Issues in Agroecology
Present Status and Future Prospectus 3

W. Bruce Campbell
Silvia López-Ortíz *Editors*

Sustainable Food Production Includes Human and Environmental Health

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Issues in Agroecology – Present Status and Future Prospectus

Volume 3

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Foreword

Are Sustainability and Production Mutually Compatible?

Selection and breeding for crop improvement have been practiced for millennia in one form or another, allowing human communities to settle and prosper, despite continued struggles against pests, diseases, and climate. Successes from the agro-industrial paradigm (using external inputs such as fertilizers and pesticides) further fueled the belief that new and improved technology would allow agriculture to be applied anywhere in the world at any time (the Green Revolution). These technologies led to a global culture of dependency on increased food production over large spatial and temporal scales and for higher levels of agricultural specialization. The need to increase food production, but at the same time to reduce farm expenses in order to maximize economic returns, has led to a rapid global expansion of modern agriculture, international market trade and dependence, and environmental and food-related human health issues. Agricultural research continues to be directed toward increasing agricultural output to insure food security for an increasing global human population, including that for lower-quality low-cost processed foodstuffs, which, while stimulating economic growth, also increase food-related health issues. These movements slow and compete with the capacity for the growth and expansion of more agroecologically oriented and healthy practices such as organic farming in the Global South, leading to reduced future economic returns, operational capacity, and increased human and environmental health issues. Despite the benefits, organic cultivation also suffers from reduced yields, higher prices, political and market management difficulties, and some equivocal environmental benefits (depending on units of measure), which further limit the growth and expansion of this form of agriculture. Thus, both commercial and organic agriculture have their drawbacks, suggesting that a more stable and attainable solution may not exist. More likely, solutions exist in the intermediate domain as a topographically complex suite of methods dynamically adapted to specific localities or regions and the conditions therein. Such a scenario, for the moment, may not be politically or economically easy to manage, especially for the Global South.

The genetic modification of crops to better withstand diseases and changing climate conditions (e.g., precipitation and temperature) and to improve yields and other economic characteristics is the most recent effort designed to reduce external inputs into agricultural systems while at the same time sustaining or improving market value and economics as well as environmental conditions (e.g., reduced pesticide residues). Despite successes in sustaining large monocultures and to compete in a global market economy, many chronic agricultural crises have yet to be resolved (e.g., loss of crop diversity, increased pest resistance, off-farm impacts, and reduced economic equitability, to name just a few).

Such issues in agriculture are highly similar to those encountered in the management of domesticated ruminants. Plant diversity on grazing lands is natural and necessary and provides ecosystem as well as economic benefits. Presently, however, large areas sustaining diverse vegetation around the world have been converted to grazing lands by reducing herbaceous vegetation or introducing exotic grass species to satisfy increasing demands for dairy and meat products. Plant diversity and structure is simplified to produce initial increases in primary production, which are followed by declining productivity, reduced self-organization, and compromised system stability over time as soil resources are depleted. As such, livestock performance under production systems based on grass monocultures for forage can be low or high if based on external energy sources such as water, fertilizers, herbicides, pesticides, and supplemental feeds. These systems are very different from those where most herbivores evolved; systems having high plant diversity and consequently high diversity and content of valuable nutrients and plant secondary compounds. Human health is linked to the soil through the plants that help to maintain ecosystems and nurture herbivores and people. Despite these benefits, livestock production systems have not sufficiently valued diversity, as evidenced by the simplification of ecological systems to maximize forage yields. The low-diversity approach of high-production forages reduces concentrations of plant secondary compounds because they limit how much forage livestock can consume in monocultures. The outcome is energy- and protein-rich monocultures of plants low in plant secondary compounds, making plants, animals, and people more susceptible to environmental hardships and diseases. To compensate for the loss of these compounds, producers have resorted to costly fossil-fuel-based fertilizers, herbicides, and insecticides to grow and protect plants in monocultures; nutritional supplements and pharmaceuticals to sustain human well-being; and antibiotics and anthelmintics to maintain the health of herbivores grazing those monocultures. For several decades parasite control has been based only on using chemical products at fixed intervals throughout the year. Yet, dependence on these chemicals as a single form of control is not economically and ecologically sustainable because of parasite populations resistant and multiresistant to the primary families of chemical products used to control them, chemicals that continue to be overused and misused, especially in the Global South. Their toxicity to animals including humans, environmental contamination, and economic cost are of increasing concern.

The five reviews contained in this volume reveal an underlying connecting current of influence; present commercial agricultural and animal management practices not only continue to erode the foundations upon which the health and welfare of crops, animals, humans, and the environment are based, they may even be altering our ability to provide corrective solutions in the future. Yet, contrasting methods are limited in how much they can produce. This is the very foundation upon which *Issues in Agroecology – Present Status and Future Prospectus* was designed because there has been such tremendous growth in food production and in the agricultural and agroecological literature, growth that requires critical assessments and syntheses from the point of view of sustainability. Are our efforts orienting us along paths toward improved sustainability or are we still suffering from politico- and socioeconomically obscured vision? Are we losing and losing touch with our agricultural roots to satisfy a production-mode perspective? Are all proposed agroecological solutions sustainable, or even feasible? This multifaceted set of questions is prevalent in each multidisciplinary review along with suggestions and supporting evidence for future corrective efforts. While not every method employed to improve sustainability will be equal in benefit in every location, or be a "magical cure" for what ails us in all circumstances, it is important to see these attempts as means of continually moving forward, of constantly exploring novel inroads in the search for improvement, of becoming or being more adaptive to changing or evolving needs. In this sense, such attempts are the results of experiential learning exercises built collaboratively from science, agriculture, education, society, economics, and trade; exercises that span large spatial and temporal scales; and multiple stakeholders from all walks of life. Continued progress toward improved sustainability is thus a necessary adaptive strategy that must be hastened with rules and regulations that also are modified to be more adaptive.

Veracruz, Mexico
Co-editors-in-Chief
June 12, 2013

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Co-editors-in-Chief
June 12, 2013

Dr. W. Bruce Campbell
Dr. Silvia López-Ortíz

Contents

The Trading and Use of Agrochemicals

Peter Hough

Abstract The use of synthetic chemicals has revolutionized agriculture, bringing at the same time huge gains in the form of increased food yields and many significant problems arising from the toxic nature of many of the formulations. The global demand for greater quantities and a certain standard of food has continued to encourage agrochemical use at the same time as the health, safety, and environmental sustainability of doing so has brought this ever more into question. Principles of agroecology have come to inform agrochemical use, but the prioritization of traditional over sustainable development in many countries and the perceived complexity of alternative strategies for improving crop yields have limited this shift mainly to the Global North. This review covers the rise of agrochemicals; assesses the costs and benefits of their production, use, and trade; and then describes and evaluates international political responses to the dilemmas that they pose to humanity.

