia (northeast Germany) and the study sites in the lignite opencast-mining areas "Welzow-Süd" (sites Welzow I, II, III, and IV) and "Jänschwalde" (site Jänschwalde)

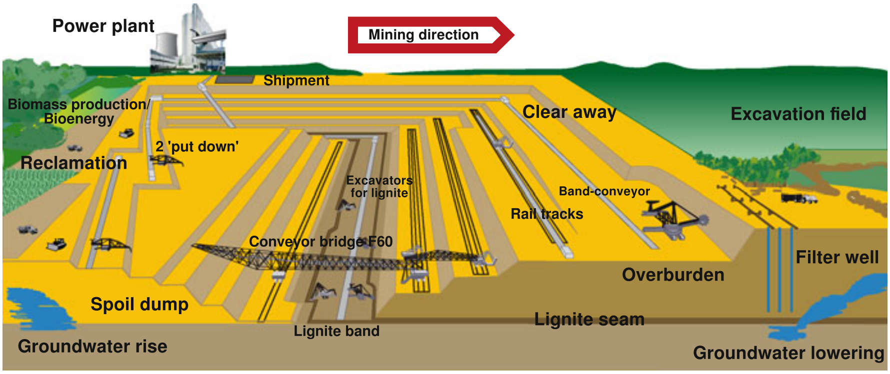

Fig. 2 Schematic opencast mine in the lignite mining district of Lower Lusatia illustrating the regionally used conveyor belt technology (DEBRIV 2006, modified)[1]

several thousands of hectares to be reclaimed. Extensive pumping of groundwater of up to 170 m^3 per minute prevents the open pit from being flooded and extends the area of impact on the water regime of the landscape up to 400 km^2. The key technology is the conveyor bridge (650 m in length) with a capacity of 60,000 m^3 overburden per hour which is directly transported by belts to the final spoil dump. After leveling by bulldozers, reclamation starts with amelioration of the dumped substrates to prepare it for the projected land use such as forestry or agriculture. In case of very acid tertiary substrates (pH_{KCl} 3 or less), the amelioration needs up to 100 Mg ha^{-1} lime (CaO) up to 1 m depth to achieve the target pH of about 7 in the first year of reclamation. The pH is checked every 3 years and readjusted by additional liming if necessary. Additionally, NPK fertilizers are typically at the rates of 100/150//200 kg ha^{-1} up to 1 m depth (Katzur and Haubold-Rosar 1996).

The chemical processes in post-mining sites differ particularly in the initial phase when compared to the pre-mining situation (Schaaf and Hüttl 2004), and the site-specific geochemical composition controls largely the element fluxes of the developing systems (Schaaf 2001). In addition, geogenic and lignite-derived C in these sandy, nutrient poor soils may play a significant role in the water and nutrient supply of the developing ecosystems. These conditions have a large influence on both above- and belowground biomass development and humus accumulation, which are important components of the ecosystem nutrient cycle. Nevertheless, reclaimed sites develop on substrates that are not equivalent to the "undisturbed" landscape. For mining-reclamation projects, it is important to select trees and shrubs that can withstand extreme conditions such as deep water table (>30 m), no initial organic matter, nutrient poor sites, and dry conditions.

Carbon Sequestration and Biomass Production at Reclaimed Mine Sites

Carbon Sequestration

Mining is an anthropogenic activity that causes severe soil disturbances (Hüttl 1998). The loss of soil organic carbon (SOC) in disturbed soil is mainly caused by a loss of topsoil, mechanical mixing of soil horizons, and increased rates of mineralization, erosion, and leaching from the exposed topsoil (Shukla et al. 2004). Soil is known to store nearly three times the amount of C contained within standing vegetation and twice that contained in the atmosphere (Eswaran et al. 1993; Batjes 1996). However, the depleted SOC can be restored by establishing an appropriate land-use system where additional C can be sequestered. The term C sequestration implies transferring atmospheric CO_2 into long-lived pools and storing it there in a way that it is not immediately reemitted (Lal 2004). Highly relevant is the process of transforming atmospheric CO_2 via the process of photosynthesis and subsequently incorporating the biomass into the soil as humus (Shrestha and Lal 2006), which is known to have the potential to act as a major sink of atmospheric C (Lal 2004). Carbon sequestration occurs when a higher C input versus C output is maintained over a certain period of time (more C is stored than is released), with the system ultimately attaining a new steady state, characterized by a greater C pool (Jastrow et al. 2007). In the soil, C sequestration depends, among other things, on the organic matter from plant or animal residues, the quantity and quality of litterfall, and the mineralization rate, which itself depends on a number of site-specific factors (Shrestha and Lal 2006; Fernández-Núñez et al. 2010). The conservation of accumulated soil C stocks requires maintenance of the conditions or practices which enabled its accumulation. Strategies for enhancing C sequestration in soil may also include reducing rates of C turnover, e.g., by planting perennials, minimizing tillage and disturbances, or maintaining a near-neutral soil pH to support growth of soil fungus (Jastrow et al. 2007). The topsoil application technique and the type of soil amendments used in land reclamation also affect the C sequestration process (Shrestha et al. 2009).

In addition, reclaimed coal- or oil-shale mine sites may be contaminated with fossil C particles; therefore, accurate estimates of soil C pools require differentiation between coal C and recent SOC derived from plant and litter (Ussiri and Lal 2008). A common method used to explore C sequestration rates in post-mine areas is the pseudo-chronosequence. Based on a chronosequence investigation of Scots pine (*Pinus sylvestris* L.) plantations on an oil-shale opencast mine in Estonia, Karu et al. (2009) reported that, in 2004, the total SOC stocks (stored in the vegetation, forest floor, and topsoil) of plantations established in 1990, 1983, and 1986 were 7.8, 34.5, and 133.4 Mg C ha^{-1}, respectively. Plant-derived SOC formed 5 % of the total ecosystem C stock for the youngest, 15 % in the second, and 23 % in the oldest stand, respectively, showing that soil contributes substantially to total C stock during early forest succession on degraded land. Amichev et al. (2008) who investigated the C sequestration potential of forests and soils of 14 sites in the Midwestern and Appalachian mine fields in the USA reported that on average, the highest C stock was in pine stands, followed by hardwood, and mixed stands: 148, 130, and 118 Mg C ha^{-1}, respectively. Shrestha and Lal (2010) investigated C sequestration at reclaimed mine sites in Ohio, USA, under pasture and forest; the highest C sequestration rate was found for the forest sites with a mean ecosystem C increase of 5.1 Mg C ha^{-1} year^{-1} across the pseudo-chronosequence, and for the pasture sites, the average rate was about 1.0 Mg C ha^{-1} year^{-1}. Chatterjee et al. (2009) reported from the same region that the SOC stocks in grassland in the 0–10 cm soil layer were 29.7, 29.5, and 9.11 Mg C ha^{-1}, for 30-, 9-, and 1-year-old stands, respectively. In a reclaimed forest stand, the SOC stock in the same soil depth was 21.9 Mg ha^{-1} (11-year-old) compared to 31.9 Mg ha^{-1} for undisturbed forest (40-year-old). These studies demonstrate that reclaiming mine lands with perennial crops (grassland) or woody crops (forest stands) is a viable approach to sequester additional C in the plant-soil system. In general, C sequestration in land-use systems on young reclaimed mine sites follows a sigmoidal curve: the sequestration rate increases within the first years after establishment of a new, productive land-use system and later, when the plant age increases and the C pools in the system are more or less filled, the rate of C accumulation decreases. Finally, the C stock in the system reaches a new – potentially higher – equilibrium (Fig. 3).

Considering the total area of human-induced disturbed land in the world which is estimated to a size of 1.96×10^9 ha (Oldeman et al. 1991), the potential of soil C sequestration for degraded land (including deserts) is estimated to range between 0.8 and 1.3 Gt C year^{-1} (Metting et al. 2001). In the United States alone, 0.63×10^6 ha of land are classified as disturbed mine lands. The estimated C sequestration potential of this land is around 1.3 Tg C year^{-1} (Lal et al. 1998). The terrestrial C sequestration potential in Europe has been estimated for forests at 363 Tg C year^{-1}, whereas the agricultural soil losses are 300 Tg C year^{-1} (Schulze 2000).

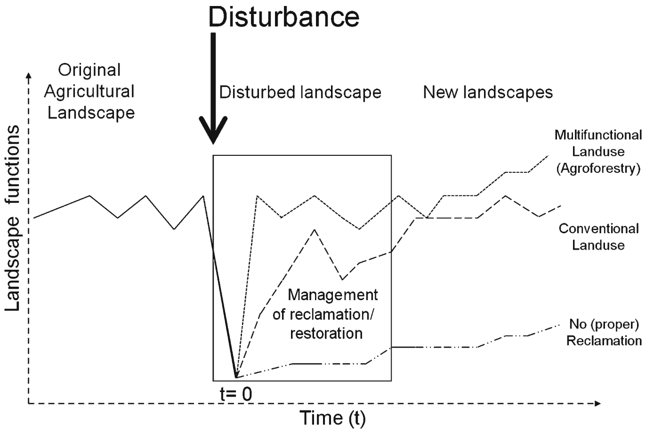

Fig. 3 A schematic presentation of the expected relative impact of different land management systems (agroforestry, conventional agriculture, improper reclamation) as measures for the reclamation of disturbed landscapes, based on the assumption that agroforestry has significant advantages over conventional agriculture with regard to landscape functionality

Options for Biomass Production on Reclaimed Mine Sites

The recent debate on climate change and the necessity to substitute fossil fuels by renewable energy sources lead to new standards also in the reclamation of mining landscapes (Berndes et al. 2003; EEA 2006). The energy mix of the future regarding production of electricity and heat will partially rely on biomass as a renewable energy source that can be used in base load power plants to produce energy at a constant rate and at a low cost. In recent years, the cultivation of biomass for energy production on arable land has increased considerably in Germany (FNR 2007) as its economic success is assured by the German legislation on feed-in agreements for electricity. But against this background, a debate has arisen on the change of historic cultural landscape and the replacement of food production by biomass production. The post-mining landscape offers the possibility to turn these conflicts into a win-win situation because (a) biomass cultivation on soils that are too poor to support food-crop production will not directly compete with classic agriculture and food production, (b) special biomass-cultivation systems adapted to the requirements of reclamation have positive effects on the development of productive soils, and (c) the production of biomass and its use for local energy supplies contributes to regional development.

Agroforestry Systems

On intensively managed land, increased biomass production could cause additional pressure on ecological functions of agroecosystems and on soil and water resources

Fig. 4 An alley cropping system on reclaimed mine sites in the mining area of Welzow-Süd (Lower Lusatia, Germany) with strips of *Robinia pseudoacacia* managed as short rotation coppices

(EEA 2006). Innovative solutions are required that ensure higher productivity without further damaging natural resources and allow adaptation to the changing climatic conditions. Combining trees and crops in agroforestry systems improves the efficiency of the utilization of resources (light, water, nutrients) and thus leads to an overall higher biomass production (Ong et al. 1996; Rodriguez and Burger 2004). Simultaneously, soil erosion and nitrate leaching are reduced and landscape biodiversity is increased (Palma et al. 2007). Agroforestry is an innovative land-use system for Europe that can combine the production of food and wood (bioenergy, timber) with ecological functions on the same field (Dupraz et al. 2005). Moreover, in marginal regions and on degraded lands, agroforestry constitutes an alternative to land abandonment and/or to deliberate afforestation, leads to diversification of land use, and offers new income possibilities (Freese et al. 2010). An agroforestry practice that is being increasingly adopted is the ACS for biomass production; it can be defined as the planting of two or more sets of single or multiple rows of fast-growing trees or shrubs, managed as SRC, in wide spacing, creating alleys within which agricultural, horticultural, or forage crops are cultivated (Fig. 4).

In the temperate zone, ACS come increasingly into focus as they offer an approach for the production of fuelwood, thus matching the increasing demand for a self-supply with bioenergy in rural decentralized areas. In the post-mining area of Lusatia, Grünewald et al. (2007) and Böhm (2008) analyzed the performance of three fast-growing tree species (poplar, *Populus* spp.; willow, *Salix viminalis* L.; and black locust) on two reclaimed mine sites where the trees had comparably unfavorable site conditions. The studies demonstrated that a sustainable supply of fuelwood is possible even under the marginal conditions of the post-mining area if trees well adapted to specific climatic and edaphic conditions are selected.

As reported by Quinkenstein et al. (2009a, b), the biomass production potential of ACS depends mainly on a number of factors such as the tree species and clone used, planting design (strip width, planting density), management (years of rotation, fertilization, pest and weed control), and soil conditions (nutrients, water availability). The tree rows in ACS can have a significant effect on crop production. The interactions between trees and crops strongly depend on the system design (tree height and distance between hedgerows), management (plowing, fertilization, harvesting), and site conditions (location, climate, soil properties). Agroforestry systems are structurally and functionally more complex than either crop or tree monocultures, and therefore, when properly managed, they are more efficient in resource (nutrients, light, and water) capture and utilization, which may result in higher yields and greater C sequestration (Nair et al. 2009). Moreover, by including trees in agricultural production systems, the amount of C stored in lands devoted to agriculture may increase, while still allowing the growing of food crops (Kürsten 2000). The productivity of mixed systems can be measured by the land equivalent ratio (LER) (Mead and Willey 1980), which compares the yields from growing two or more crops together with the yield obtained from growing the same crops in monoculture. A LER equal to or higher than one corresponds to higher yields in intercropping compared to monocropping. Grünewald et al. (2007) reported a LER of 0.98 for an ACS with *R. pseudoacacia* L./*Medicago sativa* L. established at the post-mining sites in the Lusatian region. This result demonstrates lack of competition between trees and crops even when grown under unfavorable site conditions. For the European climatic region, Graves et al. (2007) predicted a LER between 1.0 and 1.4, meaning that intercropping would be a more efficient land-use option than monocropping. Compared to the cultivation of fast-growing tree species in SRC, ACS only uses a small proportion of the total available land area for the production of woody biomass, and therefore, the total biomass produced on a hectare basis will be lower. However, ACS is considered a multispecies and highly flexible land-use management option, and the system design, the proportion of SRC strips, and the cultivation of conventional crops can be adapted according to the main production objectives.

Short Rotation Coppices

A land-use option that meets both requirements of mine-soil reclamation as well as woody biomass production for energy generation is the establishment of SRC. In these wood plantations, fast-growing trees are used for production of woody biomass, mainly for utilization in energy production. Usually, the trees in SRC are planted at high densities of up to 14,000 trees per hectare and are mechanically harvested in short intervals of between 3 and 6 years. The species used are able to resprout quickly following harvest which allows SRC to be run for 20–30 years until yields start to decline. Consequently, the main requirements for short rotation tree species are a rapid juvenile growth and a quick regrowth after harvesting. Furthermore, high levels tolerance to physical damage, nutrient-use efficiency, and site adaptability are desirable.

The tree species used widely for SRC are willow (*Salix* spp.) and poplar (*Populus* spp.). In the Lusatian reclamation area, growth experiments with SRC have shown that *R. pseudoacacia* is more productive than willow or poplar under the local growth conditions (Grünewald et al. 2007). For an ACS in the reclamation area of the opencast mine "Jänschwalde" (Table 1), Grünewald et al. (2007) found remarkable differences between height growth of *R. pseudoacacia*, *Populus* spp. (clones "Androscoggin" and "Hybride 275"), and *Salix viminalis* (clone "Carmen"). Seven years after establishment, the average height of *R. pseudoacacia* peaked at 402 cm while that for "Hybride 275," "Androscoggin," and *S. viminalis* were 265, 283, and 182 cm, respectively. After 6 years of growth, the aboveground biomass (dry matter, DM) accumulation ranged from 4.5 Mg DM ha^{-1} for *S. viminalis* to 29.8 Mg DM ha^{-1} for *R. pseudoacacia* (Grünewald et al. 2007). *S. viminalis* achieved a peak annual biomass productivity of 1.0 Mg DM ha^{-1} year^{-1} after 6 years of undisturbed growth (first harvest after a 6-year rotation). For *Populus* spp. and *R. pseudoacacia*, biomass productivity peaked after 6 years of growth, in the second rotation period of a 3-year-rotation system to 2.0 and 5.8 Mg DM ha^{-1} year^{-1}, respectively.

The large differences in productivity between *Populus* spp., *S. viminalis,* and *R. pseudoacacia* reflect differences in adaptability to site conditions; *R. pseudoacacia* appeared to be much more adapted to the given climatic and edaphic regime of the reclaimed open-pit mine.

Suitable Woody Crop Species: Black Locust

Robinia pseudoacacia is a deciduous, nitrogen-fixing legume tree that is native to eastern North America. It has a disjoint original distribution range, with an eastern section centered in the Appalachian Mountains and a western section mainly located in the Ozark Plateau (Burns and Honkala 1990). During the early seventeenth century, the species was introduced to Europe (Böhmer et al. 2001). Since then, it has been planted widely and has become naturalized not only in the temperate regions of North America and southern Canada but also in parts of Europe and Asia (Burns and Honkala 1990). Large areas of *R. pseudoacacia* in Europe were established in Hungary, where it is currently growing on about 400,000 ha, which represents more than 23 % of the total forest area (HMEW 2009; Schneck 2010). Other European countries with large stands of black locust as of 1978 are Romania (191,000 ha), France (100,000 ha), and Bulgaria (73,000 ha) (Keresztesi 1983). In Germany, according to the 2nd National Forest Inventory from 2002, the area under the species is about 34,000 ha or 0.3 % of the forested area (BMELV 2009). The current

Table 1 Selected characteristics of growth experiments with *Robinia pseudoacacia* conducted on mine sites in Lower Lusatia

	Welzow I	Jänschwalde	Welzow II	Welzow III	Welzow IV
Location	Strip mine Welzow-Süd (51° 35′ N, 14° 18′ E)	Strip mine Jänschwalde (51° 48′ N, 14° 35′ E)	Strip mine Welzow-Süd (51° 38′ N, 14° 19′ E)		
Area (ha)	<2.5	7	13.2	8.6	11.8
Establishment	1995	1996	2005	2006	2007
Elevation (*m*)	125–130	65	105–112		
Slope	Very low slope	Undulating area with characteristic valley	Very low slope	Flat	Flat
Dominant substrate (*USDA classification*)	Sandy clay loam	Loamy sand, sandy loam	Loamy sand, sandy loam	Loamy sand, sandy loam	Loamy sand, sandy loam
Bulk density (g cm^{-3})	1.60–1.76	1.60–1.70	1.40–1.80		
Total nitrogen (%)	0.02–0.04	<0.01	0.01–0.03		
Origin of R. pseudoacacia	Unknown	Brandenburg, NE Germany	Bihor, Romania	Unknown	Unknown
Average initial planting density (trees ha^{-1})	6,500	10,929	9,200	9,200	9,200
Rotation (years)	14	3, 6+3, and 9	4	(Presumably) 5	(Presumably) 5
Comment	Growth experiment with fast-growing species	ACS, abandoned in 2007	SRC	SRC	SRC
Source of data	Bungart (1999), Bungart and Hüttl (2004), Grünewald et al. (2009)	Grünewald et al. (2009)	Böhm et al. (2009), Grünewald et al. (2009)	–	–

area under black locust is estimated to be larger than 3 million ha worldwide. This is the third largest area in the world within the group of fast-growing trees after eucalyptus and poplar (Berthold 2005; Hanover et al. 1991).

R. pseudoacacia is an early successional plant in many native forest stands where it occurs and it dominates early forest regeneration (Boring and Swank 1984). The tree is a modest nitrogen fixer with rapid juvenile growth and a preference for full sun and little competition. It is comparatively tolerant against droughts and severe winters and copes well with infertile and acidic soils, tolerating a pH range of 4.6–8.2. It is found on a variety of sites but grows best in calcareous, well-drained loamy soils (Hanover 1993; Böhmer et al. 2001). Typically, the tree produces a shallow and wide-spreading root system that is excellent for soil binding, but it is also capable of producing deep roots (Kutschera and Lichtenegger 2002; Burns and Honkala 1990). Together with its ability to grow under extreme conditions and the ability to colonize bare soils, *R. pseudoacacia* became an important tree for reclaiming mine sites. During the early twentieth century, the first growth experiments were conducted in the USA (Zeleznik and Skousen 1996) when it was extensively studied and proved to be a promising species for site reclamation (Brown and Tryon 1960; Brown 1962; Zeleznik and Skousen 1996). Consequently, *R. pseudoacacia* is also widely used for erosion control measures, reclamation of disturbed areas, and amelioration of marginal, low-fertile, or dry sites. It is also used in windbreaks and shelterbelts, as a nurse crop and for honey production and as an ornamental tree (Burns and Honkala 1990; Zeleznik and Skousen 1996). Additionally, according to Baertsche et al. (1986), *R. pseudoacacia* produces livestock feed nutritionally equivalent to alfalfa (*Medicago sativa* L.) and brings forth a nutrient-rich and well-decomposable litter, which is especially beneficial for soil formation on marginal sites (Filcheva et al. 2000).

Economically, the most important attribute of *R. pseudoacacia* is its high-quality wood with a comparably high dry density from 0.7 to 0.8 $g\,cm^{-3}$ (Waitkus and Richter 2001), making it suitable for timber, poles, wood fiber, and fuel (Barrett et al. 1990; Rédei et al. 2008; Waitkus and Richter 2001). In contrast, values for the specific wood density of willow and hybrid poplar clones, as reported by Tharakan et al. (2003), range from 0.35 to 0.48 $g\,cm^{-3}$ (average: 0.41 ± 0.04 $g\,cm^{-3}$) for willow and 0.33–0.37 $g\,cm^{-3}$ (average: 0.35 ± 0.02 $g\,cm^{-3}$) for poplar, respectively. *R. pseudoacacia* is now increasingly being used for the production of woody biomass for bioenergy generation in SRC on marginal lands (Böhm et al. 2009; Grünewald et al. 2007, 2009). The wood energy yield is high compared to that of other fast-growing species with a calorific value of about 16.54 MJ kg^{-1} or 4,818 MJ per cubic meter of dry wood chips, as reported by Grünewald et al. (2007). The comparable calorific values, reported by the same authors, for two poplar clones ("Androscoggin" and "Hybride 275") ranged from 17.55 to 17.43 MJ kg^{-1} (2,886–2,854 MJ m^{-3} wood chips), and for willow (*Salix viminalis* L.), the values were 17.41 MJ kg^{-1} and 3,619 MJ m^{-3} wood chips, respectively. Slightly higher average calorific values have been reported for wood with a dry matter content of 70 %: 18.4 MJ kg^{-1} for poplar and 18.3 MJ kg^{-1} for willow (KTBL 2006), whereas Sauter and Schneider (1993) reported similar values of 17.25 MJ kg^{-1} for poplar ("Max 5") and 16.83 MJ kg^{-1} for willow (*S. viminalis*).

Average energy yields per hectare were given by Grünewald et al. (2007), who reported 32.69 and 25.49 GJ ha^{-1} year^{-1} for the two poplar clones ("Androscoggin" and "Hybride 275"), 14.45 GJ ha^{-1} year^{-1} for willow, and 113.22 GJ ha^{-1} year^{-1} for *R. pseudoacacia*, and average growth rates of 1.0, 2.0, and 5.8 Mg DM ha^{-1} year^{-1} for willow, poplar, and *R. pseudoacacia* trees from study sites on reclaimed mine sites. Other authors calculated potential energy yields (GJ ha^{-1} year^{-1}) with poplar and willow and reported values ranging between 83 to 194 and 55 to 152 for biomass productivities (Mg DM ha^{-1} year^{-1}) between 8.6 to 20 and 5.7 to 15.7, respectively (KTBL 2006). These values correspond to petroleum equivalents of 2,314–5,399 L ha^{-1} year^{-1} for poplar and 1,534–4,218 L ha^{-1} year^{-1} for willow (KTBL 2006). A further advantage of *R. pseudoacacia* is its very low wood-ash content (1.5 %), compared to 1.5–2.1 % for poplar and 2.2 % for willow, for wood samples out of the second rotation period of a 3-year-rotation treatment (Grünewald et al. 2007). This makes the black locust wood highly suitable for combustion processes.

A Case Study on C Sequestration at the Opencast-Mining Area in Lower Lusatia, Germany

Study Details

The field experiments referred to are located on mine-reclamation sites in the lignite mining district of Lower Lusatia in the state of Brandenburg, Germany (Fig. 1). The climate in the region is characterized by a mean annual temperature of about 9.3 °C and a mean annual precipitation sum of about 560 mm. During the recent past, a pronounced drought period in April/May has become more and more common, and it has turned out to be a major limitation for crop production and, especially, for establishing of new SRC plantations in the early spring. Substrates at the study sites are mainly derived from quaternary overburden sediments and dominated by sandy and clayey loams or sands, respectively. The soils are in an initial state of soil formation and characterized by a low nutrient status.

Beginning in 1995, five growth experiments with SRC or with fast-growing tree species, respectively, were established in the opencast-mining areas Jänschwalde and Welzow-Süd in the Lower Lusatian lignite mining district (Table 1). The main objective of the first experiments (Welzow I and Jänschwalde) was to identify suitable clones of trees for biomass production in the post-mining Lusatian regions. Different clones of willow and poplar as well as *R. pseudoacacia* were tested. Based on the outcomes, three short rotation coppices with *R. pseudoacacia* were established in 2005, 2006, and 2007 (Welzow II–Welzow IV) in large plots of 9–13 ha area each. Some of the experimental stands were not uniform with regard to age, initial plant density, and management. Supplementary information on the individual growth experiments, the site characteristics, and the site management are given in Table 1.

Foliage biomass in SRC of *R. pseudoacacia* was determined from three stands of 4, 3, and 2 years of age (Welzow II, Welzow III, and Welzow IV, respectively) in August 2008 (Table 1). For each plantation, average values for tree height and shoot basal diameter were determined by measuring randomly selected trees (1,294 trees in Welzow II, 1,255 trees in Welzow III, and 1,285 trees in Welzow IV). Based on these measurements, in each of the three plantations, ten representative trees were selected for measurement of height, basal shoot diameter, and growth habit. None of these trees had been cut before sampling. From each tree, all the leaves were picked and weighed. Additionally, at the end of the vegetative period, between 300 and 600 representative trees per plantation were harvested and weighed as part of another experiment (Böhm et al. 2011). A subset of this data was used in this study to investigate the C allocation between the shoots and the foliage in the *R. pseudoacacia* SRC. For a representative subsample of the leaves and the biomass, the dry weight was determined by drying the biomass samples at 103 °C till weight constancy according to DIN EN 13183–1:2002 (DIN 2002). The foliage and the shoot biomass were tested for significant differences between the different plantations with the nonparametric Mann–Whitney *U*-test (Wilcoxon 1945). All statistical calculations were performed using the GNU R software package (Ihaka and Gentleman 1996).

To quantify the soil C in the topsoil under SRC of *R. pseudoacacia*, four plantations of ages 14, 4, 3, and 2 years were sampled in November 2008 (Welzow I, II, III, and IV, respectively) (Table 1). From each plantation, six plots were selected randomly across the plantation area. Soil samples were taken at each site at three different depths (0–3, 3–10, and 10–30 cm) with five replicates for each depth and composite samples prepared for each depth. Soil carbonate content was measured with the Scheibler device according to DIN-ISO 10693 (DIN 2007). The samples were air-dried (40 °C) for determining total organic C which was measured using a CNS analyzer (Matos et al. 2011).

Results

Shoot Biomass (Yield)

As outlined earlier, field studies conducted on reclaimed mine sites in the Lower Lusatian region showed that *R. pseudoacacia* was superior to willow and poplar under the local site and growth conditions regarding the biomass production (Grünewald et al. 2007). On the Welzow I site (Table 1), the biomass productivity of two poplar clones ("Hybride 275" and "Max 1") and *R. pseudoacacia* was investigated (Grünewald et al. 2009). The plantation was established in 1995, and until the biomass measurement in 2009, the plants had not been harvested. The reported average growth increments (Mg DM ha^{-1} year^{-1}) over 14 years were 3.6 for "Max 1," 3.0 for "Hybrid 275," and 9.5 for *R. pseudoacacia*, respectively.

The good growth performance of *R. pseudoacacia* on the marginal mine soils was also confirmed by Böhm et al. (2009), who investigated the SRC plantation at the Welzow II site established in 2005. On monitoring plots randomly distributed across the plantation, they measured the shoot biomass of more than 600 individual trees as well as the height and the root basal diameter of more than 1,200 individual trees. The authors reported an average height of 3.8 m and an average root basal diameter of 4.3 cm for the 4-year-old plantation. The average aboveground woody biomass dry matter production at the Welzow II site was 3 Mg DM ha^{-1} year^{-1}, which corresponds with the results published by Grünewald et al. (2007) for *R. pseudoacacia* of the same age.

Assuming an average C content of 46.4 % in the woody biomass of *R. pseudoacacia* (Quinkenstein, personal communication, 2010), an average growth increment of 9 Mg DM ha^{-1} year^{-1}, as reported above for matured plantations, would imply an annual C storage in aboveground woody biomass of 4.2 Mg C ha^{-1} year^{-1} or a carbon dioxide equivalent of 15.4 Mg ha^{-1} year^{-1}. If the yield biomass is used for bioenergy production later on, an equal amount of CO_2 emission due to the burning of fossil fuels, or a little less if other CO_2 sources during the SRC life cycle such as emissions by the machinery are taken into account (Goglio and Owende 2009), would be prevented because of the CO_2-neutral character of renewable woody biomass. The overall energy output–input ratio of wood plantations is comparably high. Goglio and Owende (2009) calculated this ratio to be between 7 and 19 for a willow SRC, depending on the assumed annual yield, the site management (fertilization, harvesting and drying technology), the chips' transportation distance, and the energy conversion process. Maier et al. (1998) calculated the energy balance for a selection of energy crops (assumed transportation distance was 50 km, biomass conversion was not considered) and reported an energy output–input ratio for willow wood of 24 and, for comparison, a ratio of 12 for maize (*Zea mays* L.). Boehmel et al. (2008) compared six energy cropping systems in a 4-year field trial in Germany and reported, depending on their model assumptions, highest energy use efficiencies for willow with output–input ratios of 72–99 and lower values of 20–45 for energy maize.

Carbon Storage in Aboveground and Belowground Plant Parts

The biomass accumulation within the plant shoots represents the fraction of harvestable aboveground woody biomass which is frequently extracted from the SRC plantation. This C pool is an important part of the total C stock of the SRC, especially if the biomass is used for bioenergy production and therefore helps to reduce the consumption of fossil fuels. Moreover, SRC are land-use systems in which long-lived perennial plants are cultivated. In addition to the shoot biomass, C is also stored in the foliage and, especially, in the longer-lasting woody parts that survive a harvest, namely, the plant stump and the roots (Quinkenstein et al. 2009a).

The results of the foliage and shoot biomass measurements (Figs. 5 and 6, Table 2) show a significant increase in shoot biomass with increasing plantation age ($p < 0.05$) and average DM values (Mg ha^{-1}) of 2.8 (Welzow IV), 7.9 (Welzow III), and 18.7 (Welzow II).

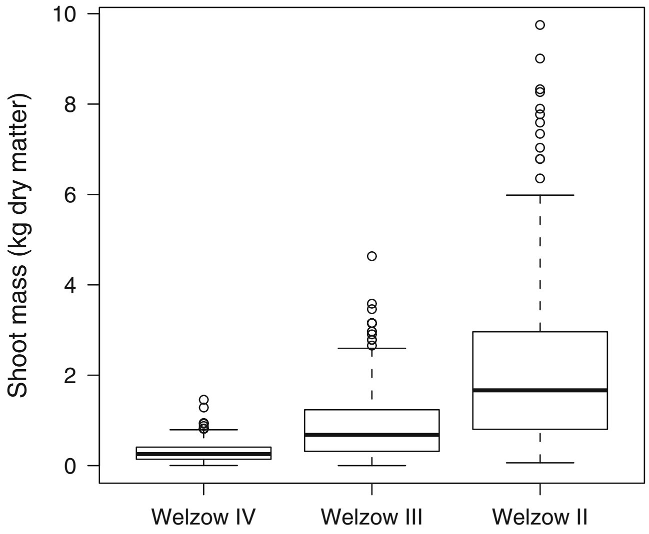

Fig. 5 Box-Whisker plot of shoot dry matter per plant for the Welzow IV, the Welzow III, and the Welzow II sites in 2008/2009 after 2, 3, and 4 years of growth, respectively ($n = 290–630$; *black bars*: median; *boxes*: lower and upper quartile; *whisker*: distribution maximum and minimum; *points*: outliers)

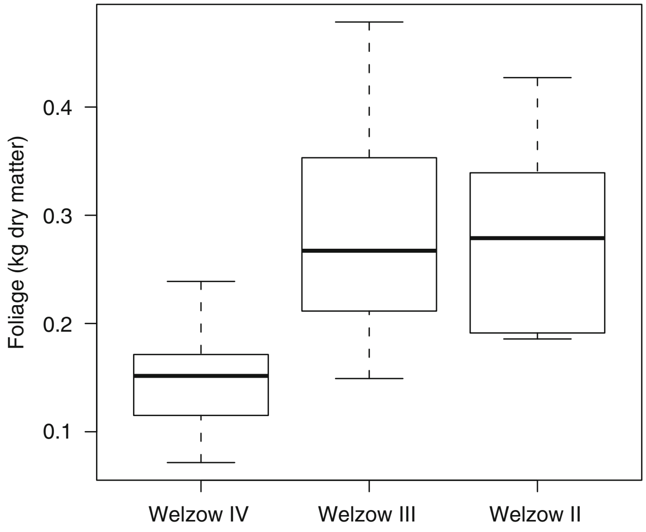

Fig. 6 Box-Whisker plot of foliage dry matter per plant for the Welzow IV, the Welzow III, and the Welzow II sites in 2008/2009 after 2, 3, and 4 years of growth, respectively ($n = 10$; *black bars*: median; *boxes*: lower and upper quartile; *whisker*: distribution maximum and minimum)

Table 2 Average foliage dry matter ($n = 10$) and average shoot dry matter ($n = 290–630$) per plant for the Welzow IV, the Welzow III, and the Welzow II sites in 2008/2009 after 2, 3, and 4 years of growth, respectively (standard deviation is given as error)

	Foliage (kg per plant)	Shoot (kg per plant)	Foliage + shoot[a] (Mg ha^{-1})year	Foliage:Shoot (%)
Welzow IV	0.14 ± 0.05	0.30 ± 0.23	4.13	32:68
Welzow III	0.29 ± 0.11	0.86 ± 0.75	10.58	25:75
Welzow II	0.28 ± 0.09	2.03 ± 1.58	21.26	12:88

[a] Assumed planting density was 9,200 trees ha^{-1} (Table 2)

The corresponding foliage biomass values were 1.3, 2.7, and 2.6 Mg DM ha^{-1}, respectively. The differences in foliage biomass are only significant ($p < 0.05$) between the youngest plantation (Welzow IV) and the other two (Welzow III and Welzow II) but not between the 3- and 4-year-old stands. The measured foliage biomass compares well with values reported in the scientific literature. Snyder et al. (2007) investigated the herbage biomass production of 5-year-old *R. pseudoacacia* stands in the southeastern USA and reported, for 0.25 and 0.5 m coppice heights, a mean productivity of 2.1 Mg DM ha^{-1} for trees planted at an intra-row spacing of 0.5 m (6,666 trees ha^{-1}) and 1.0 m (3,333 trees ha^{-1}), respectively. Burner et al. (2005) investigated the browse potential of *R. pseudoacacia* plants in Arkansas, USA. The authors sampled the shoots monthly for two consecutive growing seasons and determined across all treatments (including different fertilizer inputs) an average foliage biomass productivity of 3.5 Mg DM ha^{-1}. Papanastasis et al. (1997), however, reported from Greece a mean biomass production of leaves and consumable twigs of 1.03 Mg DM ha^{-1} for *R. pseudoacacia* stands planted at a spacing of 1.0 × 1.5 m (about 6,666 plants ha^{-1}) and annually coppiced over a period of 8 years.

Interpreting the three plantations as a pseudo-chronosequence and considering the sum for both the shoot and the foliage, the biomass production increased from 4.1 Mg DM ha^{-1} in the youngest to 21.3 Mg DM ha^{-1} in the oldest plantation. The percentage of foliage in total aboveground biomass decreased from 32 to 12 %. This was caused by a combination of a distinct accumulation of biomass within the shoot compartment in the older plants (Fig. 5) and a stagnation of total foliage biomass after the third year of growth (Fig. 6). Considering that even the oldest stand was only 4 years old, this could suggest increasing competition for light between the growing trees, which consequently causes a reduction in foliage biomass at the lower branches. Therefore, a shorter rotation interval or a lower planting density would most likely improve the biomass production efficiency of the plantation.

The C stock in the shoot, stump, and roots was investigated by Quinkenstein (personal communication, 2010) for three different aged SRC of *R. pseudoacacia* (Welzow I, Welzow II, and Welzow III). The dimensions of the stump depend on the cutting height of the harvesting machines used, which is currently about 10 cm. Therefore, the potential size of the stump pool is comparably small. Quinkenstein (2010, personal communication) reported an average share of 2 % for the stump compartment. Furthermore, it was found that the roots (sum of fine and coarse roots) contributed about 37 % to the total C stored within the plants while about 61 % was stored within the shoots. However, these may be considered as approximate values because of a high variability in the shoot:root ratios reported by Quinkenstein (personal communication, 2010) for the different aged plantations. Regardless of that, the study illustrates that in mature plantations, the amount of C stored in the roots and the stump was comparable to what is stored within the shoots. Using an estimated annual C storage of 4.2 Mg C ha^{-1} year^{-1}, this rate would imply an additional value of 0.1, 2.5, and 1.4 Mg C ha^{-1} year^{-1} stored in the stump, roots, and foliage, respectively (assuming 25 % foliage and 75 % shoot, according to the values for Welzow III in Table 2). These rates correspond to 0.4, 9.2, and 5.1 Mg CO_2 ha^{-1} year^{-1}, respectively.

Soil Carbon Accumulation

In SRC, the C accumulated within the biomass is the dominant C input source into the soil. It occurs via litterfall (aboveground as leaves, twigs, or bark pieces and belowground as fine roots or root exudates), and, thus, the C accumulated within plants is transferred into the litter layer and then, following microbial decomposition, incorporated into different soil C pools. In the Lower Lusatian region, only a few studies on soil C accumulation under SRC with *R. pseudoacacia* have been conducted yet. Matos et al. (2011) reported that SOC increased with plant age in the 0–3, 3–10, and 10–30 cm soil layers (Fig. 7), with SOC contents ranging from 10.4 to 32.1 gC kg^{-1}. The largest differences among depths were found under the 14-year-old plantation (Welzow I) where SOC declined by 41 % from the 0–3 to the 3–10 cm layer. There were no significant differences in SOC concentrations among the three soil layers in the 4- (Welzow II), 3- (Welzow III), and 2-year-old plantation (Welzow IV).

Furthermore, Quinkenstein et al. (2011) investigated the C accumulation under four SRC of *R. pseudoacacia* (sites Welzow I, Welzow II, Welzow III, and Welzow IV) down to a soil depth of up to 60 cm and a time period of 2–14 growth years. The authors reported total C stocks of up to 106 Mg C ha^{-1} for the 14-year-old plantation; using the different measurements to form a pseudo-chronosequence of growth, the authors estimated an average accumulation rate of about 7 Mg C ha^{-1} year^{-1} for the considered soil depth. However, Nii-Annang et al. (2009) working at the Jänschwalde site reported lower C accumulation rates in the topsoil (0–30 cm). They estimated a C accumulation of 3.4 mg C m^{-2} after 9 years of *R. pseudoacacia* cultivation, which corresponds to an annual accumulation rate of ~1.85 Mg C ha^{-1} year^{-1}. These studies illustrate a high potential of C storage under SRC with *R. pseudoacacia* at marginal reclamation sites. An average C accumulation rate in the soil of 3 Mg C ha^{-1} year^{-1} would mean an equivalent of 11.0 Mg CO_2 ha^{-1} year^{-1} sequestered in the soil. However, more long-term studies are needed. Such investigations should focus on the determination of turnover rates for different C pools in the soil and in the biomass and on the stabilization mechanisms of SOC in such plantations.

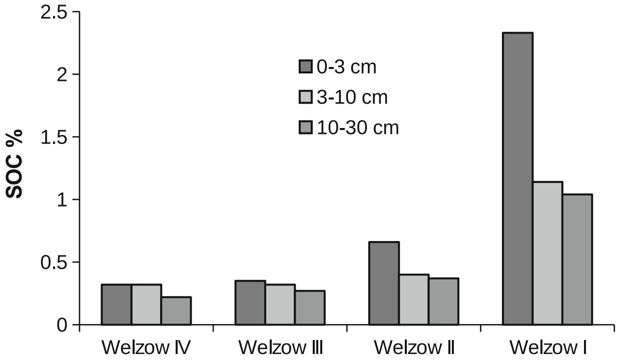

Fig. 7 Soil organic carbon (SOC) content for the Welzow IV, the Welzow III, the Welzow II, and the Welzow I sites after 2, 3, 4, and 14 years of growth, respectively (Source: Matos et al. 2011)

An Assessment of Ecosystem Services Provided by Agroforestry Systems

Agroforestry is a sustainable way of land use that integrates agricultural and forestry practices on the same land. It is of particular significance for marginal regions and degraded lands where this land-use system represents an alternative to land abandonment and afforestation, leads to diversification of land use, and offers new socioeconomic benefits including tourism and recreation. Agroforestry systems provide multiple benefits in addition to the possibility of biomass production for energy purposes. Among the ecological benefits reported from ACS are increase of C sequestration (Dixon et al. 1994; Montagnini and Nair 2004; Nair et al. 2010), climate-change mitigation and adaptation (Nair 2012), decrease of nutrient leaching (Udawatta et al. 2002; Nair and Graetz 2004; Palma et al. 2007), erosion control (Palma et al. 2007), soil fertility improvement (Schroth et al. 2003), improvement of microclimate by lowering wind velocity (Nuberg 1998) and increasing water availability (Böhm et al. 2009), support of organic farming (Jordan 2004), and enhancement of biodiversity (Burgess 1999; Klaa et al. 2005). Therefore, ACS attract more and more public attention as they offer a promising and comprising way for adapting agricultural production to climate change and providing ecosystem services (ES).

The concept of ES provides a link between ecology (ecosystem functioning) and economics (human welfare). Ecosystem services are derived from ecosystem functions which can be classified as production, regulation, habitat, and information (de Groot et al. 2002). Ecosystem functions are the physical, chemical, and biological processes that contribute to the maintenance of an ecosystem, while ES are provided by ecosystem's conditions and processes and directly or indirectly benefit human well-being (Fisher et al. 2009). Assessment of ES can be used as a tool to evaluate the success of landscape development with respect to selected target parameters for reestablishing ecosystem functions. The assessment requires evaluation of changes in ecosystem processes and structures (Farber et al. 2006). Integrated ecological-economic models provide a useful approach to valuing ES in complex, dynamic systems. However, under condition of insufficient data availability, the development of accurate models is difficult. A practical alternative is to consider the level of changes in ES derived from selected measurable parameters of the ecosystem (soil-plant system). Physical, chemical, and biological soil properties are measurable quantities which can be used to assess changes in ES.

The reclamation of post-mining landscapes primarily aims at restoring soil quality and C sequestration, which are important ES provided by land-use systems. In this context, the recovery of soil organic matter and organic matter turnover are crucial to the successful reclamation scheme in a disturbed ecosystem (Banning et al. 2008). The accumulation of SOC in the surface soil layer of reclaimed soil improves soil physical, chemical, and biological properties by reducing bulk density and increasing water-holding capacity and nutrient availability (Shrestha and Lal 2008, 2010). In general, SOC is a key attribute of soil quality vital to many of the soil functions (e.g., erosion control, nutrient cycling, and water infiltration and quality). Therefore, assessment of change in SOC is an important indicator of ES in terms of soil quality improvement and C sequestration. In a degraded, post-mining soil, changes in soil quality can be observed over a relatively short period of time (typically less than 10 years), analyzed by a pseudo-chronosequence. As demonstrated by the literature presented, establishing ACS at degraded post-mining sites in northeast Germany is a good option for accumulating SOC and restoring soil quality. Quinkenstein et al. (2011) reported an increase of SOC stocks from 22 Mg C ha^{-1} at the age of 2 years to 106 Mg C ha^{-1} at the age of 14 years for a depth of 0–60 cm under SRC in Lusatia. The total accumulation of SOC thus amounts to 84 Mg C ha^{-1} for the investigated pseudo-chronosequence. The change in SOC stocks corresponds to the change in soil quality and demonstrates the C sequestration potential of the system. Therefore, it is concluded that SRC and ACS established at post-mining sites in Lusatia have a high potential to improve soil quality and C sequestration, thereby contributing to ES.

Increase in SOC is related to biomass production. Cultivating species with a high potential for biomass production at post-mining sites indicates a high potential for SOC accumulation and improvement in soil quality. However, a comprehensive assessment of ES provided by agroforestry systems should consider (a) a biophysical assessment (e.g., potential to produce biomass and food; performance, limits, and constraints of different areas), (b) an evaluation of the C and nutrient budgets (e.g., impact of C sequestration on soil organic matter and biomass pools, as well as of microclimate modification by trees on soil organic matter stabilization processes, nitrogen and phosphate dynamics), (c) an assessment of landscape biodiversity (e.g., potential impact of agroforestry on biodiversity at the landscape scale, impact of the selected tree species on homogeneous arable lands, relationship between biodiversity and the proportion of the area occupied by nonarable (including agroforestry) and arable habitats), and (d) an assessment of benefits and sustainability (e.g., exploration of the sustainability functions and socioeconomic crosscutting issues of agroforestry systems, valuation of economic benefits of commercial and experimental agroforestry practices, assessment of the current state-of-the-art thinking on the ecosystem and economic benefits of integrating trees on farms, identification of best practice). These key issues provide current and reliable information on the interactions between land management, ES, and society. Further research is needed to document to which extent a more widespread implementation of agroforestry systems can further optimize the level of provisioning ES from a limited area of land.

Conclusions and Outlook

Surface mining is a worldwide phenomenon and causes significant landscape disturbance on the large scale leading to the complete loss of landscape functionality, composition, and structure. Management standards of reclamation – which differ distinctly and visibly among countries – aim at reestablishment of suitable land-use systems, including agriculture, forestry, surface water, areas for nature protection, and novel land-use systems such as ACS. Reclamation should be part of an integrated program of effective environmental management through all phases of mining.

In general, surface mine substrates prior to reclamation are mainly characterized by poor physical and chemical properties: strong compaction, poor water holding capacity, accelerated rate of erosion, unfavorable soil reaction ($pH < 3–4$), very low content of plant nutrients, and almost no organic C. But, reclamation has the potential for sequestration of C and improving the overall soil fertility. Assuming C sequestration as one major target parameter of the landscape development, one of the most beneficial reclamation measures is the establishment of agroforestry systems such as ACS.

Results of successful reclamation from literature show that the establishment of different trees species adapted to the specific site conditions is the most appropriate management practice to restore the soil fertility and accelerate ecological development. An additional added value can be obtained if fast-growing tree species are planted which offer the possibility to produce bioenergy. The results of the case study in Lusatia illustrate a high potential for C sequestration of SRC and ACS with *R. pseudoacacia* and therefore a high potential and effective method to mitigate CO_2 emissions caused by burning fossil fuels. A simple calculation based on the findings of the discussed studies show a C accumulation rate of about 30.0 Mg CO_2 ha^{-1} $year^{-1}$ as C in the biomass compartments (roots, stump, shoot, and foliage) or 24.9 Mg CO_2 ha^{-1} $year^{-1}$ stored in the longer-living woody plant parts (roots, stump, and shoot), respectively. Additionally, 11.0 Mg CO_2 ha^{-1} $year^{-1}$ would be sequestered as C in the soils of such land-use systems in Lusatia, Germany. Therefore, the results are of significant importance for post-mining sites in European as well as oversea countries. Long-term studies of C accumulation in SRC and ACS are essential to be able to reliably predict C storage potential of such plantations even under changing environmental conditions. Furthermore, special focus should be placed upon investigating the turnover processes within the biomass and within the soil C pools as well as on C stabilization mechanisms in soil. In this context, questions concerning the share of stabilized SOC and thus long-term C sequestration should be clarified.

End Note

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The Satoyama Landscape of Japan: The Future of an Indigenous Agricultural System in an Industrialized Society

Kaoru Ichikawa and Gregory G. Toth

Abstract Satoyama refers to an indigenous agricultural system of Japan that evolved through long-term interaction between human beings and their local environments. As in many indigenous agricultural systems, it is characterized by integrated landscapes comprised of diverse uses including, but not limited to, paddy fields, farmland, managed and secondary woodland, grasslands, irrigation ponds and canals, and human settlements, all located in close proximity to one another. In environmental terms, this land use variety translates into "biodiversity," a benefit that synergistically aids both the human inhabitants and the nature it consists of. Further benefits include sustainability, supplemental income, building materials and food, adjusting local microclimate, flood prevention, and culture preservation. Satoyama landscapes, like other systems based on indigenous knowledge around the world, have suffered a period of decline. Efforts are being taken in Japan to revive and conserve these systems and the indigenous knowledge and cultural heritage they represent, and international initiatives (e.g., the *Satoyama* Initiative) have begun to collect and distribute relevant information on these systems, such as management techniques and cultural value, in hopes of aiding biodiversity-focused land use and the associated human benefits everywhere.