Keywords Pesticides • Agrochemicals • Fertilizers • Agriculture • Organochlorines • Insecticides • Herbicides • Bhopal • Persistent Organic Pollutants • Pollution • Residues • Rotterdam Convention • Policy

1 The Rise of Agrochemicals and Their Benefits to Humanity

1.1 What Are Agrochemicals?

"Agrochemical" is the generic term for a range of chemical products used in agriculture. Typically agrochemicals are divided into two broad categories, pesticides

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and fertilizers, although it is possible to consider veterinary drugs used on farm animals, such as antibiotics or growth hormones, as a third type. However, since such chemicals are pharmaceuticals rather than formulations designed specifically for agricultural usage, the focus of this review is on fertilizers and particularly pesticides.

1.1.1 Pesticides

The term "pesticide" refers to any substance used in the control of pests as defined by humans. Such pests include insects (hence the term "insecticide"), weeds (herbicides), and also fungi (fungicides). Pesticides may also be used in ways which fall short of killing pests. The term additionally covers defoliants used to strip trees and plants of their leaves, plant growth regulators, and substances which deter insects from certain locations (e.g., mosquito repellents) or attract them away from crops (e.g., through the use of pheromones).

Pesticides can also be subdivided according to their chemical composition. Four principal categories can be identified:

1. *Natural* (botanical) – derived from plant extracts such as nicotine and pyrethrum
2. *Biological* (biopesticides) – the use of microorganisms in pest control such as the bacteria *Bacillus thuringiensis* or biochemicals such as pheromones
3. *Inorganic* **–** substances derived from minerals such as sulfur and arsenic
4. *Synthetic* (organic) – the dominant form of pesticides comprising chemical substances manufactured from combinations of carbon, hydrogen, and oxygen with other elements. Synthetic pesticides can be subdivided as:
    (a) Organochlorines (e.g., DDT, lindane)
    (b) Organophosphates (e.g., parathion, malathion)
    (c) Phenoxyacetic acids (e.g., 2,4,5-T)
    (d) Carbamates (e.g., aldicarb, propoxur)
    (e) Synthetic pyrethroids

The commonly used names of pesticides are usually distinct from their technical chemical names. The herbicide paraquat, for example, is the popular term for the chemical 1,1′-dimethyl-4,4-bipyridinium ion. Pesticides also acquire trade names and paraquat is marketed under a variety of names such as "Pathclear™" and "Gramoxone™."

The use of chemicals as an aid to pest control did not take off until the late nineteenth century, although some use was made of sulfur as a domestic insecticide prior to this time. Homer even refers to sulfur being used in Ancient Greece (Homer 1802: 271). The effects of the notorious Colorado beetles on potato crops and gypsy moths on trees in the United States prompted the entomologist Charles Riley to pioneer the use of the arsenical compound Paris Green (an acetoarsenite of copper originally used as a paint pigment) and London Purple (an arsenical dye residue) as insecticide sprays. The most extensive use of Paris Green in the immediate years after its development as an insecticide was, though, actually more as a deterrent to human pests. Roadside vines are known to have been sprayed to prevent pilfering by passersby, and a number of children were killed as a consequence (Ordish 1976: 160). Doubtless, some of the consumers of the wine from such vineyards must also have been the earliest victims of poisoning through pesticide residues that remained in foodstuffs.

Organic pesticides have their origins in the Second World War. The insecticidal properties of the original and still most notorious pesticide dichlorodiphenyl-trichloroethane (DDT) were discovered by Swiss chemist Dr. Paul Hermann Müller in 1939, and it was quickly patented. A series of other chlorine-based compounds, the “organochlorines,” were soon found to have similar properties, leading to the marketing of insecticides such as benzene hexachloride (BHC), aldrin, and dieldrin. A second branch of organic pesticides, the phosphate-based “organophosphorous” compounds, emerged as a side effect of wartime research into toxic gases by the German scientist Dr. Gerhard Schrader. After the war Schrader put his research before the allied states and revealed the potential insecticidal application of the compounds. Parathion was the first major insecticide in this group to be marketed, and others such as malathion soon followed. Further branches of organic pesticides subsequently developed include carbamates (derived from carbamic acids), such as aldicarb, and phenoxyacetic (phenol-based) acids such as 2,4,5-T.

Insecticides are, of course, poisons and can also be classified according to how they poison their pest victims. Stomach poisons are poisonous when ingested, contact poisons are poisonous when they penetrate any bodily opening, while fumigants are poisonous when inhaled. Arsenical pesticides are stomach poisons and nicotine is a contact poison. Examples of fumigants include methyl bromide and hydrogen cyanide. Most synthetic organic insecticides, though, combine all three methods of poisoning so this form of classification has become less commonly used.

Herbicides can be categorized as selective or nonselective, the former used for specific weeds, the latter usable for a range of weeds. Paraquat is a nonselective and contact herbicide that kills only the plant organs it contacts. In contrast, “systemic” or “translocated” herbicides such as 2,4-D can be transported to leaves from elsewhere in the plant such as its roots.

Fungicides or antimycotics can be applied to seeds as a protective coating (seed fungicides) or work as systemic fungicides to protect the whole plant. Sulfur compounds are prominent traditional fungicides, and methyl bromide was frequently used in this way until its recent phaseout began. Additionally, some other categories of pesticides target pests other than insects, weeds, and fungi. Larvicides are insecticides that target the pest during the larval stages of the life cycle, of which *Bacillus thuringiensis* is a prominent example. Molluscicides target snails and slugs, while rodenticides such as warfarin target rats and other larger pests.

Fig. 1 World's biggest agrochemical companies by 2007 sales and 2007 % market share

1. Bayer (Germany): $7.458 billion – 19%
2. Syngenta (Switzerland): $7.285 billion – 19%
3. BASF (Germany): $4.297 billion – 11%
4. Dow (USA): $3.779 billion – 10%
5. Monsanto (USA): $3.599 billion – 9%
6. DuPont (USA): $2.369 billion – 6%
7. Makhteshim Agan (Israel): $1.895 billion – 5%
8. Nufarm (Australia): $1.470 billion – 4%
9. Sumitomo Chemical (Japan): $1.209 billion – 3%
10. Arysta Lifescience (Japan): $1.035 billion – 3%

1.1.2 Fertilizers

A fertilizer is a substance used to improve the growth and productivity of plants. Fertilizers enhance the natural fertility of the soil or replace chemical elements removed from the soil by previous crop production. Modern chemical fertilizers include one or more of three key elements: nitrogen, phosphorous, or potassium. Most nitrogen-based fertilizers are obtained from synthetic ammonia, such as ammonium sulfite. Calcium phosphate and potassium sulfite are examples of the latter two fertilizer groups. Mixed fertilizers are combinations of two or three of these types.

1.2 The Global Agrochemical Market

The global agrochemical industry is dominated by a small group of Western-based multinational corporations. The top ten listed in Fig. 1 account for nearly 90 % of world production. However, over half of global agrochemical use is now in Asia. Of the rest, over a quarter of global use is in the Americas, 17 % is in Europe, and less than 4 % in Africa and the Middle East. Fertilizers make up 63 % of the global agrochemical market, with pesticides accounting for the remaining 37 %. Globally, the best-selling single pesticide product is Roundup™, a herbicide produced by Monsanto®. Of the US pesticide market, 70 % is comprised of herbicides, 20 % of insecticides, and 10 % of fungicides (Datamonitor 2011).

As can be seen in Fig. 2, the global market value of agrochemicals has fallen in recent years although the volume of sales has remained fairly constant. The original reason for the development and use of agrochemicals was to ensure better yields by reducing crop losses to insects, fungi, and weeds through the use of pesticides, as well as to improve the fertility of soil through the application of fertilizers.

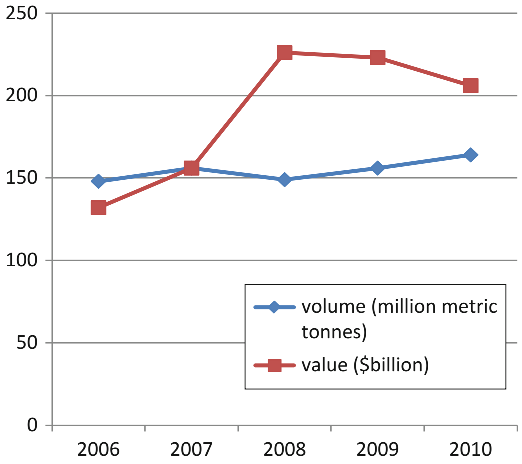

Fig. 2 The global agrochemical market from 2006 to 2010 (Datamonitor 2011)

1.3 *Agrochemicals and Food Yields*

The barrier that pests, in their various guises, pose to satisfying the goal of obtaining optimal crop yields is considerable. It has been estimated, for example, that insects destroy 13 % and weeds 12 % of crops in the United States and that each dollar invested in pesticides reaps a return of around $4 for protected plants (Pimentel 2005). Fertilizer applications are considered to increase food yields by between 40 and 60 % (Stewart et al. 2005).

It is, of course, in the overpopulated Global South that the need for optimal crop yields is most apparent, the same arena in which the prohibitive norms concerning agrochemical use are most pertinent. The moral dilemma facing the actors concerned with agrochemical politics is the stark fact that while imposing strict restrictions on their use and imports in the Global South would reduce accidental deaths and environmental pollution, it would also be likely to reduce the amount of food on the plates of already undernourished peoples. This continues to be the spur for the maintenance of agrochemical use despite the international voices calling for restraint in the name of human safety, environmental protection, and food purity. The compromise practice of adopting "integrated pest management," balancing the norms of optimizing crop yields and minimizing pesticide use, is a complex procedure making up a separate issue which is examined later.

Chemicals have undoubtedly made food and fiber production more efficient. It is estimated that while the average farmer in the United States produced enough food for himself and nine others in the 1940s, this had increased to include the farmer and 31 others by the 1970s (Green 1976: 17). The mechanization of farming, the introduction of high-yielding crop species, advances in the use of chemical fertilizers, and the application of pesticides have all helped in this regard. More recent studies continue to bear this out. Khan et al. (2010: 124), for example, posit that there has been a linear relationship between pesticide and fertilizer usage and cotton and rice production in Pakistan.

There is a correlation between the input of agrochemicals and the subsequent yield in crops, but the relationship between the two variables is not straightforward and needs to be qualified. Yields certainly do not rise in strict proportion to the amounts of pesticides used. It appears that ultimately, more pesticides do not equate to more food or fiber. A number of cases show evidence of this. “In India, where cotton growers used three million kilograms of DDT in 1970 to produce just over five million bales of fiber, DDT use had doubled but cotton yields remained the same six years later” (Norris 1982: 23). A more extreme example comes from Nicaragua, where cotton yields “fell by a total of 30 % from 1965 to 1969,” despite increased insecticide applications (Swezey et al. 1986: 9).

Partial explanations for such cases and this general trend include the raising of cosmetic standards demanded of fruit and vegetables by retailers, the unintentional destruction of natural pest predators, the use of high-yielding but more vulnerable crop species, and the move away from crop rotation to monoculture. Pimentel (2005: 230) notes that the 13 % of crops lost to pests in the United States has actually risen from a figure around 7 % in 1945, in which time there has been a tenfold increase in insecticide use. Yields have increased, but so has waste due to a shift away from the traditional practice of crop rotation. The chief cause of continued crop losses in the face of pesticide use, however, is pest resistance, which develops in the face of continued exposure to chemicals. In the Nicaraguan case, the explanation offered for the drop in cotton yields was an increase from five to nine in the number of species of resistant cotton pests that were “economically important” in the previous 10 years (Swezey et al. 1986: 9). Reducing agrochemical use can also reduce costs without diminishing the benefits. By 2002, Swedish pesticide use had declined by 68 % without any reduction in crop yields or standards, but with a 77 % decline in public poisoning incidents (Pimentel 2005: 249). Khan et al. (2010) note that increased Pakistani yields have been accompanied by increased poisonings, pollution, and insect resistance to the agrochemicals being used.

The problems posed by pest resistance and resurgence are such that even the agrochemical industry has come to question the future of purely chemical crop protection and to explore alternative options. However, despite the growth in nonchemical integrated pest control techniques, pesticide sales continue to be buoyant and they are still widely considered as an essential means of optimizing crop yields. It needs also to be remembered that many of the same chemicals have also benefited humanity in public health campaigns, such as the continuing use of the infamous organochlorine DDT in combating malaria. Evaluating the appropriateness of utilizing chemicals known to have environmental and health side effects thus needs to consider a range of pros and cons. Hence, even the most toxic of agrochemicals have their advocates, such as Roberts and Tren (2010: ix) in their defense of the “excellent powder”; “DDT is unique in its power to cheaply, effectively and safely protect poor people in poor countries against diseases.”