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Introduction

With growing awareness about the adverse impact of high-input agriculture involving heavy use of agrochemicals, the importance of traditional, integrated land use systems is increasingly being recognized. These systems are based upon indigenous knowledge (IK), developed over generations of interactions between communities and their surrounding environments. In many parts of the world, IK has considerably contributed to conservation and enhancement of biodiversity through sustainable agricultural and natural resource management practices, with the support of institutional systems based on the view that environments and societies are inexorably linked (Berkes et al. 1995). For example, diversified cropping is of particular importance as the interactions it facilitates among crops, animals, and trees create advantageous synergisms that typically allow these ecosystems to promote their own soil fertility, pest control, and productivity (Altieri 2005). However, many forms of indigenous practices are becoming endangered by modernization of farming techniques, land use dynamics, and, oddly, some of the conservation practices (Oudenhoven et al. 2010) that are based on the assumption that nature and human society are separate entities.

Satoyama is an indigenous land use system traditionally practiced in Japan and a prime example of a sustainable agricultural system based on IK. It evolved through long-term interaction between human beings and their local environments involving "frequent but undestructive exploitation and interventions by farmers" forming its mosaic-like appearance (Fig. 1) of secondary forest, water bodies, paddy fields, crop fields, and grasslands maintained through "pruning, mowing and weeding, burning, and irrigation and drainage management" (Kato 2001). However, such characteristics are contradictory to the standard concept of environmental protection that emphasizes exclusion of human impacts. In addition, satoyama landscapes, like so many other systems based on indigenous knowledge around the world, have suffered a period of decline in a changing world marked by population increase, technological advances, and an increasingly globalized economy. This chapter illustrates the importance of satoyama landscapes and indigenous knowledge, analyzes the dynamics of the system in Japan, and discusses its principles and conservation measures that may be applicable elsewhere.

The Satoyama Landscapes

Background and Essential Features

Originally, the term "satoyama" represented the woodlands that were used for supporting agricultural production and obtaining fuelwood and charcoal (Shidei 1974)

Fig. 1 The mosaic feature of the satoyama landscapes in Japan (Photo: K. Ichikawa)

in Japan. Etymologically, *satoyama* originated from “sato” meaning village and “yama” meaning wood or grassland. It implies the closeness of the woodland to villagers’ lives, not only spatially but in terms of their interdependence. The woodlands supplied numerous resources: necessities such as firewood, charcoal, organic manure, fodder, thatch, medicinal plants, mushrooms, and other edible wild plants, to name a few. Beyond sustenance, selected resources such as firewood and charcoal were also important as some of the few sources of income for farmers. Later, as the importance of satoyama and its neighboring environments became better understood by people involved with nature conservation, the term “satoyama” came to be used in a wider sense. For example, since around the 1980s, the term has often been used to mean not only woodland but also a set of land uses including woodlands, agricultural fields, settlements, irrigation ponds, and canals. While there is no unified definition, this chapter will use “satoyama landscapes” (SL) for such interlinked sets of agricultural landscapes and “satoyama woodlands” (SW) for secondary woodlands in satoyama landscapes (Takeuchi, 2003).

Satoyama landscapes are often described as being located between cities and *okuyama*, or “deep mountains.” However, clear spatial delineation is difficult because their structure, pattern, and scale are locally dependent, and the transition from SL to city or from SL to okuyama is usually continuous. In spite of these characteristics, the Ministry of Environment of Japan attempted to assess the current area of satoyama landscapes in Japan by setting criteria for the major components,

Fig. 2 A rice paddy field and adjacent woodlands in a typical satoyama landscape in Kanto District, Japan (Photo: K. Ichikawa)

that is, secondary forest, farmland mixed with secondary forest, and secondary grassland (Ueda 2002). The results show that up to 40% of the national territory of Japan is satoyama landscapes.[1] As Japan stretches from 45°51′N to 20°25’N, containing several different climate zones, the vegetation of satoyama woodlands varies. These variations are primarily the result of climatic and edaphic conditions and how they are managed. Four types of satoyama woodlands have been identified in terms of vegetation: mizunara (*Quercus crispula* Blume), konara oak (*Q. serrata* Thunb. ex Murray) (Fig. 2), red pine (*Pinus densiflora* Siebold & Zucc.), and evergreen broad-leaved species such as *Castanopsis sieboldii* (Makino) Hatusima ex Yamazaki et Mashiba and *Q. myrsinaefolia* Blume.

In many satoyama landscapes, communal use of woodlands and grasslands was established during the feudal period of Japan (commonly referred to as the Edo Era, 1603–1868). In the modernization process of the following period (Meiji Era: 1868–1912), a policy to separate land ownership into either private or public was undertaken. Extensive amounts of land that had been owned by communities were designated as public and taken away from villagers, although some were approved for collective use by communities under Civil Code as a result of farmers’ strong requests (Otsuka et al. 2009).

Biodiversity Benefits of Satoyama

As previously mentioned, satoyama landscapes present a mosaic pattern created by different land uses each with its own associated plants, constituting habitats for a wide variety of animals and insects, and resulting in a high degree of biodiversity. This structure allows various organisms to move among habitats and use different habitat types to obtain different resources (Katoh et al. 2009). This is particularly important for species such as dragonflies and frogs that live in water environments early in life and move to woodland and grassland environments as adults. Similarly, birds of prey often breed in woodlands but prey in grassland and wetlands (Azuma 2003; Washitani 2003).

In addition to this structure, management of satoyama landscapes is critical to maintaining their biodiversity. In satoyama woodlands, after trees such as *Q. acutissima* and *Q. serrata* are cut to harvest firewood and charcoal, the stumps of the trees are left to sprout so they can be harvested again after 15–30 years. Traditionally, farmers thinned and cleared the underbrush in order to obtain stems and fallen leaves and grasses needed for compost and fuels, which simultaneously allowed regeneration of new sprouts. The collection processes were closely guided, especially in communal woodlands and grasslands, by community rules that prevented overexploitation of natural resources. High species richness is maintained by these anthropogenic intermediate disturbances (e.g., coppicing) that serve to protect habitats that would otherwise be overtaken by a smaller number of competitive species. For example, without disturbance of the vegetation, bamboo grass (*Pleioblastus chino* Makino) becomes dominant in the shrub and herb layers and evergreen tree species become dominant in the tree layers in the Kanto district, which would result in a decrease of diversity (Washitani 2003). The spread of other types of bamboo, such as *Phyllostachys pubescens* Mazel ex J. Houz. which was vegetated in limited areas such as near residential zones for use as building materials and commodities, is now becoming another problem (Suzuki and Nakagoshi 2011). At an even deeper level, litter removal from the woodland floor for use as fertilizer inhibits soil eutrophication which suppresses domination of competitive species and allows diverse species to survive. Grasslands and paths between fields harbor numerous grassland species while irrigation ponds, irrigation ditches, and paddy fields are suitable habitats for aquatic macrophytes, amphibians, aquatic insects, water birds, fishes, etc. (Amano et al. 2008; Kadoya et al. 2009). Selective clear-cuts continue the mosaic theme even within landscape elements, allowing vegetation age differences among patches within forest (Washitani 2003). Due to the unique characteristics associated with various stages of forest growth, this continued succession further propagates the richness of biodiversity and host environments.

Benefits to Humans

Using the framework of the sub-global assessments (SGA) developed by the United Nations Millennium Ecosystem Assessment (MA), the Japan Satoyama Satoumi

Assessment (JSSA) identified and assessed the ecosystem services provided by satoyama landscapes and their associated changes (JSSA 2010). As mentioned above, satoyama woodlands provide a variety of materials for buildings, furniture, agricultural activities such as poles or baskets, fuels, food, and medicines; grasslands provide materials for fodder, thatch, and compost, while farmlands and paddy fields produce a variety of foods including rice. In addition to these many provisions, satoyama landscapes provide regulating services. The Science Council of Japan[2] identified and evaluated multiple functions of agricultural lands and forests including, for example, adjustment of local microclimates and air and water quality through phytoremediation, prevention and/or mitigation of flooding through retention of water in paddy fields which are framed by levees, and prevention of soil erosion through processes such as detection and repair of damaged agricultural lands at early stages.

The human inhabitants of the satoyama landscapes benefit in more ways than would be immediately apparent from their interactions with nature. For Japanese people, there is existence value to some of the species that benefit from these human influenced environments. The maintenance of secondary woodlands creates suitable environs for these species. For example, larvae of the national butterfly (Omurasaki (The Great Purple) *Sasakia charonda*) depend on the host tree *Celtis sinensis* Pers. var. *japonica* Nakai, a typical species in managed satoyama woodlands, and the adults feed on sap that is only secreted from younger *Q. acutissima* Carruth. trees. Some areas are used for shiitake mushroom (*Lentinula edodes* Berk.) production in special, aged woods, which, upon completion of their expected services, are brought back to decompose on the forest floor, providing the specific habitat necessary for the grubs of the Japanese rhinoceros beetles (*Allomyrina dichotoma*) – a valued symbol of Japanese youth and organic material for the soil.

Cultural Significance

Satoyama landscapes have and continue to offer rich cultural services. In the same long-term process between humans and nature that developed the satoyama landscapes, much traditional knowledge such as farming and forestry practices and use of medicinal plants has been accumulated (JSSA 2010). Furthermore, many Japanese regard satoyama landscapes as sources of aesthetic beauty (often describing satoyama as idyllic rural images) and value them with nostalgia for their recreational benefits. Satoyama landscapes also provide spiritual benefits: rituals and festivals hoping for or celebrating agricultural fertility are still performed in many communities.

Cultural, natural, and historical features of the satoyama landscapes are the base of the identity and uniqueness for the regions of Japan where they exist. Additionally, satoyama landscapes have become increasingly valued in the context of regional development both in urban and rural areas and are even being recognized in recent governmental policies and laws. The policy for making “attractive agricultural landscapes"[3] shows the government's recognition that the unique and beautiful scenery of agricultural areas reflects the diverse natural and cultural conditions shaped in those areas. Similarly, the "Law for the Protection of Cultural Properties" was amended in 2004 recognizing the cultural value of landscapes that have developed in association with the modes of life or livelihoods of people and the natural features of the region by including the new category of "cultural landscape."

Satoyama in Decline

Mirroring the fate of many other indigenous systems throughout the world, the number of satoyama landscapes within Japan has been in decline for quite some time. Rapid economic growth in Japan following World War II brought many changes to satoyama landscapes due to urbanization and modernization both in terms of land use and lifestyles of the inhabitants. Responding to the rapid population increases in urban areas, large-scale development projects replaced the agricultural fields and woodlands in the periurban areas, such as the outskirts of Tokyo (Ichikawa et al. 2006). A number of golf courses and other resort facilities were constructed in rural areas supported by policies aiming to boost local economies and thus correct the economic disparities that had existed between urban and rural areas. This resulted in the destruction of the natural environments of the satoyama landscapes. In rural areas, the other side of urbanization, outward migration, took effect as depopulation and aging of rural populations furthered the abandonment of the surviving wood and agricultural lands. Beyond the encroachment of these urban areas, those that continue to live in satoyama landscapes face financial difficulties as many of the products they once obtained for use and sale from the SLs are now purchased from overseas and replaced with modern equivalents, such as biomass fuels like charcoal and firewood being supplanted by fossil fuels and farmers becoming more dependent on chemical fertilizers rather than compost from woodlands. These changes decreased the need for the woodlands which were then left unmanaged, allowing the natural succession of vegetation, which in turn caused the loss of many species dependent on the environment once created by human intervention. As the SLs are the habitats and growth environments for many endangered species of plants and animals, their loss becomes a matter of conservation with "underuse" as the serious issue rather than overexploitation. In addition, the changes brought about by urban development not only diminished the number of SLs but also affected the beauty and uniqueness of those that remain, as removal of elements that no longer have a practical purpose affects the overall landscape, leading to less inspired (and less biodiverse) styles of landscapes becoming more ubiquitous. There have been several research projects within Japan highlighting the decline of SLs; two such projects that demonstrate regional uniqueness and public perception of the landscapes concerning the Tokyo Greater Area are mentioned here.

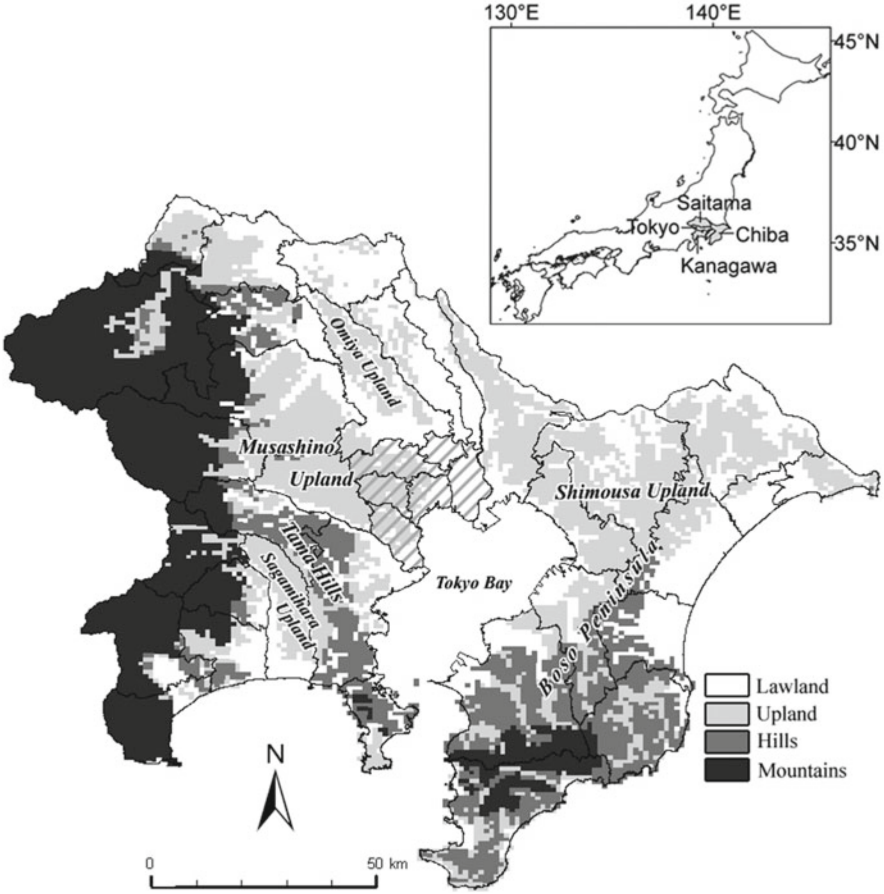

Fig. 3 Location of the Tokyo Greater Area (TGA), Japan, and the boundaries of counties and landforms. The map in the *upper right* shows the location of the TGA in Japan, which is comprised of the Tokyo Metropolis, Saitama, Kanagawa, and Chiba Prefectures. An administrative unit of "county" (one order lower than a prefecture) was used as a unit of data collection and analysis (Source: Modified after Ichikawa et al. 2008b)

Changes in Regional Differences of Landscapes in the Tokyo Greater Area

The Tokyo Greater Area (TGA) is composed of the Tokyo Metropolis and three surrounding prefectures: Saitama, Chiba, and Kanagawa (Fig. 3). Tokyo, one of the largest cities in the world today, has been the center of politics and governance in Japan for about 400 years. Beginning in the Edo Era, the central part of what is now Tokyo (called Edo) became the epicenter of Japan's feudal system with SLs spread through all the surrounding areas in order to provide for the needs of this burgeoning capital. After the end of the Edo Era in 1868, and especially after the end of World War II in 1945, rapid urbanization took place in the TGA drawing people from rural areas all over Japan. As a consequence, the population of the TGA increased from 4 million in 1884 to 12 million in 1950 and 34 million by 2009 within an area of 13,600 km^2.

The TGA varies in topographic conditions (Fig. 3) and can be divided into four major types of landforms: lowland, upland, hilly, and mountainous. Lowlands are mainly in the middle of the region from north to south. Several uplands are distributed through the middle of the region in addition to a wide area of upland called Shimousa Upland located to the east. There are some hilly areas in southern peninsula and between the uplands and mountainous areas to the west.

A recent study evaluated the structure of the landscapes of 41 counties, represented by their land use compositions[4] and major forms of woodland vegetation (Ichikawa et al. 2008b), in order to understand the regional difference of the SLs and their succession. Land use and vegetation data for 1910, 1960, 1980, and 2000 were obtained from statistical figures (yearbooks kept by local government and information from the national agricultural census). The data were analyzed using GIS in order to examine their relationship with landform. In 1910, landscapes in the TGA were diverse in structure. Throughout the TGA, land use patterns varied, with paddy fields, farmlands, and woodlands spread the most widely and urban land use occupying less than 10% of each county (Fig. 4). As a whole, land use in 1910 was generally distributed in a way that corresponded with the distribution of landform. Socioeconomic factors such as local industries, which needed fuels made of certain preferred species, also seemed to have affected differences in woodland vegetation. This was most clearly observed in counties located in the upland areas, while woodlands in eastern uplands were largely dominated by pine, and woodlands in some parts of the western uplands were dominated by broad-leaved species.

Analysis of the landscape structures in later years (1960, 1980, and 2000) showed that the arrangement of the satoyama landscapes in the TGA had largely changed. After 1960, urbanization proceeded much more quickly than before, especially within a 50 km radius of the center of Tokyo. By 2000, despite a few pairs that had initially shown the strongest correlation between land use and landform remaining similar to their initial condition, more than 25% of the areas were dominated by urban land use, regardless of landform (Fig. 5). In contrast to the increase of urban areas, paddy fields, farmlands, and woodlands decreased largely in these areas. Infrastructure development, technological advances, and landform transformation contributed to accelerated urban development; location (not suitable location) became more influential to urban development than landform. A good example for this phenomenon is the Tama New Town started in1966; it is a planned development on 2,900 ha providing housing for 340,000 people, in the Tama Hills of western Tokyo.

Drastic changes in woodland vegetation after 1910 are obvious when comparing the distribution of woodland vegetation at that time with that in 1980 and 2000. An outbreak of pine wilt disease caused by the nematode, *Bursaphelenchus xylophilus,* and air polluted with sulfur dioxide from nearby industries caused extensive damage to pine woodlands, reaching peak destruction in 1979.[5] By this time, demand for

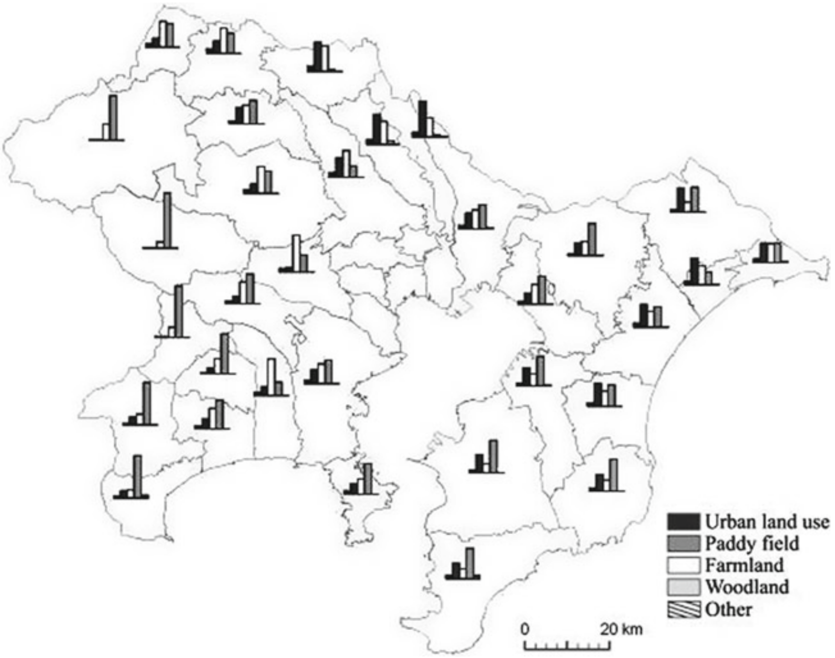

Fig. 4 Relative distribution of various land uses in Tokyo Greater Area (TGA), Japan, 1910. The data were obtained from statistical figures from yearbooks published by each prefectural government[4]

pinewood as fuel largely decreased with the shift to fossil fuels. Furthermore, a policy to extend forestation areas was promoted after World War II in response to the increased demand for new houses. These areas were subsequently used for replanting of Japanese cedar (*Cryptomeria japonica* D. Don) and Japanese cypress (*Chamaecyparis obtusa* (Siebold & Zucc.) Endl.) trees, or left abandoned during periods of low demand for land, allowing for natural regrowth of broad-leaved trees. Through these transformations, satoyama landscapes in the TGA were drastically altered by the year 2000 resulting in decreased structural diversity. Currently, landscapes within 50 km radius of Tokyo are of uniform structure, dominated by urban land use, with the remaining woodlands mainly composed of broad-leaved species and some Japanese cedar and Japanese cypress.

Local Stakeholder's Perception of Past Woodland Vegetation

The local stakeholders of three different study sites previously considered SLs (altered by the aforementioned urbanization process) were selected to conduct a questionnaire survey on their recognition of the past vegetation. Three types of local stakeholders were considered in terms of their relationship with the satoyama

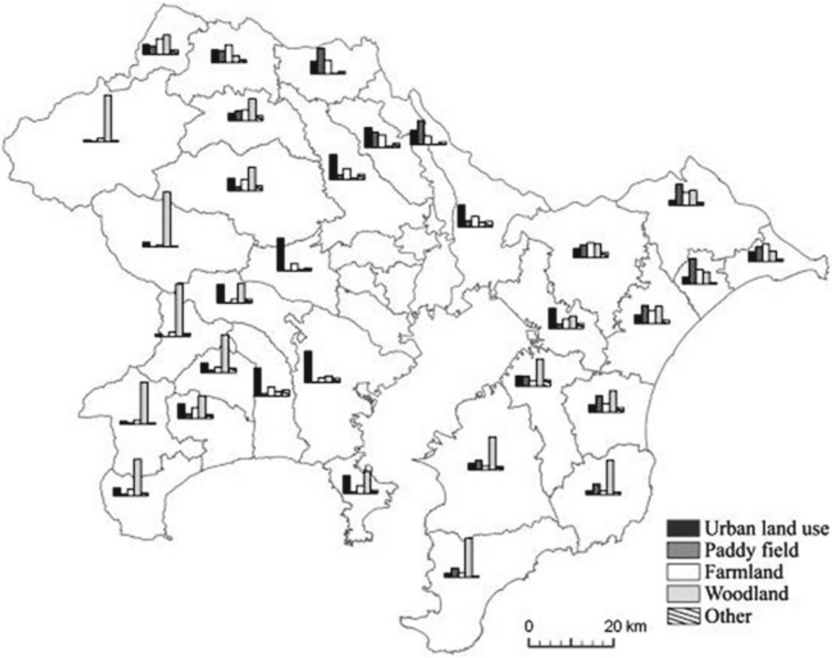

Fig. 5 Relative distribution of various land uses in Tokyo Greater Area (TGA), Japan, 2000. The data were obtained from statistical figures from yearbooks published by each prefectural government[4]

woodlands, namely, longtime residents (communities existing since before the 1920s), new residents (communities living in areas developed in the 1960s), and volunteers (from groups that work to conserve satoyama woodlands). The three selected study sites were again located within a 50 km radius of Tokyo. In the survey, the local stakeholders were encouraged to recollect their memories of the previous states of woodlands and the data so collected were analyzed.[6] This allowed for comparison of the local residents' interpretation of the past woodland in each of the study sites and the actual past condition (based on old maps and aerial photographs).

The results of the survey (Fig. 6) show that the local people's perceptions of the past woodland vegetation of these areas differed. Longtime residents, who were thought to be knowledge transmitters, knew the most, but they were few in number. The volunteers who actually manage the woodlands had less (and sometimes biased) knowledge, depending on the group's characteristics. Newer residents had the least knowledge of past woodland vegetation. Communication among these groups should be helpful in decreasing the knowledge gaps. However, even this may not be sufficient for transmission of accurate knowledge of past conditions, given that no group had a complete grasp of the information. The use of objective references such as old maps and aerial photographs should help facilitate proper understanding of the past landscape and thus improve understanding of regional characteristics in a historical context.

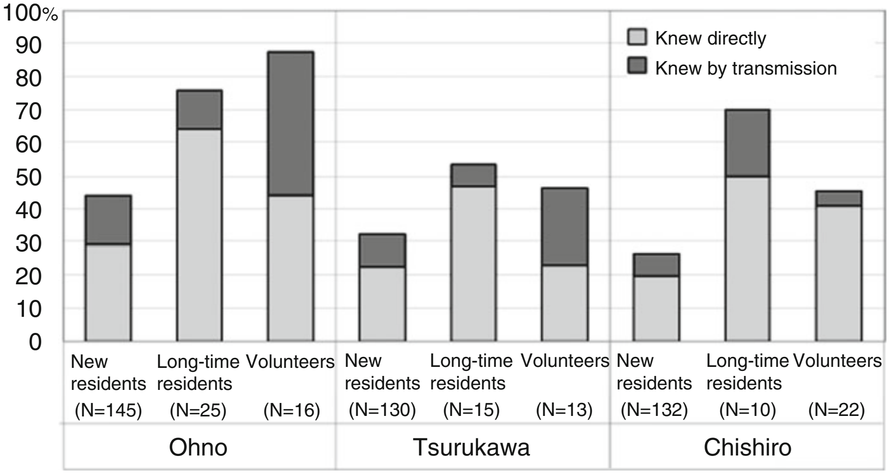

Fig. 6 Recognition of past woodland vegetation by different local stakeholders in three different study sites in Tokyo Greater Area (TGA), Japan. Three types of local stakeholders (long-term residents since before the 1920s, new residents since the 1960s, and volunteers from groups that work to conserve) in each of three different study sites were selected to conduct a questionnaire survey on their perceptions of the past vegetation[6]

Satoyama: Looking Forward

Decrease and abandonment of the satoyama landscapes during the rapid economic growth after the late 1960s ironically promoted gradual development of awareness and interest among Japanese people to the value of the satoyama landscapes. Today, many conservation and restoration efforts at local and national levels are taking place in response to the SLs' decline. A report by the Nature Conservation Bureau, Ministry of the Environment of Japan[1], counts as many as 972 volunteer groups doing activities in SLs in 1,023 fields within Japan. Another survey by the Forestry Agency records an increase in the number of volunteer groups that work in woodlands and forests. While there were only 277 groups in 1997, the number increased to 2,677 by 2009, 73% of which were working on management of satoyama woodlands.[7] Today, volunteers play an important role in the management of woodlands in urban environments.

However, considering the reasons for the decline of the SLs, it is apparent that the traditional management system in SLs will not work effectively under the present socioeconomic environment (Katoh et al. 2009) and volunteer management alone will not be enough to sustain them in perpetuity (Tsunekawa 2003). Yokohari and Bolthouse (2011) suggests the dynamic nature of SLs stems from having changed over time synchronous to the evolving needs of successive generations, necessitating recognition of the importance of contemporary needs in redeveloping relationships between communities and nature. Thus, new uses of SLs must be explored for their survival. For example, growing awareness among consumers of the need for food safety measures and environmental conservation may support the revitalization of SLs by paying attention to the growing number of certification systems to identify goods produced under environmentally friendly conditions in SLs. Certain fauna species such as the Oriental stork (*Ciconia boyciana*) and Japanese medaka fish (*Oryzias latipes*) are often used to symbolize these agricultural activities, such as reducing or not using pesticides or chemical fertilizers and flooding paddies in winter time (for restoring the biodiverse environment key to that particular species). For example, 39 brands of rice are now identified as being produced in this way.[8] Moreover, many new uses for the woody biomass from SWs as an energy source are also being explored (Terada et al. 2010). Additionally, these systems are being looked at for their ability to enhance carbon sequestration, contributing directly to climate change mitigation (Nair et al. 2009; Nair 2012). The beautiful scenery, local foods, and variety of nature and cultural activities in each satoyama landscape are expected to continue to increase tourism, revitalizing the economies of these rural areas suffering from depopulation. To promote this, the Ministry of Agriculture, Forestry, and Fisheries (MAFF) proposed in 1992 an overnight-stay activity in rural areas called “green tourism” and enacted a law to further facilitate green tourism in 1994. Moreover, the SLs provide an excellent setting for environmental education. Ultimately, efforts that do not consider the synergies and trade-offs between ecological and communal welfare are unlikely to be effective (Chapin et al. 2009).

Global Relevance of Satoyama

Satoyama landscapes are excellent examples of indigenous systems that are environmentally sustainable, biodiverse, and able to appropriately provide for their human inhabitants. Considering the variety of issues that global societies are facing, such as biodiversity degradation, poverty, climate change, and food security, the multifunctional aspect of IK systems and characteristics which support these functions should be clearly recognized. Such multifunctionality can be understood by using the framework of Millennium Ecosystem Assessment, which groups different types of ecosystem services (provisioning, regulating, cultural services). The basic overriding principles of traditional SLs that are common to most IK systems, such as the mosaic of land uses, maintenance of closed cycles of materials and wastes, and application of traditional knowledge and techniques, result in high species numbers and structural diversity (Gliessman 1998; Altieri 2005), making it an excellent example for understanding the significance of IK systems in general. A measure for assessing this agricultural landscape heterogeneity and the contribution of nonagricultural land use has been proposed by Kadoya and Washitani (2011) in the form of a Satoyama Index. While there are basic commonalities within various IK systems around the world, each landscape has distinguishing features, as each has evolved under different natural and social conditions. Comparing agroforestry in the Western

Ghats in India and SLs, Kumar and Takeuchi (2009) pointed out similarities such as basic landscape structure, multifunctionality of the system, high biodiversity, and potential to reduce carbon in the atmosphere. They also identified some of the differences including canopy architecture (the multi-tiered structure of agroforestry and the more or less unitary canopy of satoyama) and land ownership pattern (privately owned/managed agroforestry holdings vs. community local government or private ownership). Therefore, further research is necessary for exploring the realistic transference of management techniques between cultures. One manner of approach would be the deciphering of the current "black box" situation of many elements of IK systems (in which the necessary inputs and the typical outputs are understood but many of the underlying interactions are not fully charted) and further scientific understanding of the nature of these systems and the indigenous knowledge associated with them that has stood the test of time.

Just as in Japan, IK-based systems are diminishing and degrading throughout the world: victims of urbanization, industrialization, modernization of agriculture and forestry and fishery techniques, population increase, aging of rural population, and the resulting loss of biodiversity. As many of these forces are similar throughout the world (Ichikawa et al. 2010), comparing the systems, the benefits they provide, and the measures they take will help determine the next steps to follow. Based on this understanding, the *Satoyama* Initiative was initiated jointly by the Ministry of the Environment of Japan and the United Nations University Institute of Advance Studies. The International Partnership for the *Satoyama* Initiative (IPSI) was established as a platform for collaboration among a broad range of entities and organizations for conservation, restoration, and revitalization of such systems toward its vision of "realizing society in harmony with nature." The *Satoyama* Initiative builds on the understanding that if the interactions between humans and nature are properly maintained, the result is landscapes which sustain healthier ecosystems and biodiversity, while at the same time contributing to human well-being. The recognition that ecological, social, and economic aspects are linked to each other in these landscapes has led to the coining of the term "socio-ecological production landscape" to describe the target area of the *Satoyama* Initiative.

The fact that other initiatives with similar orientations exist attests to the general belief by the global community in the importance of IK. One example is the GIAHS (Globally Important Agricultural Heritage Systems) begun by the Food and Agriculture Organization (FAO) in 2002. The GIAHS refers to remarkable land use systems and landscapes which are rich in globally significant biological diversity evolving from the coadaptation of a community with its environment and its needs and aspirations for sustainable development.[9] By identification and registration of these systems, GIAHS seeks to promote international recognition, conservation, and sustainable management, supporting food security and agricultural biodiversity in conjunction with their contributions to natural landscapes, cultural heritage, and indigenous knowledge systems (Boerma 2002).

Considering the ever evolving needs of society and the current situation of SLs and other systems based on indigenous knowledge described above, adjustments and innovation are needed to respond accordingly. For example, satoyama is being considered for meeting more recent types of demands as well: the utilization of biomass for energy production and the concept of the high carbon stock potential of such systems in Japan are being studied (Yokohari and Bolthouse 2011; Terada et al. 2010), which helps set precedence for similar studies elsewhere. While these types of resources are not enough to meet the energy needs of an entire country, they may be able to provide reasonable supplements when worked into a mixed energy source system and, in doing so, provide good secondary income to the communities who are in charge of managing these environmentally crucial landscapes.

In periurban areas of Japan, even though the encroachment of cities has largely changed satoyama landscapes, there are still woodlands and agricultural lands that have "survived" the rapid urbanization; some are still privately owned by (former) farmers, but others, especially the woodlands, are designated as parks or nature conservation areas, which prevent them from being converted to urban land uses. It is important to conserve the remnants of former agricultural landscapes, as more than half of the global population lives in or around such new urban and periurban areas today. These areas are important for creating good environments and atmosphere and providing nearby places where people can go to enjoy nature.

Considering the historic and symbolic associations of woodlands and trees (O'Brien 2005), in Japan, the remaining SLs are also valuable symbols of each region's unique characteristics, history, and culture. The process of understanding the past landscapes and their changes also provides a valid context in which to identify issues, problems, and desired outcomes in planning (Marcucci 2000), as well as useful wisdom or inspiration for future management, restoration, and creation of landscapes (Antrop 2005). Recognition of the unique characteristics of regional SLs by local stakeholders, bearing in mind historical perspectives, an provides an important foundation for regional development which other countries with similar circumstances may take note of.

Conclusions

Each indigenous knowledge system is essentially location specific. Even within Japan, landscapes are regionally shaped over time based on local landform, land use, vegetation, and socioeconomic requirements. However, the basic overriding principles among SLs and other IK systems in the world, as well as issues facing them, are similar. There are also lessons others can observe in Japan in terms of treatment of such systems within an industrialized country, be it via cultural or governmental recognition. Further approaches must be explored not only to conserve or restore but also to revitalize the satoyama landscapes. These must meet with contemporary needs of the societies with which they are associated. International efforts to share information are essential in order for similar systems throughout the world to deal with common issues brought on by continuing globalization.

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South Asian Agroforestry: Traditions, Transformations, and Prospects

B. Mohan Kumar, Anil Kumar Singh, and S.K. Dhyani

Abstract The South and Southeast Asian region is often described as the cradle of agroforestry in recognition of its long history of the practice of an array of systems under diverse agroecological conditions. The multitude of systems that have evolved in the region over long periods reflect the accrued wisdom and adaptation strategies of millions of smallholder farmers to meet their basic needs of food, fuelwood, fodder, plant-derived medicines, and cash income in the wake of increasing demographic pressure and decreasing land availability. Prominent examples of agroforestry in South Asia include multifunctional homegardens, which promote food security and diversity; woody perennial-based systems furthering employment avenues and rural industrialization; fertilizer trees and integrated tree-grass/crop production systems favoring resource conservation; and tree-dominated habitats, which sustain agrobiodiversity and promote climate change mitigation. The experiences from these dominant land use systems exemplify the role of agroforestry in addressing the land management challenges of the twenty-first century such as climate change, biodiversity decline, food and nutritional insecurity, and land degradation in this highly populated region. The thread running through this chapter is that traditional agroforestry systems that have been practiced over centuries have evolved and adapted to the changing pressures. Such transformations have been a potent means to address some of the present-day global challenges; their efficiency, however, can be enhanced considerably with the input of additional resources and support.

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Introduction

South Asia comprises of the sub-Himalayan countries and the adjoining tracts to the west and the east. High levels of topographic and climatic heterogeneity are intrinsic features of this region. Important South Asian ecologies include the hilly and mountainous areas, Indo-Gangetic plains, arid and semiarid regions, and the coastal humid zones. Afghanistan, Bangladesh, Bhutan, India, the Maldives, Nepal, Pakistan, and Sri Lanka are the principal countries in this region. Most of South Asia and the adjacent territories (popularly known as the Indian subcontinent), which became sovereign nations at different times in history, share close cultural and social values, which are reflected in land use also. Rich natural resource endowments in terms of vegetation, soil, animal, and fish make South Asia a mega-biodiverse region. High demographic pressure (Table 1), however, has led to over-exploitation of natural resources including timber and non-timber forest products (Muraleedharan et al. 2005; Gunawardene et al. 2007). This, together with agricultural intensification, has resulted in rapid biodiversity losses (Kumar 2005; Vencatesan and Daniels 2008) making the Western Ghats and Sri Lanka region as well as the Eastern Himalayas "biodiversity hot spots" of the world (Myers et al. 2000).

Agroforestry systems and practices abound in South Asia, especially in countries such as India, Sri Lanka, and Bangladesh, since time immemorial (Singh 1987). Biophysical heterogeneity and the capacity of such systems to satisfy the needs and aspirations of the local people by providing them with multiple products and services would probably explain this. An attempt is made here to summarize the long history and diversity of South Asian agroforestry systems and practices; their potential to meet the ever-increasing food, fuel, fodder, and timber requirements of the society; and synthesize the available information on ecosystem services (e.g., climate change mitigation and agrobiodiversity conservation potentials) of these systems. This chapter covers broad aspects of agroforestry, from technology, economics, management, and policy in a regional perspective, and focuses on how agroforestry might be sustained and promoted as desirable land use strategies amid competing interests and pressures.

The diverse agroforestry systems practiced over centuries in this region also have undergone transformations in response to changing pressures. Although such transformations reflect the great potential of agroforestry in resolving many of the world's challenges, the level at which it is applied needs more thrust and encouragement. The focus, therefore, is on how agroforestry might be sustained and promoted as improved land use strategies amid competing interests and pressures. The approach adopted in this analysis is to review the archaeological and literary evidences and draw inferences from past experiences and current propensities. The chapter also aims to

Table 1 Land area and demographic attributes of South Asia

		Population 2008			
Country	Land area (1,000 ha)	Total (1,000)	Density per km^2	Annual growth rate (%)	Per capita GDP 2008 (US $)
Afghanistan[a]	65,223	29,840	41.7	3.5	466
Bangladesh	13,017	160,000	1,229	1.4	1,335
Bhutan	3,839	687	18	1.6	4,759
India	297,317	1,181,412	397	1.4	2,946
Maldives	30	305	1,017	1.3	5,597
Nepal	14,335	28,810	201	1.8	1,104
Pakistan	77,088	176,952	230	2.2	2,538
Sri Lanka	6,271	20,061	320	0.9	4,564
Total South Asia (excluding Afghanistan)	411,899	1,568,227	381	1.5	2,724
Total world	13,009,550	6,750,525	52	1.2	10,384

[a]Source: UN Statistics Division and FAO (2011) for all others

GDP gross domestic product

examine how the lessons learned from the region could be relevant and applicable to other regions experiencing similar social and environmental pressures.

Historical Aspects of Agroforestry in South Asia: Early Fruit-Tree Domestication

Farmers in many traditional cultures of South Asia have been domesticating fruit trees and other agricultural crops around their dwellings for millennia, primarily to meet their subsistence needs. The best example of this is perhaps the tropical homegardens, which are essentially a complex integration of diverse trees with understorey crops performing several production and service functions (Fig. 1). The prehistoric origin of tree integration in homegardens can be traced to the discarding of seeds or vegetative propagules of edible plants and other useful species collected from the forest by the early man (hunter-gatherers) near the dwellings, where they germinated and grew. Anderson (1952) described this as the “dump heap” method or incidental route to domestication. The sites around habitations provided a congenial environment for the survival of such “regenerants.” The detection and maintenance of such “volunteers” would have been the next phase. Slowly, however, the unintentional dissemination of seeds became more systematic with important species planted to ensure their utilization (Wiersum 2006). The prehistoric people may have also instinctively selected trees with larger fruit size, better quality, or other desirable features from the wild, besides supporting their regeneration. This, in turn, resulted in the cultivated populations becoming genetically distinct from their wild progenitors (Ladizinsky 1998).

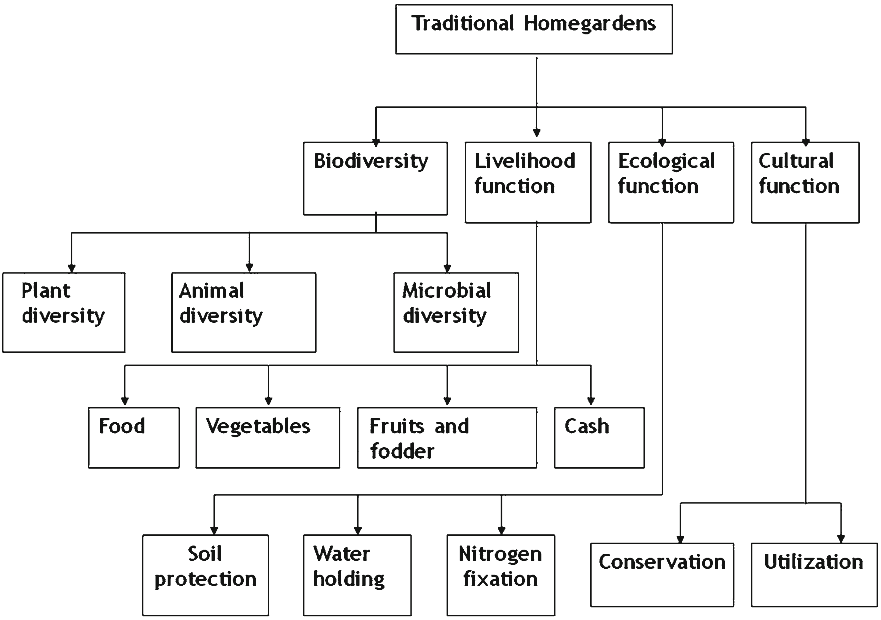

Fig. 1 The homegardens—a case from India (Based on Das and Das (2005), Kumar (2005))

Archaeological excavations corroborate early tree domestication around the settlements in South Asia. The earliest evidence of this dates back to the Mesolithic period (10,000–4,000 before present) when fruits of 63 plants including *Aegle marmelos* (L.) Corr. (bael), *Buchanania lanzan* Spreng. (chirauli-nut), *Phyllanthus emblica* L. (Indian gooseberry), *Mangifera indica* L. (mango), *Ficus* sp. (fig), *Madhuca* sp. (mahua), and *Ziziphus* sp. (ber) were reportedly eaten raw, ripe or roasted, or pickled by the inhabitants of central India (Randhawa 1980). The long history of agroforestry in South Asia (although the term *agroforestry* was not introduced until the late 1970s) is further elucidated in the early literature, as summarized below:

- Agroforestry including homegardening and rearing of silkworm (*Bombyx* spp.) and lac insect (*Laccifer lacca* Kerr) was practiced in the Indian subcontinent during the Epic era when *Ramayana* and *Mahabharat,* the two great epics, were composed (7000 and 4000 BCE, respectively; Puri and Nair 2004).
- Emperor *Ashoka*, a great Indian ruler (273–232 BCE), encouraged a system of arbori-horticulture of plantains (*Musa* spp.), mango, jackfruit (*Artocarpus heterophyllus* Lamk.), and grapes (*Vitis* spp.). As per the second of the 14 *Rock Edicts* of *Ashoka* (257 BCE), planting of medicinal herbs and trees besides shade trees along the roads and fruit plants on the wastelands was an accepted norm in those days—analogous to social forestry and agroforestry programs of the present.
- The travelogue of *Ibn Battuta* (Persian traveler; 1325–1354 CE) provides the earliest literary evidence of agroforestry from peninsular India, and it mentions

that in the densely populated and intensively cultivated landscapes of Malabar coast, coconut (*Cocos nucifera* L.), and black pepper (*Piper nigrum* L.) were prominent around the houses (Randhawa 1980).

- Plow agriculture was prevalent in Wayanad, one of the high-altitude locations in the Western Ghats, as early as in the Megalithic Age (between 400 BCE and 400 CE), and spices like black pepper, ginger (*Zingiber officinale* Roscoe), and cardamom (*Elettaria cardamomum* (L.) Maton Engl.) were often grown in association with woody perennials—as nurse (shade or support) trees, since the early Middle Ages (500–1400 CE).[1]
- The contents of the over 300-year-old book of agricultural verses in Malayalam, *Krishi Gita* (Kumar 2008), also reflect on the need to maintain better tree cover on the landscape, plant fruit trees on cleared forests, gardens, and other leftover lands, avenue planting, as well as leaving vestiges of forests in the midst of cultivated landscape—presumably for agrobiodiversity conservation and ecological balance.
- Natural history studies during the two previous centuries[2, 3] further signify that the people in the southern parts of peninsular India traditionally used their "homesteads" for a variety of needs such as food, energy, shelter, medicines, and the like.

Sustainable Land Use and Nature Conservation Ethos in Ancient South Asia

Sustainability was the underlying theme of most traditional production systems. This concept was ingrained in the minds of early inhabitants of South Asia, which is evident from the teachings of *Vedas*. For example, the *Atharva Veda* (2nd millennium BCE) hymn 12.1.35 reads:

> Whatever I dig out from you, O Earth! May that have quick regeneration again; may we not damage thy vital habitat and heart.

During the *Vedic* age, no village would be considered complete without its corresponding woodlands in and around the houses, and every village must have a cluster of five great trees, "panchavati" symbolizing the five primary elements: earth, water, fire, air, and "ether"—the totality of everything. Ancient historical chronicles from the period of King Vijaya of Sri Lanka[4] (ca. 543 BCE) such as "Maha-Wamsa," "Rajaratnacari," and "Rajawali" also exemplify that the village communities lived in harmony with the neighboring forest environment.

Numerous descriptions of trees and groves exemplifying the relationship between the Indian people and trees are also available in the early writings. For example, *Varahamihira's Brihat Samhita* (ca. 700 CE; Bhat 1981) describes the relationships between irrigation tanks and trees. *Varahamihira* provided detailed technical instructions on tank construction and prescribed the species to be planted on the embankments. The trees he mentioned[5] include several of the common fruit- and nut-yielding species that are popular even today. Agriculture by *Parashara* (*Krishiparasara*: 400 BCE), Laws of Manu or *Manusmriti* (ca. 200 BCE and 200 CE), The Epic of Fire or *Agni Purana* compiled ca. 700–800 CE, A Treatise on Agriculture by *Kashyapa* (*Kashyapiyakrishisukti* ca. 800 CE; Ayachit 2002), and The Science of Plant Life by *Surapala* (*Surapala's Vriksha Ayurveda* ca. 1000 CE; Sadhale 1996) are some of the other relevant texts from that era.

Multitude of Agroforestry Systems and Their Attributes

Diverse agroforestry systems where trees are grown with crops, and/or sometimes with animals, in interacting combinations in space or time dimensions, are practiced in the densely populated regions of South Asia (Table 2). Zomer et al. (2009)[6] estimated that about 21% of the geographical area (approximately 38.91 million ha) of this region has more than 10% tree cover, implying the overabundance of trees in the managed landscapes. According to Tejwani (2008), agroforestry (outside the forest) has more number of trees than the "State" forests. The prominent South Asian agroforestry systems include parkland systems; agrisilviculture involving poplar (*Populus deltoides* Bartr.) and *Eucalyptus* spp.; plantation agriculture involving coffee (*Coffea* spp.), tea (*Camellia sinensis* (L.) O. Kuntze), cacao (*Theobroma cacao* L.), and spices (e.g., black pepper, cardamom) in association with a wide spectrum of trees (planted as well trees in the natural forest), betel vine (*Piper betel* L.)+ areca palm (*Areca catechu* L.); intercropping systems with coconut, para rubber (*Hevea brasiliensis* H.B.K. M.-Arg.), and other trees (Figs. 2, 3, and 4); commercial crop production under the shade of trees in natural forests (e.g., cardamom); and homestead farming systems (Kumar 1999, 2005; Nath et al. 2011). Deliberate growing of trees on field bunds (risers) and in agricultural fields as scattered trees and the practice to utilize the open interspaces in the newly planted orchards and forests for cultivating field crops are also widespread in the subcontinent (Singh 1987).

Multifunctionality is a characteristic feature of agroforestry practices in South Asia, as elsewhere. Most agroforestry systems also have the intrinsic potential to provide food, fuel, fodder, green manure, plant-derived medicines, and timber resources. A new species may be chosen because of its properties, that is, food, wood, medicinal, religious, and ornamental, based on self-instinct or information passed on by neighbors and relatives. The products may be used for domestic consumption and for sale, depending on the scale of production and the economic status of the land manager. The choice of species and planting techniques adopted in such systems also reflect the accrued wisdom and insights of the traditional people who interacted with the environment for long. It is reasonable to assume that the indigenous cultivators used rational ecological approaches to maneuver the plants, which endowed sustainability to the system.