2 Problems Associated with Agrochemicals

The use, production, and transportation of agrochemicals come with several side effects, particularly with regard to pesticides since these are, by definition, poisonous substances.

2.1 Human Poisoning

Chemical pesticides are by their very nature poisonous. The toxicity of such substances can never be applicable only to the targeted pest, so they need to be produced, transported, and applied with care in order to avoid human poisoning.

A precise understanding of how widespread human poisoning from pesticides is globally has never been possible because of a lack of conclusive information on the issue in many countries. The inevitable result of this lack of hard facts is a tendency for the basic pro- and antipesticide camps to swing to extremes and make estimates based on assumptions favorable to their own causes. Independent estimates over the past decade have suggested that between 220,000 and 300,000 people per year are killed by acute pesticide poisoning from over three million severe incidents. These, though, do not include the more difficult to quantify fatalities due to cancers and other longer-term ailments (Oates and Cohen 2011; Hart and Pimentel 2002). In addition, it is widely held that large numbers of poisonings go unreported in the Global South because workers fear it may cost them their jobs and also because they do not associate such illnesses with their work. Added to this is the problem of actually proving a link between an agricultural worker's illness or death and his/her exposure to pesticides. The death of a man by cancer may be the long-term effect of having worked with carcinogenic sprays a number of years ago, but this is very difficult to prove conclusively.

2.1.1 Intentional Exposure

The first detailed and systematic study of the nature and extent of pesticide poisoning in a developing country was carried out in Sri Lanka between 1975 and 1980. The study showed that approximately 13,000 people were admitted to government hospitals for acute pesticide poisoning per year, of which around 1,000 died. The study also revealed that only a small fraction of the Sri Lankan deaths were the result of the accidental ingestion of the chemicals. Some 73.1 % of the patients were admitted after having attempted to commit suicide with the aid of pesticides (Jeyaratnam et al. 1982). Other surveys of pesticide poisonings support the findings in Sri Lanka that the majority of cases are not accidental. It is considered that one-third of global suicides are carried out with pesticides, a figure in excess of 250,000.

This is a far larger annual death toll than all of the victims of the world wars and terrorism combined (Bertolote et al. 2006).

The availability of toxic chemicals is a key explanatory factor behind this startling death toll. The phenomenon of suicide by pesticide is most pronounced in Asia where the agrochemical market is biggest and also usually less restrictive in the sale of hazardous formulations. Over half of the world's deaths of this form occur in China. In many Asian countries, it is most rife in rural regions and among younger people. Pesticides are generally less available in Africa, but the phenomenon is similar in countries with more intensive agriculture such as in Malawi where 80 % of suicides are by pesticides (Dzamala et al. 2006). The high toxicity of pesticides available in developing countries, compared to most developed countries where they have become restricted over time, is an additional factor. Overall, 99 % of pesticide suicide cases are from low- and middle-income countries. In Asia, fatalities from self-poisoning with the herbicide paraquat total 70 %, while, as a comparison, fatalities in the United Kingdom following suicide attempts with medication are 0.5 % (Gunnell and Eddleston 2003).

2.1.2 Unintentional Exposure

Accidental poisoning from agrochemicals can occur in a number of ways. Indirect poisoning, *via* contaminated food and water, is considered later as a separate issue, the focus here being on direct, accidental poisonings resulting from pesticide misuse.

2.1.3 Occupational Exposure to Pesticides

The principal victims of accidental pesticide poisoning are, predictably, the agricultural and public health workers involved in their application. Instances of this are highest in the developing world, where workers are often ignorant of the hazardous nature of their work and management is often negligent in safeguarding the health of their employees. Agricultural workers can be contaminated while mixing or spraying the chemicals, as can those entering fields after spraying, and those working in the formulation of pesticides. This problem is exacerbated by the fact that the pesticides used are the particularly toxic chemicals outlawed or restricted in most developed countries. In addition, it is important to note that the susceptibility of workers in the developing world to pesticide exposure is often higher than their developed-world counterparts, owing to the typically higher temperatures in which they work and the higher levels of malnutrition and disease to which they are prone. It is widely accepted that occupational poisoning by pesticides can be greatly diminished once the trading of particularly hazardous chemicals is brought under control, and worker safety standards in the developing countries are implemented at levels similar to those in the developed world. The scale of the global death toll from occupational exposure to agrochemicals is unclear, but studies in China have indicated an annual figure of around 17,000 (Phillips and Yang 2004). If China is assumed to have a similar proportion of occupational to suicide victims as in other Asian countries, this suggests a global figure of around 30,000 per year.

2.1.4 Long-Term Health Effects

While acute pesticide poisoning is largely prevented in the developed world, concern remains over the possible long-term health effects of prolonged exposure to pesticides by workers and members of the public. Central to this concern are the possible cancer risks involved in exposure to particular chemicals. Many pesticides have proven carcinogenic in animal testing, and this has fueled enough fear for some governments to restrict or ban chemicals principally on these grounds.

Aside from their potential carcinogenicity, the other long-term health fears associated with pesticides derive from the persistence of the organochlorine chemicals. Chemicals like DDT and dieldrin are also known to possess "lipophilic" characteristics, meaning that they dissolve in fat more readily than water, and as such they are prone to be stored as residues in human tissue. The presence of these residues has been linked to a variety of health disorders. A significant rise in Alzheimer's and other forms of dementia through exposure to organochlorine pesticides has been suggested (Hayden et al. 2010). A link between thyroid disorders and organochlorine exposure in women in farming communities of Iowa and North Carolina has also been reported (Goldner et al. 2010).

Restrictions on the use of organochlorines in many countries have not eliminated concern over long-term occupational exposure to pesticide chemicals. Organophosphate (OP) pesticides basically replaced organochlorines in British sheep-dips in the 1980s due to the worries over the persistence of the former types of chemical, but instances of "dipping flu," where farmers suffer nausea and headaches after treating sheep, have continued. Trade unions led by the National Farmers Union (NFU) and UNISON, the public service union, finally made headway in the United Kingdom in the 1990s in gaining recognition of the problem and in securing compensation for victims. The appropriately named Robert Shepherd, who worked for the Lancashire College of Agriculture, received £80,000 in an out-of-court settlement in 1998 after having to give up his job due to chronic fatigue believed to be linked to dipping the college's sheep twice a year in OP pesticides. Other studies have also shown that less direct organophosphate pesticide exposure can impact human neurodevelopment, particularly in young children (Damalas and Eleftherohorinos 2011).

Overall, 81 of the European Union's 276 legally marketed pesticides are known to have negative health impacts; 51 are carcinogenic, 24 are endocrine disrupters, 22 cause reproductive and developmental defects, and 28 can be the cause of acute toxicity (Karabelas et al. 2009).

Pesticides applied conventionally on crops may occasionally affect people other than those employed in their application. The primary avenue by which this can occur is as a result of the drifting over residential areas of pesticides originally sprayed on agricultural land. The two principal ways in which the general public has been exposed to pesticides in this manner are by the drift of chemicals used in aerial spraying and by the drift of vapor following the evaporation of chemicals after application.

The spraying of residents with pesticides dispatched aerially is a commonly recorded complaint in developed countries and has led to calls for a complete ban on this method of application. Considering that aerial spraying only accounts for a small fraction of all pesticide applications in developed countries, this would seem to suggest that poisonings resulting from this practice are liable to be far more significant in Asia, where aerial spraying is more common and generally less subject to regulation. As is the case with many aspects of the health impact of pesticides, the scale of this problem is impossible to fathom owing to the difficulty of conclusively matching symptoms of poisoning with their causal factors. This is especially so if the effects are long-term. In addition, there is a lack of data from the places where the problem is likely to be greatest, the underdeveloped world.

A landmark legal case in 1997, however, transformed the legal position of people suffering from pesticide exposure of this form, at least in the developed world [1]. A July 31st verdict of the Hong Kong High Court ordered the Swiss-based multinational corporation Ciba-Geigy to pay Kristan Phillips, an American musician, the equivalent of £19 million in compensation for illness suffered after being contaminated by the organophosphate diazinon in a Hong Kong concert hall in 1987. Phillips was forced to abandon a career as a timpanist with the Hong Kong Philharmonic Orchestra after suffering chronic exposure to the insecticide which was being sprayed on walls of the building during a rehearsal. The key witness at the trial was a British doctor, Goral Jamal, whose testimony on the various effects of organophosphate poisoning, particularly in retarding the nervous system, was accepted by the court and so opened the door to claims for compensation against agrochemical producers throughout the world. The case had particular pertinence because diazinon was at the same time being cited as a potential cause of illnesses suffered by Gulf War veterans in the United States and United Kingdom in long-running legal battles.

Another area of concern is the potential danger from the use of agrochemicals in the home. Despite the growing popularity of "organic gardening" in Europe and North America, the garden still remains the largest proportional recipient of agrochemicals. While less toxic formulations have gradually come to replace the sorts of insecticides and herbicides available in the 1950s and 1960s, the sheer presence of poisonous chemicals where families live and children play is a source of short- and long-term health concern. Approximately 57 % of pesticide poisonings in the United States—some 50,000 cases per year—involve children under the age of 6 (Litovitz et al. 2002).

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[1] Kristan Bowers Phillips vs. Initial Environmental Services Ltd. (HCPI 580/1996)

2.1.5 Poisoning due to Industrial Accidents

Accidental poisoning during the production and transport of pesticides can, of course, affect the health of the general public, in addition to those employed in the industry. This was made most dramatically evident in Bhopal, India, on December 2, 1984, when a gas leak at a plant formulating a chemical for use as a pesticide caused the world's worst ever industrial accident.

The disaster at the Union Carbide plant in Bhopal does appear to have been the culmination of circumstances close to any "worst-case scenario" imaginable for a chemical production site. The plant's end product, the carbamate carbaryl, also known as Sevin™, is not particularly hazardous (category II of the WHO Classification by Hazard), but the chemical methyl isocyanate (MIC) which is used in its production is extremely toxic. As an intermediate chemical, however, MIC did not feature on the WHO Classification by Hazard and even failed to appear on UNEP's International Register of Potentially Toxic Chemicals. Thus, Indian authorities were completely unaware that the chemical was being stored.

In addition to the fact that nobody was really aware of the nature of chemicals used at the plant, it later emerged that safety standards were also poor. One worker had been killed and three others injured by exposure to phosgene, another chemical used in the processing of MIC in 1981 during Bhopal's first year as a manufacturing unit (phosgene was one of the chemicals used on the battlefields of World War I). In the following year, a visiting safety team from Union Carbide's headquarters in the United States described the plants MIC unit in an internal report as possessing "serious potential for sizeable releases of toxic materials" (Weir 1987: 40). Such concerns were echoed in the Indian press in a series of reports by local journalist Rajkumar Keswani, culminating in an article for the Hindu periodical *Jansatta* just 6 months prior to the accident. Investigations into the accident later found numerous examples of negligence which aided the tragic gas leak. A refrigeration unit used to maintain MIC at a lower and more stable temperature had been switched off to save money, while temperature and pressure gauges were routinely ignored by workers because of their unreliability.

Added to the ignorance of the nature of MIC and the negligence over safety precautions at the plant is a third factor accentuating the Bhopal tragedy. Bhopal is a poor city and many thousands of people lived in crowded slums near to the Union Carbide plant. These people were powerless to protect themselves from the escaping fumes which spread over the ground (MIC is heavier than air). David Weir has pieced together eye-witness reports of the Bhopal tragedy to come up with a dramatic account of the night of December 2, 1984.

> Hundreds of thousands of residents were roused from their sleep, coughing and vomiting and wheezing. Their eyes burned and watered, many would be at least temporarily blinded. Most of those fortunate enough to have lived on upper floors or inside well-sealed buildings were spared. The rest, however, opened their doors onto the largest unplanned human exodus of the industrial age. Those able to board a bicycle, moped, bullock, car, bus, or vehicle of any kind did. But for most of the poor, their feet were the only form of transport available. Many dropped along the way, gasping for breath, choking on their own vomit and

> finally drowning in their own fluids. Families were separated; whole groups were wiped out at a time. Those strong enough to keep going ran 3.6 to 12 miles before they stopped. Most ran until they dropped. (Weir 1987: 16)

Estimates of the numbers of casualties vary, but it is believed that 200,000 people were exposed to the gas and 17,000 permanently disabled as a result. The immediate death toll could have been anywhere between 2,000 and 8,000, as most of the victims were not formally recorded in any way, and the killing of entire families hindered the identification process. Long-term health effects include various breathing and digestion disorders along with birth defects and spontaneous abortions. After years of legal wrangling, Union Carbide, United States, and their Indian subsidiaries were finally made liable for prosecution in 1991, opening up the way for compensation payments to 500,000 people and for the setting up of a hospital in the city to deal with ongoing ailments.