Table 2 Prominent agroforestry systems of South Asia

System	Functions	Remarks
Agrihorticultural system	Timber, fuel, fodder, medicines, non-timber forest products, and food production	Diverse fruit plants integrated with other multipurpose trees; widespread in Bangladesh, India, Nepal, and Sri Lanka
Agrisilviculture	Industrial wood and food production	*Acacia mangium* Willd., *Ailanthus triphysa* (Dennst.) Alston., *Tectona grandis* L.f., and other tree species in association with an array of food crops; *Populus deltoides* Bartr. (poplar) and *Eucalyptus* spp. are important in northern India (Terai region) and Pakistan, where poplar agroforestry increased water productivity and profitability of smallholder farmers (Zomer et al. 2007). High internal rates of return (38–40.5%) with wheat and fodder intercrops for first 7 years in an 8-year poplar cycle (Source: Pratap 2004)
Alley cropping/farming	Food, fuel, fodder, and green manure production, soil fertility enhancement, and environmental conservation	Practiced by the smallholder farmers of South Asia. Quick-growing trees and/or field crops grown in association with commercial tree crops
Aquaforestry	Fish, fruit plants, timber and firewood, nutrient cycling	In the coastal tracts of India, Bangladesh, Sri Lanka, and Maldives
Boundary/hedgerow tree planting/live fences	Fuelwood, fodder, timber, shade, and support trees for trailing black pepper vines, protect crops from roaming wildlife, domestic animals, and human interference	Trees on hedges (0.5 m apart in single rows or paired rows at 1 m apart); require frequent pruning to maintain the desired form (height, width, and shape) to encourage secondary branching to create an impenetrable barrier. Nitrogen-fixing tree genera are important
Commercial crops under the shade of planted trees	Beverage crops, tree spices, medicinal and aromatic plants, besides timber, firewood, and other tree products	Tea (*Camellia sinensis* (L.) O. Kuntze), coffee (*Coffea* spp.), cacao (*Theobroma cacao* L.), spices like clove (*Syzygium aromaticum* (L.) Merr. & Perry), nutmeg (*Myristica fragrans* Houtt.), black pepper (*Piper nigrum* L), betel vine (*Piper betel* L.) etc., require varying levels of shade for optimum growth and production

(continued)

Table 2 (continued)

System	Functions	Remarks
Energy plantations	Lignocellulosic biomass, wood, and biofuel production	Cultivation of biomass crops (e.g., bamboos, wattles, and other short rotation tree crops) and tree-borne oilseed crops (e.g., *Simarouba glauca* DC., *Jatropha curcas* L.) are gaining attention
Entomoforestry	Lac, silk worm, and honey production	Apiculture, lac culture, and sericulture. Sericulture-based agroforestry systems quite remunerative in the hilly areas of northeast India (Dhyani et al. 1996)
Fodder banks	"Cut and carry" fodder production	Designed to provide fodder during the dry season; harvested on a rotational basis providing year-round fodder
Multistoried cropping systems	Fruits, nuts, timber, and fuelwood production	Intercropping food crops with palms (*Cocos nucifera* L., *Areca catechu* L., *Phoenix sylvestris* Roxb., *Borasus flabellifer* L.), jackfruit tree (*Artocarpus heterophyllus* Lamk.), *Acacia nilotica* (L) Del., *Dalbergia sissoo* Roxb., *Paulownia* spp., *Ziziphus jujuba* Mill., *Hevea brasiliensis* H.B.K. M.-Arg., fruit orchards, and growing medicinal and aromatic plants under the shade of trees—popular throughout South Asia
Parkland agroforestry	Food, fuelwood, and timber	*Prosopis cineraria* (L.) Druce systems practiced in India and Pakistan
Shaded commercial crop production systems: coffee (*Coffea* spp.), tea (*Camellia sinensis*), small cardamom (*Elettaria cardamomum* (L.) Maton Engl.), large cardamom (*Amomum subulatum* Roxb.), cacao (*Theobroma cacao*)	Commercial crop production, timber, and fuelwood	Prevalent in the mid and high altitude zones of India, Bhutan, Nepal, and Sri Lanka. Planted shade trees as well as trees in the natural forests are used, e.g., large cardamom grown in association with alder (*Alnus nepalensis* D. Don) in Sikkim Himalayas, small cardamom grown under the shade of trees in the natural forests in the peninsular India (Kumar et al. 1995)

Shelterbelts and windbreaks	Protecting crops and livestock from high-velocity winds, reduce wind erosion, biomass energy, and wood production	Practiced in many parts of South Asia in which fast-growing trees are planted at close intervals (e.g., block planting of *Casuarina equisetifolia* J.R. & G. Forst. and *Acacia mangium* Willd. in the coastal areas)
Shifting cultivation or swidden farming	Subsistence food production	63.57 million ha in Bangladesh, India, and Sri Lanka (ESCAP 1992)
Silvopasture	Timber, fuelwood, and fodder production	Adapted tree + grass combinations contributing to forage production. *Acacia leucophloea* Willd. + *Cenchrus setigerus* Vahl. silvipasture system in the Kangeyam tract of Tamil Nadu; over 400-year-old system. In the ravines of Yamuna and Chambal, trees, shrubs, and bamboos plus grasses; for rearing the milk-producing *Jamunapuri* breed of goats and sheep
Sloping agricultural land technologies (SALT)	Fodder, firewood, soil conservation, environmental protection	Integration of soil conservation and food production strategies on steep slopes; alternate strips of timber and firewood trees with cereals (corn, upland rice, etc.) and legumes (soybean, mung bean, peanut, etc.); provides the farmers returns throughout the year
Taungya	Timber and subsistence food production	Originated in Burma and spread to different parts of the world. Field crops grown in the interspaces of forest crops during the early stages. Trees: *Shorea robusta* Gaertn., *T. grandis*, *Dalbergia sissoo*, *Acacia catechu* (L.f.) Willd., *Eucalyptus globules* (Labil.), poplar *Pinus patula* Schiede & Schltdl. & Cham.
Tropical homegardens	Food, fuelwood, fodder, plant-derived medicines, other non-timber tree products, medicines, and cash income	Cover about 8 million ha in south and southeast Asia (Kumar 2006). Kerala and Kandyan homegardens are prominent in the South Asian context
Woodlots	Timber and firewood production, fodder, lignocellulosic biomass, bio-drainage, CDM projects	Short rotation intensive cultural systems involving fast-growing tree species, e.g., poplar, eucalyptus, mangium, teak, and the like

Fig. 2 Tea+ *Grevillea robusta* (silver oak) system in Munnar, Kerala (Photo: BM Kumar)

Fig. 3 Pineapple (*Ananas comosus*) + rubber (*Hevea brasiliensis*) saplings (Photo: BM Kumar)

Fig. 4 Shaded coffee (*Coffea* spp.) production system in the Western Ghats (Photo: BM Kumar)

Transformations Over Centuries

The traditional land use systems have changed over time—as a function of the interplay of socioeconomic and technological factors. Figure 5 illustrates the paradigm shifts in this respect. In particular, agricultural transformations brought about by market economies in the recent past, especially the incorporation of exotic commercial crops (e.g., *Hevea brasiliensis*), have led to the decimation of many traditional land use systems (Kumar 2005; Guillerme et al. 2011). For example, the homegardens that constituted a predominant land use activity of the subcontinent (e.g., the Kandyan, Kerala, and other homegarden systems: Kumar and Nair 2004, 2006) of late have been showing symptoms of decline (Guillerme et al. 2011). The key drivers of this have been rising population pressure and the policies oriented toward land use intensification to meet the rising food grain requirements (e.g., monospecific production systems). The traditional landscapes and production systems, however, have been receiving some attention more recently. It is now recognized that the traditional farmers have conserved biodiversity of great economic, cultural, and social values (Kumar and Nair 2004).

Environmental concerns such as global warming, land degradation, erosion of biodiversity, loss of wildlife habitats, and increased nonpoint source pollution of ground and surface water have provided an additional impetus for the development and adoption of agroforestry around the world (Fig. 5). Furthermore, as fossil reserves (for producing nitrogenous fertilizers) and the mineral deposits of phosphates and potash are getting progressively depleted, a fertilizer crisis may be emerging. The fossil fuel reserve depletion times for oil, coal, and gas have been calculated as approximately 35, 107, and 37 years, respectively (Shafieea and Topal

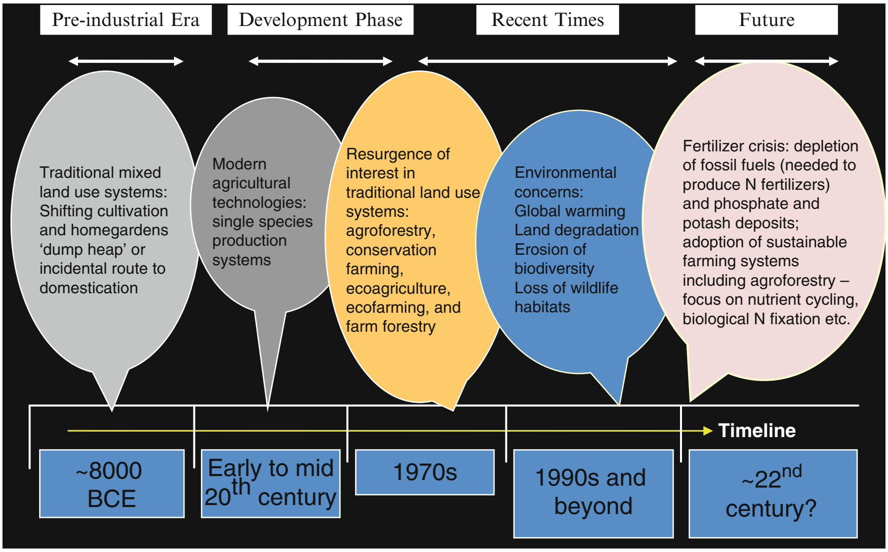

Fig. 5 Evolutionary pathways of South Asian agroforestry. Early to mid-twentieth century up until the 1970s constitutes the “development phase” characterized by the Green Revolution (Modified from Kumar and Takeuchi 2009)

2009); the implications of which are startling. Likewise, it is unlikely that phosphate rock deposits may last beyond another 100 years (Herring and Fantel 1993). With this projected fertilizer crisis, agroforestry focusing on fertilizer trees and other resource conservation and sharing mechanisms is likely to get better attention in the future.

Of late, economic incentives to the land managers also have acted as a major driver of agroforestry in certain parts of South Asia. The poplar (*Populus* spp.)-based agroforestry in northern India, especially in the lowland “Terai” areas at the base of the Himalayas, is a case in point. Following a modest beginning when four poplar clones from Australia were introduced in 1969,[7] poplar cultivation in northern India has made rapid strides. Presently, there are 70 million poplar trees in the agricultural fields of the upper Gangetic region producing 10.40 million m^3 of industrial wood (Rizvi et al. 2011). Consequent to the ban on timber cutting in the state forests of India, and the widening gap between demand and supply, the wood-based industries have no option but to depend on farmers for meeting their raw material demands (Chandra 2003).

Woodlots of other fast-growing trees such as *Eucalyptus* spp., *Leucaena leucocephala* (Lamk.) de Wit., *Casuarina equisetifolia* J.R. & G. Forst., *Acacia mangium* Willd., *A. auriculiformis* A. Cunn. ex Benth., *Ailanthus triphysa* (Dennst.) Alston., and *Melia dubia* Cav. are also becoming increasingly popular among the farmers in several parts of the Indian subcontinent. Overall, agroforestry in South Asia is being both intensified (e.g., intensive tree and crop management practices) and simplified (e.g., fewer economically important species) as a result of current policies (Guillerme et al. 2011) and economic imperatives.

To capitalize on the ecological and production functions outlined earlier, the National Agricultural Policy (2000)[8] of India stressed that "farmers will be encouraged to take up farm/agroforestry for higher income generation by evolving technology, extension, and credit support packages and removing constraints to development of agroforestry." Similar policy initiatives are in place in other countries of the subcontinent too. For example, forest tree planting on farmlands and in homegardens through social forestry was an important component of the National Forest Policy (1995) of Sri Lanka (De Zoysa 2001). This policy recognized that the homegardens and other agroforestry systems and trees on other agricultural lands play a crucial role in supplying timber, bio-energy, and non-wood forest products, while conserving the micro-environment.

Agroforestry Research in South Asia: Early Beginnings

Although agroforestry as a practice was very ancient in South Asia, the science of agroforestry is relatively new. Some research of this nature was conducted earlier but was not recognized as agroforestry (e.g., Nair 1979 and many others). Organized research on agroforestry started in India with the establishment of the All India Coordinated Research Project on Agroforestry in 1983 (ICAR 1981). The research initiatives gained further momentum with the commencement of forestry education programs in the State Agricultural Universities of India during 1985/1986 and the founding of the National Research Centre for Agroforestry (NRCAF) at Jhansi, UP, in 1988. As part of the agroforestry research initiatives, a series of workshops and seminars were held in India; the first in the series was at Imphal in 1979 involving the Indian Council of Agricultural Research (ICAR) and the International Centre for Research in Agroforestry (ICRAF). This was followed by another series of Indo-US Workshop-cum-Training sessions during 1988–1992 on various aspects of agroforestry, in which many key American resource persons participated. Exchange programs were also initiated in the 1980s in which several Indian scientists received advanced training/degrees in agroforestry and related areas from various US, UK, and Canadian universities—with support from the US Agency for International Development, the British Council, and the Canadian International Development Agency. With such programs, India was able to develop a critical mass of agroforestry scientists. Other countries in the region such as Nepal, Sri Lanka, Pakistan, and Bangladesh also followed a similar strategy, and agroforestry came of age in those countries as well. Results of a keyword ("agroforestry" + "country name") search in Scopus,[9] which returned 3,761 hits for India, 734 for Nepal, 609 for Pakistan, 546 for Bangladesh, 451 for Sri Lanka, 71 for Bhutan, 20 for Afghanistan, and 8 for Maldives, exemplify that.

Major Land Use Challenges in South Asia

Food Insecurity

Historically, food production in South Asia increased at the same rate as that of human population during the second half of the past century. However, population growth has outmaneuvered the food production trends in the past decade. According to FAO (2010), South Asia accounts for about 40% of the about 835 million undernourished people in the developing world. To make matters worse, increases in cereal yields are slowing down in all regions of the world, including South Asia, due to reduction in total factor productivity (TFP). Yet another feature of South Asian food production is that it is mostly done by smallholders: about 80% of the holdings are less than 0.6 ha in extent (Gulati 2002), and one or more types of mixed species gardens are present on these smallholdings, and these units function at low levels of productivity. Diminishing soil fertility is yet another concern (De Costa and Sangakkara 2006); although input-intensive agricultural production systems have been promoted on the small farms in the past, such systems have not made much headway because of the high costs of inputs, non-availability of resources, environmental costs, and various other socioeconomic and technological constraints.

Rising Timber and Fuelwood Needs

The gap between supply and demand of major forest products in South Asia has been widening over the past decades, leading to unsustainable extraction of wood from the natural forests and causing forest degradation.[10] The importance of sourcing raw materials for the wood-based industries from non-forest areas through agroforestry, therefore, cannot be overemphasized. The tropical homegardens, poplar-based agroforestry, and other woodlots are of special significance in this respect, as they have the intrinsic potential to provide substantial wood resources. According to some reports (e.g., Kumar and Nair 2004), the tropical homegardens provide 70–84% of the commercial timber requirements of the South Asian societies. However, these multipurpose traditional land use systems are waning in most parts of the subcontinent. In the light of the emerging challenges in meeting the timber requirements, such systems, however, should be revitalized.

Fuelwood consumption has also increased steadily paralleling population growth throughout the developing countries. Fuelwood accounts for ca. 2,300 million m^3 or 60% of the total annual wood production globally (FAO 2003). Although rising income levels and expanding urbanization make it possible for people to have access to more modern forms of energy such as oil, coal, and gas, absolute quantities of fuelwood consumption in South Asia and many other developing countries have been increasing progressively. A recent study from Bangladesh (Akther et al. 2010) indicated that a majority (94%) of households in the downstream zone of the

Old Brahmaputra River experienced fuelwood scarcity. With increasing levels of deforestation and forest degradation, fuelwood not only becomes scarcer but also its collection for household consumption becomes very arduous, a task usually assigned to women and children. In certain cases, gathering fuelwood can consume 1–5 h per day for these women (IEA 2000), implying strong social, gender, and health concerns related to the declining availability of fuelwood.

Land and Forest Degradation

Historically, deforestation and forest degradation have been critical issues threatening ecosystem stability and depleting the natural resource base. Recent FAO (2011) figures suggest that within South Asia, annual deforestation rates are 1.1, 2.2, 0.7, and 0.2% for Sri Lanka, Pakistan, Nepal, and Bangladesh, respectively; India and Bhutan, however, showed modest increases in forest cover over this period. Although no net deforestation has been reported for India, there is still diversion of forests for agriculture (shifting cultivation)—to the tune of about 9 million ha annually, particularly in the northeastern states (MoEF 2006). The National Forest Commission of India reported that about 41% of the country's forest cover has already been degraded and dense forests are losing their crown density and productivity continuously, 70% of forests have no natural regeneration, and 55% are fire-prone (MoEF 2006). On the whole, forest degradation is a still a major form of land degradation in South Asia.

Soil salinization and water logging, which render arable lands unproductive, also continue unabated in most parts of South Asia (van Lynden and Oldeman 1997; Scherr 1999; Eswaran et al. 2001; Lal 2001). Indeed, out of the world's 1,900 million ha of land affected by soil degradation, the largest area (around 747 million ha) is in Asia (Oldeman 1994). In India alone, about 121 million ha land (73, 12.4, 17.45, and 1.07 million ha of arable land under water erosion, wind erosion, chemical degradation, and physical degradation, respectively, and 16.5 million ha open forest area) are under one or the other forms of degradation (ICAR 2010). As in most other developing countries, the South Asian countries also lack capital resources to make the financial investments required to reclaim degraded lands, which further complicates the matter.

Global Warming

During the past two decades or so, concern has also grown among the scientists and public about the possible impacts of climate change on terrestrial ecosystems, especially with respect to plant growth, changes in biodiversity, nutrient recycling, and the overall effect on carbon storage in the biosphere (Rosenzweig and Hillel 1998; Kumar et al. 2005; IPCC 2007). Land use changes have contributed substantially to the rising concentration of CO_2 in the earth's atmosphere. The average annual increase for the past decade (2001–2010) was 2.04 $\mu L\ L^{-1}$ (2.04 ppm), with a predicted doubling of the pre-industrial concentrations by the end of the twenty-first century.[11] The consequences of climate change will be felt across the world and include rise in sea level, drought and flooding, and an irreversible loss of many species of plants and animals. The poor countries in South Asia are likely to be the most vulnerable to the effects of climate change (Pachauri 2012). The impact of global warming on food production in South Asia is particularly distressing as the predicted shifts in monsoonal rainfall patterns (Lal et al. 2001) may render large areas unproductive, leading to significant reductions in cereal yields.[12] So much has been written about these issues, even in this volume, so that whatever is written here will appear to be too skimpy on the one hand, and too elaborate descriptions are unwelcome in this context on the other.

Biodiversity Losses: A Cause of Concern

Erosion of farmland biodiversity is one of the most serious problems in ecosystem management today (Benton 2007). Agricultural intensification in South Asia in the past has decimated many traditional land use systems, which customarily preserved landraces and cultivars, as well as rare and endangered species. A case study in the Indian Central Himalaya indicated that as cropping intensified, the traditional crop varieties declined drastically (Maikhuri et al. 1999). Indeed, of the 3,000 varieties of rice cultivated in India before the green revolution, only 50 have survived (Shiva and Prasad 1993). Likewise, cultivation of high-yielding varieties of cereal crops in the irrigated areas of Central Himalayas exterminated the hitherto prevalent fodder trees (334–418 fodder trees per ha)—a major source of animal fodder especially during the lean seasons (Semwal and Maikhuri 1996). Introduction of exotic fast-growing trees and conversion of traditional agroforestry systems (including homegardens or their parts) to monospecific production systems also led to a declining diversity of herbaceous components such as traditional vegetable crops and ornamental plants, besides tree species (Guillerme et al. 2011). Overall, this decline in landscape diversity signifies reduced on-farm availability of green manure, fodder, and firewood resources and increased dependence on adjacent forests for these resources (Kumar and Takeuchi 2009).

Loss of biodiversity is not limited to managed ecosystems but is a serious problem in natural forests of this region too. Habitat fragmentation leading to loss of native habitat limits the species' potential for dispersal, colonization, and foraging ability. Approximately 15,000 km^2 constituting about 60% of the rainforests in Western Ghats, India, are severely fragmented to parcels of <10–2,000 ha in extent (Collins et al. 1991), contributing to species losses. The International Union for Conservation of Nature[13] reported that a total of 659 Indian species are threatened (246 plants, 96 mammals, 76 birds, 25 reptiles, 65 amphibians, 40 fishes, 2 molluscs, and 109 other invertebrates) because of anthropogenic pressures on the natural habitat. Consistent with this, Puyravaud et al. (2003) reported that among the 352 identified species and varieties of the endemic flora of Western Ghats 14% are threatened.

Agricultural Nonpoint Source Pollution

Agricultural nonpoint source pollution (NPSP) is a significant cause of stream and lake contamination in many regions of the world. Nonpoint source pollution owing to agricultural intensification constitutes a major environmental problem in the Indian subcontinent also. Pawar and Shaikh (1995) reported that ground and surface water samples from a small watershed in the Deccan Trap Hydrologic Province, India, contained anomalously high NO_3 levels (2.2–64 ppm). In another study from the Krishna basin in Belgaum district of Karnataka, India, Purandara et al. (2004)[14] also observed high post-monsoon loads of major anions and cations in the Malaprabha river (kg day^{-1}): Na (1,557–4,276), K (1,145–6,480), Ca (6,594–25,401), Mg (1,786–12,960), Cl (6,493–68,915), SO_4 (11,448–53,784), and HCO_3 (48,603–229,262)—more than 90% of which was derived from nonpoint sources.

Agricultural chemicals such as fertilizers, manures, and pesticides are the principal sources of chemical ions in stream water. Runoff from animal husbandry units, which contain predominantly high levels of organic compounds, is another source of pollutants. Lateral inflows (water that is added to the stream due to effluent seepage from groundwater, overland flow, interflow, or via small springs and seeps) transport such solute mass to the streams and rivers (Singh 1995). Although extensive studies have been carried out in many parts of the world to understand the in-stream reactions and sediment dynamics (Yuretich and Batchelder 1988; Latimer et al. 1988), such studies are rare in the South Asian context, albeit the problem is severe.

Do the Challenges and Opportunities Offer Scope for Adaptation?

Food Security, Diversified Production, and Economic Returns

Traditionally, agroforestry aimed at food production—either directly producing edible products or indirectly (facilitating enhanced and/or sustained production). Recent studies too indicated that certain food crop crops can profitably be combined with woody perennials. For instance, Asiatic yams (*Dioscorea alata* L. and *D. esculenta* (Lour.) Burkill.) and other food crops are well suited as intercrops in the coconut gardens of South Asia (Nair 1979; Pushpakumari and Sasidhar 1992; Ollivier et al.

1994). In the arid regions of northwestern India, food crops grown under *Prosopis cineraria* (L.) Druce trees produced two to three times more yield than crops growing away from trees (Shankarnarayan et al. 1987). Food diversity constitutes yet another dimension of this. Many cereals, tubers, vegetables, and forages are intercropped in such systems. The vertical stratification of canopies characteristic of agroforestry systems provides a gradient in light and relative humidity creating niches for various species groups. Most agroforestry systems are also complementary to other crop production enterprises—as they provide green manure for crop fields and cattle fodder (Table 2)—further augmenting food security and diversity.

The produces from agroforestry are also sources of minerals and nutrients for improving household nutritional security especially for at-risk populations (Kumar and Nair 2004). In experimental studies, the target families significantly increased their year-round production and consumption of vitamin-rich fruits and vegetables compared to the control group without homegardens which led to alleviation of iodine, vitamin A, and iron deficiencies (Molina et al. 1993) and made children of garden owners less prone to xerophthalmia (Shankar et al. 1998). Since little or no chemical inputs are used in such systems, the produce from agroforestry is also of superior quality. In summary, agroforestry is capable of making available diversified foodstuffs, averting malnutrition, and providing organic food materials, for which there is an emerging market even in the developing countries.

Apart from ensuring food production, such systems augment economic returns to the growers. An economic analysis of 24 agroforestry models by the Planning Commission of India (GITF 2001) highlighted high benefit/cost ratios (1.5–3) and internal rates of return (15–40%) for agroforestry. Consistent with this, Neupane and Thapa (2001) reported that introduction of multipurpose trees such as mulberry (*Morus alba* L.) for sericulture in the mid-hills region of Nepal enhanced profitability. In the Chittagong Hill Tracts of Bangladesh also, practicing agroforestry on the degraded agricultural lands improved economic returns (Rasul and Thapa 2006). Higher cash incomes may provide greater "buying power" with respect to food, especially when agriculture is not practiced, or when crops fail. The potential of agroforestry to provide alternate sources of income and employment to the rural poor which again ensures food security and diversity, therefore, cannot be overemphasized (e.g., Balooni 2003; Puri and Nair 2004; Samra et al. 2005; Dhyani et al. 2009).

Major Sinks of Atmospheric CO_2

Expanding the size of the global terrestrial sink is one strategy for mitigation of CO_2 build-up in the atmosphere. Under the Kyoto Protocol's Article 3.3, A & R (afforestation and reforestation) with agroforestry as a part of it has been recognized as an option for mitigating greenhouse gases. As a result, there is now increasing awareness on agroforesty's potential for carbon (C) sequestration (Nair et al. 2009, 2010; Kumar and Nair 2011). Indeed, the National Climate Change Action Plan of India through the Greening India Mission[15] targets 1.5 million ha of degraded agricultural lands and fallows to be brought under agroforestry. Such climate change mitigation strategies through agroforestry would also ensure greater synergy with the Convention on Biological Diversity in view of the ability to maintain high biodiversity (FAO 2004).

Basically there are three mechanisms which help reduce atmospheric CO_2 levels (Montagnini and Nair 2004; Kumar 2006): *carbon sequestration* (creating new stocks in growing trees and soil), *carbon conservation* (eases anthropogenic pressure on existing stocks of C in forests through conservation and management efforts), and *carbon substitution* (substitution of energy demand materials by renewable natural resources, fuelwood production, increased conversion of biomass into durable wood products for use in place of energy-intensive materials). While all these are relevant for agroforestry, aspects such as carbon sequestration and substitution are focused here, as quantitative data on avoided deforestation on account of agroforestry are not readily available.

Carbon Sequestration

Although variations in C sequestration potential of agroforestry systems abound owing to tree age-, site-, and tree/stand management-related factors (Nair et al. 2009, 2010), there exists a huge but untapped potential of agroforestry as a CO_2 offset mechanism (Kumar and Nair 2011). Indeed, the aboveground C stocks of mixed species tropical homegardens in Kerala (India) and poplar-based systems in north-western India are 17–36 Mg C ha^{-1} (Kumar 2011) and 21–65.62 Mg C ha^{-1} (Rizvi et al. 2011), respectively, comparable to that in the living biomass of Indian forests (41 Mg C ha^{-1}: FAO 2011). Aside from the aboveground C stocks, the "species-rich" land use systems also have a greater chance of maintaining soil organic matter relations than the "species-poor" agricultural systems in the Western Ghats of India (Russell 2002; Kumar 2005). Indeed, more than half of the C assimilated by woody perennials in such systems is transported belowground via root growth and organic matter turnover processes (e.g., fine root dynamics, rhizodeposition, and litter dynamics), augmenting the soil organic carbon (SOC) pool (Nair et al. 2010). Consistent with this, Saha et al. (2009, 2010) reported that for species-rich Kerala homegardens, the soil carbon content (SOC) within the 1 m soil profile was 119.3 Mg ha^{-1}.

Although C is a new commodity that is now traded in financial markets and there is potential for farmers adopting agroforestry to sell C in addition to the other commodities (traditional timber and non-timber), agroforestry C offset projects are a challenging task; high transaction costs being a principal deterrent. As a result, only a small proportion of the A/R CDM (Clean Development Mechanisms) projects are presently based in South Asia: just seven registered A/R CDM projects in India till mid-October.[16] Other countries in the region also have little forest carbon, CDM, and Payment for Ecosystem Services (PES) activity so far. Nonetheless, the potential for more A/R CDM projects throughout the subcontinent cannot be underestimated.

Carbon Substitution (Biomass Utilization as Carbon Neutral Energy)

Although bioenergy can make significant contributions to the world's growing needs for clean energy (Turkenburg et al. 2000), this is still an emerging concept in South Asia. The Government of India (GOI), however, regards biofuels as a feasible option for augmenting future fuel supply (PSA 2006). To promote the utilization of biofuels in the fuel mix, GOI on September 30, 2003 launched a 5% ethanol doping program for petrol in nine states and four union territories of the country. The National Mission on Biodiesel covering an area of 400,000 ha (Planning Commission 2003) is another major initiative to find a renewable alternative for the growing fuel consumption (Kumar 2010). On September 11, 2008, the GOI also issued a National Policy on Biofuels.[17] It calls for 20% blending of bioethanol and biodiesel by 2017 and augmenting indigenous production of non-edible oilseeds and biodiesel from waste/degraded/marginal lands.

A wide spectrum of hydrocarbon-yielding plants such as *Jatropha curcas* L., *Pongamia pinnata* (L.) Pierre., *H. braziliensis, Madhuca indica, Calophyllum inophyllum* L.*, Salvadora persica* L., and *S. oleoides* Decne. are constituents of agroforestry systems in different parts of South Asia. Other oil-yielding species such as *sal* (*Shorea robusta* Gaertn.), *neem* (*Azadirachta indica* Adr. Juss.), *Michelia champaca* L., and *Garcinia indica* L. too have great potential in this regard (Kalita 2008). Annual production of such oilseeds in India is more than 20 million tons (Tg), with *mahua* (*Madhuca* spp.) alone accounting for 181 Gg (1,000 tons).[18] Some of these seeds have high oil contents, for example, *M. champaca* and *G. indica* yielding 45.0 and 45.5% oil, respectively. Fatty-acid composition, iodine value, and cetane number indicate their suitability for use as biodiesel (Hosamani et al. 2009). However, such indigenous tree-based oilseeds (TBOs), despite their high bio-crude potential, have not been adequately exploited in this region (Ghadge and Raheman 2005).

This biofuel route to CO_2 emission reduction, however, is not always risk-free, especially in the populous countries of South Asia where extensive replacement of food crops by energy crops may adversely affect food availability, access, stability, and utilization.[19] Nonetheless, establishment of agroforests/bioenergy plantations appears to be a major, cost-effective method to offset fossil fuel consumption, which should be promoted. According to Lal (2001), biofuels can offset C emission through fossil fuel burning to the extent of 0.3–0.7 Pg C year^{-1}. Furthermore, the Indian National Policy on Biofuels emphasizes biofuel production from non-edible oilseeds primarily from degraded lands, which would probably offset any potential land use conflicts in this regard.

Traditional Agroecosystems to Conserve Agrobiodiversity

Integrated, dynamic, landscape mosaics with traditional land use management reflect the potential to harbor an array of species. Although substantial parts of such systems have been lost during the "development phase" (Fig. 5), the remaining agroforestry in South Asia are excellent examples of agrobiodiversity conservation. For example, the mean Simpson and Shannon-Wiener diversity indexes of tropical homegardens of Western Ghats (India) were comparable to those of the adjacent natural forest areas (Kumar et al. 1994; Saha et al. 2010; Kumar 2011). Likewise, the homegardening systems in Bangladesh are thought to be "refuges" for native and rare plants outside the natural and/or protected area systems (Kabir and Webb 2008). Nonetheless, agroforestry may not avert all species losses. With divergent life forms such as trees, agricultural crops, grasses, livestock, etc., it may act as an effective buffer to prevent such losses, especially in the smallholder land use systems (e.g., the homegardens: Kumar et al. 1994) where the "species packing" is generally greater than in the larger ones.

Reclamation of Degraded Sites, Reduced Nutrient Loading of Aquatic Systems, and Soil Fertility Enrichment

Several tree and shrub species have the intrinsic potential to remove pollutants (heavy metals, organic pollutants, etc.) from the environment and/or to render them harmless (phytoremediation). The principal application of this in the South Asian context is in the context of reclamation of salt-affected soils (Davidson 2000). In India, where an estimated 6.74 million ha of lands are affected by salinity/alkalinity (ICAR 2010), salt-tolerant tree species such as *Acacia nilotica* (L.) Del., *Dalbergia sissoo* Roxb., *Prosopis juliflora* (Sw.) DC, and *Terminalia arjuna* have been planted in association with fodder grasses for site improvement with remarkable success (Singh et al. 1992; Garg 1998). P. juliflora, in particular, has improved the physical and chemical properties of highly sodic soils soil by decreasing pH, electrical conductivity, and exchangeable sodium (Na) levels and increasing infiltration capacity, organic C, and nutrient levels (Bhojvaid et al. 1996). Use of trees and shrubs for reclaiming salt-affected/other polluted soils, therefore, offers considerable promise in reversing the process of arable lands going out of production due to soil degradation.

Agroforestry systems which integrate woody perennials with other crops also reduce the magnitude of nutrient loading of streams and lakes (Nair et al. 2010; Nair 2011). In particular, agroforestry designs of grass-shrub-tree buffers (riparian buffer) were found to be superior to grass buffers in reducing sediment losses and NPS of aquatic systems (Rigueiro-Rodríguez et al. 2008; Jose 2009; Palsaniya et al. 2011). Improvements in soil organic matter status following incorporation of tree biomass (litter, fine roots, and green manure) would also improve the infiltration capacity of soils. This is particularly relevant for soils characterized by low infiltration capacity and negligible hydraulic conductivity, where overland flow transfers the excess fertilizers remaining in the top soil layer into the streams.

The deeper and more extensive tree roots also take up more nutrients from the subsoil compared to crops with shallower root systems, implying the so-called safety-net effect (Divakara et al. 2001). In experimental studies involving bamboo-based multi-strata systems of Kerala, India, Kumar and Divakara (2001) found that

^{32}P uptake from the subsoil was greater when the bamboo clumps (*Bambusa bambos* (L.) Voss.) and dicot trees (*Tectona grandis* L.f. and *Vateria indica* L.) were close to one another, signifying a substantial potential to "capture" the lower leaching nutrient ions, when trees are grown in close proximity. By extension, nutrient leaching from soils under agroforestry systems where trees are a major component will be substantially lower than those from treeless systems. In addition, the deep-reaching tree roots can pump out excess soil water (bio-drainage),[20] which is of special relevance to salt-affected soils. Annual water use by 3-to-5-year-old *Acacia nilotica* trees was 1,248 mm on the severely saline site and 2,225 mm on the mildly saline sites in Pakistan and the plantation water table fell from 1.7 to 2.9 m below surface (Khanzada et al. 1998). N_2-fixing trees and shrubs have the additional potential to enrich site fertility, which is of special relevance considering the high losses of N from agroecosystems (Kumar et al. 1998) and the impending fertilizer crisis (Fig. 5). Prevention of land degradation by wind erosion is yet another attribute of agroforestry in the arid and semiarid regions (Pathak 2002). Agroforestry thus plays a major role in the rehabilitation of wastelands such as deserts, ravines, and gullies.

Lack of Public Policy Support

Although the traditional agroforestry systems are sustainable production systems that conserve site resources and agrobiodiversity, these are not yet supported by comprehensive public policies (Guillerme et al. 2011). The commodity-centric agricultural policies and the forest policies favoring exotic species in the past have adversely affected the prospects of agroforestry as a land management system in many parts of South Asia. Indeed, "modern" agroforestry technologies (agroforestry practices that have been developed recently with research backing—involving either improvement of traditional practices or introduction of new ones) have not been widely adopted in India (Puri and Nair 2004) despite considerable promotional efforts.[21] Case studies regarding the impact of public policies on tree farming and agroforestry dynamics are also rare (Guillerme et al. 2011). Nonetheless, a plea was made in 2001 to review and amend the outdated or conflicting laws and harmonize them in view of the new challenges of rising wood requirements of the society and increasing pressures on remaining natural forests (Mohanan et al. 2002). The forest policies of Pakistan (1955, 1962, and 1991) also reflect the importance of farm forestry; however, very little was translated into practical measures due to socioeconomic and technological constraints (Akbar et al. 2000).

Most public policies also do not take into account the environmental services rendered by agroforestry or even by the farmers. The focus is on the most profitable and marketable crops or trees ("push" toward commercial agriculture, which may not last long in view of an imminent fertilizer crisis; Fig. 5), often neglecting the dimensions of domestic consumption and agrobiodiversity conservation. In the global context of the challenges associated with food security, climate change mitigation, poverty alleviation, and preservation of environment and biodiversity, a reorientation of the public policies in the realm of agroforestry is warranted as most of the small and marginal farmers in most parts of South Asia still rely on agroforestry for their subsistence (e.g., homegardens: Kumar and Nair 2004).

Lessons Learned

With increasing human population pressure and mounting levels of land degradation, arable lands are becoming scarce the world over. This, coupled with the adverse effects of enhanced atmospheric CO_2 levels, would exaggerate the threat to global food security in the twenty-first century. And nowhere else will the detrimental effects be as severe as in the South Asian region, the most densely populated geographical zone on earth. In particular, agricultural lands in South Asia are scarce, and site degradation is most severe in the irrigated lands where intensive cultivation has been practiced. Furthermore, the global warming–induced rise in sea levels may submerge substantial parts of agricultural and other lands in countries such as Maldives, Bangladesh, India, and Sri Lanka (IPCC 2007), which may aggravate the problem of food scarcity, besides causing other problems. As explained, agroforestry emerges as a promising land use option capable of addressing most of these problems. Clearly, there are case studies and “success stories” of agroforestry from South Asia that can probably be replicated elsewhere in the tropics experiencing similar problems.

The first and foremost in this respect is the tropical homegardens (Kumar and Nair 2004, 2006). Although productivity in these traditional agroforestry systems compared to intensive monocultures is modest, diversified production and income generation in perpetuity are its intrinsic features. Homegarden products such as fruits, nuts, rubber, resins, medicines, spices and oils, as well as the materials to make household, hunting, fishing and agricultural implements are cardinal to promote food security. Most of these are also subsistence production systems, yet their role in generating additional cash income cannot be overlooked. In addition, the tropical homegardens may act as refuges for native and rare plants and conserve agrobiodiversity including the preservation of endangered species and cultivars. Considering the multifarious roles performed by such gardens, there is a clear need to revitalize such traditional land use systems, which are on the decline due to socioeconomic and technological factors.

Agroforestry practices including the tree-based smallholder production systems offer great potential to create new jobs in the rural areas, and thus, to a certain extent, reverse the process of transmigration to urban areas. That is, the great diversity of products from agroforests provides opportunities for development of small-scale rural industries and for creating off-farm employment and marketing opportunities. This capacity of agroforestry for rural employment generation through industrialization, however, is complex and has not been adequately emphasized in the past. Nonetheless, considering the potential for raw material production especially for the wood-based industries, many industrial firms are now entering into "buyback" contracts with local communities and small farmers to grow wood on their agricultural lands. The spread of the poplar-based agroforestry in northwestern India and the associated industrial development is a case in point.[22] Furthermore, through farm forestry and "Purchase at Gate" schemes, the Hindustan Newsprint Limited, Vellore, a public sector organization in India,[23] and through similar other schemes (Puri and Nair 2004), wood-based industries in India procure substantial quantities of industrial raw materials from farmers. Quite apart from providing food products and industrial raw materials, agroforestry tree products constitute a source of biofuels for the rural households and can offset industrial/automobile fossil energy consumption (e.g., tree-based oilseeds and lignocellulosic biomass crops: Achten et al. 2008). The prevailing dilemma, however, is that large-scale diversion of croplands for raising biofuel crops may result in conflicts with food security. This, nonetheless, may not be a serious constraint if the biofuel program targets the degraded lands.

To surmount the problem of land degradation also, agroforestry emerges as a promising option. Indeed, agroforestry designs of grass-shrub-tree systems are superior to grass buffers in reducing sediment losses and checking soil erosion on sloping lands. Rehabilitation of saline, alkaline, and water-logged soils through bio-drainage by planting *Eucalyptus* at specified intervals also has been successfully demonstrated.[24] Moreover, by using agroforestry technologies developed at the Central Soil Salinity Research Institute, Karnal, the State Forest Departments, non-governmental organizations (NGOs), National Wasteland Development Board (NWDB), and other developmental agencies in India have rehabilitated more than 1 million ha of salt-affected soils, particularly the village level community lands, areas along road side, canals, and railway tracts (Puri and Nair 2004). The Tree Growers Co-operatives (Gujarat, India) focusing on fast-growing trees and tree-based oilseed crops is another spectacular example of promoting agroforestry on farmlands and wastelands (Misra 2002).

New self-nourishing systems of stand management (e.g., fertilizer trees) that mimic the natural ecosystems where significant quantities of N are added via the biological fixation pathway have potential for adoption in the low fertility sites. Nitrogen-fixing trees and organic matter recycling processes may be a potent mechanism for future crop nourishment. A major role for agroforestry today, however, lies in the domain of environmental services such as climate change mitigation (carbon sequestration), phytoremediation, watershed protection, amelioration of NPS, and biodiversity conservation. Although certain CDM projects involving smallholders have been initiated as outlined before, more efforts are necessary for developing a suitable mechanism to reward the rural poor for environmental services (PES). Besides, it will require appropriate research interventions, investment, and above all a forward-looking agroforestry policy to address these issues.

Although the rate of return to investment in research on tree crops is quite high (88%: Garrity 2004), enterprise development and enhancement of tree-product marketing have been neglected. Furthermore, a question often posed is: If agroforestry is so wonderful, why is it that it is not making much headway? Perhaps the "downside" of agroforestry has not been adequately focused by researchers. Aspects such as competitive interactions (for nutrients, water, and light), impediments relating to governmental procedures in tree harvesting, lack of extension support, allelopathy, displacement of food crops with trees, and other potential land use conflicts may be relevant in most South Asian countries. For large-scale adoption of agroforestry, the following prerequisites are seemingly essential: improving the marketing and processing of agroforestry products involving public-private partnerships; product diversification and value addition; development and promotion of substitutes and/or supplements for costly, imported external inputs (e.g., fodder trees, fertilizer trees); creating an enabling environment and exploring new avenues for dissemination of agroforestry-related technologies; training and capacity building in agroforestry among all major stakeholders including policymakers highlighting the benefits of agroforestry and the constraints impeding its adoption; and partnering with a broad range of actors. Above all, for the potential of agroforestry to be effectively harnessed, there is an urgent need for an appropriate policy and institutional environment that provides farmers with clear incentives to plant and protect trees that contribute to both ecosystem function and rural livelihoods.

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Agroforestry in the Amazon Region: A Pathway for Balancing Conservation and Development

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Abstract This chapter argues for a broader conceptual domain provided by agroforestry practices as a key pathway for the reorientation of agricultural systems in the Amazon toward modes of production that combine productivity and sustainability. A contextualization of the multiple expressions of current agroforestry development in the Amazon shows that, contrasting with homegardens and shifting cultivation, ubiquitous in the region, planned or organized agroforestry systems are still minor elements of the agricultural landscape, often arising from farmers' experimentation or resulting from initiatives funded by international cooperation. A "multichain" approach focusing on both established markets as well as "secondary chains" is suggested as a pathway

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for agroforestry to go beyond subsistence toward income generation and to reduce the constraints faced by Amazon farmers to intensify land use. The costs and risks presented by practices leading to intensification, aggravated by problems in regional infrastructure, limited access to adequate technical and financial services, and insecure land tenure require equitable development policies and programs to support such initiatives. A stronger policy identity for agroforestry in the region should thus recognize the provision of both economic goods and ecosystem services, and this chapter argues that given the carbon stored in agroforestry systems, the framework of environmental international agreements is an opportunity to combine environmental and livelihood benefits through the design, promotion, and dissemination of agroforestry strategies. A review of policies that can influence adoption of sustainable land use systems in the Amazon region attests their operation in a fragmented manner. These policies must be set as a cohesive whole, being agroforestry the common thread to support and link initiatives to reduce poverty and hunger, curb deforestation and CO_2 emissions, and to mitigate climate change. Agroforestry will be then an effective strategy to bridge gaps between policies, and particularly in linking environmental opportunities with economic realities, while enhancing the livelihoods of smallholders, traditional communities, and indigenous peoples in the Amazon.

Keywords Agroforestry policy • Land use intensification • Payment for Environmental Services • Sustainable livelihoods

Introduction

The Amazon region and its peoples are at a crossroads regarding trade-offs between conservation and agriculture. The current context of deforestation and natural resource degradation in the Amazon[1] means that cases of successful sustainable resource management that exist in the region increase in importance and merit greater visibility. Among such positive examples are a number of agroforestry

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initiatives; these cases, however, need to be better understood, strengthened, and scaled up and out for the realization of an agroecological transition (sensu Altieri 2002) under which Amazonian nature and society are not in permanent opposition but rather seek an equilibrium. As recently stated by the United Nations Special Rapporteur on the right to food, in the context of ecological food and energy crises, *the most pressing issue regarding the needed reinvestment in agriculture is not how much but how to produce*.[2] In this chapter, we argue that the broader conceptual domain provided by agroforestry practices is a key pathway for the reorientation of agricultural systems in the Amazon toward modes of production that combine sustainability with the progressive realization of the right to adequate food and other components of human welfare. We examine principal aspects involved in achieving this potential and argue for a stronger policy identity for agroforestry in the region, aimed at both the provision of economic goods as well as recovery of ecosystem services, the latter through landscape restoration of cleared areas such as degraded pastures that result from moving agricultural frontiers. While ecological restoration can be quite expensive on its own, recuperating such areas with agroforestry systems that combine production of food, commodities, and timber products may be a viable alternative. Before discussing the role of agroforestry as an alternative and more sustainable form of development for the Amazon, we summarize the present socioeconomic, environmental, and political context of the region, with special regard to the forces driving deforestation.

Deforestation and the Present-Day Amazonian Scenario

Concerns about deforestation in the Amazon initially were related to loss of biodiversity and habitat and to impacts on traditional peoples. At present, however, global climate change has become an increasingly important issue, as the region is not only a contributor to greenhouse gas emissions resulting from conversion of forest to systems with much less biomass (such as pastures) but also a probable victim of heating and drying as the effects of climate change become more pronounced (Cochrane and Barber 2009; Malhi et al. 2009; Nepstad et al. 2004; Nobre and Borma 2009). Current programs for regional economic and infrastructure development, notably hydroelectric dams (Fearnside 2009; Fearnside and Graça 2009) and roads such as the highway linking the Amazon to the Pacific,[3] coupled with continuing migration to Amazon frontier areas and population growth (Carr et al. 2009; Perz et al. 2005), are likely to contribute to more deforestation, land degradation, and biodiversity loss, with drastic impacts on the livelihoods of the region's most vulnerable occupants and on the Amazon environment itself. In Brazil, an analysis of human development indicators in frontier regions shows that these indicators tend to increase as deforestation begins, accompanying the conversion of natural capital, such as timber, but then decline as the frontier evolves and extensive ranching becomes the predominant land use (Rodrigues et al. 2009).

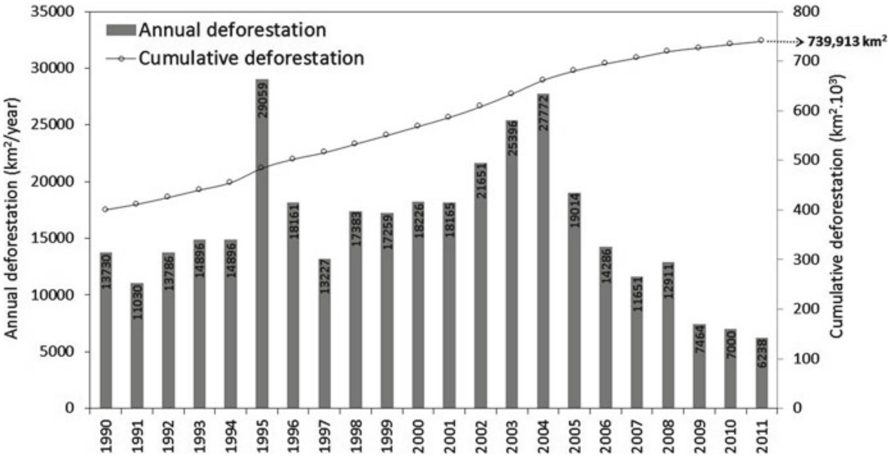

Fig. 1 Annual deforestation rates and cumulative deforestation in the Brazilian Legal Amazon, 1990–2011[4]

Nearly 85 million ha of Amazon forest have been cleared since the 1970s, mostly in Brazil (Malhi et al. 2008), where 62.2% of the cumulative land deforested up to 2007 was occupied by pastures. In productive terms, however, 25% of this area under pasture can be considered as degraded or "weedy".[5] Nonetheless, Brazil's cattle herd is now the second largest in the world, with an estimated 205 million head, and the beef sector represents 2% of Brazil's GDP,[6] the equivalent of more than US$ 40 billion in 2010. More than one third of Brazil's cattle[7] is currently raised in the Legal Amazon.[8]

Figure 1 shows annual deforestation rates and cumulative deforestation in the Brazilian Amazon from 1990 to 2011. The significant reduction in deforestation observed in recent years results from advances in satellite monitoring of deforestation activities, more effective enforcement by government agencies, the creation of new protected areas, advocacy by major international organizations and companies, and to falling commodity prices during the period (chiefly beef and soy) (Nepstad et al. 2009). Nevertheless, the new increase in deforestation (Fig. 2) detected in 2011[9] indicates that in light of the competing pressures, control mechanisms are still insufficient.

Although practices have been changing, many agricultural or pasture areas were installed with minimal or no regard for the maintenance of riparian buffer strips to protect hydrological resources, much less for the connectivity that is important to other landscape functions such as supporting biodiversity. According to some climatologists, if 30% of the Amazon is deforested, the ensuing impacts on soil properties, local and regional hydrological cycles, and climate will ultimately lead to a "tipping point," resulting in a self-feeding cycle of intensification of dry seasons, wildfires, and increasing savannization (Malhi et al. 2009; Nepstad et al. 2009; Nobre and Borma 2009). This point may be reached if present land use practices are

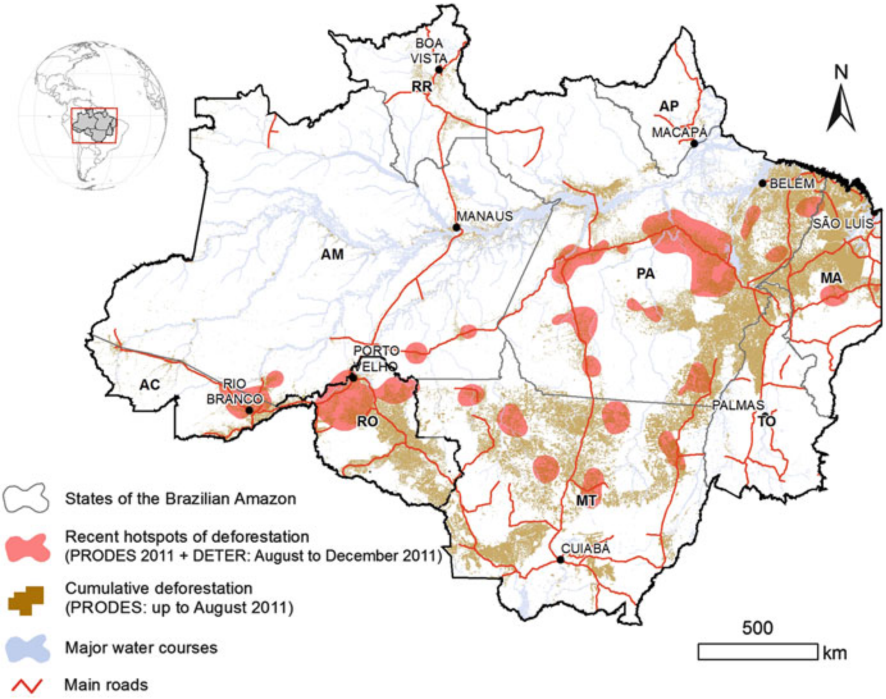

Fig. 2 Cumulative deforested area and recent hotspots of deforestation in the Brazilian Amazon (Map by R. Trancoso)

continued, and the Amazon remains a principal outlet for feeding a growing human population. National environmental goals related to climate change mitigation and adaptation can, however, lead to the convergence of economic and ecological objectives, with ecosystem restoration being supported by mechanisms such as payments for environmental services. This brings the possibility of implementing more environmentally friendly forms of land use that would otherwise not be adopted by farmers due to higher initial costs or fewer short-term benefits.

The remainder of this chapter will address the role of agroforestry in providing possible solutions for the Amazonian dilemma of balancing conservation and development. We begin by describing the traditional context of agroforestry in the Amazon and positive examples that have arisen in recent years as possible pathways to be followed. This chapter then addresses agroforestry research in the Amazon region and why this has not necessarily been associated with adoption! It then examines what are perceived as major constraints for broader adoption, and implications for agroforestry policy, including the role of agroforestry in supporting climate change mitigation mechanisms. Although the general focus of this chapter is the Brazilian Amazon region, examples from neighboring countries in the Amazon lowland rainforest biome are also discussed.

Agroforestry as a Traditional Land Use in the Amazon

The cultivation of trees in agroforestry systems (AFS) in the Amazon dates from long before the European arrival, as evidenced by the number of tree species, mainly fruit-bearing, that were domesticated by indigenous peoples (Clement 1999) and the reports of the first Europeans to explore that region in the sixteenth century (Miller and Nair 2006). Many of these species continue to be cultivated in homegardens; some have become commercial successes, such as the peach palm (*Bactris gasipaes* Kunth). Products obtained from trees, principally native cacao (*Theobroma cacao* L.), were a prime factor in the Portuguese occupation of the Amazon valley in the seventeenth and eighteenth centuries. In the nineteenth century, the growing industrial demand for the latex of the rubber tree, *Hevea brasiliensis* (Willd. ex A. Juss) Müll. Arg, caused an economic boom in the Amazon, only to collapse with the rise of plantation rubber in Asia in the first decades of the twentieth century (Homma 2003; Weinstein 1983).

The Amazon's extractive forest products contribute to Brazil's economy as well, with the fruit of the açai palm (*Euterpe oleracea* C. Mart) in first place (US$ 91.5 million in 2009), followed by the kernels of the babaçu palm (*Attalea speciosa* C. Mart. ex Spreng.; US$ 69.1 million), and Brazil nut (*Bertholletia excelsa* Bonpl.; US$ 29.8 million). In 2009, these three products constituted 49% of the total of the non-timber forest production in Brazil.[10] The spatial distribution of production of these three products across the municipalities of the Brazilian Legal Amazon is presented in Fig. 3. While the revenue from these products represents less than 0.01% of Brazil's gross national product (GNP), it constitutes a significant contribution for rural low-income Amazon families, as opposed, for instance, to the US$ 1.5 billion derived in that same year from timber extraction, an industry with a highly skewed value chain and proportionally lower benefits to local dwellers. The social importance of extractive products in rural regions is recognized by the National Plan for Promotion of Market Chains for Products of Socio-biodiversity (PNPSB), launched in 2009, under the coordination of various ministries.

Landscapes inhabited by indigenous people, traditional communities, and smallholder farmers, and their associated socio-biodiversity products highlight the fuzzy limits between agroforestry and forest management in the humid tropics, as these products are often obtained through land management systems that comprise forms of agroforestry (Brondizio 1999, 2005; Manzi and Coomes 2009; Porro 2005; Schroth et al. 2003). In addition, NTFP and agroforestry tree products (AFTP) face similar marketing challenges in that collectors or farmers generally live in rural areas with poor road access and no electricity, so opportunities are generally limited to those products that are not perishable.

Besides areas of forest under strict conservation, the case not only of protected areas such as parks and similar categories but also legally defined riparian buffers, the Amazonian scenario includes extensive areas of forest used by traditional communities for collection of extractive products as well as areas slated for selective logging, theoretically in accordance with principles of forest management. In Brazil, various

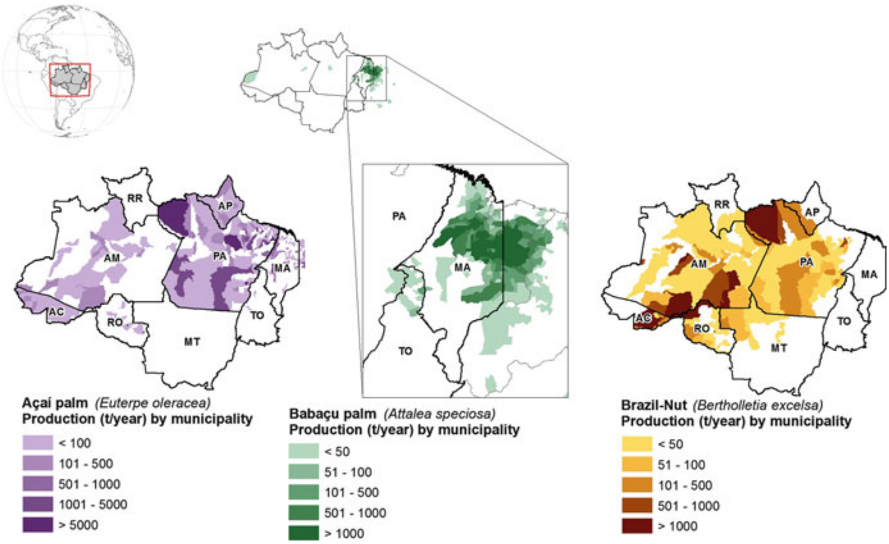

Fig. 3 Spatial distribution of production of the three main extractive forest products: açaí palm (*Euterpe oleracea*), babaçu palm (*Attalea speciosa*), and Brazil nut (*Bertholletia excelsa*) in municipalities of the Brazilian Legal Amazon (Source: IBGE 2009) (Maps by R. Trancoso)

categories of protected areas involving such sustainable use are legally recognized, such as National Forests (FLONAs) and State Forests (FLOTAs), Extractive Reserves (RESEX) and Sustainable Development Reserves (RDS), as well as three categories of agrarian reform projects that are "environmentally differentiated." However, even traditional communities established in RESEX, RDS, and environmentally differentiated agrarian reform projects are liable to convert forest to pasture (Gomes 2009; Vadjunec et al. 2009),[11] a trend that can only be reverted by supporting well-designed systems that combine the extraction of forest products and agroforestry practices, with value chain development for timber, NTFPs and AFTP. To be a politically and economically viable proposition, however, such support must be considered in the context of ecosystem services and the possibility of providing significant environmental co-benefits to society as a whole. In the remainder of this section, we discuss some of the traditional agroforestry practices that are part of the cultural heritage in various countries of the Amazon. The locations of the agroforestry initiatives discussed in this and in the next section are mapped in Fig. 4.

Ecuador

In the Ecuadorian Amazon (Fig. 4[1]), some 54% of the land under tropical forests belongs to 11 indigenous groups. Kichwa and Shuar communities traditionally practice

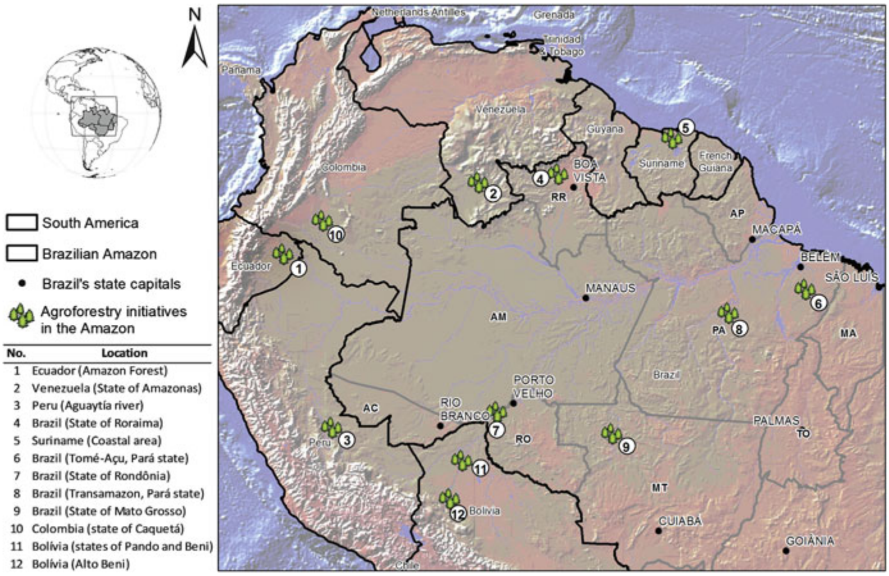

Fig. 4 Location of agroforestry initiatives in the Amazon region discussed in this chapter (Map by R. Trancoso)

the *chakra* system, in which small-scale shifting cultivation evolves into a shaded agroforestry system (AFS). In this system, cassava (*Manihot esculenta* Crantz) and banana (*Musa* sp.) provide food for domestic consumption, while cacao supports household income and forest species provide fibers and seeds for crafts, medicines, and other goods and services, such as community-sponsored tourism.[12] The *chakra* combines conservation and production attributes within an integrated resource management system. Organizations producing cacao within *chakras* are seeking to consolidate a niche in the European market, with direct contributions to the preservation of local culture.[13] Ecuador's aromatic cacao is produced under shade and combined with high value timber species, such as Spanish cedar (*Cedrela odorata* L.), mahogany (*Swietenia macrophylla* King), laurel (*Cordia alliodora* (Ruiz & Pav.) Oken), and chuncho (*Cedrelinga cateniformis* Ducke). Production and internal capacity, however, are not yet sufficient to supply the growing demand due to the combination of low productivity of cacao plots, limited generation and dissemination of technology, and the lack of modern infrastructure to provide this high-quality cacao at a broader scale.[14]

Venezuela

In the Venezuelan state of Amazonas, indigenous farmers of the Huottöja, Jivi, Curripaco, and Baré ethnic groups in the municipalities of Atures and Autana (Fig. 4[2]) are diversifying their agriculture with the introduction of perennial crops and enhancing their traditional production areas, called *conucos*. Comparable to *chakras* in Ecuador, *conucos* are swidden fields for staple crop production (in this case, cassava being the most relevant) that evolve into shaded systems (Freire 2007). The species showing the best results include peach palm, barewa or cupuaçu (*Theobroma grandiflorum* (Willd. ex Spreng) K. Schum), cocura (*Pourouma cecropiifolia* C. Mart.), guada (*Dacryodes microcarpa* Cuatrec.), seje (*Jessenia bataua* (C. Mart.) Burret), manaca (*Euterpe precatoria* Mart.), túpiro (*Solanum sessiliflorum* Dunal), temare (*Pouteria caimito* (Ruiz & Pav.) Radlk.), rubber, and guama (*Inga edulis* C. Mart.).

Suriname

In Suriname, the most important agricultural system for subsistence and sale of surpluses is shifting cultivation, practiced by the Amerindians and the Maroons.[15] In the coastal area (Fig. 4[5]), adjacent to vegetable plots and grazing lands, practically every smallholder farmer maintains a homegarden, where several fruit trees and to a lesser extent service trees are grown. Multiple, diverse outputs from the homegardens include some of intangible value, such as plantain (*Musa* sp.) leaves used as plates during cultural events. Tree presence reduces weed growth and contributes to control erosion, while nitrogen-fixing trees add the element to the systems.[16]

Peru

In addition to homegardens and swidden fields traditionally established by indigenous communities (Coomes and Burt 1997; Denevan and Padoch 1987), agroforestry in the Peruvian Amazon increasingly includes improved fallows and multistrata systems. One important example is successional agroforestry practiced on alluvial soils on the banks of the Aguaytía river (Fig. 4[3]), where the abundant and homogeneous regeneration of white bolaina (*Guazuma crinita* C. Mart.) is managed in fallows. After 5–6 years of fallow, and little or no silvicultural treatments, farmers cut down 50–80 trees per ha, with a yield of 17–29 $m^3\ ha^{-1}$ of timber. After two more years, the remaining trees are cut down and the cycle restarts (Castillo 2009).

Brazil

Timber management in fallows is also practiced by indigenous peoples of the Macuxi and Wapixana ethnic groups in the savanna region of the state of Roraima (Fig. 4[4]), northern Brazil. These groups carry out swidden agriculture in islands of dry forest scattered throughout the savanna, and during the cropping cycle, they protect and manage the coppices of *Centrolobium paraense* Tul., a timber highly valued for

Fig. 5 Homegardens with a diversity of useful species are a common feature in traditional communities in the Amazon (Parauari River, Amazonas, Brazil) (Photo: R.P. Miller)

house construction and firewood. After 4 years, coppices in fallows can reach sizes sufficient for use as house posts, beams and roof rafters.[17]

Amazonian homegardens (Fig. 5), besides being the prehistoric locus of tree domestication and improvement, continue to have an important role today, not only in food security and income generation but also as "laboratories" where farmers test new species and practices, and multiply germplasm for transfer to and between fields or exchange with other households (Miller et al. 2006). The potential role of homegardens in agroforestry development is clearly illustrated by the example of Japanese-Brazilian colonists in Tomé-Açu, state of Pará, a reference for national and international agroforestry researchers and advocates. Established in the 1930s, these families used their homegardens to test the adaptation of exotic species to local conditions, as well as to experiment with native species, becoming successful with exports of black pepper (*Piper nigrum* L.) in the 1950s (Yamada and Osaqui 2006). Black pepper monocultures, however, were decimated by diseases in the 1970s, forcing farmers to develop alternatives including multistrata systems with cacao and a number of tropical fruits (Subler and Uhl 1990; Yamada 2009). From the mid-1970s to the early 1980s, they successfully introduced Hawaiian Sunrise Solo papaya (*Carica papaya* L.) and were able to supply regional and national

Fig. 6 Agroforestry systems developed by farmers of Japanese descent in Tomé-Açu, Pará, are regarded as one of the most successful examples of agroforestry in the Amazon region. Shown here is a system combining paricá (*Schizolobium amazonicum*), açaí (*Euterpe oleracea*), and cupuaçu (*Theobroma grandiflorum*) (Photo: R. Porro)

markets.[18] Tomé-Açu's Multipurpose Agriculture Cooperative's (CAMTA) market integration has considerably expanded in the past two decades, relying on a processing plant capable of producing annual volumes of 3,000 t of fruit pulp and able to store 1,000 t, with a growing emphasis on açai (Fig. 6).

CAMTA has developed strategies for responding to environmental and economic challenges and has discovered important principles of adaptation, diversification, innovation, and shared decision making. However, ethnic identity has played an important role by helping unite members and by linking the cooperative to Japanese markets and financial capital. Adoption of similar agroforestry practices by non-Japanese-Brazilian farmers in the region has been slow, however (Piekielek 2010). It is still uncertain whether the factors limiting more widespread adoption are lack of education, capital, or entrepreneurship and business training, or a combination of these, and the Tome-Açu example does raise questions as to how successful agroforestry systems are related to case-specific aspects of ethnicity, culture, and traditions.

Although the success of CAMTA (Fig. 4[6]) is still paramount when examining commercial agroforestry in the Amazon, a number of other agroforestry experiences initially supported by government programs or NGOs have achieved moderate success, some of them for more than two decades. An examination of these cases will be the focus of the next section.

Successful Cases of Externally Supported Agroforestry Initiatives in the Amazon

Beginning in 1995, the Demonstration Projects (PDA) component of the Pilot Program to Conserve the Brazilian Rain Forest (PPG-7) supported initiatives fostering the conservation and sustainable use of natural resources with the participation of local communities.[19] Agroforestry was one of the major elements of the projects[20,21] and the PDA database[22] thus constitutes a reference for assessments of planned agroforestry initiatives in the Brazilian Amazon. Some of these initiatives are presented below.

Founded in the late 1980s, the Association of Agrosilvicultural Smallholders of the RECA Project, which in Portuguese stands for Intercropped and Dense Economic Reforestation, in Vila Nova California, Rondonia state (Fig. 4[7]), has about 1,500 ha under agroforestry production, the main crops being cupuaçu (for frozen fruit pulp) and peach palm (for palm hearts), both exported to European markets.[23] Over time, RECA farmers faced challenges in sustaining productivity and avoiding site degradation. Studies by INPA, Brazil's National Institute for Amazon Research, however, found that these problems could be solved if nutrient exports in the form of crops were counterbalanced by supplementation in the form of composted processing residues, manure, limestone, and the addition of N_2-fixing plants (Alfaia et al. 2004, 2009).

Near the city of Altamira, on the Transamazon Highway in Pará (Fig. 4[8]), cooperatives that emerged in the last decade as part of an alternative vision of regional sustainable development led by the Foundation for Life, Production and Preservation (*Fundação Viver, Produzir, Preservar*, FVPP) are producing organically certified cacao in agroforestry systems (Schwartzman et al. 2010). Although cacao has been the most important cash crop produced in the region through agroforestry since the 1970s (Mendes 2005), diversified production systems developed in the framework of the Organic Production Program are steadily gaining visibility due to the quality and productivity of cacao, with access to organic market niches resulting in a local price premium of up to 40% over the price for noncertified cacao (Silva et al. 2009). As an additional incentive, there is the prospect for cacao AFS to be accepted as a permitted land use in properties' "Legal Reserve"[24] of forest cover (see the discussion later in this chapter).

In the northwestern portion of Mato Grosso state (Fig. 4[9]), more than 1,400 ha of improved AFS have been installed by colonists and extractivists, prioritizing shaded coffee, cacao, peach palm, native timber, and species for frozen fruit pulp. The initiative, funded in part by the Global Environmental Facility (GEF) and the state government, with support of the United Nations Development Program (UNDP), also distributed over a 10-year period approximately a million tree seedlings of assorted species to help recuperate degraded landscapes.[25] As part of this project, a study of the species composition in 83 2,000 m^2 agroforestry plots in 43 landholdings showed that native canopy species count for 36% of the most frequent individuals in AFS, including Brazil nut and *Bagassa guianensis* Aubl., a timber species valued for carpentry and construction. These figures point to a complementary role of agroforestry in conserving valuable species that are threatened in Amazonian forests.[26]

Cattle production under silvopastoral systems is still incipient in the Amazon, particularly in Brazil, and certainly presents major challenges for widespread adoption. However, in Caquetá (Fig. 4[10]), the state of the Colombian Amazon with most relevant agricultural development, and where ranching is the principal activity for the local rural economy, an ongoing process of diversification is leading to the formation of silvopastoral and other AFS with positive results.[27] Farmers with on average 50 ha of pastures allow some natural tree regeneration as well as establishing small areas with woody species to provide forage (Guayara et al. 2009). These farmers are convinced of the need to diversify their production systems and reduce the area devoted to grazing. Other emerging agroforestry initiatives in Caquetá are perennial crops in multistrata systems, combined with grazing areas and forested plots. Predominant are AFS based on the integration of rubber, cacao, timber species such as *Cariniana pyriformis* Miers, *Cedrelinga cateniformis* Ducke, *Cedrela odorata* L., *Cordia alliodora* (Ruiz & Pav.) Oken, and *Tectona grandis* L. f. and Amazonian fruit species (*Eugenia stipitata* McVaugh, *Borojoa patinoi* Cuatrec., cupuaçu, and *Theobroma bicolor* Bonpl.).

Wealthier farmers of the Andean Amazon slopes in Ecuador also tend to invest in ranching and have been increasingly intensifying their systems through the integration of pastures with trees and shrubs for multiple uses, in various combinations of species, spatial and temporal arrangements. In an area where the dairy industry has been increasingly installing processing plants, these farmers usually benefit from fertile soils, are close to markets, and served by paved roads. Credit and rural extension services are fairly accessible, while commercial firms provide needed supplies and inputs for silvopastoral development.[28]

Since 1992, rural communities in Beni and Pando in the Northern Amazon region of Bolivia (Fig. 4[11]) are implementing a participatory Community Development Strategy with support from the Institute for Society, Agriculture and Ecology (IPHAE, *Instituto para el Hombre, Agricultura y Ecología*), a locally based Bolivian NGO. A prominent activity is the production of cupuaçu, cacao, peach palm, Brazil nut, açaí, majo (*Oenocarpus bataua* C. Mart.), and a number of valued timber species as components of AFS targeting agro-industrial use. More than 15 communities are implementing and managing AFS with cacao, with an average production greater than 700 kg of dry seed per ha. In total, IPHAE has contributed to the implementation of more than 1,500 ha of AFS focused on food security and sustainable production chains (Llanque et al. 2009). The conditions are now set for organic and eco-social certification, which will enable access to export markets. Increased production led to the establishment of the first cupuaçu processing company in Bolivia, "*Madre Tierra Amazonía,*" formed with private capital and having as its largest shareholders the communities themselves. Furthermore, peach palm, which was unknown in the region, begins to position itself in the local market, principally as a staple feed for pigs raised by smallholder families. Alto Beni (Fig. 4[12]) is another region in Bolivia with important agroforestry developments, with emphasis on the enrichment of organically grown cacao with valuable perennial woody species (Vega and Somarriba 2005).

In the so-called Suriname Forestry belt, inland from the coastal region, taungya systems implemented by the government's Forest Service (LBB) were common during the 1960s and 1970s. Cassava, pumpkin (*Cucurbita maxima* Duchesne ex Lam.), ginger (*Zingiber officinale* Roscoe), and pineapple (*Ananas comosus* (L.) Merr.) were grown in young plantations of *Pinus caribaea* Morelet, *Cordia alliodora* (Ruiz & Pav.) Oken, *Cedrela odorata* L., *Swietenia* spp., and *Eucalyptus* spp.[29] However, armed conflict in the interior from 1986 to 1992 virtually decimated the infrastructure of the Forest Service, and the forest plantations were abandoned.[16] Despite difficulties and constraints, the Centre for Agricultural Research in Suriname (CELOS) is attempting to revitalize agroforestry research in the country and has achieved some successes with the introduction of *Gliricidia sepium* (Jacq.) Kunth ex Walp. for improved fallows and as a service tree submitted to regular pruning, in systems including groundnuts (*Arachis hypogaea* L.) and black gram or *urdi* (*Vigna mungo* L.).[16] The introduction of palm species such as *Attalea maripa* (Aubl.) C. Mart. in agroforestry is particularly seen as a potential practice to aggregate the benefits of valuable palm fruits.

This brief overview with snapshots of both traditional and externally supported agroforestry initiatives in the Pan-Amazon by no means intends to be comprehensive but rather has the objective of illustrating the diversity of both agroforestry and social-environmental contexts in the Amazon. It is clear, however, that contrasting with homegardens and shifting cultivation, which are ubiquitous in the region (as is the case with many parts of the humid tropics), examples of planned or organized AFS in the region are mostly small-scale and minor elements of the agricultural landscape. It is also apparent that there are commonalities across the countries with Amazonian territories that result in low adoption of AFS, despite the fact that AFS have been on the international development agenda for at least three decades. The next sections address these common challenges and limitations, focusing on three principal aspects: research achievements and perspectives, constraints to adoption, and policy prospects for agroforestry in the Amazon.

Research and Dissemination Efforts in Amazon Agroforestry

In the Brazilian Amazon, institutional efforts with regard to agroforestry research date back approximately 35 years. In 1975, Paulo de Tarso Alvim, of CEPLAC, Brazil's cacao board, planted the first agroforestry experiment in Manaus that was a little more complex than providing shade for cacao. This was followed by INPA which installed its "fruit-salad" agroforestry system with six fruit trees and then the "food forest" system in 1978, with a mix of peach palm, jackfruit (*Artocarpus heterophyllus* Lam.), and breadfruit (*A. altilis* (Parkinson) Fosberg) (van Leeuwen et al. 1997). During the 1989–1991 period, six regional centers of the Brazilian Enterprise for Agriculture and Livestock (Embrapa) were renamed as Agroforestry Research Centers (*Centros de Pesquisa Agroflorestal*), theoretically indicating a shift in research priorities from monocultures and pastures toward agroforestry. A recent survey by Brienza Júnior et al. (2010) of agroforestry literature for the Brazilian Amazon from 1980 to 2005 identified nearly 500 publications, potentially providing lessons to be used in agroforestry research planning and in the formulation of agroforestry policies and programs. A similar effort is being conducted by the World Agroforestry Centre (ICRAF), through the development of a web portal that provides open access to a database comprised of more than 2,500 scientific and technical publications (manuals, project reports) relating to agroforestry in the Brazilian (1,629), Peruvian (688) and Colombian (249) Amazon since 1980. The portal[30] allows access to the publications' abstract, or to the complete documents, according to authors' licensing. The database of publications on the Brazilian Amazon has been available since 2010, and the ones for the Peruvian and Colombian Amazon will be integrated in 2012.

Although the volume of research conducted in recent years has led to some advances, in many cases, progress has not been made to the point of offering clear-cut solutions. Even after three decades of research, agroforestry is still not recognized as a viable strategy for regional development, in part because of insufficient capacities of training institutions such as agro-technical schools and Amazon universities. With some exceptions, these institutions tend to operate under traditional mindsets that do not enable students and future professionals to address the multiple aspects of agriculture in a landscape perspective, nor the diversity and local particularity of agroforestry alternatives that farmers themselves may have developed. This context is not conducive to developing processes of participatory research focusing on innovations, which should be supported by dedicated extension services to Amazon smallholder farmers and communities. One of the major challenges for the widespread adoption of agroforestry is how to set up mechanisms for the continuous sharing and flow of local and scientific knowledge between institutions that produce or compile information and a variety of end users. Related to this is the dissemination of successful practices at the pilot level to similar contexts, so that they are progressively applied, adjusted, and validated. At the same time, a number of agroforestry initiatives with practical results have been insufficiently monitored by research institutes and universities, such that technical information (growth rates, suitability of species mixtures, and market prices) needed by financial institutions to create credit options for agroforestry is not currently available.

During a recent meeting (December 15–16, 2010) sponsored by ICRAF in Belém, Pará, the more than 30 researchers and technicians present clearly indicated some of the gaps in research/extension that prevent agroforestry from reaching its potential in the region. The conclusions of the meeting include:

- Research institutions and universities have generated a vast amount of data and information on agroforestry, but this has not trickled down to the various end users, whether farmers, extension agents, or agricultural technical schools.
- The best examples of successful AFS have been generated by creative farmers. However, these systems generally are specific to local social, economic, and ecological conditions and may not be applicable in other situations.
- "Farmer experimenters" have a fundamental role in deriving information from complex systems, as these are often out of the grasp of conventional agronomic research methods.

- Farmers and their associations must be heard when research priorities and agendas are being established.

Obviously, inadequate research and extension is only one facet of the problem of low adoption. The eight Brazilian Congresses on Agroforestry Systems (CBSAFs) held since 1994 have always had a strong Amazonian focus and have accumulated results of research efforts that clearly show in a number of situations and examples that agroforestry makes sense from social, economic, and environmental perspectives. As such, it is no longer necessary to ask: W*hat is the potential role of agroforestry in the Amazon?* But rather: *Which mechanisms can support the achievement of this potential?* If agroforestry is to go beyond subsistence toward income generation, prime considerations must include a better understanding of the reality of markets and economic issues, as well as the constraints faced by Amazon farmers to land use intensification. These issues and constraints are the main subject of the next section.

Constraints for Agroforestry Adoption in the Amazon

Many agroforestry projects and programs introducing supposedly sound management options have had little success in terms of adoption and impact. This lack of success has often been attributed to market problems, "resistance" by farmers, and limited support from government, among other factors. In this regard, the development of agroforestry in the Amazon requires deeper discussions on the opportunities and limitations of low-income producers to participate in value chains for their products as a means of reducing poverty through engagement with the private sector (Humphrey 2005; Kaplinsky 2000).[31]

In tropical Latin America, these products have often included certified coffee and cacao (Kilian et al. 2005).[32] Although international markets for these products have experienced high volatility over recent years, including sustained price drops, as was the case for coffee in the late 1990s and cacao in the early 2000s, demand has grown for organic, high-quality, and fair trade certified cacao and coffee. Participation in organic certified markets, however, requires a long-term commitment to sustainable and relatively restrictive production modes, as well as collective business organization to access group certification, obtain minimum volumes, and forge strategic alliances with downstream stakeholders. Meeting these requirements can imply in considerable costs for small producers and their enterprises (Weber 2011).

The sustainable livelihood framework (Scoones 1998) linking inputs (assets) and outputs (livelihood strategies), connected in turn to outcomes, which include income and employment, as well as wider framings, such as well-being and sustainability, has highlighted the need of many rural households to find ways to combine subsistence with market-oriented agriculture and to balance on-farm with off-farm income sources (Stoian 2005). The prospects for achieving pro-poor value chain development may be enhanced through a "multichain" approach[33] focusing on identifying and responding to opportunities for more established markets (e.g., coffee and cacao), as well as those for "secondary chains" (e.g., non-timber forest products, fruits, timber).

In some situations, participation of agroforestry producers in value chains depends on access to economically viable collective enterprises that link to distant buyers and also provide critical services to their members, such as credit and technical assistance. Although there have been positive experiences with links to international and national markets for coffee, cacao, Brazil nut, and other products, the development pathways of those successful enterprises have often been long and winding and have depended on considerable support from government and NGOs (Bebbington et al. 1996).[34] Identifying more effective and efficient alternatives for supporting these enterprises is critical for improving the marketing options of smallholders.

Besides collective enterprises, individually owned small and medium enterprises also can provide the link to value chains for agroforestry products. Improvements in drying, storing, grading, processing, packaging, branding, and negotiating can greatly improve profitability. In the GEF/UNDP project in NW Mato Grosso, Brazil, for example, portable sawmills operating at a cost of US$ 200 per processed cubic meter lead to a daily profit of US$ 948 for farmers who processed 4 m^3 timber per day (PC Nunes, personal communication, October 2010). Dissemination of effective small-scale timber processing units can provide to those farmers planting timber trees the equivalent to what small-scale processing facilities for cacao and coffee represented to farmers at other stages of entrepreneurial success worldwide. However, government regulations and the policy-legal frameworks often discriminate against small-scale enterprises in the forest sector, favoring products and practices more suited to larger operations (Kaimowitz 2006). In the case of portable sawmills in Mato Grosso, legal restrictions and bureaucratic barriers to the sale of native timber species means that sawn lumber can only be sold locally, to neighbors in the same colonization project.

Besides the lack of training opportunities for small-scale agroforest-based enterprises, as well as the scarcity of technical and market information, there are limitations in the supply of rural credit suitable to specific conditions of agroforestry producers. Available sources of rural credit are usually inadequate for forestry operations and even more for agroforestry. Except for specific credit policies such as Brazil's North Region Constitutional Fund (FNO) Forest and the National Family Agriculture Program (PRONAF), such as PRONAF Forestry and PRONAF Eco, interest rates and grace periods are incompatible with smallholders' conditions and with the production schedules of many native species. Information about available sources of credit does not flow as it should from financial agencies to extension agents and farmers. Furthermore, taking on credit can be a great risk for smallholders who do not have safety nets that buffer against the potential problems involved in more intensive input-based agriculture in remote areas.

Agroforestry development efforts will continue to meet with failure if they do not acknowledge or engage with the issues discussed in this section: improved market chains, recognition of livelihood frameworks, support for collective enterprises, and appropriate credit options. Of equal importance is an understanding of the underlying social dynamics comprised by specific livelihood strategies often involving nuances of ethnicity, religion, occupation, gender, and age issues, all of which govern individuals and communities' relations to broader economic and political systems.

Beyond these issues, the lack of adoption of agroforestry's technological and management options may be related to the costs involved in intensification of land use, which may be out of reach for most smallholders. Where agricultural frontiers are still open to colonization, intensification is certainly more costly to farmers than extensive options – such as deforesting new areas. Although perennial crops make a significant difference in household income and stability in regions such as the Transamazon highway in Pará (Walker et al. 2000), these crops require initial investments often beyond most farmers' means, and annual cropping followed by pasture establishment remains the norm in most frontier regions. Lastly, it must be kept in mind that low-income farmers and traditional communities in the Amazon are usually distant from a condition of fully accessing their rights associated with citizenship. The removal of constraints for an effective dissemination and an enhanced adoption of agroforestry in the Amazon thus require equitable development policies and programs that could support these initiatives, which is the focus of next section.

Public Policies and Support for Agroforestry: How to Increase Effectiveness?

Although public policies for the Amazon have begun to engage in a more comprehensive approach to the sustainable management of natural resources, a number of contradictions are still in place. In Brazil, for example, while control mechanisms such as real-time satellite monitoring of deforestation have made significant progress in reducing forest clearance, other government initiatives support activities directly or indirectly associated with pressure on forests and ecosystem integrity, such as highways and hydroelectric dams, programs for the expansion of large-scale oil-palm plantations, and funding for meat-processing facilities. Meanwhile, most attempts to support practices and products linked to the sustainable use of Amazon's social and biological diversity have had less concrete results due to institutional weakness, lack of investment, reduced levels of participation by land users, poor governance, and limited exchange of information.

Despite these drawbacks, Brazil has a broad range of agricultural, environmental, financial and land tenure policies and programs directly or potentially linked to agroforestry development. While recent changes in this policy framework bring opportunities for new developments in agroforestry, many challenges still remain to make intensification of production systems financially possible to smallholders. In this section, we address some of the principal opportunities and challenges to agroforestry that can be considered as belonging to the domain of policy.

Land and Tree Tenure

Innovative policy and institutional approaches involving Amazon communities are needed to assure that farmers have secure title and will benefit from investments in their lands and forests. Regulations that restrict the harvesting and selling of timber from planted trees of valuable species, for example, increase farmers' uncertainty about such investments, and discourage tree planting. Particularly for species threatened with extinction and listed in the Convention on International Trade in Endangered Species (CITES), for example, mahogany, farmers simply cannot obtain permits for their harvest, even when it is clear that the trees were planted. Such restrictions caused by legal framework prevent farmers from installing and expanding their AFS and will become an increasingly important concern as more farmers plant native timber species as part of their systems.

The New Forest Code

Not all developments in the political arena can be classed as positive. The polarization of interests between conservation of forests vs. agricultural land use recently came to a head in the debate over the reform of Brazil's Forest Code (Law 4771). The original Code, established in 1965, defines, among other items, the legal limit for the minimum width of strips of riparian forest to be kept along watercourses and the areas of Legal Reserve of forest to be maintained on rural properties, according to biome. The new version, approved by the Congress in May 2012 relaxes a number of these provisions and amnesties past deforestation that exceeds legal limits, all in the name of benefitting farmers.

Unfortunately, agroforestry has been absent in this debate, despite its potential contribution to offer alternative and more environmentally friendly forms of land use and to defuse the polarization of interests that has established a dichotomy between trees and agriculture. Paradoxically, a recent report by the Secretariat of Strategic Affairs of the Presidency (SAE/PR) indicates the existence of very significant amounts of degraded agricultural lands with potential for silviculture and suggests the creation of a national policy for planted forests, with the goal of doubling the area under plantation forestry over 10 years (Secretaria de Assuntos Estratégicos 2011).[35] Although the focus of such a policy would apparently be on monocultures, significant social and environmental gains are still possible. Technicians involved in teak plantations in northwestern Mato Grosso indicate that silvicultural enterprises directly employ approximately 30 times more workers than do cattle ranches on an equivalent sized area.

Definition of the legal framework encompassing AFS (in their multiple expressions) is indeed critical for policies and programs to promote agroforestry. In 2009, the Brazilian Ministry of Environment issued technical norms and procedures for the use of vegetation within the landholders' forest reserves through sustainable management and other measures, as well as procedures for restoration and rehabilitation of Permanent Preservation Areas (APP) and Legal Reserves (RL) established by the Forest Code. In 2011, the National Environment Council (CONAMA) issued regulations for the recuperation of APPs. These dispositions, however, only address the use of AFS for the rehabilitation of areas subject to environmental regulation, such as APPs and RLs, and do not consider agroforestry's productive functions.

Payment for Environmental Services

Federal and state policies in Brazil have advanced regarding the recognition of ecosystem services provided by forests and the role of local communities in maintaining or enhancing these services. A first attempt in this direction was the Pro-Ambiente program (*Programa de Desenvolvimento Socioambiental da Produção Familiar Rural*), which after being discussed by NGOs and rural workers' movements from 2000 to 2003, in 2004 became a project sponsored by the Ministry of Environment. Pro-Ambiente was designed to compensate farmers for adopting environmentally friendly practices in ten sites in the Amazon. However, a number of difficulties, the principal being the lack of a legal definition as to how government can pay individual farmers for environmental services, led to the program being discontinued (Mattos 2006).

From the operational viewpoint at least, more success has been shown by the *Bolsa Floresta* program sponsored by Amazonas state, now reaching almost 8,000 families in 15 extractive and sustainable development reserves (RESEX and RDS) and a state forest. The program focuses on four components: (a) investments in sustainable production; (b) investments in health, education, transportation and communications; (c) strengthening of associations and visibility of the program; and (d) payments to families that reduce deforestation.

In September 2011, the federal government launched the *Bolsa Verde*, targeting low-income families that receive benefits in other federal programs and live in either RESEX or environmentally differentiated colonization projects. In order to receive this benefit, funded by the Ministry for Social Development (MDS) and administered by the Ministry of Environment (MMA), along with the Ministry of Agrarian Development (MDA), heads of families must agree to comply with the management plans for the reserve or project, which place limits on certain activities, such as the amount of forest area that can be annually converted to agriculture. An estimated 14,000 families from over 100 extractive reserves in the Amazon will be included in the first phase of this program.

The Forest Code was also a benchmark for Payment for Environmental Services to farmers. The former code established the legal percent of land that must be set aside as Legal Forest Reserve (80% of the area in the Amazon), including riparian forests for landholdings with less than 400 ha. The new code modified this rule, and intrinsically, what is the accepted "additionality," or the percent over the legally protected forest that a farmer must keep, which could be the subject of a contract to be sold as Environmental Services (e.g., water regulation and quality, carbon stocks, biodiversity, or all these services as a bundle). Again, changes in the Forest Code will intensify the debate on legal frameworks, PES, positive and negative feedbacks of economic incentives, and the role of AFS.

Extension

Unfortunately, rural technical assistance and extension services have been viewed as a burden for public budgets in Brazil since the early 1990s, rather than as investments in sustainable development strategies (Caporal 2006). Moreover, existing services lack preparation and knowledge for working with agroforestry. Nevertheless, since 2003, the MDA has included the concept of an "agroecological transition" in its extension policies. Furthermore, Operation Green Arc[36] has prioritized agroforestry systems and has boosted financing mechanisms and the training of extension agents to help farmers access credit. A direct consequence of these actions was the recent positive change in Brazilian rural credit policy, through which MDA authorized that, as of August 2011, an initial set of agroforestry systems would be eligible for loans. Thirty-two combinations of two perennial species are listed, such as açaí, cacao, coffee, citrus, and Brazil nut, associated with other fruit or timber trees. The species included are 12 fruit trees (with a predominance of citrus), nine timber trees, four palms (for various uses), three commodity crops, two nut trees, and two beverage crops, representing possibilities for both the Amazon and Atlantic Rainforest biomes. While perhaps still insufficient to meet the range of needs of each user community, this initiative is a positive step in supporting AFS through financial mechanisms.

Agroecological Management and Institutional Markets

Although not directly targeting agroforestry, other recent government initiatives looking toward more sustainable agricultural practices include the Federal Program for the Environmental Adjustment of Rural Properties, known as "*Mais Ambiente*" or Environment Plus, and the National Agroecology Program, recently announced by the Environment Minister. In terms of establishing demand for agroforestry products, the Food Acquisition Program (*Programa de Aquisição de Alimentos, PAA*) for direct purchase of several family farm-originated products and the National School Feeding Program (*Programa Nacional de Alimentação Escolar, PNAE*) have created channels for small-scale farmers to market their products to schools and other government buyers. Both programs encourage agroecological management and have the advantage of targeting relatively stable and usually local markets.

Municipal Level Initiatives

A promising source for municipal level investments in agroforestry and other sustainable land use options is *ICMS-Ecológico* or ecological value-added tax on goods and services (VAT) (May et al. 2002). According to Brazil's federal law, 25% of VAT must return to municipalities, and a proportionally small but significant share of the proceeds from such taxes (17 and 12%, respectively, for state level and interstate transactions) goes to those municipalities with part of their land area in conservation units, including indigenous territories in certain states. These revenues, however, with some exceptions, are currently incorporated into the overall municipal budget. An ongoing policy research project[37] aims to offer a different perspective for the calculation (considering agroforestry in private lands as part of the area under forest cover) and suggests the creation of municipal funds for the sustainable use and conservation of forests to be governed by a council composed of government and civil society representatives. Such a proposition will encourage municipalities to maintain the integrity of their protected areas and stimulate comanagement mechanisms with smallholders and local communities. Nonetheless, incorporation of AFS in ICMS initiatives appears to be incipient, and no information is available at the moment as to whether any municipalities have regulated the mechanism to favor AFS or any other tree planting option.

Some Conclusions with Regard to Policy

There is a broad collection of policies that can influence adoption of agroforestry in Brazil and the Amazon region, ranging from land tenure policies, land use policies, rural credit, research and extension policies, as well as opportunities for exploring subsidies and programs geared toward environmental issues. However, all of these operate in a fragmented manner, and not as a cohesive whole of what could be a more comprehensive policy for the Amazon, with agroforestry as a common thread for supporting and linking various government initiatives related to reduction of poverty and hunger, reduction of deforestation, reduction of CO_2 emissions, and mitigation of climate change.

One of the first questions to be asked in regard to a more comprehensive policy for agroforestry is how to bring the accumulated experience and local success stories to another level, the much sought-after "scaling-up." This task involves a set of disparate social actors, ranging from small-scale farmers to bureaucrats in the nation's capital, and for these different actors to interact positively, agroforestry must be presented as a crosscutting concept that links a number of themes, including poverty reduction, food security, climatic benefits, and biodiversity conservation. While obtaining the support of these sectors of society and a coalition of government agencies for a national agroforestry, policy or policies and related programs represent a great challenge; bringing these different stakeholders together signifies the possibility of creating a broad base of economic, political, and technical support, especially if regional differences are respected and represented. In recent years, policy initiatives in Brazil, such as the National Policy on Traditional Peoples and Communities, which became law in 2007, or the National Policy for Territorial and Environmental Management of Indigenous Lands (signed on June 5, 2012), have involved a series of regional consultations, and if a similar mechanism is used to generate a national agroforestry policy, this policy would certainly be more attuned to local needs than would a policy created only in government offices! As agroforestry comprises a great variety and complexity of arrangements and options, even within the same biome, any policy propositions must be flexible enough to absorb these regional differences and realities.

Agroforestry and Climate Change Mitigation: An Additional Way Forward

Agriculture, Forestry and Other Land Uses (AFOLU) represent over 30% of anthropogenic greenhouse gas emissions (GHG), and the agricultural sector accounts for almost half of these (Parry et al. 2007). In some Amazonian countries, 70% of human-induced annual emissions of carbon dioxide (CO_2) are caused by deforestation and forest degradation (PNUMA and OTCA 2008). Besides providing globally valued hydrological, biodiversity and cultural services, the Amazon forest is recognized as one of the major terrestrial carbon reservoirs of the world. Saatchi et al. (2007) estimate total carbon in the Amazon basin's forest biomass in the order of 86 PgC ± 20%, equivalent to 33–53% of the amount globally stored in tropical forest biomass (Parry et al. 2007). Carbon stock varies according to forest types, intensity of use, altitudinal gradient, among other factors, and Table 1 summarizes results of studies of such stocks across a range of Amazon forest typologies. The restoration of degraded areas using land use systems with high carbon stocks, such as agroforestry, combined with the conservation of existing forests, is one of the most cost-efficient options to mitigate climate change (Parry et al. 2007; Stern 2006). Moreover, the fundamental feature of directly contributing to livelihoods is the best argument for agroforestry's role in climate change mitigation in the Amazon. Nonetheless, this will only be true when overall benefits (derived from mechanisms rewarding carbon sequestration, avoided deforestation, and reduced emissions) are channeled to local stakeholders such as rural traditional communities and smallholder farmers at a significant scale (Hall 2008). How this will work on the ground, however, is not yet clear, as most market-driven carbon projects tend to focus on large areas of forest, involving lower transaction and implementation costs and further permanence than initiatives involving smallholders groups.

During the most recent United Nations Framework Convention on Climate Change (UNFCCC) Conference (COP-16; 2010), Reduced Emissions from Deforestation and Forest Degradation in Developing Countries (REDD +) was approved as a mechanism to promote activities aiming to conserve and increase biomass in forests, enhancing their carbon sink function. REDD+ entails conservation, sustainable forest management, and increased forest carbon stocks in developing countries. Also in 2010, REDD++ was proposed by institutions outside the UNFCCC framework to include agricultural practices that prevent deforestation. Under the proposed REDD++ framework, producers using trees in their systems would be eligible to receive carbon credits rewarding their contribution to reduce deforestation and to restock terrestrial carbon through various land use types. The amount of carbon stored in agroforestry systems depends on the species and their density, age and management, and factors such as soil type and organic matter, local climate, and specific landscape features (Nair et al. 2010). Table 2 summarizes assessments of carbon content for AFS in the Amazon region.