The Bhopal disaster, as we have seen, was a consequence of a set of particularly dire circumstances. As such it has been evaluated by many within the chemical industry as a fluke, a one-of-a-kind disaster unlikely to occur again. A speaker at the “Chemistry After Bhopal” conference in London in 1986 compared the disaster to the sinking of the Titanic, an undoubted tragedy, but not justifying the abandonment of sea travel (Dudley 1987: x). Many skeptics of pesticide production safety, however, turn the Titanic analogy on its head, as they believe Bhopal, rather, represents the tip of an iceberg, with a vast number of smaller accidents lying submerged from public and political view. Weir, in his book *The Bhopal Syndrome*, argues that the tragedy is continually repeated in “mini-Bhopals” and “slow-motion Bhopals” (Weir 1987: ix), in which unseen poisoning occurs. The determination to learn the lessons of the Bhopal tragedy led to the setup of a “No More Bhopals” network at a 1985 Nairobi conference on development organized by the Environmental Liaison Center and the International Coalition for Development Action.

While it is fair to consider Bhopal as a unique accident in terms of its scale, many examples of “mini” and “slow-motion Bhopals” can be found. In 1976, over 500 kg of toxic vapor was released after an explosion at a chemical plant in Seveso, Northern Italy, after a buildup of pressure. Trichlorphenol and dioxin TCDD, a constituent of the infamous “Agent Orange,” used as a jungle defoliant during the Vietnam War, pumped out to form a large cloud around the plant, although no acknowledgment of this was made to nearby villages for 4 days. Within 3 weeks pets and crops had died, 30 people were hospitalized with burns or liver pains, and one person had died. The principal health impacts at Seveso were long-term however, owing to the highly teratogenic nature of the released gases. Accurate medical records were not kept in the aftermath of the disaster, but Dr. Alberto Columbi conducted research revealing that even by 1978 birth defects were at a rate of 53 per thousand in the areas around Seveso, compared to an average of below 5 per thousand in the Lombardy region as a whole (Dudley 1987: 107). The Catholic Church became involved in the issue, when some women contaminated by the poison flouted Italian law and had abortions performed.

The fact that tragedies can occur outside the glare of the sort of media interest shown at Bhopal is seen in the case of the PT Montrose DDT plant at Cicadas, Java. Suspicions that the plant had been secretly burning off waste at night were confirmed by an investigation conducted by WALHI (Indonesian Environmental Forum) and KRAPP (Indonesian Network Against the Misuse of Pesticides) in 1985. It emerged that, over time, 25 villagers had been killed as a result of this action (Weir 1987: 65).

Several major industrial disasters involving fertilizers have also occurred, largely due to the explosive nature of ammonium nitrate, which has also seen such products used by terrorist groups for incendiary devices. The explosion of a ship carrying this fertilizer at port killed 561 in Texas City in 1947 and is one of the worst industrial accidents in history. More recently, 31 people were killed and 200 injured as a result of an explosion in 2001 at a storage hanger at the Atofina Grande fertilizer plant near Toulouse, France, which created a 50 m-wide crater, and in 2007 at Monclova, Coahuila, Mexico, when a trailer crash left 40 dead.

2.2 Environmental Pollution

The fact that all pesticides are by their nature toxic substances means that any contamination of unintended targets with them is potentially hazardous and thus undesirable. The most environmentally hazardous organic pesticides and some other organic chemical compounds created for industrial purposes have, in recent decades, come to be known as Persistent Organic Pollutants. These compounds, frequently referred to by the acronym “POPs,” are defined by the United Nations Environment Programme as “chemical substances that persist in the environment, bioaccumulate through the food-web and pose a risk causing adverse effects to human health and the environment” (UNEP 2009). Fertilizers tend to be less inherently toxic, but can also become significant pollutants if used in excess.

Once again, however, it can be seen that there are different levels of concern over this phenomenon. To some actors, the evidence of environmental damage due to agrochemical use is enough to warrant the outright abolition of their use in any capacity, whereas others merely wish to see them used with some consideration for their ecological consequences. As with human poisoning, the actual extent of pollution by agrochemicals is unclear and disputed by scientists and political actors alike. Traces of pesticides can be found in the soil, in the water, in the air, and in unintended crops and animals, but there is little consensus as to when this equates to pollution at a level at which we should be concerned. Most insecticides and herbicides that are sprayed do not hit their target and, instead, can contaminate the air, water, and soil with a variety of environmental consequences. Those pesticides that do hit their intended destination may still end up killing more than that target when they pass down the food-chain and are ingested by other organisms.

Aside from such “collateral damage” resulting from chemicals accidentally missing their intended target or willfully being employed in ways for which they were not designed, the chemical properties of POPs can cause them to be environmental hazards well away from the fields where they have been applied. Since they are so slow to break down and tend to be stored in fat, POPs can end up deposited in animals thousands of kilometers from where they were used. In a phenomenon known as the “grasshopper effect,” chemicals, like DDT and carbofuran, after evaporating in the warmer climes where they tend to be used, can then be carried around the globe in the atmosphere or water in a series of “hops” of evaporation and deposition and then build up in food-chains remote from where they are used. Hence, polar bears, at the top of Arctic food-chains, have been found to be contaminated by POPs (Tenenbaum 2004).

2.2.1 Forms of Agrochemical Pollution

2.2.1.1 Soil

The soil is the principle recipient of agrochemicals, the source of which may be deliberate or accidental. Unlike the intentional entry of pesticides into the soil, which is usually a precise procedure, accidental or collateral entry is indiscriminate and affects a much wider land area, including areas where their presence may be wholly undesirable. Much of the pesticides intended for crop application clearly will miss their target or wash off the plants into the soil beneath. To this can also be added the entrance of pesticides into the soil from crop residues, leaf-fall, and root deposits. A less voluminous but more widespread source of pesticides which enter the soil is by atmospheric fallout. Small amounts of pesticides have been detected in raindrops and atmospheric dust, which are absorbed into the soil on reaching the ground.

Whether the presence of an agrochemical in the soil constitutes an environmental problem or not depends somewhat on its persistence. A quickly degrading chemical will not be likely to disrupt the ecosystem greatly, but a highly persistent chemical may have biological effects beyond the period of its usefulness. Four types of such biological effects can be environmentally damaging. The chemical residues may (i) survive long enough to affect succeeding crops, (ii) affect soil organisms, (iii) leach into water, or (iv) cause long-term damage to soil fertility. The effects of residues on living organisms within the soil can also be summarized into four categories. They may (a) be directly toxic, (b) cause genetic resistance, (c) be passed on to other organisms, or (d) have sublethal effects on behavior or reproduction.