Among Amazonian countries, Brazil's position at the UNFCCC is well known for not accepting a binding mechanism for reduction targets proposed by Annex I members (Forneri et al. 2006). Therefore, in terms of climate change mitigation programs in 2010 Brazil started to implement more diffuse emission reduction actions through the Amazon Fund,[38] with financial resources voluntarily provided by the governments of Norway and Germany. Among other objectives, these resources can be used to promote productive alternatives to avoid deforestation, which can include agroforestry. Brazilian civil society institutions, on the other hand, are preparing contributions to the Sectorial Plan for Mitigation and Adaptation to Climate Change (Decree no. 7390/2010) which includes the consolidation of a "Low Carbon Emission Agriculture" *(Agricultura de Baixo Carbono*, ABC). Launched in 2010 by the Ministry of Agriculture, Livestock and Supply (MAPA), with funds on the order of US$ 1.25 billion, one of the goals of the ABC program[39] is to increase to 4 million ha the area under Crop-Livestock-Forestry integration,[40] the agroforestry-based proposal presented by Embrapa, consequently reducing emission of 18–22 million Mg of CO_2 eq. Although the figure of 4 million ha can be considered small in regard to the total area under agriculture and ranching, the accomplishment of this target would represent a very important first step in consolidating viable land use alternatives.

Regardless of which mechanisms will be approved and implemented at the international level, mitigation actions should not be disconnected from actions targeting adaptation to climate change (Nair 2012). Modeling exercises involving the prediction and evaluation of future impacts of climate change on the distribution of key agricultural species in the Peruvian Amazon, for instance, suggested a shift in the areas with favorable climatic conditions for these species. The negative impacts of these changes can be minimized through the regulation of local site conditions by agroforestry management, thus enhancing smallholders' capacity for adaptation and decreasing the vulnerability of their agricultural systems.[41]

Table 1 Carbon fixation and accumulation in different forest types in the Amazon region

Forest type	Management system/ type/age	Aboveground (Mg C ha^{-1})		Belowground (Mg C ha^{-1})	Source
		Average	Total		
Forest	Undisturbed	258.3	148.0		Rodrigues et al. (1999)[42]
			158.9	32.4 (40 cm)	Fujisaka et al. (1998)
			161.7		Alegre et al. (2000)[43]
			277.7–337.5		Yquise et al. (2009)[44]
			294.0		Palm et al. (2004)
			322.0 ± 20		Salimon et al. (2011)
			367.0	98.8	Callo-Concha et al. (2002)
	Managed/logged	140.5	85.1	95.9	Callo-Concha et al. (2002)
			105.8 ± 23.7		Fearnside et al. (2007)
			116.7	43.6	Lapeyre (2003)[45]
			122.8–293.7 (40 y.)		Alegre et al. (2000)
			126.3 (6 y.)		Yquise et al. (2009)
			150.0 (123–185)		Palm et al. (2004)
	Palm forest (*Mauritia flexuosa*)	118.7	97.6–139.9	315.5–433.5	Guzmán and Arévalo (2003)[46]
	Lowland, flooded forest (*varzea*)	109.0	80.0		Klinge et al. (1995)
			138.0		Tsuchiya and Hiraoka (1999)

(continued)

Table 1 (continued)

Forest type	Management system/ type/age	Aboveground (Mg Cha^{-1}) Average	Aboveground (Mg Cha^{-1}) Total	Belowground (Mg Cha^{-1})	Source
Forest fallow	20 years (y.)	62.0	62.0		Lapeyre (2003)
	15 y.	132.2	100.0		Brown and Lugo (1990)
	15 y.		117.5	39.9	Lapeyre (2003)
	15 y.		126.1–185.3		Alegre et al. (2000)
	12–14 y.	128.1	128.1		Feldpausch et al. (2004)
	7 y.	34.0	26.4		Denich et al. 2005
	4–6 y.		54.4		Feldpausch et al. 2004
	5 y.		11.2		Rodrigues et al. 1999
	5 y.		43.9		Alegre et al. (2000)
	3 y.	16.4	18.7–20.9		
	21 months		9.7		Denich et al. (2005)
	2 years enriched	19.0	13.0		Rodrigues et al. (1999)
	21 months enriched[a]		19.3		Denich et al. (2005)
	21 months enriched[b]		24.7		
	Undetermined age	55.5	43.0 ± 6.5		Fearnside et al. (2007)
			68.0	34.3 (40 cm)	Fujisaka et al. (1998)
Fallow after shifting cultivation	5 years	9.2	6.9 (4.3–9.61)		Palm et al. (2004)
	5 years; enriched		11.5 (9.5–13.4)		
	23 years	93.0	80.5–101		

[a] Enriched with *Acacia auriculiformis* (2 × 2 m)

[b] Enriched with *Acacia auriculiformis* (1 × 1 m)

Conclusions

Considering the variety of land use situations and diverse social contexts found in the Amazon, agroforestry practices have an important role to play in helping to meet the short- and long-term needs of environmental conservation and the economic well-being of the Amazon population, as components of sustainable land use systems that avoid further deforestation and support local livelihoods, provide environmental services, and envision improved governance.

A variety of successful experiences with agroforestry exist in Brazil and other countries with territories in the Amazon Basin (Smith et al. 1996; Porro 2009). Most of these are empirical, arising from farmers' experimentation, or have resulted from externally supported projects or initiatives, often funded by international cooperation, that have helped to build and reinforce social-technical networks for agroecological practices in the Amazon. Although Brazil has a 30-year record of research in AFS that has generated significant knowledge, the link to the practical experiences has been insufficient. While a research orientation toward a greater recognition of farmers' roles in generating and testing new technologies is an important step, proper public policies also are necessary to achieve the objective of securing landscapes and rural livelihoods. On a property level, an important starting point is the goal of a greater presence of trees on farms, in keeping with the idea of an "evergreen agriculture" now used by the World Agroforestry Centre to address the direct interface of agroforestry with intensive agricultural systems (Garrity et al. 2010). This potential can also be achieved in situations and arrangements where agricultural production occurs sequentially and/or adjacent to forested landscapes which is the situation of many smallholders, traditional communities, and indigenous peoples in the Amazon. Agroforestry has an equally important role to play in the Amazon's already cleared landscapes, through restoring forest cover and increasing stocks of biomass. However, clear financial incentives must be in place if agroforestry is to be used for landscape recuperation, as this is generally more costly than implementing agroforestry strictly for production purposes.

Clearly, agroforestry must be seen as a crosscutting concept in order to achieve its full potential in the context of Amazonian and the humid tropics in general. As a broader strategy of dynamic and sustainable natural resource management, agroforestry should be capable of bridging gaps between policies, and particularly linking environmental opportunities with economic realities. In particular, the search for policy alternatives to the impacts resulting from drastic changes in land use in the Amazon acquires a critical dimension for those vulnerable social groups whose livelihood is strictly dependent on agriculture and forestry. Facing restrictions posed by ever-decreasing entitlements to land and resources, these peoples need specific tools and mechanisms to assist the adjustment of their traditional production systems to the environmental challenges of the twenty-first century. From a demographic viewpoint, frontier regions in the Amazon now have a generation of youths or young adults who, unlike their colonist parents, generally migrants from other parts of Brazil, grew up in the Amazonian environment and have a much better understanding of local realities.

Table 2 Carbon fixation and accumulation in different agroforestry and tree crop systems in the Amazon region

Land use system	Management system/type/age	Aboveground (Mg C ha^{-1})		Belowground (Mg C ha^{-1})	Source
Complex agroforests	Multistrata; 7 years	44.3	15.5–49.5		Schroth et al. (2001)
	Multistrata		19–47		Lapeyre (2003)
	Multistrata[a]		58.6		Alegre et al. (2000)[\]
	Multistrata + *Centrosema pubescens*		59.0		Callo-Concha et al. (2002)
	Multistrata		61.2 (47.5–74.7)		Palm et al. (2004)
	Homegarden	84.8	84.8	110.5	Callo-Concha et al. (2002)
	Lowland agroforest	134.3	134.3		Santos (2002,[47] 2004)
Simple agroforests	Peach palm based[b]	45.0	45.0		Gonçalves (2010)[48]
	Cacao based[c]	68.9	96.5–104.7		Yquise et al. (2009)
	Cacao based[d]		72.03		
	Cacao based[e]		26.2		Callo-Concha et al. (2007)
	Cacao based[f]		45.1		
	Coffee based[g]	88.7	80.1	113.5	Callo-Concha et al. (2002)
	Coffee based[h]		97.2		Rodrigues et al. (1999)
Tree crop plantation	Coffee	11.0	8.7–12.5		Palm et al. (2004)
	Annatto (*Bixa orellana*)	18.9	15.5–22.3		Elias et al. (2002)
	Cacao	19.0	19.0		Teixeira et al. (1994)
	Rubber	25.9	25.9		Teixeira et al. (1994)[49]
	Oil palm	41.4	41.4		Alegre et al. (2000)
	Peach palm, Oil palm; rubber	47.0	27–61		Palm et al. (2004)
	Rubber; 30 years	74.0	74.0		Alegre et al. (2000)
Silvopastoral	Pastures; native trees	86.7	33.3	86.4	Callo-Concha et al. (2002)
	Pastures + Brazil nut, mahogany, *Schizolobium amazonicum*; 15 years		140.0		Gonçalves (2010)

Grasslands	Degraded pastures	3.5	4.2	93	Callo-Concha et al. (2002)
			5.7		Rodrigues et al. (1999)
			2.85		Palm et al. (2004)
			1.8–3.1		Alegre et al. (2000)
	Improved pastures	5.4	7.6	19.6 (40 cm)	Fujisaka et al. (1998)
			6.0		Rodrigues et al. (1999)
			4.8		Alegre et al. (2000)
			3.1		Palm et al. (2004)
Crops	Cassava	3.4	3.4		Alegre et al. (2000)
	Maize	7.8	7.8		
	Rice	16.8	16.8		
	Plantain	24.4	16.2		
			21.1–35.9		Lapeyre (2003)

[a] *Bactris gasipaes, Cedrelinga cataeniformis, Coffea arabica, Inga edulis, Colubrina glandulosa, Elaeis guineensis*

[b] Peach palm intercropped with native long-cycle timber trees (15-year time horizon)

[c] Cocoa intercropped with *Inga edulis* (6- and 8-year-old)

[d] Cocoa intercropped with *Guazuma crinita* (3-year-old)

[e] Cocoa agroforestry; 5-year-old

[f] Cocoa agroforestry; 12-year-old

[g] Coffee intercropped with native long-cycle timber species

[h] Coffee intercropped with rubber; 3-year-old

If provided with suitable information, support, and incentives, this generation is capable of making significant changes in patterns of land use.

While agroforestry appears to be a promising alternative to mitigate environmental degradation, as a component of integrated natural resource management and biodiversity-conserving practices, it is not a panacea and must be part of a broader set of policies striving for sustainability on various fronts. In this context, the framework of international agreements that will define the mechanisms for REDD++ should be seen as an additional opportunity to combine environmental benefits with benefits to the livelihood of rural communities in the Amazon through the design, promotion, and dissemination of agroforestry strategies.

End Notes

1. In this chapter, Amazon region is defined according to the boundaries of the entire Amazon lowland rainforest biome or "Amazonia sensu latu" proposed by the Amazon Cooperation Treaty Organization according to hydrographic, ecological, and biogeographic criteria, comprising the combination of (a) Amazonia sensu stricto (the area of the Amazon and Tocantins river basins dominated by the Amazon lowland rainforest biome, including also minor other forest and non-forest vegetation types and their associated fauna) and (b) the Amazon lowland rainforest types of the biogeographically defined Gurupi and Guiana subregions. The Amazon region thus comprises approximately 6.7 million km^2, the greater part (65%) of which is in Brazil. Significant areas, however, make up the territories of adjacent countries: Peru, Bolivia, Colombia, and Ecuador. Although not strictly part of the Amazon basin, neighboring areas of Venezuela, Guiana, Suriname, and French Guiana are considered part of the Amazon biome due to biological similarities of the flora and fauna (Eva and Huber 2005).
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Mainstreaming Agroforestry in Latin America

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Abstract Agroforestry covers between 200 and 357 million hectares in Latin America, including 14–26 million hectares in Central America and 88–315 million hectares in South America. Commercial silvopastoral systems and shaded tree-crop systems (involving crops such as of coffee, *Coffea* spp., and cacao, *Theobroma cacao* L.) are the most prominent agroforestry examples in the region. Agroforestry has permeated into multiple sectors of modern Latin American societies and is now included in the agendas of the international community; in national laws, institutions, and policies; in a growing body of science and technology; and in the practice by farmers, ranchers, and other land users. In this chapter, we explored the status and trends of Latin American agroforestry in five sectors: (1) rural development, (2)

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international cooperation, (3) science and technology, (4) legal-institutional-policy (public and private) frameworks, and (5) education and training. The analysis considered various geographical levels, including the Latin American subcontinent, the Central America region, and three countries individually – Nicaragua, Colombia, and Peru. This article shows the notorious relevance of agroforestry in Latin America and concludes that agroforestry has developed significantly, but unevenly, in sectors and countries in Latin America. Simultaneous actions are needed in all sectors and countries to mainstream agroforestry and to increase its visibility in modern Latin American societies

Keywords Education and training • Legal and institutional framework • Public and private policies • Shaded coffee and cacao • Silvopastoral systems

Introduction

Agroforestry has been practiced since agriculture began, although it has been studied as a scientific discipline for only 30 years (King 1989; Nair 1993b). Thematically, agroforestry evolved differently in the developing countries of Africa, Asia, and the Americas. In Africa, agroforestry research and development (R&D) attention centered on food production systems (mostly grains) in seasonally dry and semiarid areas. Trees and shrubs (mostly fast-growing, N_2-fixing legumes) in crop fields were promoted to increase soil fertility and to sustain crop productivity (Kang 1993; Buresh and Cooper 1999). Researchers in Africa also mastered the use of fodder trees and browsing by wild and domestic animals in arid and semiarid regions, as well as the domestication of indigenous fruit and nut trees for the enrichment and intensification of tree-based agroforestry systems (Leakey et al. 2012). Researchers in Africa approached agroforestry from an agronomic perspective; their research focused on food production systems and on the supporting role of the woody perennial in the maintenance of soil fertility (hedgerow intercropping and improved fallows).

In Asia, most prominent agroforestry research had a "forestry perspective" to agroforestry; their R&D focused on tree-crop-based systems at the forest end of

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the agriculture – forest continuum. Rubber [*Hevea brasiliensis* (H.B.K.) Muell.-Arg.] and damar (*Shorea* spp.) agroforests have been studied in detail. Equal attention was given to the highly diverse, highly structured, but also highly modified forest gardens and fruit forest gardens of Southeast Asian countries (Michon and de Foresta 1996). Food production systems based on both homegardens and traditional land fallowing and mulching systems also received considerable R&D attention in highly populated Southeast Asia (Cairns 2007).

In Latin America,[1] R&D attention was focused principally on silvopastoral systems and in multistrata systems with tree crops (Somarriba et al. 2001). Some attention has been given to traditional, food-based, fallowing and mulching systems (Thurston 1997; Kass and Somarriba 1999), and to homegardens (Coomes and Ban 2004; Barrera-Bassols and Toledo 2005; De Clerck and Negreros-Castillo 2000, Pool et al. 1982). The Latin American approach to agroforestry came from a focus on commercial agriculture with tree crops and livestock production systems, but, possibly more than in any other region, included a strong biodiversity conservation focus too (Vandermeer and Perfecto, 2005). Andean countries, with large areas of humid Amazonian forests, have focused their agroforestry research on improved fallows to reduce soil degradation by slash-and-burn agriculture (Alegre et al. 2005), alley-cropping with *Inga edulis* Mart. to reduce soil erosion (Salazar et al. 1993; Alegre and Rao 1996), silvopastoral systems to recover degraded pasturelands (Arevalo et al. 1998), tree domestication [e.g., *Calycophyllum spruceanum* (Benth.) Hook. f. ex Schum., *Cedrelinga catenaeformis* (Ducke) Ducke, *Bactris gasipaes* H.B.K.] for improved AF systems (Cornelius et al. 2006), and multistrata systems to reduce net emissions of greenhouse gases (Palm et al. 2002; 2004). In what follows, a more in-depth analysis is presented on the area coverage and current knowledge on silvopastoral, shaded coffee and cacao systems in Latin America.

Area Under Agroforestry in Latin America

The need of planners, developers, and policy makers for reliable and quantitative estimates of area, economic, and social importance of agroforestry has motivated various researchers to address the issue. The inventory of agroforestry systems in the world was one of the first endeavors undertaken by ICRAF in the 1980s. Nair (1993b) concluded that "irrespective of the sociocultural differences in different geographical regions, the major types of agroforestry systems are structurally similar in areas with similar ecological conditions. Thus, agroecological regions can be taken as a basis for design of agroforestry systems." He described the three major (tropical) regions for agroforestry [FAO categories: humid/subhumid lowlands, dry regions (semiarid and arid), and highlands] and listed the most prominent agroforestry systems per region. A total of ten major agroforestry systems were listed for all three regions. A world map of agroforestry systems was then constructed linking agroecological conditions to agroforestry systems. For Latin America, the map allocated silvopastoral systems to large areas in South America and tree-crop-based agroforestry systems to both Mesoamerica and South America. The Caribbean region was not considered at this scale of the map. Neither area estimates per region nor per agroforestry system were given; furthermore, the analysis was confined to tropical regions (Nair 1993b). Latin America agroforestry is practiced in tropical, subtropical, and temperate regions and in a wide range of altitude and rainfall levels.

Dixon (1995) estimated the area suitable worldwide for agroforestry in 585–1215 million hectares. Nair et al. (2009) "guesstimated" the total world area under agroforestry at 1,023 million hectares, by assuming that 20% of the land under arable and permanent crops was agroforestry, 15% of the pasturelands were silvopastoral systems, and 5% of forest area was under agroforestry management. They did not provide area estimates for agroforestry in Latin America. Zomer et al. (2009) conducted a global study of trees on farms using remote sensing data, included 13 geographical regions (including Central and South America), and estimated the area under agroforestry for 10 or 30% tree cover in agricultural land (crop + pasture lands). Worldwide, at >10% tree cover in agricultural land, they estimated an area of 10 million km^2 under agroforestry. This estimate is remarkably close to Nair et al. (2009) "guesstimate."

In Central and South America, 98 and 40% of agricultural land, respectively, have more than 10% tree cover. If a more restrictive 30% tree cover minimum level is considered, still 52% (269,503 km^2) and 23% (3,888,466 km^2) of agricultural land in Central and South America, respectively, are under agroforestry (Zomer et al. 2009). These findings are corroborated by a detailed inventory of forests and trees outside forests (which included various forms of silvopastoral systems, fallow land, tree crops, homegardens, and agroforestry with annual crops) in Nicaragua. It was estimated that, on average, 57% of the continental area of Nicaragua (130,000 km^2) was under agroforestry. When considered separately, 73% of the agricultural land (3,208,399 ha) and 45% of pasture lands (4,430,344 ha) were under agroforestry, respectively (Instituto Nacional Forestal).[2] In Colombia, agroforestry is estimated to cover 20 million hectares in total,[3] including 16.8 million hectares in silvopastoral systems (40.2% of total pasture area in the country, 41.67 million hectares) and 3.42 million hectares of tree-crop systems (58.2% of total agricultural area in the country, 5.87 million hectares). Tree density is increasing in the agricultural landscape in Latin America, as exemplified by a 50-years apart, rephotographing study in Western Honduras (Bass 2004).

We compiled the area under agriculture (165,978,000 ha), forest (860,481,000 ha), and pastures (533,762,000 ha) in Latin America (http://faostat.fao.org, last accessed: November 6, 2011) and estimated the area under agroforestry using (1) Nair et al. (2009) "guesstimates" and (2) Zomer et al. (2009) ranges of estimates of agroforestry area under varying tree cover thresholds. With #1, the area under agroforestry in Latin America was estimated in 161 million hectares including 85 million hectares of silvopastoral systems, 33 million hectares of agroforestry systems with annual and perennial crops, and some 43 million hectares in forest-based agroforestry systems. With #2, and considering 30 and 10% tree cover minimum thresholds, the area under agroforestry ranged between 200 and 357 million hectares, respectively.

Fig. 1 Cattle ranchers in Latin America retain in their pasturelands many valuable native tree species that regenerate naturally at the site, as illustrated by this example from the Pacific, seasonally dry region of Costa Rica (Photo author: Muhammad Ibrahim)

Silvopastoral Systems in Latin America

Commercial silvopastoral systems are prevalent throughout Latin America. Grazing under natural and planted forests represents a common form in many parts of the region (Fig. 1). Such practices in temperate and subtropical Argentina and Chile are the subject of many publications in technical journals (for instance, in *Revista Argentina de Producción Animal, Agriscientia*) and in the proceedings of national symposia. Silvopastoral systems for arid and semiarid zones in central and northern Chile and grazing under Chaco vegetation in Argentina, Bolivia, and Paraguay are well-established silvopastoral practices that have been investigated in some detail (Ovalle et al. 1982; Zelada 1986; Ormazábal 1991). The use of tree and shrub fodder in livestock production systems has been studied in detail and applied in Cuba (numerous articles in *Revista Cubana de Ciencia Agrícola, Pastos y Forrajes, Zootecnia Tropical*) and CATIE (Centro Agronómico Tropical de Investigación y Enseñanza) in Costa Rica.[4]

In Central America, traditional ranching systems retain a relatively high tree density and diversity of dispersed trees in pastures and in live fences (Cajas-Girón and Sinclair 2001). More than 90% of farmers surveyed in Costa Rica and Nicaragua retained trees in their pastures and 49–89% used live fences (Harvey et al. 2005). The combined cover from these traditional systems can vary between 8 and 29%, equivalent to 19–53 trees ha^{-1}.[5] These systems are often dominated by no more than five species representing >55% of the total abundance. These widely used traditional silvopastoral systems not only make important contributions to farm productivity, including increasing the resilience of cattle farmers to drought but also make important contributions to biodiversity conservation, e.g., by serving as steppingstones to facilitate movement of wild biodiversity.

In the past, research on silvopastoral systems focused solely on sustainable cattle production. Today's focus has shifted to land management systems that simultaneously provide family livelihoods and ecosystem services. The value of retaining and managing trees in pastures is widely recognized by Central American cattle ranchers; e.g., dispersed trees in pastures provide shade for livestock and when properly managed with nutritious species also provide forage, especially during the dry season when forage is scarce. In the seasonally dry Pacific region of Costa Rica, fresh fruit production in the dry season was 26, 36, and 86 kg/adult tree, respectively, for *Guazuma ulmifolia* Lam, *Samanea saman* (Jacq.) Merr., and *Enterolobium cyclocarpum* (Jacq.) Griseb.[6] The use of these species in integrated feeding systems should be further studied.

Impacts of managing tree cover on cattle farms are important not only at the farm scale but also at the landscape scale. For example, riparian forests on cattle farms can contribute to water filtration and hence improve water quality for downstream communities, and networks of unpruned live fences and riparian forests can provide critical corridors for plant and animal biodiversity (Harvey and Haber 1999). In studies conducted in Costa Rica, Harvey (2000) counted 2.3 seedlings m^{-2} under connected windbreaks compared to 0.9 seedlings m^{-2} in non-connected windbreaks. In a heavily fragmented landscape in Central Nicaragua, 65% of forest fragments were connected to an adjacent forest fragment by at least one live fence (Harvey et al. 2005).

The effect of tree cover on pasture growth underneath depends on the tree species, tree age, and management. Tree species with light, high, narrow, and open crowns permit greater light transmittance (usually the limiting factor for pasture growth) and therefore have less negative effects on pasture productivity than species with dense, low, closed crowns.[6] Hence, farmers can increase the density of timber trees using species with tall stems and small light crowns [e.g., *Cordia alliodora* (Ruiz & Pav.) Oken*, Cedrela odorata* L.*, Platymiscium pleiostachyum* Donn. Sm.] while retaining a lower density of species with larger and denser crowns that adversely affect pasture productivity and floristic composition (shade favors broad-leaved species vs. graminaceous species). Furthermore, farmers may select species that in addition to shade and timber also produce nutritious forage and fruits for animal consumption [e.g., *Gliricidia sepium* (Jacq.) Kunth ex Walp.*, Guazuma ulmifolia* Lam.].[7]

Profitability of small dairy farms can be increased, especially when labor costs increase, through diversification with high valued timber species such as *Cordia alliodora.* For example, the marginal net income from dairy farms (mean size 10 ha) with traditional pasture systems was 208 US \$ ha^{-1} $year^{-1}$ compared to 1980 US \$ ha^{-1} $year^{-1}$ with pastures which included *Cordia alliodora* for its timber value (Holmann et al. 1992). Wider adoption of improved silvopastoral systems is limited because of high financial risk, incomplete knowledge, limited access to capital and markets, and poor genetic livestock (Jansen et al. 1997). However, better and more secure markets are now opening for silvopastoral production systems as a result of various certification schemes (SAN Sustainable Agriculture Network)[8] and payment schemes for ecosystem services (Rapidel et al. 2011).

Shaded Coffee and Cacao in Latin America

Coffee and cacao cover 5.41 and 1.63 million hectares in Latin America, respectively, with notorious variations between countries (Table 1). Our "guesstimate" is that 83% of cocoa is grown under shade (i.e., 1.35 million hectares are agroforestry). Only Ecuador (50%), Colombia (25%), and Brazil (7%) have significant areas of cacao cultivated in open-sun conditions.[9] Shaded coffee offers a different picture. For example, we "guesstimate" that the use of shade is only 10% in Brazil (the major producer, with 37% of total area under coffee in Latin America) and 60% in Colombia. In Costa Rica, 70% of the coffee is cultivated under shade; in the remaining Central American countries, 90% of all coffee is produced under shade.[10] This 90% estimate of shade coffee holds also for Mexico (Moguel and Toledo 1999), and we "guesstimate" that it also applies to the rest of Latin American coffee-producing countries (Peru, Bolivia, Venezuela, Haiti, Jamaica, and Cuba). These results depart from earlier concerns that the push for coffee intensification would lead to the replacement of 40% of shaded coffee with intensive, open-sun cultivation (Rice and Ward 1996; Rice 1999). It is estimated that nearly three million hectares of coffee are cultivated under shade in Latin America (Fig. 2).

A considerable amount of research has been devoted to shaded coffee (*Coffea arabica* L.), shaded cacao (*Theobroma cacao* L.), and other multistrata systems with native Amazonian fruit and timber species (Clement 1989; Miller and Nair 2006;[11] Porro et al. 2012). A five-class classification for cacao (Rice and Greenberg 2000) and coffee (Moguel and Toledo 1999) production systems has been widely adopted: (1) unshaded cacao monocrop, (2) specialized shade (monospecific shade canopies of a locally adapted species of *Gliricidia, Inga, Leucaena, Erythrina,* or *Albizia*), (3) productive shade canopies (cacao-plantain, cacao-rubber, cacao-fruit, or cacao-timber intercrops), (4) mixed shade canopies, and (5) rustic (in Brazil, rustic cacao is known as cabruca).

Many studies report on the capacity/potential of these five types of shaded cacao/coffee agroforestry systems to recycle and conserve the carbon and nutrient capitals of the site (Beer et al. 1990; Hartemink 2005; Gama-Rodríguez et al. 2011: Rita et al. 2011) and to conserve biodiversity at both the plot and landscape level (Perfecto et al. 2003; Schroth et al. 2004; Schroth and Harvey 2007). Agroforestry with shaded tree crops has been shown to be a much better alternative to sustain biodiversity than intensive monocrops but not as good as the natural forests (Perfecto et al. 2003; Schroth and Harvey 2007). A growing body of research is being published on trophic and other types of ecological interactions in shaded cocoa systems (van Bael et al. 2007a, b). Studies to understand the ecophysiological basis of the shade-crop yield relationship have also been undertaken (Da Matta 2004; Zuidema et al. 2005;

Table 1 Area under cacao and coffee in Latin American countries

	Coffee		Cacao	
	ha	Source	ha	Source
Brazil	2001340	FAOSTAT (2009)	680000	COPAL (2000)
Costa Rica	97614	ICAFE (2007)	4588	IICA, CATIE (2010)
Mexico	690000	Avalos-Sartorio (2002)	82064	SAGARPA (2004)
Peru	342600	FAOSTAT (2009)	59800	IICA, Ministerio de Agricultura (2009)
Ecuador	280000	Programa Andino de Competitividad para la cadena del café (2001)	415615	MAGAP (2011)
Panama	30000	FAOSTAT (2009)	5435	FAOSTAT (2009)
Guadeloupe	46	FAOSTAT (2009)	0	
Jamaica	11256	FAOSTAT (2009)	5535	FAOSTAT (2009)
Colombia	869000	Agrocadenas Colombia (2005)	104000	FEDECACAO (2011)
Haiti	90397	FAOSTAT (2009)	21963	FAOSTAT (2009)
Honduras	230000	FAOSTAT (2009)	1443	MEJÍA,CANALES (2009)
Belize	46	FAOSTAT (2009)	121	FAOSTAT (2009)
Nicaragua	152543	MAGFOR, INAFOR, FAO (2008)	12781	MAGFOR, INAFOR, FAO (2008)
Paraguay	2700	FAOSTAT (2009)	0	
El Salvador	153846	FAOSTAT (2009)	515	FAOSTAT (2009)
Venezuela	207143	INE (2007)	65126	INE (2007)
Cuba	26600	FAOSTAT (2009)	5089	FAOSTAT (2009)
Bolivia	26373	FAOSTAT (2009)	8852	PNUD (2008)
Guatemala	249200	MAGA (2011)	3990	MAGA (2011)
Dominican Republic	830	FAOSTAT (2009)	153201	MINISTERIO DE AGRICULTURA (2010)
Total	5415832		1630118	

Sources: XX Reunion ALPA (2006), COPAL (2000), Environment Department Papers (2004), FAOSTAT (2009), FEDECACAO (2011), IICA, CATIE (2010), IICA, Ministerio de Agricultura Perú (2009), ICAFE, INEC (2007), INE (2007), MAGFOR, INAFOR, FAO (2008), Ministerio de Agricultura y Desarrollo Rural, Observatorio Agrocadenas Colombia (2005), MAGA (2011), MAGAP (2011), Mejía, Canales (2009), MINISTERIO DE AGRICULTURA (2010), Murgueitio (2005), PNUD (2008), SAGARPA (2004), Programa Andino de competitividad para la cadena de café (2001), Avalos-Sartorio (2002), http://www.agricultura.gob.do/LinkClick.aspx?fileticket=ENacoBUbJxQ%3d&tabid=86&mid=807&language=es-DO

de Almeida and Valle 2007). These models show the detrimental (but not linear) effect of shade on per plant yield and suggest that using shade makes a lot of sense when the site is suboptimal for the crop. A rich literature is now published on the taxonomic composition, species richness, and abundance patterns of a large number of taxa found in coffee and cacao production systems in Central America (Somarriba et al. 2004; Harvey et al. 2006; Harvey and González-Villalobos 2007; Deheuvels et al. 2011), southern Mexico (Perfecto et al. 1996, 2005), and Bahía, Brazil

Fig. 2 In full blossom. Open-grown *Erythrina poeppigiana* (Walpers) O.F. Cook trees used as shade over coffee in Turrialba, Costa Rica (Photo author: Olivier Roupsard)

(Faria et al. 2007). Modeling and the evaluation of ecosystems services, such as carbon accumulation in tree biomass, have also received a lot of attention in recent times (van Oijen et al. 2010; Rapidel et al. 2011). The quantitative assessment of the balance of mass, water, and radiation in shaded coffee systems at the micro-watershed level is currently under way in Costa Rica (Gomez-Delgado et al. 2011).

Numerous studies have looked at the productivity (biological and financial) of shade cacao systems. Shade design and management to optimize yields has been studied (Sánchez et al. 2002; Bentley et al. 2004; Somarriba and Beer 2011). The impact of the harvest of timber trees on cacao yields and management costs has shown that the value of timber easily offsets the cost of repairing the cocoa plant to pre-damage conditions and the non-perceived income from cocoa yields during the repairing phase (Ryan et al. 2009). Similar conclusions have been presented for the extraction of timber in shaded coffee (Somarriba 1992). A specialized bibliographic data base on agroforestry with cacao is available at http://biblioteca.catie.ac.cr/inaforesta.

The Multidimensional Nature of Agroforestry in Modern Society

Agroforestry is a prevalent land use in Latin America as demonstrated above. Possibly as a result of this, agroforestry is fully integrated into modern Latin American societies. There is ample evidence of this. For example, (1) farmers continue practicing agroforestry on their farms; (2) governments, nongovernmental organizations (NGOs), and other institutions provide technical agroforestry services to farmers; (3) a rich palette of opportunities for formal education and short-term training in agroforestry are available to various target groups (from farmers to Ph.D. students); (4) agroforestry scientific knowledge is created and translated into technologies and educational materials; (5) funding is allocated to agroforestry by private sector, governments, NGOs, bilateral and multilateral cooperation agencies, etc.; (6) laws and institutions have been created to regulate and develop agroforestry resources; (7) governance institutions and mechanisms are in place for certain agroforestry production systems (e.g., coffee and cattle ranching sectors in Latin America); and so on.

In what follows, the status and trends of five agroforestry sectors at three geographical scales are analyzed: Latin America as a whole, the Central American region, and three countries individually (Nicaragua, Colombia, Peru). The five agroforestry sectors considered were (1) rural development; (2) international cooperation; (3) science and technology; (4) legal, institutional, and policy (public and private) frameworks; and (5) education and training.

Rural Development

Development projects, NGOs, and other organizations in Latin America frequently emphasize agroforestry in their portfolios of recommended land use alternatives. Agroforestry is specifically mentioned in the operational strategies of important international NGOs such as CARE and Catholic Relief Services. A country example can illustrate the situation. In Nicaragua, agroforestry was well represented in the portfolios of 33 NGOs and other development organizations in 2010 (Appendix 1).

International Agroforestry Cooperation in Latin America

There is a consensus among development strategists that agriculture in the twenty-first century will have to reduce global hunger, poverty, and environmental damage, including greenhouse gas emissions, by maintaining and enhancing ecosystem services while increasing sustainable production and safeguarding nutritional quality (MEA 2005; IAASTD 2009). Agroforestry is perfectly suited to address the goals of the adapted mosaics model of the Millennium Ecosystem Assessment (Cork et al. 2005; i.e., shifting the focus of agricultural sector initiatives from sustainable production to the provision of a wide range of goods and ecosystem services), the Millennium Development Goals (Garrity 2004), the Clean Development Mechanism of the Kyoto Protocol (Nair et al. 2009), and various UN conventions.

Various developments support the hypothesis that agroforestry will remain relevant for Latin American farmers in the foreseeable future. For example, certification schemes, facilitating access to markets and/or providing price premiums, such as Rainforest Alliance or Starbucks' C.A.F.É. practices that promote farming with trees (SAN Sustainable Agriculture Network[8]), are increasing in prevalence, importance, and popularity. Payment for Environmental Services (PES) has added a new economic incentive for maintaining or adopting agroforestry[12] (Rapidel et al. 2011). Second, large agribusiness corporations, such as Mars, McDonalds, Kraft, Nestle, and Wal-Mart, are promoting a tree-based agriculture, and in the near future, entry to the supply chains of these large corporations will be conditioned to sustainable practices, such as farming with trees (Millard 2011). Finally, access to international markets for wood-based products is changing in ways that will favor timber production in agroforestry systems. For instance, Forest Law Enforcement, Governance and Trade (FLEGT) regulations increasingly limit sale of timber (e.g., in Europe) if legal harvesting cannot be demonstrated (van Dam and Savenije 2001). In Latin America, many agroforestry systems may produce high value timber (usually underestimated in national statistics) in a sustainable way.

Science and Technology

Scientific articles in peer-reviewed journals and books are usually taken as proxy for describing the health, productivity, quality, and other attributes of science in a particular field of knowledge (e.g., agroforestry). The analysis of 812 journal articles on Latin American agroforestry retrieved by a comprehensive search of the Web of Science bibliographic databases showed that (1) the number of agroforestry articles published annually in Latin America increased sharply between 1990 and 2005, although it seems to have stabilized between 2006 and 2011 at an average annual rate of roughly 60 articles per year (Fig. 3); (2) geographically, research has a strong concentration in Mexico, Costa Rica, and Brazil; (3) thematically, research is highly concentrated on shaded coffee, biodiversity studies, and silvopastoral systems; and (4) research results are published in a wide array of journals; *Agroforestry Systems* (Springer) is the most popular journal among researchers, followed by *Agriculture, Ecosystems and Environment*, *Forest Ecology and Management*, *Biodiversity and Conservation*, and *Biotropica*, just to mention the top five.

A large amount of technical literature on Latin American agroforestry is published each year (mostly in Spanish, but also in Portuguese and French) as technical reports by national, regional, and international centers [e.g., CATIE, FHIA (Fundación Hondureña de Investigación Agrícola), CIAT (Centro Internacional de Agricultura Tropical), EMBRAPA (Empresa Brasileira de Pesquisa Agropecuaria), and the network of INIAs (national research institutes)]; student theses; and papers in various widely read regional technical journals (e.g., *Agroforestería en las Américas, Boletim do Desenvolvimento e Pesquisa Rural, Turrialba, Revista Argentina de Producción Animal, Agriscientia, Zootecnia Tropical, Revista Veterinaria, Revista Cubana de Ciencia Agrícola, Pastos y Forrajes, Zootecnia Tropical*, and others). A comprehensive inventory and analysis of this knowledge is pending.

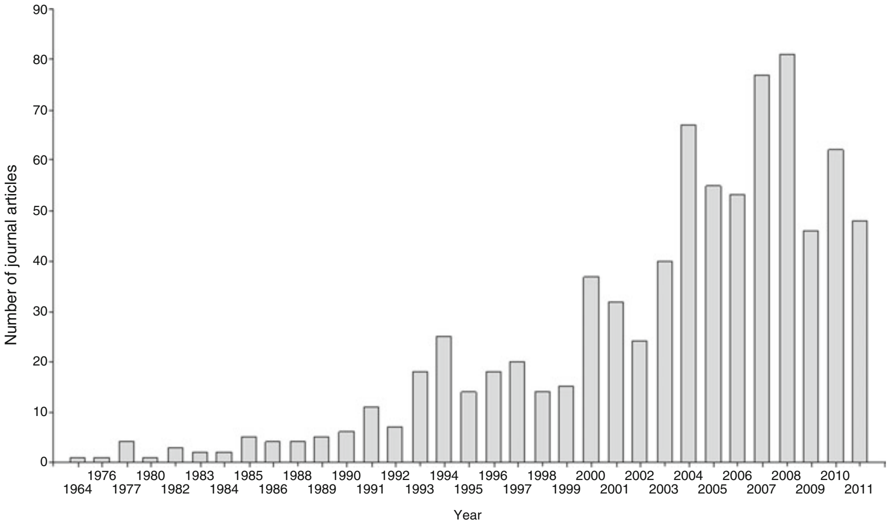

Fig. 3 Number of journal articles (Web of Science) published annually on Latin American agroforestry

Agroforestry Education and Training

Agroforestry has been incorporated (unevenly in themes and geographic coverage) into Latin American training and education programs since 1982 (Lassoie 1990; Nair 1993a; Budowski 1994; de Jong 1994; Krishnamurthy and Rodriguez 1994). During the following decade, the predominance of forestry faculties teaching agroforestry decreased and the subject became a resort of agronomy (or related) faculties (Dubois 1990); this situation remains today. Agroforestry university education is now offered either as a full degree (bachelor, master, and Ph.D. levels), as complementary courses in the curricula of related degrees (e.g., agronomy, forestry, natural resource management, animal production), or as a subject within a course (e.g.,, the *Taungya* systems are studied as part of a course syllabus on tropical silviculture). A comprehensive analysis of the position of agroforestry in the university and nonuniversity education systems in Latin America is warranted, but is beyond the scope of this chapter. However, as examples, the current status of agroforestry education in Nicaragua and Colombia are presented below.

In Nicaragua, nine universities and technical education centers currently offer agroforestry education[13]; three of them offer a full agroforestry degree (bachelor's level). In Colombia, agroforestry degrees are offered by five universities,[14] including two master's degrees.[15] Agroforestry is included as a course in related degrees, or as lectures in the syllabus of a course, in various universities in both Nicaragua and Colombia. In the latter, nonuniversity, technical education is offered (including virtual education) by five universities and by the government.[16]

Legal-Institutional-Policy (Public and Private) Frameworks

Appropriate legal, institutional, and policy (public and private) frameworks are required for the further development of agroforestry in modern society. As in other agroforestry sectors, important advances are evident, but advances are uneven between countries. For instance, forestry laws in most countries may not at all consider trees in agricultural lands. Regulations (usually excessive) and procedures (usually long, tortuous, and expensive) in place for natural forests are extended to trees in farms. A good example is found in the issuing of permits for the harvest and transportation of timber from agroforestry systems in Central America. The rationale is simple: complex and lengthy procedures to obtain a permit stimulate farmers to enter the illegal market. This is negative for both the farmer and agroforestry development. First, because farmers receive a lower price for their illegal timber; they also risk facing economic loss and legal penalties if discovered. Second, farmers in these conditions will not be encouraged to plant or retain many trees on their farms. Studies in Costa Rica, Honduras, and Belize have shown that farmers who use simplified legal procedures to harvest and transport their timber retain more timber trees in their farms (and obtain higher financial returns) than those who harvest and transport their agroforestry timber illegally.[17]

The seven Central American countries differ widely in the size, complexity, and update of the body of laws and policies that have direct implications on agroforestry (Appendix 2). Three countries (Panama, Honduras, and Nicaragua) have complex, tiresome, demanding requirements and procedures for issuing a permit to harvest and transport agroforestry timber. On the other hand, Guatemala, Belize, and El Salvador have designed a simplified protocol for issuing permits to farmers; but, in practice, only Guatemala and Belize have an operational procedure in place (Scheelje 2009; Chavarria 2010). The positive impact of the simplified procedure on the attitude of Guatemalan and Belizean farmers, toward retaining and using more timber trees in their farms, gives hope for similar achievements in the other Central American countries.

The Way Forward

The overviews presented in previous sections demonstrate that agroforestry has achieved significant developments, albeit unevenly, in all sectors and countries in Latin America. An increasingly globalized framework for future agroforestry R&D in Latin America points to the following opportunities and considerations when designing new initiatives and policy instruments in this region.

Rural Development

A systematic review of the enormous agroforestry experience of Latin American NGOs is needed to clarify the real benefits and limitations of agroforestry to sustain farm production and provide ecosystem services in rural, urban, and peri-urban areas. Despite previous attempts to quantify and document agroforestry technologies used and promoted by these NGOs,[18] much more can be learned from the experience of these NGOs as well as from farmers.

Agroforestry practices used by farmers can be enriched and improved by incorporating currently available scientific and technical knowledge. For example, a specific gap in our knowledge is silviculture in agroforestry systems to maximize timber quality as well as quantity within the constraints posed by the management needs of understory crops or pastures. An additional unrealized potential is offered by the hundreds of native fruit tree species that could be promoted in agroforestry systems. In this latter case, a closer link with both the private sector and a focus on the value chain are necessary to determine the real potential and limiting factors for the marketing of these highly varied products in national or even international markets. Most native fruit species are only appreciated locally though the increasing interest in developed economies in novel, exotic, natural, and "healthy" crops suggests that exciting opportunities exist for entrepreneurs. The market dimension of agroforestry products and ecosystem services needs to be developed.

International Cooperation

An increasing interest in South-South cooperation is providing new opportunities for mainstreaming agroforestry in Latin America. For example, all regions need better, cheaper, and consistent (comparable) monitoring, reporting, and verification instruments to facilitate more widespread implementation of payments for ecosystem services offered by agroforestry systems. Research is needed to assess how agroforestry systems can increase adaptation (Schroth et al. 2009), resilience to climate change (Nair 2012), and variability at the farm and landscape scale. Agroforestry research and development should focus on the economic viability, feasibility, and comparative advantage of agroforestry systems in the provision of ecosystem services compared to other land use systems.

Science and Technology

Latin American agroforestry scientific output needs a significant boost above current level. The geographical coverage of research and technology development in all countries of the region should be comparable at least to that given currently in Mexico, Costa Rica, and Brazil. Finally, agroforestry research themes emphasized in Latin America (currently concentrated on shaded coffee, biodiversity studies, and silvopastoral systems) should be diversified to include, at least, agroforestry for food and nutritional security in rural and peri-urban households, and for the provision of ecosystem services at both the plot and landscape scales.

The so-called gray literature also needs to be "mined" when making a synthesis and digesting available agroforestry knowledge and experience as the foundation for technical and training support. This literature is the main source of knowledge for agroforestry extension officers and practitioners, given that scientific articles in

English are either not accessible or unreadable (language barrier) to most field Latin American agroforesters. We need to understand and improve the mechanisms that permit scientific knowledge published in English, in peer-reviewed journals, to be translated into technical literature, educational materials, and AF field practice in Latin America.

Education and Training

All countries need to review and upgrade their education and training programs to properly (1) address the UN conventions and global development goals, (2) consider the multifunctional nature of agroforestry (Leakey 2012), and (3) embrace the diversity of cultures, actors, and traditional agroforestry systems in Latin America (IAASTD 2009). Well-designed protocols, course contents, educational tools, and supporting materials for various key target groups (from farmers to Ph.D.-trained scientists) and agroecological regions are urgently needed. The use of emerging information communication technologies must be mainstreamed in agroforestry education and training. Virtual platforms should be used to expand the coverage of high-quality, low-cost education and training in Latin America.

Legal, Institutional, and Policy Frameworks

Latin American countries differ widely in the level of development of their legal, institutional, and policy frameworks for agroforestry. Some policy-oriented research has been published (Follis and Nair 1994; Current and Scherr 1995; Place and Dewees 1999; Lehrer 2009), but this agroforestry sector, with potential for large and long-term impacts, requires special and preferential attention due to its complexity, specificity, and conflicting interests. Institutionally, agroforestry has expanded greatly in some countries (e.g., Brazil and Colombia) but not in others (e.g., Bolivia). For example, in Brazil, agroforestry is central to EMBRAPA's (Empresa Brasileira de Pesquisa Agropecuaria) Amazonian research network and is specifically addressed in the Brazilian national policy and institutional framework (Porro et al. 2012). Brazil is the only Latin American country known to the authors to have a professional organization for agroforesters.[19]

Conclusions

Agroforestry has expanded notably, albeit unevenly, in various sectors of modern Latin American societies. To mainstream agroforestry, simultaneous actions are needed in all sectors. The relevance of agroforestry as a valuable land use system for poverty reduction and conservation of the environment seems assured in the near future. However, agroforestry needs more visibility to policy and decision makers to attract the support needed to ensure that it complies with the expectations poised on it by modern society.

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Appendixes

Appendix 1. Research and Development Institutions and NGOs Implementing Agroforestry Projects in Nicaragua in 2010

ACRA (Cooperiamo lo Sviluppo-Italia). www.acra.it; Asociación para la Diversificación y el Desarrollo Agrícola Comunal (ADDAC). www.addac.org.ni; Asociación Coordinadora indígena y Campesina de Agroforesteria Comunitaria Centroamericana (ACICAFOC). www.acicafoc.org; Asociación Pueblos en Acción Comunitaria (PAC). www.apac.org.ni; Agencia Española de Cooperación Internacional para el Desarrollo (AECID). www.aecid.org.ni; ADA (Cooperación Austriaca para el Desarrollo-Austrian Development Agency). www.ada.org.ni; CARE International. www.care.org.ni; CATIE (Centro Agronómico Tropical de Investigación y Enseñanza). www.catie.ac.cr/nicaragua; Catholic Relief Services (CRS). www.crs.org/nicaragua; CIAT (Centro Internacional de Agricultura Tropical). www.ciat.int.ni; Cuenta Reto del Milenio (CRM). www.cuentadelmilenio.org.ni; Cooperación Alemana-Nicaragua (GIZ y DED). www.gtz.de; Centro Humboldt. www.humbolt.org.ni; Ecomercados. www.ecomercados.org; FADCANIC (Fundación para la Autonomía y desarrollo de la Costa Atlántica de Nicaragua). www.fadcanic.org.ni; FUNICA (Fundación Nicaragüense de Investigación Agrícola y Forestal). www.funica.org.ni; FONDEAGRO (Fondo para el Desarrollo Agropecuario)-MAGFOR-ASDI-Agencia Sueca para el Desarrollo Internacional. www.fondeagro.org.ni; IICA (Instituto Interamericano de Cooperación para la Agricultura). www.iica.int.ni; IDR (Instituto de Desarrollo Rural). www.idr.gob.ni; INTA (Instituto Nicaragüense de Tecnología Agropecuaria). www.inta.gob.ni; INAFOR (Instituto Nacional Forestal)-PASOLAC. www.inafor.org.ni; IPADE (Instituto para el Desarrollo de la Democracia). www.ipade.org.ni; Lutheran World Relief (LWR). www.lwr.org; MAGFOR (Ministerio Agropecuario y Forestal). www.magfor.gob.ni/paicepan/html; MARENA (Ministerio de Recursos Naturales y Ambiente). www.marena.gob.ni; Nitlapan (Instituto de Investigación aplicada y de Desarrollo Local)-UCA. www.nitlapan.org.ni; Oxfam-GB Internacional. www.

oxfam.org/es/development/nicaragua; Unión Nacional de Agricultores y Ganaderos (UNAG). www.unag.org.ni; UNICAFE (Unión Nicaraguense de Cafetaleros)-FONTAGRO (Fondo Regional de Tecnología Agropecuaria). www.unicafe.org.ni; UNA (Universidad Nacional Agraria). www.una.edu.ni; SIMAS (Servicio de información Mesoamericano sobre Agricultura Sostenible). www.simas.org.ni; Visión Mundial. www.visionmundial.rog.ni.

Appendix 2. Laws and Policies with Implications on Agroforestry in Central American Countries

Guatemala: Constitución de la República (1985); Ley Forestal (Decreto 101–96); Reglamento de la Ley Forestal (Resolución JD INAB No. 1.43.05); Reglamento PINFOR. (Resolución JD INAB No. 1.01.2007); Reglamento Transporte Productos Forestales (Resolución JD INAB No. 1.13.2004); Normativa interna INAB: aprovechamiento de árboles aislados en potreros; Ley MARN (Decreto 90–2000); Código Municipal (Decreto 12–2002); Política Forestal de Guatemala (1999).
Belize: Forest Act (1927), Forests Act Subsidiary (1927); Chicle Protection Act (1935); Private Forests – Conservation Act (1945); Forest Fire Protection Act (1962); Timber Industry Act (1955); Protected Areas Conservation Trust Act (1996); National Parks System Act (1982); Wildlife Protection Act (1982); Measures of Wood Act (1910); Forestry policy of British Honduras (1945).
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End Notes

1. In this chapter we focus on Latin America an area that spans from Mexico (30° N) to Chile (53° S), although we exclude Brazil and Guyana because Brazilian agroforestry (with an emphasis on the Amazon) is presented in a separate chapter (Porro et al. this volume).
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Land Health Surveillance: Mapping Soil Carbon in Kenyan Rangelands

Tor-Gunnar Vågen, Finn A. Davey, and Keith D. Shepherd

Abstract Land health surveillance is a methodological framework for measuring and monitoring land health—the capacity of land to sustain delivery of ecosystem services—for the purpose of targeting agroforestry and other sustainable land management in landscapes, and assessing their impacts. It is modelled on scientific principles used in surveillance in the public health sector, which has a long history of evidence-informed policy and practice. Key elements of the science methodological framework are (1) probability-based sampling of well-defined populations of sample units; (2) standardized protocols for data collection to enable statistical analysis of patterns, trends, and associations; and (3) multilevel statistical modelling of land health attributes at different scales, including in relation to satellite imagery for spatial interpolation. The framework was applied in assessing soil carbon in Kenyan rangelands in Laikipia. Systematic probability-based field sampling provided a robust baseline on condition in the study area. Infrared spectroscopy was used in the laboratory as a rapid low-cost tool for estimating soil carbon concentration. The georeferenced soil carbon values were modelled to reflectance values of fine resolution (2 m) satellite imagery and spatially interpolated over the 100-km^2 sampling block. The combination of methods makes soil carbon baselines feasible at a landscape level in land management projects and provides much additional information on soil and vegetation health for targeting interventions. The land health surveillance approach could form the basis for evidence-based decision making on land management at project, national, and even continental levels.

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Keywords Ecosystem services • Land health • Rangelands • Soil carbon

Introduction

There is increasing recognition of the importance of safeguarding land health—the capacity of land to sustain delivery of essential ecosystem services—for global development and environment (MA 2005). Despite much attention paid to land degradation indicators and assessments (e.g. Vogt et al. 2011; Winslow et al. 2011), there is still a lack of scientifically sound approaches for defining, measuring, and monitoring land health at different scales. Basic problems include lack of proper sampling frames that permit inference to the population level from well-defined sample units (Cochran 1977) and lack of consistent measurement methods that can be applied across diverse landscapes so that results can be compared in wider spatial and temporal contexts. There is little hope for making progress on assessing land degradation until proper baselines and monitoring systems are put in place. Land health surveillance, developed by the World Agroforestry Centre, is an approach designed to overcome these limitations and is modelled on scientific approaches that have been used for decades in public health monitoring (Box 1).

Land health surveillance aims to provide high-quality spatial data on land health problems and risks to (1) help target sustainable land management interventions and (2) provide a baseline and method for monitoring changes in land health over time to be able to assess trends and impacts of interventions. The approach combines (1) consistent, georeferenced field measurements of vegetation and soil conditions and soil sampling, (2) use of new light-based (spectral) techniques for analyzing large numbers of soil samples at low cost, (3) use of remote sensing data to provide land health metrics at national to regional scales, and (4) scientific

Box 1: Surveillance Science Principles

- Case definitions are used to specifically and consistently diagnose health problems.
- Standardized screening tests are used to consistently assign individual samples to cases.
- Sampling designs are used to make inferences about the health of target populations.
- Sample units that make up the population are unambiguously defined.
- The frequency of health problems in populations (prevalence/incidence) is assessed.
- Association between health indicators and risk factors is assessed using statistical (risk quantification) models.

Source: Shepherd and Walsh (2007)

workflows that combine field, laboratory, and remote sensing data in statistical models to provide digital maps and quantitative information designed to support specific decision problems.

The Land Degradation Surveillance Framework (LDSF) is the basic field sampling methodology being applied in the Africa Soil Information Service which is sampling 60 randomized sentinel sites (10 × 10 km sampling sites) throughout sub-Saharan Africa (Fig. 1). This is the first ever attempt at taking a ground-based, unbiased, population-level sample of African land condition. For example, these data enable quantitative analysis of the relationships between woody cover and distribution and soil health (Fig. 1).

In this chapter, we illustrate some results of applying the LDSF methods in a rangeland management project in Laikipia, northern Kenya. The field measurements were conducted by a small private conservation company, Wajibu MS, in partnership with local communities, as part of a holistic rangeland management project in North Laikipia. A key feature of holistic management is the use of livestock to improve degraded and denuded lands, for example, by planned grazing to allow recovery periods for grass growth, rotation of bomas for manure management, and removal of unwanted invasive plant species. The land health surveillance methods were deployed to provide a baseline and monitoring framework for measuring impacts on land health at a landscape scale. The focus of this chapter is mapping soil carbon, as this is a key soil quality indicator.

Study Area

Field sampling was conducted in two LDSF sites encompassing 10,000 ha each within a 40,000 ha area, centred on the Sanctuary at Ol Lentille. One site was in the south (Ol Lentille) and one in the north (Kipsing) of the project area (Fig. 2). The project site is located 75 km northwest of Nanyuki in north central Kenya, transcending the borders of North Laikipia and Isiolo Districts, in the Mukogodo Division of Laikipia District, and Oldonyiro Division of Isiolo District. The study area falls under semiarid to arid agroecological zones and is a part of the Upper Ewaso Ng'iro North River Basin. The southern part is characterized by vertiginous highlands and rolling plateaus with an altitude of 1,600–1,800 m, while the northern section sits on an alluvial flood plain with altitudes of 1,100–1,250 m. Rainfall distribution is bimodal with peaks of "long rains" mid-March to mid-June and "short rains" mid-October to mid-December. Six broad vegetation types can be characterized: dense woodland, open woodland, sparsely shrubbed woodland, open shrubbed grassland, open grassland, and closed grassland. Woody species in the study area predominantly belong to the Mimosoideae family, while Eragrostea, Chloridea, and Stipeae families are the most dominant Gramineae. Historically, the area was used for dry-season grazing by nomadic pastoralists, but in recent years, burgeoning population and government development policies have led to increasing permanent settlements in the area.

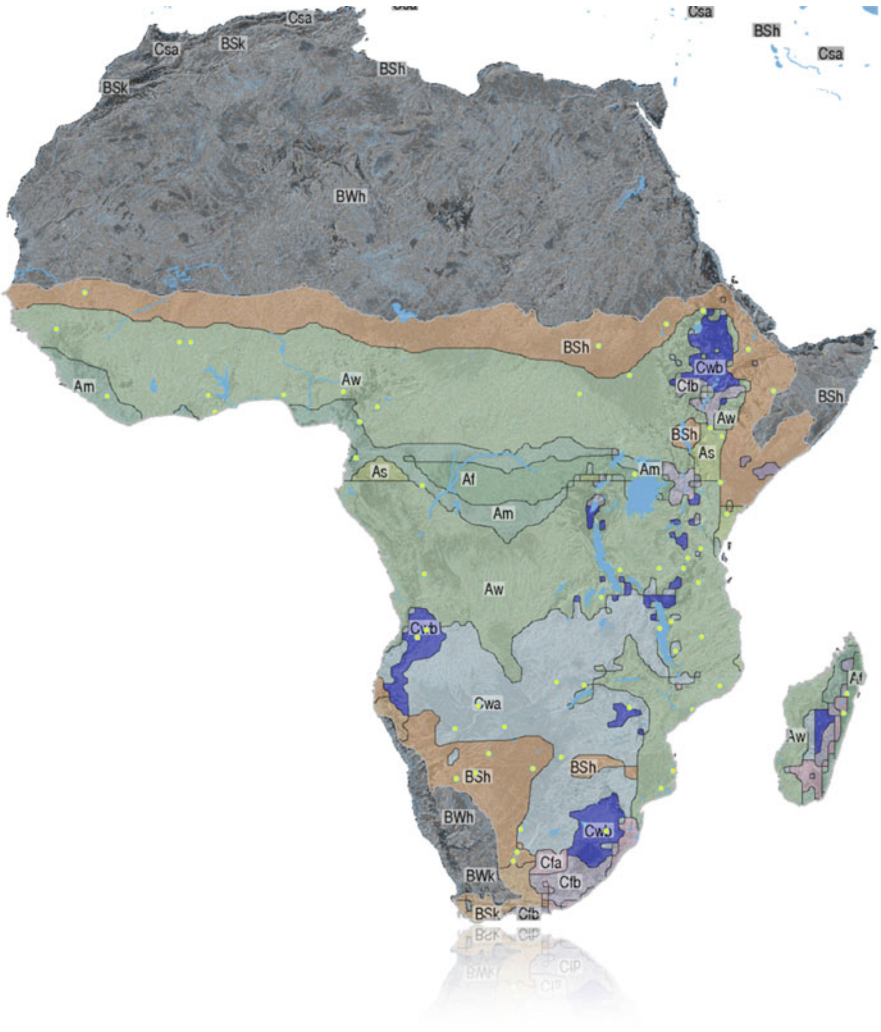


Fig. 1 Land health surveillance sampling frame deployed in the Africa Soil Information Service (www.africasoils.net). Sixty 10×10 km sentinel sites are randomly located, stratified on major climate zones. Each sentinel site contains 160 spatially stratified randomized 1,000-m^2 plots in which ground measurements are made. Within each plot, observations and soil samples are taken from 100-m^2 subplots. Soil is characterized using infrared spectroscopy

Measurements

Sentinel sites may be selected at random across a region or watershed or may be placed to represent areas of planned activities (interventions) or special interest (Fig. 2). Within each site, 16 tiles (2.5×2.5 km in size) are created, and random centroid locations for clusters within each tile are generated. Each cluster consists

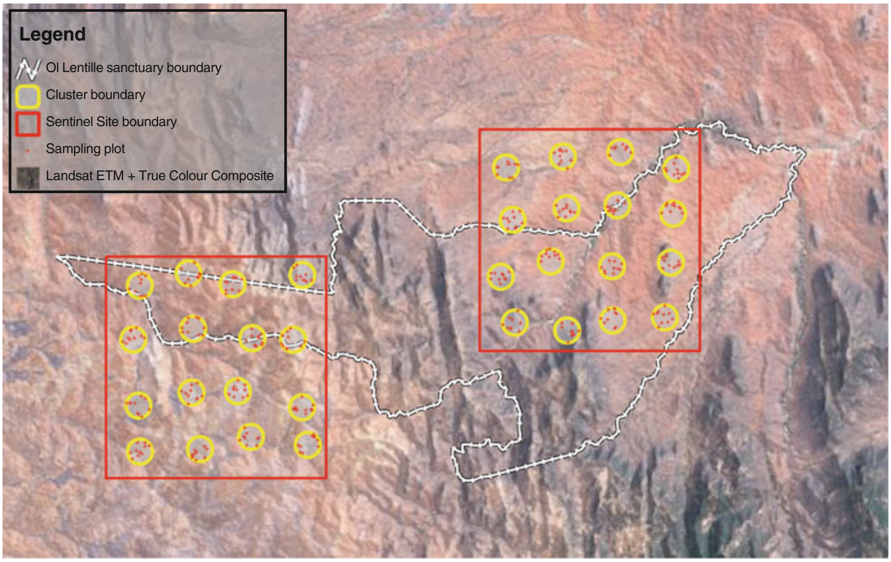


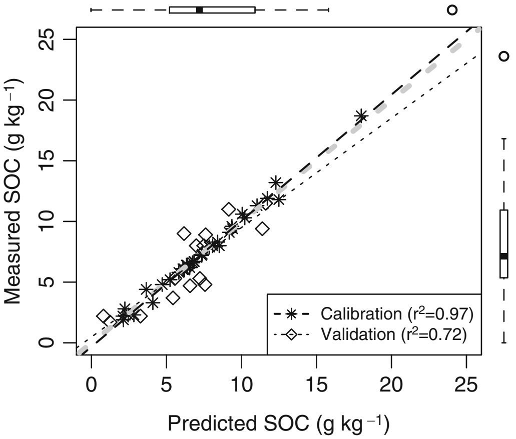
Fig. 2 Overview of the Sanctuary at Ol Lentille and the two LDSF (Land Degradation Surveillance Framework) sites in Laikipia, Kenya, included in this study

of ten plots, with randomized centre-point locations falling within a 564-m radius from each cluster centroid (Fig. 2). Thus, sentinel sites have two (or in some cases three) levels of randomization, which minimizes local biases that may arise from convenience sampling. Each plot has an area of 1,000 m^2 and consists of four subplots of 100 m^2 each. The coordinates of the plots are loaded onto a GPS (Geographic Positioning System), which is then used to navigate to each point.

Georeferencing and infiltration measurements are completed in the centre of the plot, and soil samples are composited to the plot level from the subplots for topsoil (0–20 cm) and subsoil (20–50 cm) depths. Soil samples are recovered using a soil auger and soil mass of samples recorded to allow calculation of soil carbon stocks on a soil volume basis. Soil depth to restrictions is recorded. A range of observations and measurements are made at the plot level to provide comprehensive information on ecosystem condition. These measurements have been designed and tested to be feasible under the difficult conditions in rural Africa. Further details of the protocol are given in Vågen et al. (2010a, b). A sentinel site can be completed by a small field team (five people) within 12–16 days, depending on the terrain and accessibility.

Soil infrared spectroscopy (Shepherd and Walsh 2007) is used as the main soil analytical tool due to its low-cost and high-throughput capability. Conventional soil testing methods are performed on 10–20 % subset of samples and calibrated to the infrared spectra, typically using partial least squares regression or multilevel regression models. For high-resolution mapping of soil organic carbon (SOC), QuickBird imagery was used and models developed based on Minimum Noise Fraction (Green et al. 1988) transposed image reflectance values, which were related to measured SOC

Fig. 3 Measured SOC, soil organic carbon (log g kg^{-1}), using combustion against values predicted from near-infrared spectroscopy for calibration and validation data sets



values, allowing for prediction of SOC concentrations in the study area. The result is a wall-to-wall carbon map. Analytical methods are described in Vågen et al. (2010b) and Aynekulu et al. (2011).

Results and Discussion

The calibration of soil organic carbon concentration to near-infrared diffuse reflectance spectra was robust, as evidenced by the prediction performance of a hold-out validation set (Fig. 3). Predictions of SOC concentrations in the study area based on QuickBird MNF components are also robust, relative to near-infrared (NIR)-predicted values (Fig. 4) with an adjusted R^2 of 0.82. In Fig. 5, the resulting map of SOC concentrations for the Sanctuary at Ol Lentille and surrounding areas is shown. Low carbon values are observed along the sandy river courses, and high values in hilly areas with higher tree densities. On average, Ol Lentille has about 3 g SOC kg^{-1} higher concentrations than Kipsing.

The soil carbon information can be combined with other information on soil physical degradation risk, soil fertility status, topographic data, and vegetation characteristics to assist in targeting agroforestry and sustainable land management interventions. For example, areas that have low soil organic carbon levels (relative to areas under good vegetation cover and similar soil texture) but low prevalence of other constraints may be prioritized for kraaling to increase manure inputs and increase grass productivity. Areas with low soil carbon saturation in areas with otherwise good soil fertility potential may be targeted for conservation agriculture practices incorporating trees. Areas with inherent soil physical constraints such as restricted soil depth and low infiltration capacity, but with currently low tree cover, can be flagged as environmentally sensitive or marginal areas to which afforestation efforts may be directed.

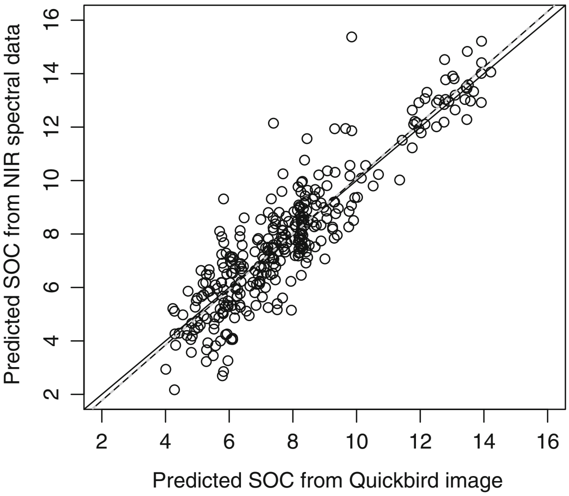


Fig. 4 Soil NIR-predicted values of SOC versus QuickBird Minimum Noise Fraction-predicted soil organic carbon for the study area in Laikipia, northern Kenya

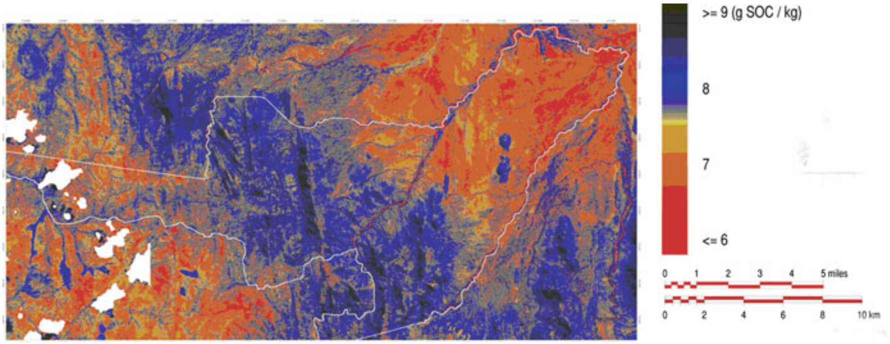


Fig. 5 *Map* of topsoil SOC (g kg^{-1}) for the Sanctuary at Ol Lentille and surrounding areas, Kenya

Conclusion

Combining systematic ground measurements and soil sampling with high-throughput soil analytical methods based on infrared spectroscopy and remote sensing imagery, linked up using multivariate multilevel statistical modelling, has potential to enable land and soil health monitoring in landscapes. Routine use of these tools at different scales can help land users and governments make better, evidence-informed decisions on land management as part of everyday policy and practice. Further work is needed to combine the various indicators of land and soil health into a framework for providing specific land management recommendations.

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Gender and Agroforestry in Africa: Who Benefits? The African Perspective

Evelyne Kiptot and Steven Franzel

Abstract This chapter examines women's participation in agroforestry relative to men and the challenges and successes they experience. Women's participation is hampered by socioeconomic, cultural, and policy issues that vary within and across locations. The degree of women's involvement relative to men in practices such as soil fertility management and fodder production is fairly high in terms of proportion of female-headed households participating but is low as measured by the area they allocate to these activities and the number of trees they plant. The lesser involvement reflects women's lack of resources, particularly labor, their heavy workload, and perhaps their greater aversion to risk. Women dominate the production and processing of indigenous fruits; however, they are confined to the lower end of the value chain (retailing), which limits their control over and returns from the production process. The recommendations arising from the review include (1) facilitating women to form and strengthen associations, (2) targeting women's associations, (3) helping women to improve productivity and marketing of products considered to be in women's domain, and (4) improving women's access to information.

Keywords Adoption • Fodder • Indigenous fruits • Soil fertility • Tree product markets

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Introduction

Since the 1995 women's conference in Beijing, donors, policy makers, and development practitioners have pointed out the critical role of gender in development programs[1,2] (Doss 2001; IFAD 2003; World Bank 2007; IFPRI 2007; Quisumbing and Pandolfelli 2010). There is a general consensus that gender inequalities in areas such as ownership and access to resources, land tenure systems, education, extension, and health have contributed to lower agricultural productivity and higher poverty levels. Given that gender matters in all spheres of production, there has been a lot of documentation on gender issues in agricultural production. However, very little is understood about gender and adoption of agroforestry technologies, where perennial trees and shrubs are deliberately grown on the same land management system as annual crops and/or livestock. This chapter intends to fill this gap by presenting a review of the participation of women relative to men in various agroforestry practices across the African continent. The aim is to come up with strategies that increase women's adoption of agroforestry and the benefits they receive, thus ensuring gender equity. Participation is viewed from a broader perspective and is guided by four research questions: (1) What is the proportion of women participating in agroforestry? (2) Who manages agroforestry technologies? (3) Who benefits from agroforestry and how? (4) Who has access to agroforestry information? Each of the questions is analyzed by agroforestry practices including fodder production and utilization, soil fertility improvement technologies, and indigenous fruit and vegetable production. This chapter draws on lessons learned to make recommendations on how to promote gender equity in agroforestry.

The focus on gender participation in agroforestry practices is important for various reasons. Agroforestry is a common system of production throughout Africa (Zomer et al. 2009). At the center of this type of farming system are women farmers who are frequently responsible for managing trees, and, as with other agricultural enterprises, they do most of the work especially during the initial stages of establishment, that is, planting, weeding, and watering[3] (Gerhardt and Nemarundwe 2006). However, despite their heavy responsibility, women's decision-making power in households is limited to by-products of men's trees and subsistence crops that involve less-advanced technologies and have low returns on labor (Rocheleau and Edmunds 1997). Secondly, agroforestry is a low-cost system that uses minimal external inputs and offers a diversity of products and services such as fodder, food, timber, fruits, and soil fertility improvement. It offers immense opportunities to women, who in most cases cannot afford to adopt high-cost technologies due to their severe cash and credit constraints. There are four different ways women farmers can supply their families with basic household products: collect them from off the farm, buy them, grow annual crops, or practice agroforestry (Table 1). Collecting off the farm requires only labor, but women's time is scarce and supplies are often located at too great a distance from the farm. Purchasing fuelwood, fodder, and fruits is an option, but women are acutely cash-constrained. Annual crops are options for providing fodder, and a few fruits require land and labor which are often scarce. Agroforestry has obvious advantages relative to the other three options. It uses relatively little land and labor as trees can be planted

Table 1 Resource requirements of options that rural women use to obtain agroforestry products such as fruits, firewood, and fodder

Resource/means	Collect off farm	Buy	Grow annual crops	Practice agroforestry
Resource requirements				
Land	0	0	High	Low
Labor	High	0	High	Low
Capital	0	High	Low or 0	Low or 0

Source: Authors' observation

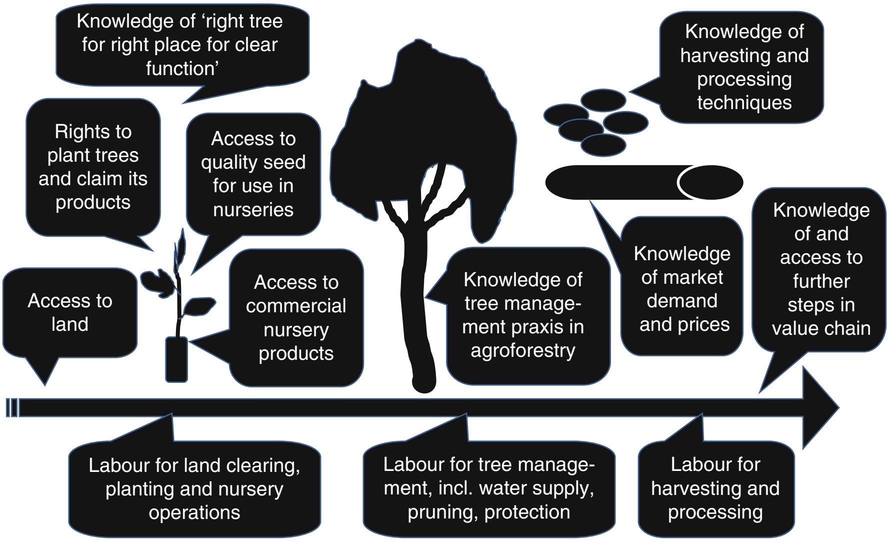

Fig. 1 Interaction between people and trees: key points where gender analysis is needed

around the homestead and on field boundaries. Weeding is only necessary during early growth, and if trees are mixed with annual crops, then no extra weeding is required. Furthermore, little or no cash inputs are used for the purchase of tree seeds/seedlings. However, agroforestry also has two features that may limit women from participating: (1) it is knowledge intensive, involving skills that many farmers lack, such as how to establish nurseries or to prune trees, and (2) tree seeds may not be easily available. A third factor is that women are increasingly assuming leadership roles and decision making in the absence of men in many households. Female-headed households (FHHs) account for 30% of all rural smallholder households in Malawi (Gladwin et al. 2001) and over 50% in western Kenya.[4] This is due to a number of reasons, the main one being rural-to-urban migration of men in search of off-farm income, leaving the responsibility for obtaining food, fuelwood, fodder, and other tree products for the family to women.

Agroforestry requires access and rights to land, planting material, knowledge, capital, and labor (Fig. 1). However, women remain disadvantaged due to cultural, sociological, and economic factors. Such factors include limited access to resources and household decision making. Resources that are directly linked to agroforestry are those related to land and trees, finance, extension information, labor, and technology. Furthermore, many African societies have taboos that prohibit women from undertaking certain activities, which may limit their participation in developmental interventions such as agroforestry. These factors have implications on the adoption of agroforestry interventions, and, therefore, it is important to highlight them.

Areas Where Gender Imbalances Exist

Land and Tree Tenure

Women in Africa have limited rights to land except in isolated cases. This is because land tenure systems in many parts of Africa grant rights to own and dispose of land to adult males.[5] While there is tremendous variation across the African continent, the bottom line is that in patrilineal societies, women's rights are often through ties to their husbands, and these rights may cease to exist upon divorce, widowhood, or failure to have a son.[6] Even in matrilineal societies such as in western Ghana, women do not possess inheritance rights. Land is transferred from a deceased man to his brother or nephew (sister's son) in accordance with the decision of the matrilineal clan (Quisumbing et al. 2001).

Tree tenure is the right to own and use trees. Different parts of trees and any benefits from their harvesting, sale, or use may entail different rights of ownership and use among men and women. However, men usually have the overall authority as pertains to tree products that are considered to have high returns. For instance, women among the Luo and Luhya communities of Nyanza and Western Provinces of Kenya, respectively, have rights of collection and use of fruits but are restricted from harvesting fuelwood of high-value timber trees such as *Markhamia lutea* (Benth.) K. Schum and *Albizia* spp. (Bradley 1991; Rocheleau and Edmunds 1997). A species such as *Sesbania sesban* (L.) Merr., which is good for fuelwood and soil fertility improvement, is considered a woman's tree, and therefore, they have the authority to plant, manage, use, and dispose it off as they please. Rocheleau and Edmunds (1997) report that among the Akamba community of eastern Kenya, tree planting and felling were primarily a male's domain, while women enjoyed use and access rights to fodder, fuelwood, fiber, fruits, and mulch. Tree products such as charcoal, logs, timber, large branches, and poles are considered a male domain.

Domesticated fruit trees of commercial and economic importance such as *Mangifera indica* L., *Carica papaya* L., and *Citrus sinensis* L. are planted and harvested by both men and women in many parts of Africa. There are, however, certain fruit trees that are considered to be traditionally feminine crops because they are considered subsistence and grown around the homestead. Bush mango (*Irvingia gabonensis* Aubry-Lecomte ex O'Rorke Baill), bread fruit (*Artocarpus altilis* Parkinson Fosberg), oil bean tree (*Pentaclethra macrophylla* Bent.), bananas (*Musa sapientum* L.), and plantains (*Musa paradisiaca* L.) are planted and processed by women in the humid lowlands of West Africa (Nwonwu 1996). In the parklands of West Africa, women are responsible for the collection and processing of *Vitellaria paradoxa* C.F. Gaertn. (shea nut), and, therefore, men normally retain these trees for their wives (Schreckenberg 2004).

Household Decision Making

Gender-related decision making which is often linked to intrahousehold resource allocation is an important determinant of the adoption of agroforestry technologies by both men and women. There is considerable evidence that women's decision-making power in households is limited to by-products of men's trees and subsistence crops that have low cash returns on labor and involve less-advanced technologies[7] (Abbas 1997; Rocheleau and Edmunds 1997). Furthermore, women normally have obligations to provide labor for male-controlled fields (Abbas 1997). In western Kenya, the general understanding among the Luhya community, for instance, is that the husband, as the head of household, has the overall control of the household resources, and, in that capacity, everything in the household is viewed as belonging to him.[8] The wife is therefore expected to seek the opinion of her husband and ultimately his consent before going ahead with any plans that may bring about any changes in the allocation of the household's resources. In a study in western Kenya that tested the adoption of hedgerow intercropping in the early 1990s, David (1998) noted that decision making among the Luo and Luhya was not rigidly divided by gender domains, although men had significant decision-making power, especially in cases where there was conflict in the use of resources, that is, how much of the pruning to be used as mulch or fodder. Among the Akamba community of eastern Kenya, male heads of households are the main decision makers on matters of tree planting as recorded in 45.6% of the cases studied.[9] Cases where both husband and wife made decisions about tree planting were 21.1%, while 14.4% of decision making was made by women who either had husbands working away from home or were widows. As regards to who makes decisions on harvesting of tree products, women's decision power in Malawi was dependent on the part of the tree: women's influence on harvesting decisions decreased with corresponding increases in men's influence as decisions moved from twigs to the trunk.[8]

Access to Financial Resources

Access to financial resources such as credit is linked to women's access to property, land, education, and information.[10] Restricted ownership of land impedes women from obtaining guarantees, which would enable them to secure access to credit from formal financial institutions (Quisumbing and Pandolfelli 2010). To overcome this limitation, women in many parts of Africa have devised innovative means of getting credit such as joining informal saving clubs popularly known as "merry go round" or "chama" in Kenya (Kiptot 2007) or "tontines" in Senegal (Guerin

2006). Unfortunately, these clubs may not provide them with enough capital to start big income-generating projects. Kabeer (2005) and Quisumbing and Pandofelli (2010) caution that access to financial credit alone may not be sufficient to escape poverty if women invest in microenterprises that have low cash returns.

Labor

Labor is the only resource that women in many parts of Africa have at their disposal. However, they are disadvantaged in that they face greater difficulty obtaining male labor needed for particular tasks such as land preparation and tree pruning (Swinkels et al. 2002). In Benin, for instance, women rice farmers have difficulties cultivating their fields on time and transporting their grain to storage rooms after harvest due to discrimination in access to a motor-cultivator driver. This leads to late planting and harvesting, consequently leading to significant yield losses (Kinkingninhoun-Mêdagbè et al. 2010). In many parts of Africa, men have claim over women's labor, but women do not have similar claim over men's labor. For example, females in male-headed households in Benin are obligated to work in fields controlled by men, which take precedence over their own (Abbas 1997). Another similar problem faced by women is their difficulty in obtaining sufficient labor during peak labor activities (Swinkels et al. 2002). Peak season labor periods vary by farming system, but the times of land preparation and weeding are commonly the most acute. Not only are women unable to obtain needed male labor, they are also unable to hire labor because of cash shortage. Further exacerbating their crop performance and well-being, peak season periods often coincide with periods of acute food shortages, when women are weakest and may have to work as laborers on others' farms in order to feed their families. Their inability to mobilize labor for managing their farms in an optimal fashion often puts them on a downward cycle of poor farm yields, inadequate resources for managing their farms, and further reductions in yields.

Education and Extension Visits

The uptake of new technologies is often influenced by farmers' contact with extension services. Several studies have shown that women have lower access to agricultural extension than men. In Malawi, for instance, 19% of women had access to extension compared to 81% of men (Gilbert et al. 2002). In Uganda, women had an average of 1.13 contacts with extension compared to men's 2.03 (Katungi et al. 2008). Figures released by UNEP/GRID-Arendal[11] show that although 70% of agricultural work in Benin and Zimbabwe is carried out by women, there are less than 10% female extension staff. In addition, most of the extension services are focused on cash crops (men's crops) rather than food and subsistence crops, which are considered to be women's domain. These statistics are confirmed by a study carried out in 1998 by CIMMYT[12] on how gender affects the adoption of innovations in Ghana. They found that on average, women reported fewer contacts with extension agents, and a large proportion of women reported no extension contacts at all.

Lack of Appropriate Technology

Most women in sub-Saharan Africa undertake their activities manually due to lack of suitable household, farm, and processing technology. For instance, women in Burkina Faso use 3–4 days to prepare fermented seeds of *Parkia biglobosa* Jacq. R. Br ex G. Don., while extraction of shea nut butter is a physically strenuous and time-consuming exercise (Teklehaimanot 2004). Technologies to improve crop production are also limited for women farmers. The use of animal traction is known to substantially reduce the demand for women's labor, yet most of them lack access to this valuable technology.

Customs/Taboos

Cultural beliefs have strong influence on agroforestry adoption. They include ritual prohibitions against planting or using certain trees, regulations on where trees may be planted, limitations on who may plant trees, and legislation set by national government. It is difficult to make any generalization about cultural norms and customary rulings because they vary for different people in different areas. They are, however, powerful determinants of peoples' actions and often hold more local influence than rules and legislation set by national government. In western Kenya, tree-planting activities are dominated by men, and the concept of tree owners has been effectively sustained through well-manipulated cultural practices (taboos) resulting in fewer women than men participating in tree activities.[8] Taboos advanced in western Kenya are that if a woman plants a tree, she would become barren or her husband would die. Nwonwu (1996) reports that among the Ibo of southeastern Nigeria, women are not allowed to climb certain types of trees such as the oil palm (*Elaeis guineensis* Jacq.), coconut palm (*Cocos nucifera* L.), or raffia palm (*Raphia farinifera* Gaertn.) Hyl. It is regarded as an abomination if they did so. These taboos and prohibitions were too much of a risk for many women in the past, but with modernization and a high rate of male migration, women are increasingly going against taboos and planting trees. Ipara (1993) reports that of the 25% of women who braved and planted trees in western Kenya, none reported receiving any repercussions.

Agroforestry Technologies

This section presents background information about agroforestry technologies assessed in this chapter. The technologies are grouped according to the products and services they generate. The first two groups, improving milk production and soil fertility, mostly involve agroforestry technologies introduced over the last 20 years and are focused on eastern and southern Africa. Indigenous fruit and vegetable production and processing involve mostly traditional practices and include examples from throughout sub-Saharan Africa. Findings are categorized by technology because most studies dealt with a particular technology. But, in reality, the concept of technology is sometimes not clear, as when a particular agroforestry arrangement has multiple products. For example, a particular tree's leafy biomass may provide fodder and soil fertility, and its woody biomass may provide fuelwood.

Use of Fodder Shrubs to Boost Milk Production

Most livestock in Africa are found in mixed smallholder farms characterized by their small size, limited production resources, and low income levels. The shortage of fodder coupled with the low quality of feed is the greatest constraint to improving livestock productivity and reproductive performance, especially during the dry season (Winrock International 1992). Despite demonstrated advantage of the use of herbaceous legumes as high-quality fodder, their use has not been widely adopted by small-scale farmers. The low adoption has been partly attributed to the scarcity and high cost of the legume seed (Paterson et al. 1998). In contrast, there has been considerable adoption of fodder shrubs in the highlands of East Africa to provide the much-needed protein to dairy cows (Franzel and Wambugu 2007; Wambugu et al. 2011). The World Agroforestry Centre (ICRAF) and a range of national research and development partners in Kenya, Uganda, Rwanda, and Tanzania developed fodder shrub practices in the 1990s. The shrubs are easy to grow, are capable of withstanding repeated pruning, and they compete very little with food crops. The plants mature in 9–12 months and are then ready to be cut periodically and fed to cows and goats. The shrubs are grown in hedges along boundaries and pathways or in lines to form terraces, thus reducing erosion and providing firewood. *Calliandra calothyrsus* Meisn. is the most commonly grown species.

Soil Fertility Improvement

One of the most serious constraints to the sustainability of agriculture in sub-Saharan Africa is declining soil fertility. In the past, African farmers managed soil fertility on their farms by fallowing their land. As population increased, fallowing of land declined, with many farmers adopting intensified land use practices that required fertilizers to replenish nutrients. Many African states subsidized fertilizer prices to stimulate fertilizer application, but these subsidies were later removed. The removal of such subsidies, due to structural adjustment policies, has substantially increased costs for many farmers who now cannot afford fertilizers (FAO 2001). This has exacerbated the problem of declining soil fertility, leading to reduced crop productivity (Sanchez et al. 1997).

To address these challenges, scientists have in the past two decades experimented on low-cost agroforestry options for soil fertility replenishment. Three of the most promising options are the use of improved tree fallows,[13] biomass transfer, and mixed intercropping (Niang et al. 1996; Sanchez et al. 1997; Thangata and Alavalapati 2003; Kiptot 2008). Improved tree fallows are the deliberate planting of fast-growing leguminous trees or shrubs in rotation with crops. Biomass transfer is a technology where biomass from shrubs/trees grown on or off the farm is cut and incorporated in the soil as green manure when planting crops. Mixed intercropping involves planting nitrogen-fixing trees that can tolerate continuous and heavy pruning in a regular pattern with crops such as maize (*Zea mays* L.). By providing nutrients to crops, these technologies can potentially help farmers improve their soils and incomes, thereby improving food security.

Indigenous Fruit and Vegetable Production and Processing

Food insecurity, poverty, and malnutrition are some of the major challenges that face sub-Saharan Africa. In Nigeria, for example, 70% of the population lives below the poverty line,[14] while in Cameroon the figure is 40%, rising to 55% in the forest region (Schreckenberg et al. 2006). Africa is also facing a serious problem of not being able to feed its people (FAO 2006). As a matter of fact, it is estimated that 60–80% of rural households in Malawi, Zambia, and Mozambique run out of food for as long as 3–4 months per year (Akinnifesi et al. 2004). Those most at risk are women and children. Through the ages, most of these people have relied on wild plants for food during periods of famine. These plants also provide other products such as medicine, spices, and livestock feed. In a survey conducted in Malawi, Zambia, and Zimbabwe, 26–50% of households confirmed to have reduced vulnerability to food insecurity by collecting indigenous fruits from wild plants (Akinnifesi et al. 2006).

Several studies have acknowledged the fact that indigenous fruits are rich in nutrients in addition to having the potential to generate income to many rural households. In Zimbabwe, for example, wild fruit trees represent about 20% of the total woodland resource use by rural households (Campbell et al. 1997) with women and children being the main beneficiaries. They collect, consume in both fresh and processed forms, sell, and use the proceeds to buy food and other household goods (Ramathani 2002). In West and Central Africa region, indigenous fruits are important components of local diets*; Dacryodes edulis* G. Don. H. J. Lam, for example, is a staple food for 3–4 months of the year with palm oil being the main cooking fat. As one moves to the

Sahel, it is replaced by shea butter (Schreckenberg et al. 2006). The shea tree not only provides edible fruits and nuts to make butter but also fodder for livestock. In eastern Africa, households in dry areas consume indigenous fruits such as shea, tamarind (*Tamarindus indica* L.), *Vitex doniana* Sweet, and baobab (*Adansonia digitata* L.)[15 ,16]. Despite the importance of indigenous fruit trees in the livelihoods of rural people in Africa, they are seldom planted by farmers because they are perceived as nature's gifts. Massive deforestation is reducing the availability of these valuable resources. In view of this, ICRAF and its national partners have in the past decade been undertaking research aimed at domesticating priority fruit tree species in western, eastern, and southern Africa to enhance the potential of these trees for increasing the income and food security of rural people. Tremendous progress has been made with domestication efforts in southern Africa focusing on species such *Sclerocarya birrea* A. Rich. Hochst., *Uapaca kirkiana* Muell. Arg., *Strychnos cocculoides* Baker., *Vangueria infausta* Burch., *Parinari curatellifolia* Planch. ex. Benth., *Ziziphus mauritiana* Lam, baobab, *Syzygium cordutum* Hochst. ex Krauss, and *Vitex* spp. (Akinnifesi et al. 2006; Leakey et al. this volume). In western and central Africa, focus has been on species such as shea, *P. biglobosa,* D. *edulis, I. gabonensis*, and *Garcinia kola* Heckel (Ayuk et al. 1999a, b, c; Leakey et al. 2004; Degrande et al. 2006). In eastern Africa, priority has been given to shea, tamarind, *V. doniana*, and baobab[15, 16] (Okullo et al. 2003).

Gender Participation in Agroforestry Practices

This section critically examines agroforestry practices from a gender perspective across Africa. Four questions were formulated to evaluate women's participation in agroforestry in relation to men:

1. What is the proportion of women participating in agroforestry?
2. Are women able to manage agroforestry technologies, that is, carry out the needed operations?
3. Who benefits from agroforestry and how?
4. Who has access to agroforestry information?

These questions are examined by the technologies discussed in the previous section.

What is the Proportion of Women Participating in Agroforestry?

In a study on the achievements and impact of a fodder project in the central highlands of Kenya, Wambugu et al. (2001) found that out of 2,600 group members involved in establishing fodder shrub nurseries, 60% were women. Female-headed households accounted for 15% of all planting households which is only slightly lower than the proportion of female-headed households (18%) in central Kenya (Kimenye 1998).

The high participation of women was facilitated by project extension staff, who targeted women's groups or groups with mostly women members.

On soil fertility management, a review of ten studies (Table 2) undertaken in Kenya, Zambia, Uganda, and Malawi on factors likely to affect the adoption of improved fallows, biomass transfer, and mixed intercropping technologies showed that in all except two studies, gender was not a significant variable affecting the use of soil fertility technologies. These findings are consistent with most reviews in the literature on gender differences in agricultural production. For example, Quisumbing (1996) found that most studies on differences in technical efficiency between male and female farm managers showed insignificant differences. That suggests that female farmers are as efficient as male farmers if individual characteristics and input levels are controlled. In another review of several studies on gender differences in nonland agricultural inputs, Peterman et al. (2010) found that most of them did not find gender a significant variable influencing the adoption of inputs such as inorganic fertilizer and improved seed.

In western Kenya though, Place et al. (2004) reported that women used improved fallows and biomass transfer technologies more than men, who more often used fertilizer (Fig. 2). In Zambia, Phiri et al. (2004) showed that there were no significant differences between proportions of men and women household heads practicing the use of improved fallows nor were there any significant differences between single women and female heads of households who were married even though single women are often disadvantaged when compared to female heads whose husbands work away from home. Surprisingly, Peterson found a higher proportion of single females planting improved fallows than married females in eastern Zambia; the latter probably needed permission from their husbands who may have prevented them from testing improved fallows.[17] Phiri et al. (2004) found that in four Zambian villages, 32% of males and 23% of females planted improved fallows. There was considerable variation within villages with one having more females than males planting improved fallows. According to Phiri et al. (2004), this variation could be attributed to the presence of active women's groups. These findings suggest that the use of improved fallows for replenishing soil fertility is gender neutral; women farmers are as actively involved as their male counterparts. However, women in Zambia had smaller plots than men, 332 m^2 for women compared to 679 m^2 for men. Since the same percentage of males and females stated that they had obtained enough planting material, it appears that females wanted smaller plots than males (Franzel et al. 2002b). This may be attributed to the heavy workload that women bear, land constraints, or risk aversion (Franzel et al. 2002b; Keil et al. 2005).

Women's participation in indigenous fruit and vegetable enterprises is much greater than that in fodder production and soil fertility management because indigenous fruits in sub-Saharan Africa are considered a domain for women and children (Campbell 1987). A probable explanation for this perception is that markets for these products are not well developed, and, therefore, men consider them to be of subsistence category. But there are also concerns in the literature that as these products attain more of a cash-crop status, the benefits may shift from women to men.[18]

Table 2 Analysis of studies on factors affecting adoption of soil fertility options with gender as a variable

Country	Technology	Gender significant	Gender insignificant	Comment	Author
Zambia	Improved fallow		✓	Men and women equally planted improved fallows, but women had smaller plots	Phiri et al. (2004)
Zambia	Improved fallow		✓	Same as above	Keil et al. (2005)
Kenya	Improved fallow		✓	Both men and women equally practice the use of IF	Kiptot et al. (2007)
Kenya	Improved fallow		✓	Women practice the use of IF and biomass transfer technologies more than men	Place et al. (2004)
Malawi	Mixed intercropping		✓	Both men and women equally practice mixed intercropping of *Gliricidia sepium* and maize	Thangata and Alavalapati (2003)
Uganda	Mixed intercropping	✓		Adoption was higher for men than women farmers	Buyinza and Wambede (2008)
Kenya			✓	Men and women equally practiced the use of biomass transfer	Kiptot (2008)
Kenya	Biomass transfer	✓		Adoption was higher in male-headed households than in female-headed households	Obonyo and Franzel (2004)
Western Kenya and southern Africa	Improved fallow		✓	Both men and women equally practice the use of IF	Franzel (1999)
Zambia	Improved fallow		✓	Both men and women equally practice the use of IF	Ajayi et al. (2001)

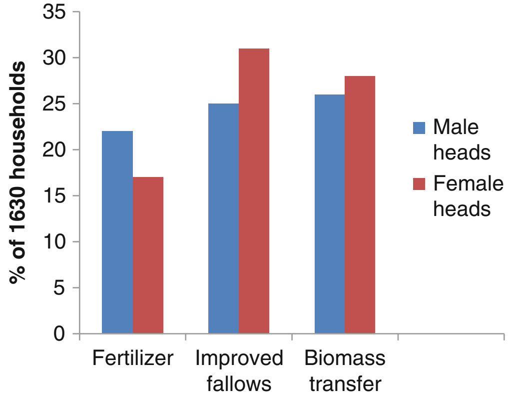

Fig. 2 Use of soil fertility management options by gender of household head, western Kenya (Source: Place et al. 2004)

Since fruits are considered a women's domain, men in Mali maintain shea trees in the cropland because they are a key source of income for their wives. In the shea-growing region of Benin, Schreckenberg (2004) found out that 90% of women were involved in collecting nuts/fruits of the shea tree. Other tree products that are frequently collected by women and children in West and Central Africa are *P. biglobosa, D. edulis, I. gabonensis,* and *Ricinodendron heudelotii* Baill. Pierre ex. Pax. In southern Africa, common species collected by women are *S. birrea, U. kirkiana, V. infausta, Azanza garkeana* F. Hoffm. Exell and Hillc., *Z. mauritiana*, and *S. cocculoides.* In eastern Africa, common species are shea, tamarind, *V. doniana*, and baobab. Other studies that have reported similar findings of women and children being the main collectors include Kalaba et al. (2009) in Zambia and Campbell (1987) in Zimbabwe.

In Benin, household heads normally reserve nuts of the shea tree for their female relatives. When the fruits are in season, women start collecting shea fruits from common parklands where competition from other women is stiffer. This is normally done on their way to and from the agricultural fields. In a day, women collect head loads of up to 47 kg. When the shea fruits from the common parklands have been exhausted, women turn to their husbands' field to collect the shea fruits. In Cameroon, a study of gender and commercialization of *Gnetum africanum* Welw by Kanmegne et al. (2007) found that women and children are the main collectors of the leaves, which are used as a vegetable. They accounted for 80% of the collectors, while men accounted for less than 5% of collectors. Men considered *G. africanum* activities, and especially collection, to be time consuming and unrewarding compared to cacao (*Theobroma cacao* L.) harvesting, a traditional source of income for men. And the fact that *G. africanum* income comes in at a time when cacao is harvested renders it unattractive to men.