2.2.1.2 Water

As with the soil, agrochemicals may enter water sources either deliberately or accidentally, although instances of the former are far fewer. Relatively tiny amounts of pesticides are applied to streams, ponds, and reservoirs in order to protect fish, attack weeds and algae, and control insects which breed in water. These sorts of practices are generally restricted in the West by firm legislation. In the United Kingdom, for example, the local water authorities are required to be contacted before any spraying operations in or around freshwater areas can be undertaken. In some developing countries, though, the deliberate addition of pesticides to freshwater for the purposes of fishing has been reported on a number of occasions.

The unintentional contamination of groundwater remains the more serious problem however. Agrochemical residues can enter water through drift and atmospheric fallout in the same way as they do in the soil, but also in a number of other ways. Chemicals in soil may enter nearby water through runoff or be carried there with eroded soil particles. Pesticides also may make up some of the industrial effluent regularly pumped into streams and rivers. They may be the wastes from fabric plants practicing mothproofing or from the manufacturing, formulating, and packaging stages of production in an agrochemical firm. Similarly, sewage will often contain pesticide traces such as the bactericides found in some soap and cosmetic products. In addition, spills of pesticides into rivers have been known during the storage and transportation of the chemicals. Hundreds of tons of pesticides and other chemicals were washed into the Rhine at a Sandoz warehouse in Basel, Switzerland, in November 1986, after a fire was brought under control with hoses.

The effects of a cumulative input of pesticides into groundwater can also be lethal to the organisms which live there. An increase in the mortality of bacteria, fungi, algae, aquatic invertebrates, amphibians, reptiles, or fish will disrupt the food-webs of which they are a part and their parent ecosystems. The fact that pesticides concentrate in the tissues of aquatic organisms more readily than in terrestrial life forms exacerbates this problem. Of most concern to humanity is the effect on some fish populations through such pollution, either by direct poisoning or indirectly due to a depletion of their traditional prey. The presence of pesticides in groundwater can also have sublethal effects on aquatic life. The raising of water temperature due to pesticide presence or the entry of chemicals into fish brains or nervous systems can impact their behavior and reproductive capacities. The most serious consequence of this behavioral change occurs when a species of fish develops resistance to a pesticide to which it has been exposed. When this happens, these fish can carry once lethal amounts of chemicals within themselves and then pass them on to the next organism in the food-web.

The runoff of fertilizers into freshwaters is a key cause of the pollution known as cultural eutrophication resulting from the unnatural accumulation of phosphates, nitrogen, and or other plant nutrients. The consequent growth of algae, vegetation, or microorganisms on the water surface blocks light and increases oxygen use with sometimes devastating effects on aquatic life through the creation of "dead zones." The world's largest "dead zone" is in the Gulf of Mexico into which the Mississippi River empties, and others exist in the Baltic, Black Sea, and Lake Eerie.

2.2.1.3 Air

Pesticide droplets have been detected in the atmosphere over most parts of the globe. Clearly therefore, they are capable of falling to earth many miles from the areas where they were originally intended to be applied.

Pesticide vapors enter the atmosphere in many ways. A significant proportion of pesticides may be lost during spraying, by drifting in the wind, or through evaporation. Volatilization can also take place on secondary deposits of pesticides. Some particularly persistent substances, such as DDT and dieldrin, remain long enough as surface residues after falling with rain, that they are subject to evaporation again. Other routes by which pesticides enter the atmosphere include the escape of vapors from pesticide manufacture and formulation plants and the introduction of residues within dust storms originating in agricultural areas.

Though the density of pesticides which fall to Earth from the air is far less of a hazard to man and the environment than the pollution of soil and water, concern remains at the buildup of toxic vapors in the atmosphere. Even with the progressive phaseout of the most toxic of agrochemicals, the persistence of POPs ensures that many used years ago remain in the atmosphere.

A different form of environmental hazard due to the existence of certain pesticides has become apparent over the last 20 years. The soil-fumigant methyl bromide was in 1992 confirmed as a significant agent in the depletion of the ozone layer. A UNEP report concluded that around half of all methyl bromide applications to the soil are ultimately emitted into the atmosphere, where their capacity for ozone destruction is at least 30 times greater than that of organochlorine compounds, such as the infamous “CFCs” (chlorofluorocarbons). The report estimated that between 5 and 10 % of annual global ozone depletion was attributable to methyl bromide (UNEP 1992).

2.2.1.4 Wildlife

Although water and soil contamination are a known source of faunal exposure to agrochemicals, the greatest route by which wildlife come into contact with pesticides is through the contamination of their food sources. It may be the case that the effects of pesticides on soil-inhabiting organisms are limited, but the impact on some predators by these organisms can be far more profound. Birds are far more subject to taking in pesticide residues in this way as their bodies break down harmful chemicals less readily than do mammals. The birds most vulnerable are those at the top of food-chains, the birds of prey. Persistent chemicals such as DDT and dieldrin end up deposited in these creatures *via* small birds who feed upon contaminated insects in the soil. The birds of prey are left with the biggest deposits from having accumulated the toxic residues of all organisms below them in the food-chain. This process is known as biomagnification. In the United Kingdom, the Eurasian sparrow hawk (*Accipiter nisus* L.) was made nearly extinct for 25 years because of direct poisoning from their prey and the thinning of their eggshells due to pesticides. The birds began to reemerge in the late 1970s once the residues of organochlorine pesticides used in the 1950s had finally begun to disappear (Newton et al. 1992: 31).

In the United States alone, where restrictions on chemical use are among the most stringent in the world, it is estimated that every year between 6 and 14 million fish and around 5 % of the total honeybee population are killed as a result of exposure to pesticides (Pimentel 2005). Globally, figures substantiating the environmental impact of pesticides are predictably sketchy, but certain well-documented cases give a hint at the scale of damage. For example, forensic analysis has proven that at least 4,000 Swainson's hawks (*Buteo swainsoni* Bonaparte) in Argentina were killed as a result of eating caterpillars that had been sprayed with a newly imported organophosphorous insecticide, monocrotophos, during the summer of 1995–1996 (Goldstein et al. 1999). In Kenya, hundreds of lions and vultures are known to have been killed between 2004 and 2009 as a result of exposure to a form of carbamate insecticide known as carbofurans, recognized as POPs. Carbofuran products, which are completely prohibited from use in the European Union and highly restricted in the United States, are designed to protect corn and other crops but, owing to their toxicity, are also fatal to other animal species and are known to have been used by cattle herders to eliminate mammalian prey by lacing animal carcasses and leaving them as traps (Howden 2009).