Apart from collecting fruits, women are also involved in processing in order to add value to fruit tree products. For instance, in Benin, shea kernels are processed into local butter. This process is very laborious and not a very profitable business, and, as a result, very few women are involved. In some parts of Benin such as the Bassila area, women who make butter also make traditional soap from leftover and

Table 3 *Calliandra* fodder management and adoption in Embu District, Kenya

	N	% of farms with *Calliandra*	Average no. of *Calliandra* trees
All farm households	300	16	89
Male-headed households	272	17	80
Male-managed farms	59	18	35
Joint-managed farms	179	17	120
Female-managed farms	34	16	20
Female-headed households	28	11	89

Source: Wanyoike (2001)

rancid butter. This soap is sold locally, and it is said to have skin-healing properties (Schreckenberg 2004). In southern Africa, products that women process from indigenous fruits/nuts are alcoholic and nonalcoholic beverages, confectionaries, additives for other foods, dried whole fruits, oil, and butter.[19]

Are Women Able to Manage Agroforestry Technologies?

Although men and women are both involved in managing trees planted on farms, the literature confirms that women do most of the work, especially at the initial stages of tree establishment. In studies conducted in Tanzania and in Zimbabwe (Gerhardt and Nemarundwe 2006), it was noted that in over 60% of Tanzanian households, women are responsible for managing trees while in over 80% of Zimbabwean households, women are responsible for watering young seedlings. This trend is confirmed by Franzel et al. (2002a) in a study undertaken in Embu, Kenya, to determine early stages of adoption of calliandra fodder. It was found that although 91% of households using calliandra fodder were male headed, in 89% of these households, females were responsible for managing calliandra. A similar scenario was observed in Uganda[20] whereby in over 80% of households with calliandra, women were involved in management. It is interesting to note that husbands who managed their farms in Uganda did so jointly with their wives. In another study in central Kenya[21] on management and adoption of calliandra by gender, it was noted that farms managed jointly by men and women had many more trees than those managed solely by men or women perhaps because the jointly managed farms had access to pooled labor provided by both spouses (Table 3).

Comparing survival rates of trees on farms of male- and female-headed households is one indicator of the gender differences in tree management. The results of such analyses are mixed. In a sample of 129 households planting fodder shrubs in Kenya, male-headed households had somewhat higher tree-survival rates than women-headed ones (45% as compared to 31%), but the differences were only marginally significant ($p=0.08$) (Steven Franzel: pers. observation). Possible reasons for low survival rates could have been less labor availability for maintaining the seedlings or a lack of knowledge about how to maintain them. In eastern Zambia, survey data on *S. sesban* supports the hypothesis that women are able to manage improved fallows as well as men. In farmer-designed, farmer-managed trials planted in 1995/1996, half of the participants were women, and they had somewhat higher survival rates for *S. sesban* than men. For example, 47% of women but only 29% of men had survival rates for *S. sesban* of over 75%, 6 months after planting. For *Tephrosia vogelii* Hook. f., men had somewhat higher survival rates. Men and women reported similar problems with similar frequency and did not differ in the number of times they weeded their trees (Franzel et al. 2002b).

Who Benefits from Agroforestry?

Women's rights to tree products are usually limited to products that are considered to have little or no commercial value. These products are mainly indigenous fruits and vegetables, fodder, and mulch. In Kenya, while only men had the right to harvest all trees, over 50% of women had the right to use *S. sesban*.[22] This is because *S. sesban* only provides green manure and fuelwood, products that are not considered to be important to men. Although calliandra as a fodder has been shown to be profitable to farmers, no studies in the literature have been found that show the direct benefits in economic terms that accrue to women. An economic study undertaken in several sites in Kenya and Uganda showed that beginning in the second year after planting 500 calliandra shrubs, a farmer's net income increases by about US $101 to US $122 a year by substituting dairy meal with calliandra. On the other hand, if a farmer uses calliandra fodder shrubs as a supplement for dairy meal, the farmer's income increases by US $62 to US $115 a year. This is about 5–10% of the total income from the farm. The study did not, however, look at how much women received from the sale of milk or what percentage of women had access to the income from the sale of milk. The cash that farmers saved by using calliandra as a high-protein feed supplement to their livestock instead of having to purchase dairy meal accounted for 46% of the cost of the cattle enterprise in the central Kenya farming system (Muriithi and Franzel 2001). The funds so generated are used to pay school fees and general household improvements. In addition to boosting milk production, other benefits from fodder shrubs include improved animal health, fuelwood which is a direct benefit to women, improved nutrition of the family, seedling sales, high-quality manure, bee forage, and stakes for vegetable production in addition to environmental benefits such soil erosion control (Franzel and Wambugu 2007). It is reasonable to assume that women share some of these benefits, particularly the nonfinancial ones such as access to home-grown fodder; furthermore, availability of firewood from the prunings frees up women's labor for other productive enterprises. A detailed study is needed to quantify the actual benefits in monetary terms that women get by using calliandra on farms.

Low-cost agroforestry technologies for replenishing soil fertility are attractive to women farmers because they involve low inputs but high returns. Apart from the obvious benefit of improving soil fertility, reflected in the high maize yields, they also provide fuelwood and reduce the incidence of weeds such as *Striga hermonthica*

Del. Benth. Although a review of literature does not give the direct benefits that accrue to women farmers in financial terms, it appears likely, from the results of focus group interviews with Zambian women, that women do benefit.[17] An economic analysis undertaken by Franzel et al. (2002b) showed that agroforestry-based soil fertility management options were more profitable than farmer's prevailing practices despite forfeiting two seasons of cropping. Provision of fuelwood from improved fallows is a benefit to women farmers as it reduces their burden of having to travel long distances in search of it. Various studies in Kenya, Uganda, and Zambia have shown that improved fallows do indeed generate considerable amounts of fuelwood with the amount varying depending on the species. For instance, 5–42 Mg/ha was generated within 1–3 years in western Kenya (Swinkels et al. 1997); 24–27 Mg/ha after 2 years in southwestern Uganda (Siriri and Rausen 2003); 10 Mg/ha after 2 years in eastern Zambia (Sanchez 1995); and 13.7–21.7 Mg/ha after 2.7 years in coastal Kenya (Jama and Getahun 1991).

Jama et al. (2008) reported from western Kenya that a farmer planting 0.01–0.08 ha (typical size of land planted to improve fallows in the region) could harvest fuelwood that would last a typical household between 11.8 and 124.8 days depending on the species and fallow duration. This would increase to 268.7 and 1173.7 days if farmers increased the area planted to 0.25 ha. Mugo (1999) estimates that women who collect fuelwood for cooking far away from the farm spend on average 130 h per year, as compared to only 36 h spent by those who harvest fuelwood from their own farms. The implication for this is that the time saved by having an on-farm wood supply can be diverted to other productive chores such as weeding, planting food crops, processing, food preparation, and income-generating activities. Women farmers who practice improved fallows therefore benefit tremendously from the fuelwood collected which is considered a secondary product. Fuelwood in western Kenya, one of the most densely populated areas in Africa, is so scarce that a majority of households use crop residues and cow dung for cooking, resources which would normally have been plowed back to the farm to increase crop productivity (Mugo 1999).

In contrast to other agroforestry products, women receive substantial financial benefits from indigenous fruits and vegetables (Table 4). In southwestern Burkina Faso, earnings from shea nut kernel sales ranged from US $15 to US $35 per annum which represented 20–60% of women's income in rural areas.[23] In a study of the contribution of the shea tree to local livelihoods in Benin, Schreckenberg (2004) found that it provided only 2.8% of household income. The income may seem small, but it is significant to women in Benin because they are able to control it, is a source of lump sum income, and is obtained with no investment other than labor. According to a study by Boffa et al. (1996), 66% of women interviewed controlled income from shea production, while 27% shared the control with their family members with a paltry 7% being controlled by the head of household. According to Schreckenberg (2004), income from kernel sales in Benin varied from US $7 to US $36 per annum, which for many women was sufficient to cover a substantial part of their annual expenditure.

Table 4 Financial benefits from agroforestry products

Species	Product	Country	Annual revenue in US $	Who benefits?	Source of information
Vitellaria parodoxa (shea tree)	Kernels	Benin	7–36	Women	Schreckenberg (2004)
Vitellaria parodoxa (shea tree)	Kernels	Burkina Faso	15–35	Women	Crélerot (1995)
Parkia biglobosa (neré)	Fermented seeds	Burkina Faso	39	Women	Teklehaimanot (2004)
Dacryodes edulis (safou)	Fruit	Cameroon	80–160	Men and women	Ayuk et al. (1999a)
Dacryodes edulis (safou)	Fruit	Cameroon	555	Men and women	Fondoun and Tiki Manga (2000)
Ricinodendron heudelotii	Fruit	Cameroon	97	Women	Ayuk et al. (1999b)
Irvingia gabonensis	Fruit	Cameroon	56	Men and women	Ayuk et al. (1999c)
Irvingia gabonensis	Kernels	Cameroon	101	Men and women	Ayuk et al. (1999c)
Gnetum africanum	Leaves	Cameroon	2,629	Women	Fondoun and Tiki Manga (2000)

Other fruit tree species that contribute significantly to the total household income in West Africa include *P. biglobosa, D. edulis, R. heudelotii*, and *I. gabonensis. P. biglobosa* fruit known as néré in French is highly commercialized in Burkina Faso with women solely responsible for the sale of fermented seeds. According to Teklehaimanot (2004), the revenue earned is about US $39 per household accounting for 28.8% of the total income per annum while in Cote d' Ivoire, néré accounted for 4% of the total household revenue compared with 2% from the shea tree. In Cameroon, farm level production of *D. edulis* fruits (safou) ranges from US $80 to US $160 per collector with about 41% sold and the rest being used for household consumption (Ayuk et al. 1999a). Both men and women earn cash from *D. edulis* sales. Fondoun and Tiki Manga (2000) report an even higher average annual income (US $555) from *D. edulis* per participating household. The level of production for *R. heudelotii*, an important woman's crop, is estimated at US $97 per participating household per annum, while *I. gabonensis* fruits and kernels, sold by both men and women, are estimated at US $56 and US $101 per annum, respectively (Ayuk et al. 1999b, c). A combination of these makes a substantial contribution to women's income. Income from *G. africanum* is quite substantial with annual average revenue of US $2,629 among participating household in southern Cameroon (Fondoun and Tiki-Manga 2000). The fact that *G. africanum* is collected throughout the year gives women a constant supply of cash.

A substantial proportion of indigenous fruit products is consumed by households. For example, 59% of *D. edulis* is consumed by the household (Ayuk et al. 1999c). Shea butter is a major ingredient in most kitchens in semiarid West Africa, while *I. gabonensis* kernels are used as an essential sauce ingredient in southern Cameroon. The fermented seeds of néré are ground into a pungent nutritious spice normally added to soups and stews throughout West Africa. The pulp is used to make drinks; the green pods are eaten as a vegetable during the dry season and are also used for medicinal purposes (Teklehaimanot 2004).

In the Tabora Region of Tanzania, indigenous fruits are consumed in large quantities with 44% of farmers getting them from natural forests while 36% buying from the market.[24] Women participating in a collaborative project managed by the Tumbi Agricultural Research and Training Institute (ARI-Tumbi) are generating income through processing and selling of jam, wine, and juice, earning US $12 to US $30 per week through sales of juice. Selling of wine gives them an average of US $13 per week.

Agroforestry Product Markets: Who Benefits?

Another way of assessing benefits is looking at agroforestry product markets. Many studies have reported that women are often involved in marketing agroforestry products, particularly those that are considered a domain for women and children such as indigenous fruits, spices, and vegetables. However, their involvement is mostly confined to the small retail trade. In a study of production and marketing of safou in Cameroon, Awono et al. (2002) noted that women dominate the collection of the fruit and take it to the market, where they dominate the retail trade (95% of retailers are women). Men, on the other hand, account for 71% of wholesale traders. This gender difference is confirmed by Schreckenberg (2004) who found that women in Benin also dominated the retail trade of shea kernels and butter. In Cameroon, Kanmegne et al. (2007) found out that in the trading of *G. africanum,* 93% of retailers were women. The few men involved dominated the wholesale trade, which requires significant capital which men usually obtain from selling cacao. In addition, wholesale trade involves less market time but often a lot of travel which many women cannot undertake due to household responsibilities. But even where women are involved in production and collection of agroforestry products, their involvement in marketing may be limited by the mode of transport used. For example, in Tanga, Tanzania, where farmers collect calliandra leaves for processing into leaf meal, 11 of 17 collectors interviewed were women, whereas 10 of 11 traders were men. Bicycles were usually required for trading but were not considered culturally acceptable for women.[25]

A further analysis of marketing of safou revealed that women traders received lower marketing margins per sack than men: US $6 for women against US $7 for men (Awono et al. 2002). This may be because men sell more sacks per transaction than women. Most women traders do not have enough capital to increase their stocks of safou. Furthermore, examining the relationship between marketing margins and level of education showed that the highly educated traders are more successful. Given that women's literacy level is lower than men's, they are relatively disadvantaged. Traders who are highly educated have access to better market information (marketing channels and prices) and are therefore in a better position to make informed decisions on where to purchase and dispose of stocks without making any losses. Since women involved in marketing of agroforestry products are confined to retailing, they fail to benefit equitably from the growing national and international markets.

Who Has Access to Agroforestry Information?

Empirical evidence since the 1990s has documented gender disparities in access to agricultural information[1, 2, 26] (Quisumbing 1996; Katungi et al. 2008). Access to agroforestry information is no exception; fewer women than men are reached. In a study to determine the effectiveness of various dissemination methods in reaching men and women farmers to advise them about managing calliandra fodder shrubs on farms in central Kenya, it was noted that fewer women than men had received at least one extension visit; when farms were categorized by the gender of the manager, about 10% of jointly managed farms and male-managed farms had received at least one visit compared to only 5% of female-managed farms.[21] This is a further confirmation that delivery of extension information is biased against women. This bias has been attributed to several factors. First, sociocultural barriers inhibit extension agents, 80–95% of whom are men, from communicating with female farmers.[11] Second, there is a general perception that since men are the decision makers, any extension message should be passed on to them.[2, 26] This latter assumption has been shown by Abbas (1997) and Gladwin et al. (2001) to be flawed. This is because households are complex institutions with different roles and responsibilities and members may have separate spheres of decision making with reference to production, income, and expenditures. Third is the perception in some places, surprising though it may seem, that women are not farmers.[2]

For the few women who are able to access extension information, some lack basic education, and, therefore, their ability to access and use technical information is compromised.[26] Basic education places farmers in a better position to perceive potential benefits of adopting new innovations. Women's literacy levels as a proportion of men's levels are increasing, reaching 63% in West and Central Africa over the period 2000–2004 and 85% in eastern and southern Africa (UNESCO 2007). However, women's literacy levels are still low: Benin (48%), Cameroon (36%), Tanzania (33%), and Zimbabwe (15%) (UNESCO 2002). This has implications on the adoption of agroforestry innovations. But the lack of education does not necessarily prevent farmers from adopting new practices. In Embu District of Kenya, women who were using calliandra fodder shrubs had lower education than men: an average of 7 years of schooling for men and two for women.[21] Considerable differences were further observed in male and female attendance in extension events in Embu District, Kenya. For example, a higher proportion of farmers in male-headed households (20%) than in female-headed households (8%) had attended field days.[21] This is further confirmed by a survey on gender participation in mass awareness activities in Uasin Gishu District, Kenya, where men participated in about twice as many mass awareness activities as women.[22] Men who had not attended field days in Embu District, Kenya, cited lack of awareness of the time and venue of the field days as the main reason while women cited lack of time as they are normally involved in household chores all day long.[21]

Recommendations on How to Promote Gender Equity

This section proposes various technological, policy, and institutional recommendations to promote gender equity and to increase women's adoption of agroforestry and the benefits they receive. We focus on recommendations which affect agroforestry in particular and which are based on research reported in this chapter. Beyond the constraints specific to women and agroforestry, there are structural problems in the agricultural sector, for example, low returns and lack of investment that affect both men and women. This section does not address these problems or make recommendations which are more applicable to agriculture in general, for example, the need for better market infrastructure. Recommendations will of course need to be location specific and based on the households' needs and circumstances, which can only be determined after undertaking a gender analysis. Household members will need to be involved in the planning, implementation, and evaluation of the various interventions. Participatory methods for doing this are well documented (Ashby 1990; Gonsalves et al. 2005).

Technological Interventions

Domestication of Important Agroforestry Species

Many tree products that benefit women are collected from wild populations in forests, woodlands/rangelands, parklands, or on farms. For centuries, this has been possible without impacting negatively on the environment. However, increasing population and trade have increased the demand for these products and, through deforestation, reduced their supply. These factors have led to the degradation of agroforestry trees such as *P. biglobosa, V. parodoxa*, and *G. africanum*. Evidence of degradation has been shown in terms of reduced densities and population structure (Gijsberg et al. 1994; Kelly et al. 2004). In Uganda, the parklands are characterized by old trees of *V. parodoxa* with no regeneration (Okullo et al. 2003). Apart from fruits and kernels, the leaves of *G. africanum* are also in very high demand both locally and internationally. An estimated quantity of 3,600 tons of *G. africanum* leaves is shipped annually to Nigeria from Cameroon and exported to European countries and the USA.[27] In order to meet the demand, women walk several kilometers to search for it. During harvesting, the trees that *G. africanum* vines grow on are often felled, creating widespread damage. In some cases, harvesters uproot the whole vine. The high demand coupled with unsustainable harvesting methods is leading to scarcity of valuable agroforestry tree products.

Promoting participatory domestication initiatives that integrate local and scientific knowledge will facilitate the integration of these valuable species into appropriate farming systems, thereby resulting in technologies that are economically, socially, and ecologically acceptable. Participatory domestication initiatives led by ICRAF and national partners have seen farmers in West Africa domesticating tree species such as shea, *D. edulis, I. gabonensis*, and *P. biglobosa* (Lovett and Hag 2000; Schreckenberg et al. 2002; Leakey et al. 2004; Degrande et al. 2006; Leakey et al. this volume). The end products of these initiatives are appropriate cultivars and propagation methods that meet a range of market and producer requirements. Market requirements include fruit with desired size, taste, and color. Extending the fruiting periods is also important so that producers, especially rural women, can have a year-round flow of cash from agroforestry products.

In addition to cultivars that meet market requirements, women need cultivars that are easier to harvest. Women are constrained when it comes to harvesting because most fruit trees are very tall, and women have to rely on men to harvest the tree products, often at a fee. Those women without assistance end up relying on fallen fruit whose quality is compromised. Cultivars are needed that are of reasonable height so that anyone, even children, can harvest the fruits without having to climb a tree. An additional hindrance is the taboo in West Africa that prohibits women from climbing certain trees. Smaller trees have the additional benefits of taking up less land, a resource which is often very limiting for women farmers.

Development of Postharvest Storage Methods

Many agroforestry products have a very short shelf life, particularly fruits and vegetables, which are mostly collected and marketed by women. Ramathani (2002) and Kadzere et al. (2006) reported that postharvest handling and transport are the major causes of losses of perishable agroforestry products. Karaan et al. (2005) reported that, in Zambia, collectors and wholesalers attributed the loss of fruits to poor handling 82.9%, rotting 11.4%, heat 2.9%, and inappropriate containers 2.9%. For instance, *D. edulis* lasts only 5 days which makes it very difficult for women to market it, and they, therefore, often dispose off their products at throw-away prices to avoid incurring huge losses. It is therefore important to come up with appropriate techniques of improving the postharvest quality of on-tree- and off-tree-ripened fruits. In addition, wholesale traders normally store their produce in large heaps on the open ground with no cover to protect from rain, sun, and wind. The bulk storage affects the quality of the fruit because those at the bottom of the heap are squashed while those at the top are baked by the sun thereby leading to huge loses. Development of low-cost storage boxes would go a long way in helping reduce losses incurred.

Development of Appropriate Agricultural and Processing Techniques

The problem of limited shelf life can be addressed through processing which ensures supplies for periods of shortage and can improve the quality of agroforestry tree products. Where there is market demand for such products, marketing of processed products can also increase women's incomes. Most women still use ancient processing techniques. For example, Teklehaimanot (2004) reported that 80% of shea butter in Mali and Burkina Faso is made traditionally. Traditional extraction techniques for shea butter are time consuming and physically strenuous; they also require huge amounts of fuelwood and water and have a low extraction efficiency, creating a significant drain on these scarce resources. The preparation of fermented seeds of *P. biglobosa* in Burkina Faso, compressing leaf meal in Tanzania, and extraction of *R. heudelotii* nuts in Cameroon are other examples where women's traditional processing methods of agroforestry tree products are laborious. Simple, low-cost techniques for processing in these cases could help women reduce labor requirements and wastage while improving productivity and maintaining nutritive quality. Tools and practices to help women reduce the time taken and drudgery of tasks will free women's time, which can be used in other productive activities such as attending extension sessions. Potential processing techniques need to be screened for their profitability and sustainability. Development of efficient agricultural and processing techniques of tree products also needs to be accompanied by capacity building. Women need to develop their business and marketing skills in addition to processing techniques. Key skills needed include how to assess demand, develop business plans, negotiating skills, and record keeping. An important issue is whether training in tree product processing and marketing should involve individuals or groups. This depends on the particular situation. Experience from Tabora, Tanzania, shows that training the participants in groups is more cost efficient than training them as individuals.[28] Furthermore, even when group enterprises fail, capable individuals carry on with the activities using the skills learned.

Development of New Products

Once women can effectively produce raw and processed agroforestry tree products for local markets, they can seek opportunities in developing new products. For women to compete favorably, and also have an edge, they need to move away from the traditional products into a diversity of high-value products such as oil, soap, juices, body lotions, wine, and leaf meal. Such new products need to be carefully assessed, however, taking into account projections of risk, profitability, competition, and economies of scale. This diversification can often be done using the same raw materials. For instance, women engaged in calliandra fodder production in the high-potential areas of eastern Africa can also package calliandra leaf meal for sale in agrovet shops and to other dairy and poultry farmers as a fodder supplement as is already being done in Tanga, Tanzania, with *Leucaena leucocephala* (Lam.) de Wit. Producers, who are usually women, collect *Leucaena* from the wild and then dry and crush the leaves into leaf meal. Next, the meal is packed into bags and sold to owners of stall-fed dairy and poultry enterprises.[25] Women in southern and western Africa are already producing various products from indigenous fruits, but the range needs to be increased so that they have an edge in marketing. In East Africa, product development from indigenous fruits is still at its infancy, and, therefore, efforts need to be stepped up to empower women to venture in new products.

Policy Interventions

An enabling policy environment is critical in making sure that agroforestry benefits women. In order to ensure that women benefit from agroforestry, gender-sensitive policies need to be put in place. These are grouped into four key areas: extension services, access to market information, microfinance, and land tenure reforms.

Access to Extension Services

The weakness of many extension systems, particularly public ones, has been widely acknowledged (Davis 2008). Christoplos (2010) notes that complaints against extension concerning gender may be merely "shooting the messenger" because gender bias is grounded in social norms, for example, discouraging women from becoming extension agents. Moreover, gender biases in extension may be due to wider policy biases, such as those promoting cash crops, which men dominate, and ignoring subsistence crops, which women may benefit most from. To ensure that agroforestry extension services benefit women, deliberate gender-sensitive interventions need to be put in place including:

- Training more women extension officers, particularly to serve communities that have strong traditions that prohibit male extension officers from interacting with women farmers.
- Ensuring that at least half of those who participate in any activity are women.
- Ensuring that extension activities address different interest groups, that is, women are more interested in products such as fruits, fuelwood, and vegetables while men are more inclined toward trees for timber and poles.
- Targeting women's enterprises. Women may not be interested in many "cash crops" because they know they will not control the income generated. Helping women improve incomes from enterprises considered to be in women's domains may be of more interest and benefit to them (Christoplos 2010).
- Targeting women's groups for assistance. This chapter has shown the effectiveness of targeting such groups as a means of disseminating information and technology to women.
- Finding out from women which periods of the season and day they are most free to meet and holding meetings/field days/seminars at these times.
- Holding separate meetings for men and women.
- Organizing video show sessions for women who are not able to participate in tours.

Access to Market Information

The rise of market information systems based on information and communication technologies (ICTs) offers great potential for improving smallholder access and returns. But to our knowledge, none of these organizations have programs specifically targeting market information on agroforestry to women. Some type of public-private partnership is likely required in which a donor or government project subsidizes the targeting of market information services to women. Such a program might involve subsidizing the provision of handsets to women or specialized training on how to use the service. Knowledge is power, and with access to market information, women farmers can greatly reduce losses due to wastage for lack of buyers as they will be able to make informed decisions about when to produce, what to produce, for whom to produce, and when and where to sell their agroforestry produce. They will also have strengthened bargaining power and save precious time and money as they will only leave their homes when they are sure they have a buyer for their agroforestry products.

Improving Women's Access to Finance from Microcredit Institutions

Access to finance from credit institutions is discussed in section two as one of areas where women are disadvantaged. According to the World Bank (2007), women in developing countries receive less than 10% of available credit. This is mainly due to lack of land title deeds, which are normally used as collateral in rural areas. For women to access financial credit, governments need to intervene to encourage the development of rural microcredit institutions with regulations friendly to women. Intervention can be in the form of accepting other forms of collateral such as machinery, furniture, and any other tangible assets that women own. The capacity of existing social organizations such as women's groups needs to be strengthened so that they may access credit individually but use the group as collateral. A good example of such an innovative approach in Kenya is known as *Fanikisha* and is being implemented since 2008 by Equity Bank which partnered with United Nations Development Programme (UNDP), United Nations Industrial Development Organization (UNIDO), International Labour Organization (ILO), and the Ministry of Finance. The aim is to increase women's access to credit. The program targets women who lack assets that can be used as collateral.[29] By accessing credit, women would be in a better position to adopt the use of improved agroforestry practices and technologies and operate bigger businesses thus increasing their contribution to household income which may consequently improve their decision-making power in households.

Finally, instead of providing free equipment to women's groups, as many NGOs and projects do, institutions would be better off helping the groups to link to financial institutions and, if necessary, subsidizing the credit that groups receive to purchase the equipment themselves. This approach helps ensure that groups link to financial institutions, that a proper business plan for using the equipment is prepared, and that NGOs and projects will be able to serve more groups since they are only paying a portion of the costs of the equipment.[20]

Land Tenure Reforms

As discussed in Sect. 2, women in Africa customarily have limited rights to land. Moreover, what rights they have may cease to exist upon divorce, widowhood, or failure to have a son.[6] In order to protect women, African governments should enact land policy laws that:

1. Require spouses to have joint ownership of land in order to prevent men who are customarily owners of land from disposing of it without their wife's consent. In the absence of such laws, it should be mandatory for men selling land to have written consent from the spouse.

2. Grant widows the right to their husband's land.
3. Allow daughters to inherit land from their parents.

These policies, if put in place and enforced, will ensure that women have equal rights to land which may consequently lead to secure land tenure.

Institutional Interventions

Women producers in sub-Saharan Africa are trapped at the production end of the value chain. In order for women to come out of this trap, governments, NGOs, and the private sector need to intervene by facilitating women to form and strengthen their groups and associations, linking them up with markets and industry. By engaging in collective action, women would be able to gain a more powerful position in the agroforestry products value chain which is advantageous in several ways: stronger bargaining power; bulk sales/purchases of inputs; ensuring a sustainable supply of products; reduction in transaction costs; attract more and larger buyers; access outside resources, such as extension and development assistance; access to the lucrative fair trade and other certified markets; and above all be able to contribute to the policy formulation process.

Strengthening women's groups at the community level is critical, as is helping such groups to federate across larger areas. There are several examples in the literature where women have come together and, through the facilitation of various institutions, are currently reaping the benefits of agroforestry. In southern Africa, PhytoTrade Africa has been helping southern Africa's natural products industry to achieve rapid growth while ensuring its long-term sustainability and social equity through product development, market development, and supply chain development. In 2006, 30,000 producers in seven southern Africa countries (93% women) sold raw materials to.[31] In Burkina Faso, 400,000 rural women have been working with the UN Development Fund for Women (UNIFEM) and the Centre Canadien d' étude et de Coopération Internationale (CECI), a Canadian NGO, which has been facilitating them to process and market shea nuts. UNIFEM linked these groups to a French cosmetics company known as L'Occitane that purchases shea butter directly from the Union des Groupments Kiswendsida (UGK), a network of more than 100 women's groups. This ensures that a greater share of the revenue goes to producers who are women instead of middlemen. In addition, the company provides training in quality control and pays for the shea butter in advance (Harsch 2001).

Conclusions

This chapter has shown that agroforestry has the potential to offer great benefits to women. However, their participation is hampered by socioeconomic, cultural, and policy issues that vary within and across locations. These issues, if addressed, will go a long way in ensuring that more women participate in agroforestry with greater benefits accruing to them. Several promising approaches to improving women's benefits from agroforestry are documented in this chapter. For example, while the enterprises in women's domain are often low value, there are cases where collective action and marketing interventions have helped raise values and incomes, as with indigenous fruit processing and marketing in Tanzania. Further, while extension services are biased toward men, the targeting of women through women's groups has helped, in some instances, to raise the proportion of women beneficiaries to about half, as in the case of fodder shrubs in Kenya.

This chapter was guided by four research questions which were tackled accordingly based on data available. Our coverage was limited to articles published in English, so there was bias toward Anglophone Africa. Moreover, the technologies assessed tended to be found, or at least reported on more frequently in eastern and southern Africa. Another shortcoming was that most subjects could not be addressed adequately due to lack of data. Studies on gender and agroforestry are very limited, and small sample sizes in addition to the tremendous diversity often restrict the possibility of generalizing from them. Research to fill these gaps will enable the scientific community, policy makers, and development practitioners to understand more fully the extent to which women across Africa are involved in agroforestry, and thereby facilitate the development and implementation of initiatives that take into account gender issues and generate greater benefits for women. Priority research areas for further investigation include:

(a) Measuring actual income women receive from agroforestry, relative to nonagroforestry enterprises and also relative to what men earn. It is also important to assess how agroforestry contributes to sustainable livelihoods.
(b) Assessing the effectiveness and impact of alternative extension methods on women's participation and benefits.
(c) Determining how different categories of women, for example, female heads of household, women in male-headed households, and youth, benefit from agroforestry.
(d) Identifying success stories across Africa and assessing the factors that have contributed to their success.
(e) Documenting cultural beliefs/taboos regarding tree planting and how they influence adoption of agroforestry by women across the African continent.
(f) Determining how to help women to increase their participation in marketing and the amounts they earn from marketing.

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Incentive Mechanisms for Smallholder Agroforestry: Opportunities and Challenges in the Philippines

Delia C. Catacutan, Rodel D. Lasco, and Caroline D. Piñon

Abstract Incentives generally imply something that contributes to or serves as motivation to accomplish a task, which may lead to rewards. Today, "incentives" are used in many agriculture and forestry initiatives in developing countries to promote wider adoption of agroforestry. In this chapter, we have used the experience from the Philippines to illustrate how, in the midst of various challenges, global and locally designed incentive mechanisms can stimulate smallholder investments in agroforestry. The global carbon market has opened up opportunities for agroforestry through which smallholders benefit from carbon trading. At the national level, a plethora of policy incentives exist for agroforestry, but smallholders hardly benefit from such policies due to lack of information and resources to leverage policy implementation. We conclude that incentives can facilitate the adaptive capacity of smallholders and can stimulate agroforestry investments. We suggest that national institutions should catalyze international carbon incentives for smallholders, while local governments should be primed to address smallholder needs through locally designed incentive mechanisms. Ultimately, effective coordination and linkages are needed to harmonize global, national, and local incentive mechanisms for smallholders to have optimal benefits from agroforestry.

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Introduction

The multiple ways in which smallholder agroforestry can strategically address forest and agricultural issues on local livelihoods, economic development, and climate change adaptation have been recognized by both local and international environmental programs (FAO 2011).[1,2] In Southeast Asia, considerable progress has been made in terms of policies and programs in the forestry sector that facilitated investments in agroforestry, which have resulted in significant expansion of forest areas in the region. Vietnam in particular, achieved its targeted increase in forest cover by 43 % in 2010, by implementing incentive programs for smallholders to plant more trees and integrate the same on farms (FAO 2011). In the Philippines, the forest area expanded with additional 7.2 million ha in 2003—of this, an equivalent 6.5 million ha of trees plantations were established in forestlands, while the 0.65 million ha that were planted with trees were in smallholder farms outside the forest area (Pulhin et al. 2006).[3] The multiple benefits that farmers derive from agroforestry are well founded. In terms of income in developing countries, agroforestry contributed 29 % to agriculture's gross domestic product (GDP) and 65 % in labor force and is a major source of livelihoods for three billion people in rural areas (Bank World 2007). Experiences of smallholder agroforestry in the region also show that externalities from cultivation can be reduced, made less vulnerable to climate change, and even harnessed to deliver more environmental services (Pasicolan 2007).[4,5] However, in spite of the viability of agroforestry, it is constrained by various factors including farmers' inability to invest in the system, inadequate institutional structures for facilitating information flow, and lack of market incentives (Catacutan and Duque-Piñon 2009).

The concept of incentives is defined according to the context in which it is used, but generally, it implies something that contributes to or serves as motivation to accomplish a task, which may lead to rewards. The concept is explained further in the Methods section. Incentives are widely used for promoting smallholder agroforestry. At the global level, the Clean Development Mechanism (CDM) and Reduced Emissions from forest Degradation and Deforestation (REDD) are popular mechanisms that offer a range of incentives that smallholders can benefit from direct payments for carbon and noncash incentives such as capacity building. Later, REDD+ has been introduced as a mechanism that goes beyond deforestation and forest degradation and includes the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks, enabling forested developing countries to sell carbon credits to interested buyers in markets or receive financial support from conservation funds in order to reduce deforestation and degradation rates.[6] The implementation of CDM and REDD+ projects is however plagued with challenges due to myriad challenges in developing countries. Nevertheless, it is expected that smallholders can still immensely benefit from CDM and REDD+ projects—with effective facilitation and appropriate support, smallholders can aggregate to produce tradable carbon credits.

Smallholders are key players in the agriculture sector but their contribution to economic growth has not been optimal relative to its potential. In analyzing the global perspectives of smallholder agriculture, Tinsley (2004) emphasized the need for understanding the limited resource endowments of smallholders vis-á-vis their roles in meeting societal expectations for sustained provision of food, fiber, and environmental services (Catacutan and Duque-Piñon 2009). Accordingly, interest turned to small-farm families in developing countries because they constitute the most numerous farmer group in the world (World Bank 2007). However, despite their number, the contribution of smallholders to economic progress, food security, and environmental development is often less regarded. When it comes to development programs, national governments often concentrate on large-scale farmers because they have operational resources to manage their land, are easier to work with, and are more responsive to suggestions (Tinsley 2004). Hence, national governments are criticized for undermining the potential of smallholders to meet the requirements of economies of scale of production.

In the Philippines, smallholders constitute about 90 % of the farming population and represent around 21 % of the country's total labor force.[7] The Philippines' Magna Carta for Small Farmers (Republic Act 7607) defined smallholders as natural persons dependent on small-scale subsistence farming as their primary source of income, while the Land Bank of the Philippines categorized smallholder farmers as actual tillers of lands not exceeding 5 ha.

Several reforestation and agroforestry projects are underway, and some of them are intended for registration with the Philippines' CDM Executive Board. But with apparent lack of success of forestry projects globally under the CDM (Thomas et al. 2010), some sectors have advocated payments for avoiding deforestation under the REDD+ mechanism. Even so, the design and implementation of REDD+ projects will be neither simple nor straightforward, given the complexity of the social, economic, environmental, and political dimensions of deforestation.[8] It is also not easy to communicate the mechanism or attract various players, since many of the underlying causes of deforestation are generated outside the forestry sector, and alternative land uses tend to be more profitable than conserving forests. Thus, amidst an array of incentive mechanism, their long-term sustainability depends on a number of factors, including diverse socioeconomic characteristics of smallholders, effective governance, secured forest carbon tenure, benefit sharing, and integration of locally appropriate adaptation and mitigation actions (LAAMA) into climate change policies and programs at the national level (FAO 2011).[9] This corroborates with Tinsley's (2004) insinuation to review and improve national government policies, to harness the potential of smallholders to advance with viable agricultural enterprises, and to benefit from a range of incentive mechanisms. For agroforestry, this involves enhancing provision of incentives while removing disincentives that discourage smallholder investments in integrating trees on farms.

The objective of this chapter is to examine, based on a set of case studies, the need for complementing global and national mechanisms with locally designed incentives where smallholder farmers have more access and influence. The Philippines, where the vast majority of the farming community are smallholder farmers and where global and locally designed incentive mechanisms are being tried, presents an excellent case study scenario for undertaking such a study.

Research Method

The method used in the study was mainly qualitative, based on policy reviews and action-research in agroforestry-related incentive mechanisms. The first set of case studies includes three sites in northern Philippines where carbon incentives are the main focus, namely, the municipalities of Tanay in Laguna province, Peñablanca in Cagayan, and Kalahan in Nueva Viscaya. The second case study in the southern Philippines that focused on local incentives for a range of sustainable agriculture practices was in Lantapan municipality, Bukidnon. The analysis was built on a previous study of policy incentives for vegetable agroforestry conducted by Catacutan and Piñon in 2009. The case studies on forest carbon projects focused on output or performance-based incentives such as credits from carbon sequestered from agroforestry and forestry initiatives, whereas the locally designed mechanism focused on a range of incentives to stimulate performance.

Agroforestry Incentives

Enters et al.[10] present the types of incentives in Fig. 1. Incentives are categorized as remunerative and moral. Remunerative incentives are financial or material rewards in exchange of acting in a particular way, while moral incentives are particular moves that are regarded as acceptable that results to increase in self-esteem or recognition. Remunerative incentives can be either direct or indirect. Direct incentives influence returns to investments directly, while indirect incentives have an indirect effect in changing the overall situation. Indirect incentives are further categorized into variable and enabling. Variable incentives are economic factors that may be implemented to affect the net return of an investment, while enabling incentives are factors that affect decision-making with greater impact because of wider coverage. For this study, incentives are viewed as external prompts provided by the global community and national and local government through policies and programs to which farmers respond, either positively or negatively. Conversely, disincentives refer to those that discourage, hinder, or deter positive responses or actions to occur.

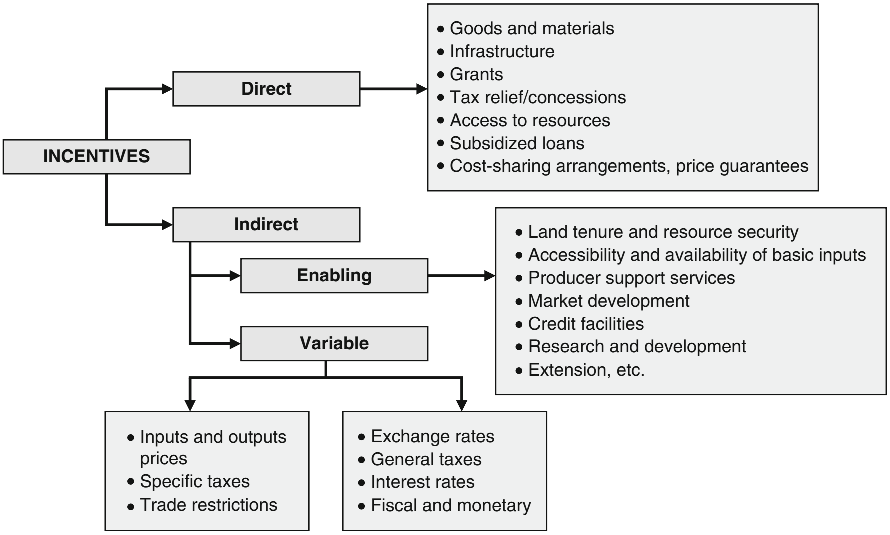

Fig. 1 Types and examples of incentives that can stimulate adoption and investment for agroforestry development among smallholder farmers (Adapted from Enters et al. 2004)

Forest Carbon Market

The emerging forest carbon market provides a range of incentives for smallholder agroforestry and forestry through such mechanisms as REDD, REDD+, CDM, and the voluntary carbon schemes (Table 1). The Philippines has great interest in participating in CDM forestry projects given the need for reforestation and rehabilitation of about 9 million ha of public forestlands (Villamor and Lasco 2009). These include critical watersheds, forest reserves (including those under the management of other government agencies and government-controlled corporations), and forestlands under the National Integrated Protected Area System, including areas with 50 % slope and altitudes as high as 1,000 m above sea level (masl). The total area of these forestlands is about 5 million ha (FMB 2001)—a large portion of which needs to be either protected or rehabilitated.

Various Philippine forest types contain large carbon stocks, which could be released to the atmosphere if not protected. Indeed, since the 1500s, deforestation of 20.9 million ha of Philippine forests contributed 3.7 10^{15} gC to the atmosphere, of which 2.6 10^{15} gC were released this century (Lasco and Pulhin 2000). However, recent data from the Department of Environment and Natural Resources (DENR) show that the rate of deforestation has tapered off and that the forest cover is showing signs of expansion. In this case, it will be hard for the country to receive or even expect payments for reducing deforestation because the baseline shows that deforestation is already declining even without incentives or carbon payments. However,

Table 1 Agroforestry incentives and (expected) results within the carbon market and national policy framework in the Philippines (2009–present)

	Within the forest carbon market (REDD+, CDM, voluntary market)		Within the existing national policy framework	
Beneficiary hierarchy	Incentives	(Expected) Results	Incentives	(Expected) Results
National level	Capacity building Financial flows from global funds	Meeting NAMA targets (nationally appropriate mitigation actions)	Various	Increased efficiency of forest, agroforestry, and agricultural investments
Local government level	Capacity building	Improved forest management and capacity to manage carbon projects.	Various	Increased efficiency of forest, agroforestry, and agricultural investments
	Financial flows from global and national funds	Reinvestment of carbon income into agroforestry development or forest management activities		Improved forest/watershed management
	Share of carbon payments			High carbon-development pathway
Community level	Capacity building	Improved community forest management	From various national policy incentives in agriculture and forestry sectors: communal land tenure, property rights	Improved social capital
	Financial flows	Enhanced provision of watershed/forest environmental services	Capacity building	Reduced resource/forest conflict
	Community-based land/forest tenure	Improved social capital		Increased community incomes
	Share of carbon payments	Reinvestment of carbon income into community development projects		Improved extension and social services Enhanced environmental services at landscape scale

Household level	Capacity building	Improved human capital	Capacity building	Increased human capital
	Land/forest tenure	More investments in agroforestry and other sustainable agricultural practices	Land tenure and property rights	Increased farm production
	Cash income from sale of CO_2	Increased income from carbon	Crop insurance	Improved farm management
	Noncash/in-kind	Diversified livelihoods	Access to or subsidized credits/loans	Increased income, lifestyle, and well-being
			Input subsidies, grants	
			Cash payments/rewards	
			Tax reliefs/holidays	
			Access to information, markets, and extension services	

in reality, forest degradation (e.g., tree cutting) is taking place even if the forest area is increasing. Cutting trees inside the forest through various forms of logging is rampant, which could lead to lower biomass and carbon stocks. For example, logging in Mindanao has led to a decline of aboveground carbon stocks by about 50 % or 100 10^6 g C/ha (Lasco et al. 2006). However, no data is available on the extent of biomass degradation in Philippine forests.

Recently, the Philippine National REDD+ Strategy (PNRPS) was completed by an expert team, composed of representatives from various civil society groups, academic and research institutions, local governments, and the DENR including bureau representatives. Furthermore, the National Framework Strategy on Climate Change has incorporated REDD+ as a key result area for climate change mitigation. Likewise, Presidential Executive Order No. 881 included REDD+ programs, action plans, and related mechanisms within the scope of coordination by the Climate Change Commission and mandated the DENR as the operational implementing agency for REDD+. Recently, the PNRPS has been endorsed by the DENR to the Commission for official adoption.

Incentives and Disincentives Within the Existing Policy Framework

Catacutan and Piñon (2009) reviewed key national policies in the forestry and agriculture sectors to examine if national policy incentives for agroforestry existed and to understand how small farmers benefited from such incentives. The review found that although there was a plethora of national policy incentives, their benefits were hardly felt by smallholders for two reasons: (1) smallholders had limited access to information on national policies, and (2) they had little or no resources to leverage policy implementation. National agencies were slow in communicating new policies and often lacked funding to implement and monitor policy performance on the one hand, and local governments lacked human, technical, and financial resources to implement national policies on the other. Oftentimes, the policies were misinterpreted or poorly understood. As a result, the implementation of national policy incentives has been slow and weak.

Moreover, many policy incentives in the forestry and agriculture sectors appeared to be much less intended for smallholders. One example is the 2005 Upland Agroforestry Program, which aims to promote equitable distribution of opportunities and income in developing agroforestry through public-private partnerships. Whereas the smallest area that could be applied should be no less than 50 ha, the farmer is also required to submit a proof of financial and technical capability to undertake agroforestry. At the same time, the farmer should incur the cost of survey, mapping, and formulation of agroforestry development plans. In the end, the national government would be entitled to a share of the gross revenue and other benefits from the agroforestry farm. Obviously, the incentives under this program were biased toward large-scale or well-to-do farmers who could afford the initial investments required in setting up a 50 ha agroforestry farm. Conversely, smallholders could not benefit from this policy incentive due to lack of money to incur the initial investment cost or leverage this policy incentive—the program has thus turned out to be a disincentive for smallholders. Another laudable national policy incentive was the Crop Insurance Law (Presidential Decree 1467), which was implemented by the Philippine Crop Insurance Corporation. As part of the Philippine Government's risk management and social protection strategy, the law was passed to protect farmers against loss of crops, livestock, and agricultural assets due to natural calamities, pests, and diseases and other hazards. The law incorporated a number of incentives, but the inability of smallholders to cash out the premium payment was a disincentive. The underlying issue was lack of funding—the Philippine Crop Insurance Commission who administers the law received only a small fraction of the intended budget from the national treasury. As a result, it failed to reach out the targeted smallholders in rural areas and was compelled to focus on farmers that had access to formal credits with financing institutions. Inadvertently, the law is favoring medium-to-large-scale farmers, in the same way as credit programs have been favorable to large farmers due to the inability of smallholders to meet the credit requirements. In view of the above, we recommend that local governments create locally appropriate incentives to offset national policy gaps and effectively address smallholder needs in a timely manner. This is propitious since local governments are imbued with powers to use policy measures to address local issues.

Case Studies

Case Study 1: Incentives from Carbon Forestry

In response to the emerging global carbon market, there has been interest in climate change mitigation projects in the Philippines from the government, nongovernment organizations, local communities, private sector, and the donor community. Currently, three CDM forestry projects are being developed, all using some form of agroforestry and tree planting. The first of these is the Laguna Lake Development Authority (LLDA)-Tanay Streambank Rehabilitation Project (Lasco et al. 2010a). The main objective is to reduce greenhouse gases (i.e., CO_2) in the atmosphere while helping to rehabilitate the Tanay watershed and providing socioeconomic benefits to local people. The main proponents of this project are the Municipality of Tanay and the LLDA, with support from World Bank. The bank provided technical assistance and funding for data gathering and packaging the project into CDM. In addition, the carbon credits from the project will be purchased by the bank's Biocarbon Fund, through an emission reduction purchase agreement. An indigenous people's (IP) organization, which had committed a portion of its land that was donated to them by the local government to this project, is the leading project implementer. The IP community will plant and maintain the trees for carbon sequestration. The Tanay LGU will provide technical inputs including selection of appropriate species, seedling propagation, and planting techniques. The project involves establishment and management of a 52 ha forest consisting of pure forest plantation and agroforestry in Cuyambay, Tanay, Rizal. Native tree species to be planted include narra (*Pterocarpus indicus* Willd.), dao (*Dracontomelon dao* (Blanco) Merr. & Rofe), ipil (*Intsia bijuga* Colebr.*)*, molave (*Vitex parviflora* Juss.), cashew (*Anacardium occidentale* L.), and kakauate (*Gliricidia sepium* (Jacq.) Steud). The project estimated a total net carbon benefit of 20.8 Gg CO_2-eq with a value of about USD 140,000 at USD 5 per Mg CO_2-eq, over a 20-year period. This amount is expected to benefit local people particularly smallholders, in terms of additional income, and in turn encourage them to further invest in agroforestry.

The second is the Conservation International's (CI) Philippine Peñablanca Sustainable Reforestation Project. With funding from Toyota Motors Corporation, the project aims to promote forest restoration, forest and biodiversity conservation, and alternative livelihood through reforestation, enhancement planting, and agroforestry (Toyota Motor Corporation and Conservation International).[11] The project aims to develop 2,500 ha of degraded lands in five villages and expects to (1) increase household incomes from direct payments for successful establishment and ensured growth of seedlings, as well as from the sale of harvested fruit trees in agroforestry farms; (2) improve capacity in forest establishment and management, agroforestry, soil and water conservation, mulching, pest control, and marketing; and (3) gain positive changes in environmental values, attitudes, and practices. The reforestation component covers 1,800 ha with up to 372 farmer participants who will receive direct compensation for tree planting activities at a rate of PhP 4.50/seedling (about US$ 1.07 at PHP42 per US$). During the first year of implementation, farmers also earn a quarterly income from maintaining the trees at PhP1.50/tree (US$ 0.04). The agroforestry component covers 700 ha with up to 628 farmers involved in fruit-tree production (e.g., mango and other fruit trees). The average annual income per farmer is estimated at PhP 6,369 or US$ 151.64 (at PhP20/kg or US$ 0.48 per mango fruit) from as early as year 5. Cash crops will be intercropped in between fruit trees, which will further add income to farmers.

The third is the Kalahan Forestry Carbon Project. The Ikalahan Ancestral Domain covers 58,000 ha of mountainous forest and farmlands and is located in the provinces of Nueva Ecija and Nueva Vizcaya in northern Luzon. The Kalahan Educational Foundation (KEF), an indigenous community-based organization, aims to convert 900 ha of marginal and abandoned agricultural lands into a productive tree-based system while protecting the watershed, enhancing biodiversity, and improving landscape beauty. The project will be implemented by KEF, in collaboration with various stakeholders including the Ikalahan-Kalanguya indigenous communities, local NGOs, the DENR, the project monitoring team, and the funding organization. KEF will catalyze community organizing, while the project monitoring team measures the carbon sequestered and assess project impacts, and the funding organization provides financial resources to cover the project establishment and monitoring costs. It is estimated that the 900 ha forest area will sequester about 90.0 Gg CO_2-eq for 20 years under the medium tree growth scenario. The incentives for indigenous smallholders will be multiple, including capacity building on various management and technical aspects of a forest carbon project, recognition of project ownership, incomes from nonforest and agroforestry products, additional income from sale of CO_2, and potentially other environmental services such as water and biodiversity conservation.

Case Study 2: Local Incentive Scheme for Sustainable Agriculture and Agroforestry

The Lantapan Municipality in Bukidnon province, in southern Philippines, became interested in adopting an incentive policy that stimulates smallholder investments in a wide band of sustainable agriculture practices, including agroforestry. Adopted in 2009, the 5-year incentive program was a result of a transactional process of negotiations between and among scientists, policy makers, and local stakeholders that was facilitated by the World Agroforestry Centre (ICRAF). The main objectives of the incentive program are to (1) encourage smallholder investments on land use that improve livelihoods and enhance environmental services, (2) enhance social capital, and (3) improve the capacity of the local government in delivering extension programs. The incentive program has explicit links to climate change adaptation and mitigation and is conceivably a comprehensive social safeguard mechanism that advances adaptive capacity at the local level. It consists of seven types of direct and indirect incentives (Table 2). Input subsidies, subsidized insurance premiums, and microfinancing are considered direct incentives, whereas improved extension services, infrastructure, and marketing support are enabling incentives. A farmer must be a resident in the area for at least 1 year with small-to-medium farm size, typically ranging from 0.5 to 5 ha, while a farmer group should have demonstrated good track record to be eligible to any of the incentives provided.

Table 2 Types of incentives provided by the local government for smallholders adopting sustainable agriculture and agroforestry practices in Lantapan, Bukidnon, Philippines (2009)

	Incentive types	Description
1.	Input subsidies for crop production and NRM-based livelihood projects	Financial and material input subsidies, such as planting materials (timber and fruit seedlings, banana tubers, corn and vegetables seeds, etc.)
2.	Provision of improved extension services	Accessibility to agricultural technologists (ATs) for readily available assistance and facilitation (e.g., tree registration, school on air, demonstration farms, exposure trips, Farmer Field School, Technology Training)
3.	Subsidized crop insurance	Facilitation between farmers and the crop insurance program, subsidies in premium payments
4.	Microfinancing support	Credit assistance in cash or in-kind, reduced transaction cost in processing credits and loans, farmer linkages with financing institutions
5.	Infrastructure support	Farm-to-market roads, pre-and-post harvest facilities, solar driers, etc. for organized farmers
6.	Cash rewards and recognition	Cash rewards and recognition of individual farmers and farmer organizations, support for trainings and field visits
7.	Support for marketing	Access to market information, linkages and network, price monitoring, technical assistance on enterprise development, and production and marketing analysis services (PMAS)

The program is open to both existing and potential adopters of soil and water conservation and agroforestry practices. It provides technical assistance for farm planning to ensure that farm activities conform to standard practices (Table 3). Farmers can also avail of assistance from the local government to register their planted trees with the DENR, to help farmers defray the costs involved in the tree registration process and protect them against unscrupulous transactions when securing permits during harvesting and transporting timber. Crop insurance is usually attached to the input subsidy scheme, although crop insurance alone or vice versa is also an option. In this scheme, farmers can avail of technical assistance in preparing farm plans, cropping calendar, etc., in order to meet the requirements of the Department of Agriculture's crop insurance scheme—the transaction costs of reaching out and facilitating smallholders is thus borne by the incentive program, which has been the limitation of the national crop insurance scheme, as described above.

Through the incentive program, the municipal government also targets 52,000 trees to be planted throughout the locality in the next 3 years. A presidential program called "4Ps" (Pantawid Pamilyang Pilipino Program), which targets 3,000 households for tree planting on private lands, is also implemented in conjunction with the incentive program where it prioritizes adopters of agroforestry and conservation practices. The 4Ps is a national poverty reduction strategy that provides grants to extremely poor households to improve their health, nutrition, and education.

Table 3 Areas of concern and sustainable agriculture practices as basis for provision of incentives in Lantapan, Bukidnon, Philippines (2009)

Key areas of concern	Standard practices
1. Farm productivity	Reduce dependence on inorganic fertilizers, pesticides, insecticides, etc. Employ integrated crop management, including biological control and integrated pest management Increase production of and application of organic fertilizer, such as animal wastes, green and vermi-composts, etc. Diversify farm crops with trees and livestock Plant crops that are resistant to drought or excessive rain Develop cropping calendar based on market demand
2. Soil management	Apply crop rotation, green manure, cover cropping, mulching, etc., to build up soil nutrients Reduce soil erosion through soil and water conservation (SWC) techniques such as contour plowing and hedgerows (e.g., natural vegetative strips [NVS]) No burning of crop residues Reduce/zero/ridge tillage/cultivation
3. Water management	Apply efficient water management techniques, such as rainwater harvesting and drip irrigation, small farm reservoirs
4. On-farm biodiversity	Provide areas for natural regeneration of native plants/species Provide corridors of biodiversity
5. Capacity building	Farmers undergo training on sustainable farming, farm enterprise management, etc.

The Provincial Government of Bukidnon commended this municipal initiative and complemented this effort through its Provincial Greening Program, where infrastructure projects and financial assistance are based on tree growing activities. Under this program, forest volunteer guards of Mt. Kitanglad Range National Park (MKRNP) are to be compensated for every 1-year-old tree planted in the park. The provincial government also uses regulatory measures, requiring all local governments, private companies, and small-scale miners to maintain a tree park before permits are issued or renewed. Finally, the provincial government instituted recognition and award schemes (moral incentives) for the cleanest and greenest municipality in the province to encourage sustainable practices—all these are anchored in the provincial vision for food security and poverty alleviation.

In its nascent stage, the incentive program has already attracted support from nongovernment organizations, private companies, national agencies, and donor-funded projects such as the World Bank's Mindanao Rural Development Project. Furthermore, a USAID-funded Biodiversity Conservation Project in MKRNP, which aims at sequestering 5,000+ Mg C in 20 years and builds the capacity of forest volunteer guards, is also implementing a 50 ha agroforestry project in line with the municipal incentive program. Clearly, the Lantapan local government has demonstrated how incentives can be used to remunerate positive externalities from sustainable land use and how locally designed incentives can promote agroforestry and various sustainable agriculture practices.

Discussion

For smallholders, rising cost of inputs, pests and diseases, and climate variability have altogether led to crop failures, whereas poor market access and infrastructure, weak institutional support, and lack of price support have led to income losses. According to Lantapan farmers, vegetable agroforestry has a lot to offer, but at the same time, they struggle to raise the capital requirement and manage associated risks. Mercado et al.[12] mentioned that the introduction of vegetables in tree-based systems can be very sensitive to climatic variation, not to mention the competition issue of light, nutrient, and water between crops and trees. Meeting the initial cost of adoption is thus a challenge, not to mention market volatility of agricultural crops and uncertainty in timber prices.

In the case study on local incentives, both direct and indirect incentives were effective in promoting adoption of agroforestry by smallholders. Farmers are now increasingly integrating trees with vegetables. In Fig. 2, for example, farmers intercrop Musizi (*Maesopsis eminii*) with string beans (*Phaseolus vulgaris*). Incentives through input subsidies help small farmers recover from successive crop failures, while crop insurance protects the investment. The locally crafted incentive program enabled the local government to leverage outside support for a variety of incentives and to tap the global carbon market. An important aspect of the program is the way in which the local government is responsively addressing smallholder needs in a

Fig. 2 Musizi (*Maesopsis eminii*) with string beans (*Phaseolus vulgaris*) as alley crop (Photo by Caroline Piñon)

sensible manner while offsetting the weakness of national policies in reaching out to a multitude of smallholder farmers.

With regard to carbon incentives, the cases examined are still incipient; however, these and other initial experiences provide important lessons for future consideration (Lasco et al. 2010b). First, income from carbon credits is not sufficient to recover the cost of tree planting. Using standard DENR costs, planting and maintenance costs amount to about USD 1,000/ha in the first 3 years. In contrast, income from carbon credits is estimated to be about USD 250/ha for 10 years only (at 5 Mg C ha^{-1} $year^{-1}$ and USD 5/MgC). This implies that carbon credits are best used as a supplementary source of income for farmers; at the outset, this should be communicated to farmers to avoid raising expectations. Second, the transaction costs of forestry CDM projects are enormous and can be as high as USD 200,000.[13] This proves to be the greatest barrier to project fruition. One way to overcome this barrier is to partner with a potential buyer who may be able to cover the upfront costs as in the case of Laguna Lake Development Authority and World Bank and Conservation International. Third, national rules and regulations for forest carbon projects need simplification. Currently, forestry projects have few takers because of their high transaction costs and complexity. Adding more hurdles will further discourage potential project developers and local communities. Fourth, project developers and the government must also explore the voluntary carbon market, which has more flexibility than CDM.

Another issue is the property rights of local communities who have vital roles in forest conservation (Lasco and Pulhin 2003). Once new financing schemes are available, property rights issue may become important for local communities who lack secure land rights. Competition on who will control forest lands may intensify. In the Philippines, many upland areas are being claimed by IPs. Such claims may be ignored in favor of establishing climate-change forests. Thus, the national guidelines for initiating forest carbon projects should have adequate provisions for respecting the rights of IPs. As a requirement for forest carbon project development, the environmental impact assessment system and the prior and free informed consent process should ensure that culture, traditions, and indigenous property rights are taken into consideration. Existing policies and procedures embodied in the Indigenous People's Rights Act should also ensure that the rights of IPs are fully safeguarded. When it comes to incentives, recognition and provision of property rights may be preferred by IPs. However, despite the above challenges, it appears that the global carbon market can spur interest in tree planting and agroforestry development at national and local scales. With the completion of the national REDD+ strategy, various sectors are now exploring the possibility of implementing pilot projects in the Philippines with great support from the European Union.

The Philippine experience in the carbon market is similar to what many developing countries are experiencing (Thomas et al. 2010). To date, only 14 forestry projects were registered with CDM out of a total of 3,500 applications[14] because of the countless requirements and complex process for CDM registration. Clearly, there is a need to reexamine the rules governing the implementation of forestry projects under CDM. Looking forward, the design and rules for REDD+ should be crafted bearing in mind the lessons from the lack of success of the CDM. Failure to do this could hamper uptake of REDD+ financing anywhere in developing countries. But while the CDM and REDD+ mechanisms are strenuous, the Lantapan case study has shown that localized incentives are more legitimate, practical, efficient, realistic, and easily accessible. Incentives developed at the local level are also favorable to farmers since they have more chances to influence their design and implementation. However, the emergence of local incentives depends on the capacity and determination of local governments in a decentralized setting. It is obvious that the immediate requirement to advance local incentives is a decentralized governance system. With decentralized power and authority, local governments are able to develop their own plans and allocate resources. By leveraging on local resources, local governments in developing countries can emulate the experience in Lantapan and initiate appropriate incentive mechanisms that stimulate agroforestry investments in their areas.

In summary, there is a range of policy incentives in the forestry and agriculture sectors at global, national, and local levels, and despite their pitfalls, they provide opportunities for smallholder agroforestry. Although the incentive mechanisms studied were relatively new, multiscale benefits to agroforestry are foreseeable (Table 1). The general lesson running through the case studies is that incentive mechanisms should be designed, if not adjusted, in ways that meet the country's unique conditions, as well as the specific needs of smallholders.

Conclusion

Undoubtedly, smallholder agroforestry can have significant contributions to domestic and global agendas of food production and provision of environmental services. Today, incentives are increasingly used at global, national, and local levels to induce adoption and incite smallholder investments in agroforestry. Global mechanisms such as CDM, REDD, and REDD+ and/or national, provincial, and municipal incentive mechanisms, despite their challenges, provide opportunities for smallholders to obtain economic benefits. Such benefits, albeit obstructed, will accrue overtime providing a foundation for farmers to advance with viable agroforestry enterprises. These incentives also serve as social protection for smallholders from the impacts of climate change or market failures. However, REDD and CDM rules and processes need be adjusted to suit to country-specific needs and contexts and to encourage project developers and local communities; otherwise, the incentives these mechanisms bring will be useless. We conclude that national institutions can serve as catalysts in channeling international carbon benefits to small farmers, which can also spur local initiatives as well as create new partnerships with the private sector, but at the same time, local governments should be primed to address smallholder needs in more practical and sensible ways. Locally inspired incentives can complement global incentive mechanisms that are still in flux, due to overstandardization and inflexibility of rules. But ultimately, effective coordination and linkages should be established to harmonize global, national, and local mechanisms, for smallholders to have optimal benefits from agroforestry.

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Agroforestry Research and Development: The Way Forward

P.K.R. Nair and Dennis Garrity

Abstract The remarriage of trees and crops under a new banner – agroforestry – was accepted as a development vehicle more than three decades ago with high expectations about addressing several land-management problems. The role of research in that paradigm was conceived initially as an inductive and experiential approach to and learning from existing traditional systems and practices. It gradually evolved into a more deductive and experimental approach of hypothesis testing and development of predictive capability. Over time, agroforestry research has thus been transformed into a rigorous scientific activity. The research agenda, which started with a high priority on soil fertility and other biophysical forms of tree–crop interactions, has, over time, encompassed more emphasis on socioeconomic issues, and it has moved on from plot and field level to landscape and ecosystem levels. With the emergence of environmental issues and food security as preeminent areas of research interest in land-use disciplines in general, agroforestry research has also engaged intensively in those areas, with emphasis on capitalizing on the ecosystems services of agroforestry systems such as carbon sequestration, biodiversity conservation, and degraded-land rehabilitation. The vast potential of agroforestry for addressing the major land-management challenges of the twenty-first century has now been well recognized, thanks to these global efforts during the past more than three decades of work. Research and development efforts in the next 15–20 years should strive to focus on bringing agroforestry to the mainstream of science with the needed rigor for exploiting this potential at various spatial levels (ecosystem, regional, and global) for the benefit of the land and its present and future users.

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Introduction

It was toward the latter part of the twentieth century that the age-old practice of growing trees and crops together on the same unit of land became recognized as a promising approach to land use by the scientific and developmental communities. This coming of age of agroforestry was signified by the establishment of ICRAF, the World Agroforestry Centre, in 1977[1] as the focal point of organized global efforts in developing these traditional forms of land use to address some of the land-management problems that were not addressed, but were often exacerbated, by developments in commercial agriculture and forestry. Subsequently, agroforestry gradually became a major component or activity of the programs of many international, regional, national, and local institutions, both public and private, dealing with various branches of agriculture, forestry, and allied disciplines. Thanks to the collective efforts of the various institutions and countless millions of agroforestry practitioners, today agroforestry has carved out a distinct niche as a robust land-management discipline, and it is now recognized as being at the heart of the global community's commitment to banish hunger and poverty and rebuild resilient rural environments.

The developments in the discipline worldwide during the past three decades have been quite substantial. A set of practices that used to be denigrated as being *in search of science* has now been transformed into a science-based integrated discipline of land management. Various facets of this transformation are summarized in the previous chapters of this book by leading professionals in different aspects of the discipline. This chapter synthesizes these developments and examines the way forward, that is, the opportunities and challenges ahead in research, and summarizes the role of agroforestry in addressing the major land-management problems of the twenty-first century.

Agroforestry: A Brief History of Development

In order to examine the opportunities and challenges in proper perspective, it is important to review – albeit briefly – the historical developments in agroforestry. The establishment of ICRAF signifies the institutionalization of agroforestry but certainly not the beginning of agroforestry per se. Indeed, agroforestry is a practice that is as old as agriculture itself, and it has been prevalent for many centuries in different parts of the world, especially under subsistence farming conditions. Home gardening, a major agroforestry practice today and one of the oldest forms of agriculture in Southeast Asia, is reported to have been associated with fishing communities living in moist tropical regions about 13000–9000 B.C. (Kumar and Nair 2004; Nair and Kumar 2006). Agroforestry in Europe is reported to have emerged when domestic animals were introduced into forests for husbandry around 4000 B.C. The dehesa (animal grazing under trees) system of Spain is reportedly 4,500 years old (Mosquera-Losada et al. 2012). It was only during the past three decades, however, that these indigenous forms of integrating trees with crop and animal production were brought under the realm of modern, scientific land-use scenarios. The establishment of ICRAF provided a much-needed institutional identity for focusing on these underappreciated or bypassed land-use practices.

The initiatives to bring the age-old practices of growing crops and trees together into the realm of science were motivated by several factors (Bene et al. 1977). The Green Revolution of the 1970s did not reach large segments of the poorest farmers, particularly those in the less-favorable agroecological environments. At the same, land-management problems such as tropical deforestation, fuelwood shortage, soil degradation, and biodiversity decline were escalating. The search for strategies to address these problems focused greater attention on the ways in which farmers had been combining the production of trees, crops, and livestock on the same land-management unit and created a much greater appreciation of their inherent advantages. At the time, most of the international agricultural research centers (IARCs) of the CGIAR[2] system and the national programs were focusing on individual food crops and the production technologies for monocultural or sole-crop production systems of these crops. However, the farmers, especially the poorer farmers, were often cultivating their crops in mixed stands of more than one season and were commonly nurturing trees in their cropping systems. In such circumstances, the production technologies developed for individual crops were seldom wholly applicable to these systems.

These shortcomings were widely recognized by a large number of scientists and policy makers. Consequently, there was renewed and heightened interest in the concepts of intercropping and integrated farming systems, beginning in the 1970s. Research results from different parts of the world indicated that in intercropping systems, more effective use was made of the natural resources of sunlight, land, and water (this would later be termed “niche complementarity”); that they had beneficial effects on managing pest and disease challenges; that there were advantages in growing legumes and nonlegumes in mixtures; and that, as a result of all these interactions, higher yields could be obtained per unit area when multi-cropping systems were compared to sole cropping systems (Papendick et al. 1976). These multiple cropping principles were extended to tree-based cropping systems as well, leading to the development of interesting concepts such as multistoried cropping (Nair 1979), which would later become recognized as shaded perennial systems, a major form of agroforestry (Nair 1993). These efforts also brought to light the many gaps in knowledge related to intercropping, and the need became clearer for a more scientific approach to intercropping research with respect to various aspects such as crop physiology, agronomy, yield stability, biological nitrogen fixation, and plant protection (Nair 1979).

Although there are several reports about agroforestry in the temperate regions of the world since very early times (Long 1993), organized efforts directed toward science-based agroforestry had a slower beginning in the temperate region than in the tropics. As Jose et al. (2012) state, J. Russell Smith created an early interest in agroforestry through his classical work "Tree Crops: A Permanent Agriculture" (Smith 1950) in which he argued that "an agricultural economy based almost entirely upon annual crops such as corn and wheat is wasteful, destructive of soil fertility and illogical." However, it was not until the 1970s that the push for ecologically and socially friendly management approaches such as agroforestry gathered momentum, as the general public became increasingly aware of the environmental consequences of commercial agricultural and forestry practices that focused solely on the economic bottom line, and they started demanding greater environmental accountability in the deployment of land-use practices (Garrett 2009).

Thus, the motivations for initiatives in agroforestry research were distinctly different in the tropics and the temperate regions. Given that the structure and management of land-use systems are determined not only by the biological components but also the site-specific ecological features and the local social and cultural characteristics, such differences between the tropics and the temperate zones are common in all forms of land use, be it agriculture, including animal production, or in forestry. These ineluctable differences manifest themselves in the nature, characteristics, objectives, and expectations of agroforestry practices in the two broad geographical regions; nevertheless, the practices in both regions encompass the same concepts and principles.

Three Decades of Research in Agroforestry

The image of agroforestry and the directions in agroforestry research have changed considerably during the past three decades. Agroforestry was conceived and promoted in the 1980s as a sustainable approach to land management that was not being satisfactorily addressed by agriculture and forestry. Arising from this, the development community embraced the "new" concept with unprecedented enthusiasm as an almost magical development vehicle with perceived relevance to "difficult" and "fragile" environments (Nair 1998). Research was conceived as a handmaiden to major development projects – most of them hastily prepared – to foster and backstop their implementation by providing results of immediate application.

Thus, the early research efforts during the "first decade" (1980–1990) were based on inductive and experiential reasoning with only a modest contribution of deductive and experimental approaches. Inevitably, these efforts were based on data and assumptions derived from research in related areas; they focused on gathering information from successful, existing agroforestry systems, and they resulted in various databases of a descriptive nature. Considerable efforts were also devoted during this period to developing the concepts and principles of agroforestry, as well as to methodology development, by analysis and synthesis of relevant research results from areas and disciplines related to agroforestry. A major activity was the development of the "diagnosis and design" (D & D) approach, a social-science-rich, multidisciplinary, land-use system-evaluation procedure developed specifically for agroforestry (Raintree 1987).

These efforts provided the theoretical and conceptual framework for the nascent discipline. Although these concepts may be taken for granted today, their importance

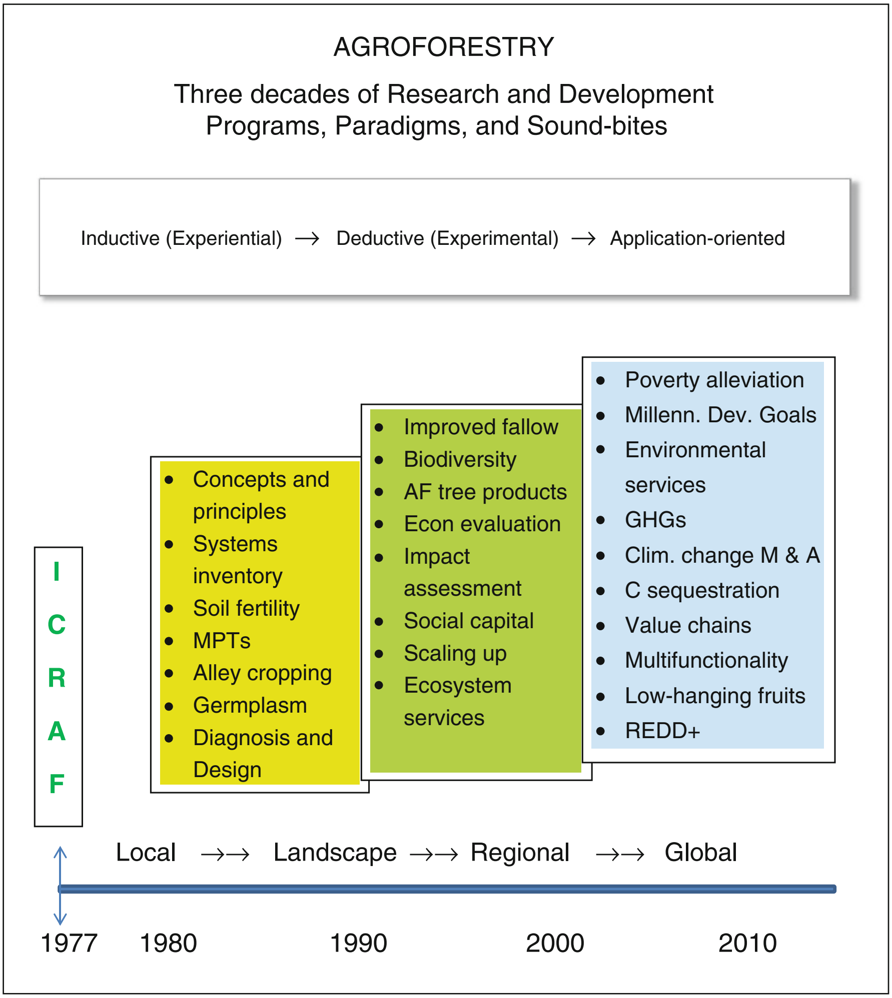

Fig. 1 Major programs, paradigms, and "sound bites" (talking points) in agroforestry research and development during the more than three decades since the beginning of such organized global efforts

in providing a solid foundation upon which to build future research strategies should not be underestimated. The empirical research that was initiated during that decade was dominated by soil fertility-related investigations, multipurpose tree screening and evaluation, and development and evaluation of prototype technologies such as alley cropping (Fig. 1).

During its "second" decade (1991–2000), agroforestry research moved on to more empirical research. The *science* of agroforestry was better established through more emphasis on hypothesis development and testing, with more predictive and process-oriented research results being incorporated to strengthen its theoretical foundations (Sanchez 1995). Socioeconomic evaluations and programs also achieved more

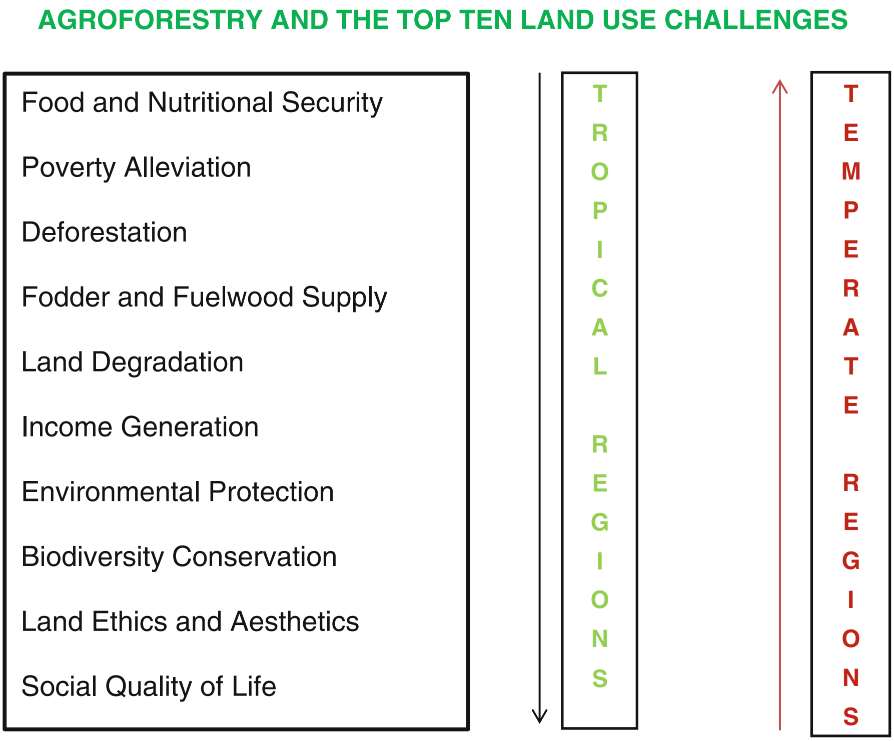

Fig. 2 The major land-use problems in the tropical and industrialized (temperate) regions of the world, in addressing which agroforestry could play a role. The directions of the *arrows* indicate that the items listed from *top* to *bottom* are in descending order of importance in the tropics and in the reverse order in the temperate (industrialized) regions (Source: Adapted from Nair 2007)

prominence during this period in tandem with the biophysical issues. A related development during the period was the formulation of quantitative and computer-based models to describe specific aspects of agroforestry such as tree–crop interactions and soil fertility changes. Significant gains were also obtained by applying these scientific principles to addressing specific land-management issues such as managing the *Imperata*-infested grasslands, capitalizing on the biological nitrogen fixation of tropical leguminous trees and shrubs through technologies such as improved fallows and biomass transfer technologies, enhancing the ecological and economic benefits of shaded perennial agroforestry systems, improving the profitability of smallholder farming systems of Africa through the commercialization of agroforestry tree products, and scaling-up the benefits of agroforestry through large-scale adoption (Fig. 1). Advances made in a number of these areas have been well articulated in several chapters in this book. It needs to be emphasized that although agroforestry has a role in addressing the major land-use problems and issues in both tropical and temperate (industrialized) regions, the relative importance of the issues in the two major regions are in somewhat opposite directions as indicated in Fig. 2.

The directions of tropical agroforestry research since 2000, that is, during the "third decade," evolved in tandem with the key contemporary land-use issues of the day, focusing on problem-solving and adaptation but without reducing the importance of making advances in science. This shift was driven in part by the dynamics of research funding, and the increasing expectations that the application-oriented results from agroforestry research should be fulfilled through wider-spread impact. As environmental issues such as climate change and biodiversity assumed a greater prominence in the global development agenda and as the Millennium Development Goals (MDG) became a rallying point for hunger and poverty alleviation, agroforestry efforts increasingly addressed these issues and paradigms.

Given the potential of agroforestry to provide ecosystem services such as carbon sequestration, agroforestry began to achieve some prominence in the deliberations in the international arena related to the major global conventions on climate change, biodiversity conservation, and land degradation. Agroforestry was included in global programs such as REDD+ (reduced emission from forest degradation and deforestation) related to climate change mitigation and adaptation. The carbon sequestration potential of agroforestry systems has perhaps become the single most "popular" topic of research in agroforestry during the past few years. Other ecosystem services such as biodiversity conservation and water quality enhancement have also getting significant attention.

Today, although ICRAF is the only major institution devoted exclusively to agroforestry, agroforestry is a major component or activity of the programs of many international, regional, national, and local institutions, both public and private, dealing with various branches of agriculture, forestry, and allied disciplines. The institutional affiliations of the authors and reviewers of the chapters presented in this book (a total of 130 professionals from institutions in 33 countries) in itself bear testimony to the very wide spread of the discipline around the world. Thanks to the collective efforts of the various institutions and the countless millions of agroforestry practitioners, agroforestry is now recognized as a distinct form of land management, as an interface between agriculture and forestry. It would be a worthwhile exercise to undertake an evaluation of the return on investments in agroforestry research, compared with other relevant land-use disciplines, during the past three decades.

Agroforestry: The Way Forward

If it is accepted that the main goal of agroforestry research should be to generate technologies for solving the land-management problems that we set out to address more than 30 years ago and that research should be a means rather than an end in itself in the era of dwindling research support, it is imperative that we prioritize the research agenda of agroforestry for the twenty-first century. Long lists of research topics that appear in many chapters in this book and elsewhere that are characteristic of most such general articles on agroforestry need to be combined, coordinated, and prioritized. Table 1 gives some general areas and topics, which deserve consideration while setting the agroforestry agenda for technology generation in the future.

Table 1 Some agroforestry research topics of high-potential impact in the next two decades (through 2030)

Research focus	Topic and nature of research	Geographical regions of high-impact potential
Components of AF systems: trees	Improvement of indigenous and underexploited trees: • Trees for food, fruit, fodder; fertilizer trees • Trees with high-value products such as medicines and specialty products	Tropics: • Subsistence farming areas, especially in sub-Saharan Africa • High-potential areas, esp. in the tropics
Components of AF systems –crops: the "agro" part	Developing crop varieties and cultivars that can perform reasonably well under conditions of reduced supply of growth factors (light, water, nutrients, etc.)	Global
Exploitation of ecosystems services	Climate change mitigation and adaptation – understanding the influence, on C sequestration: • Soil qualities and soil management • Plant species diversity	Global
	Water quality enhancement: reducing nonpoint source pollution	Industrialized countries
	Understanding biodiversity conservation – C sequestration nexus	Global
System management for exploiting production and protection values of trees	Devising agroforestry system management for solving specific land-management problems: • Land degradation (erosion control, amelioration of extreme soil reactions, control of soil fertility decline, etc.) • High carbon stock rural development pathways • Biodiversity conservation	Global Specific examples: Soil conservation hedgerows Riparian buffer Windbreak/green walls (arid/semiarid lands) Acid and alkaline soil reclamation Stepping stones for landscape connectivity
Enabling policy environment	• Role of government vs. non-state policies in encouraging agroforestry adoption	Global
	• Evaluation of existing national and regional policies to determine how they create agroforestry adoption incentives	Evaluations at various spatial scales (local, regional, national) and for specific aspects of agroforestry
Landscape- and ecosystem-level research	• In general, agroforestry research has focused on plot- and field-level studies • Environmental issues such as climate change and biodiversity require more landscape- and ecosystem-level research	Applies equally to both tropical and temperate regions

Taking Agroforestry in the Mainstream of Science

The strength and credibility of a scientific discipline can best be gauged by the nature and volume of scientific high-quality publications in the subject. Notable among these indicators of the development of agroforestry include the international scientific journal *Agroforestry Systems*[3] published since 1982. However, agroforestry research results have not been confined to the pages of that journal alone. Indeed, today there is hardly any scientific or technical journal related to the land-use disciplines that does not feature papers dealing with aspects of agroforestry. This is a complete turnaround of the situation that existed 30 years ago when there were few scientific journals that published papers in this subject area. Other major landmarks in the development of agroforestry are the peer-reviewed book series *Advances in Agroforestry*[4] published since 2004, the North American Agroforestry Conferences held every alternate year since 1989, and the World Congresses of Agroforestry (WCA)[5] that have been convened every 5 years since 2004. All of these significant developments have hastened the progression of agroforestry to the forefront of applied science disciplines.

Considering the situation that existed 30 years ago, the development of agroforestry as a science-based discipline has indeed been rapid. Somarriba et al. (2012) reported a substantial increase in the number of journal articles (Web of Science) on agroforestry in Latin America published during the past decade (since 2001) compared with the previous two decades. The trend in other parts of the world and globally is different. Notwithstanding these impressive developments, the body of scientific knowledge on agroforestry is still weak in several areas. Serious efforts are needed to overcome these shortcomings and bring agroforestry into the mainstream of science. These include:

- Updating and upscaling the research base to meet the criteria of research quality such as peer-reviewed publications that stand the test of time in high-impact journals.
- Long-term investigations and chronosequence studies to understand the rate processes of various mechanisms in the biological and environmental fields, for example, in many of the reported results of soil carbon sequestration (in the context of climate change mitigation and adaptation), there are no reference points on which to base the comparisons; projections about the potential of agroforestry systems on climate change mitigation and adaptation that are not based on such rigorous datasets could be wishful thinking.
- The "why's and how's" of observed behavior are seldom reported in agroforestry research studies. Research often stops at reporting what was observed without explaining the reasons for the observed behavior; it is not uncommon that the experiments are planned to gather such critical data, which cannot be determined after concluding the experiments.
- Ground truthing of models and estimates: The importance of validating the results from models and estimates – of which there is a proliferation – needs special emphasis.

Bridging the Gap Between Knowledge and Application

Nearly a billion hectares of agricultural landscapes, that is, about half of all farmed land on earth, were reported to have more than 10 % tree cover according to a detailed survey a few years ago (Zomer et al. 2009). The area under agroforestry is reported to have increased by five million hectares in Niger alone during the past two decades through the spread of farmer-managed natural regeneration (Reij et al. 2009). Nair (2012) estimates the total area of land worldwide with the potential to be under agroforestry management in the foreseeable future as 1.6 billion hectares. The drivers underpinning such a transformation are increasingly favorable. We are now well positioned to capture the promise of agroforestry to impact the lives of millions of people and our environment. But the gap between what we already know in agroforestry and the extent to which that knowledge is applied – that is, the knowledge that is transferred to the practitioners – is widening. While we endeavor to intensify technology transfer efforts, we also need to continuously replenish and update the stockpile of our technical knowledge. Thus, we need a two-pronged approach in agroforestry research and development: Intensify research in key areas with potentially wide applicability of the results and intensify efforts in technology transfer, which itself will need research support to develop new and innovative approaches, that is, on the science of scaling-up. Research is the key in both areas: Research aimed at developing new technologies, as well as new techniques and methods for effectively transferring new knowledge and technologies to the land user, particularly the most disadvantaged.

The foregoing chapters in this book suggest that the key areas of thrust for research with wide application potential include the following (Table 1):

Tropical regions

- Domestication and exploitation of indigenous trees
- Food security
- Adoption and scaling-up
- Policy

Temperate regions

- Environmental amelioration (water quality, NPS pollution, C sequestration)
- Ecosystem services and their valuation

Global issues

- Carbon sequestration, climate change mitigation, and adaptation
- Economic benefits
- Markets and policy

Achieving Impact at Scale

The practice of agroforestry in developing countries is a mix of traditional systems and newly configured systems (Ajayi and Place 2012). There is a general perception that the level of adoption of agroforestry technologies in the tropics has generally lagged behind scientific and technological advances attained in such technologies, thereby reducing their potential impacts (Mercer 2004). Other publications, however, have confirmed that some specific agroforestry practices, both traditional and new, have been adopted by millions of smallholders[6] (AFSP 2010). For example, the recent rejuvenation of the centuries-old parkland agroforestry systems of the Sahel through the spread of farmer-managed natural regeneration has been documented to have occurred on nearly five million hectares by 2008 in Niger alone (Reij et al. 2009). Another traditional practice, the agroforest systems in Indonesia, has been managed by hundreds of thousands of smallholders, though there are several threats to this system (Kusters et al. 2008). Smallholder timber production, which followed upon decades of deforestation, has now spread across millions of hectares in India and China.[7] Tree–crop agroforestry, including coffee (*Coffea arabica*, *C. robusta)*, cacao (*Theobroma cacao*), tea *(Camellia sinensis)*, cashew (*Anacardium occidentale)*, and oil/resin trees such as shea (*Vitellaria paradoxa*), is widespread across the tropical world.

In addition to these traditional systems, new ones are being upscaled. There is increasing attention to a range of systems for soil improvement or fertilizer-tree systems, including conservation agriculture with fertilizer trees, especially in the southern African countries (Garrity et al. 2010). Recent data have revealed that Evergreen Agriculture (tree–crop intercropping) is being widely practiced in many countries in Africa, building successfully on proven indigenous farming technologies, where complexity is a common feature of the agricultural system. The most "dramatic" example is Niger, as indicated above. The experiences of Zambia, Malawi, Niger, and Burkina Faso indicate that the principles are applicable to a broad range of food crop systems, if accompanied by adequate testing and farmer engagement. The farming practices embodying these principles are unique to each country, but they exhibit important similarities. Currently, 17 African countries are engaged in developing Evergreen Agriculture scaling-up initiatives, along with India and Sri Lanka in South Asia.[8]

The Role of Agroforestry in Addressing the Major Land-Management Problems of the Twenty-First Century

Food Security

During the past several years, attention has been growing worldwide that agroforestry has a much more significant role to play in addressing the crisis of food security and environmental resilience than had previously been perceived. This has been driven by greater recognition that the standard approaches to addressing food insecurity in the small farm sector through conventional seed-fertilizer approaches have not produced the desired breakthroughs anticipated, particularly in the rainfed, dryland agroecosystems in the tropics, most notably in Africa (Garrity et al. 2010). Out of the estimated one billion undernourished people in the world, the most severe deprivation is increasingly concentrated in sub-Saharan Africa, which is currently home to three-quarters of the world's "ultra-poor" (less than US$0.50 per day) and has experienced a significant increase in the number of ultra-poor since 1990.[9] Approximately 218 million people in Africa struggle with hunger daily, about 30% of the continent's total population, which is projected to grow from the current 800 million to 1.8 billion by 2050 (United Nations 2004).

Crop output in Africa has been increasing, but this is largely driven by the expansion of cultivated land rather than productivity gains; cereal yields have been stagnant, and crop production per capita has been declining for decades.[10] Chemical fertilizers are an important means of restoring soil fertility, but fertilizer prices are escalating, putting them further out of reach for most farmers. Fertilizer use by smallholder farmers has remained at the very low levels of about 8–10 kg of nutrients per hectare. Climate change is increasing the risks of devastating droughts. These conditions prevent more than three out of four farmers from using chemical fertilizers to increase their crop yields. Most farmers are forced to grow the same food crops, year after year, on the same plot of land, without adequate fertilization or soil replenishment measures. Surveys are finding that farmers are becoming overwhelmingly concerned about how to reverse their declining soil fertility. The use of fertilizers by smallholders to replenish their soils is often not economically feasible, due to high prices and the risk of drought stress. The consequences are land degradation, low yields, persistent poverty, and widespread malnutrition (Lal 2009).

Reversing the trend of soil fertility depletion in African farming systems has become a major development policy issue on the continent.[11] Restoring the soil health is often the first entry point for increasing agricultural productivity because soil nutrient depletion is extreme in most areas where farmers have small holdings (Sanchez and Swaminathan 2005). The most urgent need is to increase biomass production in the farming system with richer sources of organic nutrients to complement whatever amounts of inorganic fertilizers that a smallholder farmer can afford to apply. The integration of fertilizer trees into food crop agriculture is a promising, but underappreciated, approach to accomplishing this. A number of recent advances in agroforestry based on the use of fertilizer trees and other trees have produced a range of promising approaches to accomplishing this.[12] This portfolio of options is now referred to as Evergreen Agriculture.[13]

Evergreen Agriculture emphasizes the application of sound, tree-based management practices, and the knowledge to adapt these to local conditions, in order to optimize fertilizer and organic resource-use efficiency for greater crop productivity. It is also compatible with reduced tillage, increased residue retention on the soil surface, and other principles of conservation agriculture, in situations where these practices are feasible and appropriate. Scientists have been evaluating various species of fertilizer trees for many years, including *Calliandra, Sesbania, Gliricidia* and *Tephrosia* (Akinnifesi et al. 2010). Currently, *Faidherbia albida* is showing particular promise as a cornerstone of Evergreen Agriculture. Unlike most other trees, *Faidherbia* sheds its nitrogen-rich leaves during the early rainy season, making it highly compatible with food crops. This indigenous African acacia is already a component of farming on farms across the continent as explained later in this chapter.

Smallholder food security is, however, not only a function of increased crop production. Pathways to increasing food security also include the ability to increase livestock production in integrated crop-livestock-tree systems, which are dependent on greater sustainable sources of high-quality fodder (Herrero et al. 2010). The impact of fodder tree production and income among smallholder dairy farmers in East Africa has emerged as a major area of agroforestry impact[14] (Place et al. 2009). Additional pathways to smallholder food security are also achieved through the production of higher-value products that are sold for increased income, and the husbandry of tree crops, such as timber, also increases the farm asset base (Garrity 2004). The integration of trees into crop- and livestock-production systems opens up opportunities for all of these pathways on the small-scale farm.

Climate Change Adaptation and Mitigation

Climate change adaptation and mitigation are generally treated separately in the global negotiations and in project implementation, but in agriculture and natural resource management, such a dichotomy is illogical (Matocha et al. 2012). The two are inextricably linked at the level of land use. Agroforestry is a key approach to the integration of climate change adaptation and mitigation objectives, often generating significant co-benefits for local ecosystems and biodiversity. Synergies between climate change adaptation and mitigation actions are particularly likely in situations involving income diversification with tree and forest products. These options also reduce the susceptibility of land-use systems to extreme weather events, enhance of soil fertility, and favor the conservation and restoration of forest and riparian corridors. Thus, adaptation considerations need to be included in mitigation efforts.

Nair (2012) evaluated the role of agroforestry in climate change adaptation and mitigation and concluded that while existing multistrata and tree intercropping systems will continue to provide substantial climate change mitigation benefits, large-scale initiatives in grazing land management, working trees in drylands, and establishment of vegetative riparian buffer and tree woodlots are the most promising agroforestry pathways for both adaptation and mitigation.

Addressing the issue of food insecurity and global warming through the sequestration of carbon in soils and in the biota, along with payments to resource-poor farmers for the ecosystem services rendered, would be a timely win–win strategy (Lal 2010). This is particularly true for systems incorporating fertilizer trees on croplands, deploying species such as *Faidherbia* or *Gliricidia*. Consequently, there is considerable interest in the creation of biocarbon investment funds to channel carbon offset payments from developed countries to stimulate more carbon sequestration while simultaneously enhancing the livelihoods of smallholders and the environment. These investments will encourage development pathways resulting in higher carbon stocks at a whole landscape scale (Garrity et al. 2010).

Most forest conversion to agricultural land in Africa is due to clearing by subsistence farmers. A sustained elevation in smallholder crop productivity through the expansion of tree–crop intercropping (i.e., Evergreen Agriculture) can result in significant co-benefits by providing a basis for reducing the overall rate of deforestation. Biocarbon investment funds could provide resources to expand farmers' capacity to contribute to the reduction of global carbon emissions while growing more food and providing other sustainable development benefits. Such investments assist smallholder food crop agriculture to become more resilient to adverse climate change by reducing yield losses due to drought.[15]

Ecosystem Services

The potential role of complex agroforests and other types of agroforestry systems have gained attention as the urgency of increasing food production has encountered growing concerns about the loss of biodiversity and other ecosystems services (van Noordwijk et al. 2012). Agroforestry systems are noted as an integrated, multifunctional solution to production with conservation and are a major form of ecoagriculture (Scherr and McNeely 2007). Thus, they are an alternative or complement to the segregated approach of agricultural simplification that has been the dominant paradigm of modern agriculture, where ecological functions are substituted by technical means and external inputs (Sanchez 1995; Green et al. 2005). This has led to increasing interest in quantifying the trade-offs between integrated and segregated landscapes.

The role of agroforestry in achieving biodiversity conservation goals has gained accelerating attention in recent years. There is an emerging trend toward major public investments for rewarding farmers for rewarding farmers for the ecosystems services that their properties provide to society, in both the developed world and the emerging economies such as China and India. This suggests that the integration of trees into agricultural systems will be a major issue in the coming decades.

Conclusion

More than 30 years ago, agroforestry began to attract the attention of the international development and scientific community, primarily as a means for increasing and sustaining agricultural production in marginal lands and remote areas of the tropics that were not benefited by the Green Revolution. Today, thanks to the results of the research that has been done in this area, agroforestry has been recognized as having the potential to offer much more toward ensuring not only food security in poor countries but also environmental integrity in poor and rich nations alike. Investments in agroforestry research during the past three decades – albeit modest – have yielded significant gains in our understanding the role of trees on farmlands and the ecological and economic advantages of integrated farming systems. Agroforestry is now on a firm scientific footing and is well on its way to becoming a specialized science at a level comparable to those of crop science and forestry science.

More needs to be done, however, to bring agroforestry into the mainstream of science. Agroforestry researchers have to position themselves to ensure that the perceived benefits of agroforestry are rigorously quantified because only what gets measured gets recognized and managed. The global community is still only beginning to recognize the potential benefits of these underexploited systems to address some of the most intractable land-management problems of the twenty-first century, such as food security, climate change mitigation and adaptation, and rehabilitation of degraded ecosystems. As we move forward to vigorously exploit these potential benefits, we will witness the coming of age of a valuable and sustainable land-management tool for the future.

End Notes

1. ICRAF, the International Council for Research in Agroforestry, originally set up as a "nucleus" in 1977 in Amsterdam, the Netherlands, was moved to its permanent headquarters in Nairobi, Kenya, in 1978. Later it was renamed as the "centre" (instead of a council). Now it is known as the World Agroforestry Centre, but the original acronym (ICRAF) is retained.
2. CGIAR (Consultative Group of International Agricultural Research) system www.cgiar.org (Last accessed: 30 April 2012)
3. *Agroforestry Systems*, an international journal published by Springer, Dodrecht, the Netherlands, since 1982 (www.springer.com).
4. Advances in Agroforestry, published by Springer, Dordrecht, the Netherlands, is a book series (series editor: P. K. R. Nair). Each book, usually focused on a specific topic, is a collection of peer-reviewed chapters authored by leading experts in the subject, and each volume is edited by one or a small group of editors. Nine such books have been published in the series during 2004–2011.
5. The Inaugural Congress (WCA1) was held in Florida, USA, in 2004. It was a highly successful event in terms of the numbers of participants (nearly 600), countries (82), and organizations represented and in the breadth and scope of presentations and discussions. The 2nd World Congress (WCA2) was held in Nairobi, Kenya, in 2009 (http://www.worldagroforestry.org/wca2009/). It eclipsed WCA1 in every aspect, with the participation of about 1,200 delegates from 96 countries.
6. AFSP 2010 Agroforestry Food Security Programme, Annual Report 2010. World Agroforestry Centre, Liongwe, Malawi.
7. Zomer R, J Bossio DA, Trabucco A, Yuanjie L,Gupta D C, Singh VP 2007. Trees and water: Smallholder agroforestry on irrigated lands in Northern India. Colombo, Sri Lanka: International Water Management Institute. 47p. (IWMI Research Report 122).
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