2.2.1.5 Crop Losses

Pesticides may also be responsible for damaging farm crops when the chemicals become volatile or unintentionally come into contact with crops other than those they are intended to protect. The drift of vapor from neighboring crop fields, the effects of herbicide residues which have remained in the soil after application on a different crop in a previous season, or changes in the nature of a pesticide due to climate can all be causes of crop losses. Pimentel (2005) estimates that beneficial crop losses amounting to $1.5 billion occur every year in the United States.

It can be proven that pesticides and fertilizers sometimes pollute the environment and poison the organisms that inhabit it, but the overall significance of this to the natural world is still open to debate. The influence of agrochemicals is one of many inputs determining the balance of nature, alongside far less contentious human practices such as building reservoirs and dams or fishing. While the wholesale contamination of the environment by carefree pesticide or fertilizer applications is clearly undesirable, minor changes to an ecosystem need not necessarily be viewed as ecologically damaging. Yet, judging whether the net result of such change is desirable is difficult to discern and subject to dispute by the political actors affected by environmental agrochemical pollution.

2.3 Agrochemical Residues in Food

Human poisoning by agrochemicals can also occur indirectly, through the consumption of contaminated foodstuffs or drinking water. As with all areas of agrochemical pollution, the extent to which the presence of residues in food represents a threat to human health is unclear and hotly disputed between competing stakeholders. High doses of agrochemical toxins have been responsible for a number of acute poisonings and even deaths of people eating the contaminated produce. The worst food poisoning epidemic of all time occurred in Iraq in 1971–1972 due to the consumption of bread made from wheat grain treated with an organochlorine fungicide. In total, 6,530 local farmers and members of their families were admitted to hospitals with varying symptoms and 459 died. The fact that the symptoms took at least 60 days to appear contributed to the size of the catastrophe (Al-Tikriti and Al-Mufti 1976).

Direct poisoning of this sort results from an ignorance of the hazardous nature of pesticides. Reports from developing countries abound with stories of farmers continuing to spray right up until harvesting time in the face of heavy pest infestation. Pesticides have even been known to be used in fishing. Alongside the effects of such wanton misuse of pesticides, food produce can also be contaminated accidentally by spray drift or by a leakage of the chemicals during storage.

Such cases represent extreme instances of poisonings resulting from malpractice, but the subtler health impact of agrochemical residues remaining in foodstuffs after their normal application has emerged as a major health and consumer issue over the last 50 years. The rise to prominence of organic food, grown without the aid of any chemical pesticides or fertilizers, is testament to public concerns about the presence of potentially toxic residues in their food.

Agrochemicals can also enter the human body *via* drinking water from two forms of contamination. First, agrochemicals applied deliberately or accidentally to rivers and lakes may be carried into aquifers. Second, pesticides or fertilizers can gradually leak into groundwater supplies *via* the soil. As with occupational exposure, the long-term health impact of consuming small traces of agrochemical residues remains a concern. Excessive concentrations of nitrates in drinking water have been linked in studies to the potentially fatal infant condition known as “blue baby syndrome” (McIsaac 2003). Pesticide residues that are carcinogenic or linked to birth defects and other ailments do remain in foodstuffs, but generally at levels too low to produce scientific certainty on a causative link (Oates and Cohen 2011; Hamilton and Crossley 2004). Another area of concern is the “cocktail effect” of different combinations of agrochemical residues. Pesticides are often used in combinations and it has been shown that chemicals that are comparatively safe individually can acquire dangerous properties when combined with other chemicals in a process known as *synergism*.

Some pesticides are used not to save a crop from pest destruction, but merely to maintain its appearance to a particular standard. Consumer expectations ensure that retailers demand blemish-free products from farmers and exporters, although there are no discernible health risks inherent in partially brown bananas or lettuces containing a few holes in their leaves. Maintaining the cosmetic value of products leads to the spraying of crops until close to harvesting, a practice which increases the likelihood of residues in the final product. Similarly, consumer demand for fruits and vegetables out of season means that chemicals are often used on stored produce to avoid insect or fungus attack. The residues of hormones given to promote growth in cattle are also prominent health concerns, often linked to cancers and reproductive problems. Steroids used in beef have been linked to the lowering of sperm counts

(Swan et al. 2007). The threat posed by hormones is taken very seriously in Europe, where extensive national and European Union restrictions are in place, but has not prompted the same level of political response in North America where their use remains prominent.

The human health significance of traces of agrochemicals that remain in foodstuffs is subject to great debate. The agrochemical industries defend themselves by pointing to rigorous testing procedures for new products. As well, they argue that national legislation on permissible levels of residues on imported and home-grown foods is also rigorous and more than sufficient to ensure consumer safety. Prominent US scientist Bruce Ames has argued that excessive caution over the carcinogenicity of pesticide residues is absurd given that fruit and vegetables naturally contain carcinogenic chemicals that can even be counterproductive, given that resultant public fear leads to lower consumption of such foods which leads to greater cancers and other ailments (Ames 1984). This argument is, though, disputed by others who observe that human exposure to natural carcinogens in food cannot be compared to that from added synthetic chemical residues because it has been an ongoing process for over a million years, allowing for adaptation (Richter and Chlamtac 2002).

2.4 International Trade in Agrochemicals

The introduction into the Third World of Western agricultural technology in the 1960s and 1970s, known commonly as the “Green Revolution,” created a dependence on pesticides produced in the West and opened up a massive new trade, flowing from North to South. Despite the growth of Asian agrochemical production, most of the Global South’s pesticides are still imported from the big chemical corporations based in the North.

International regulation of pesticide trading has, until recently, been extremely lax and certainly not kept in step with municipal law in the developed states. Awareness of the hazardous nature of many substances used for pest control has gradually seen the most toxic chemicals becoming banned or restricted in the West with rigorous safety guidelines for their application developed. Many pesticides that are banned and withdrawn from use domestically in the developed world, however, have continued to be marketed to the Global South where many states have weak regulatory procedures or lack the resources to efficiently enforce those that do exist. The response of many agrochemical firms to greater scrutiny of their produce by health and environmental groups in the West has been to redirect their goods to such less restrictive markets. Following the banning of DDT in the United States because of its carcinogenic qualities, some chemical companies turned to Third World trading partners to stave off losses from accumulated stocks of the chemical. Weir and Schapiro (1981) revealed that over 25 % of the exported pesticides from the United States were unregistered, with their destination invariably being a less developed country. Often the main importers of such products are subsidiary bodies of the companies manufacturing them in the first place.

The flood of particularly toxic pesticides into the Global South, backed up by persuasive advertising, has accentuated the problems which arose when such products were used widely in the West, as specialized knowledge on pesticides is much scarcer and levels of illiteracy prevent workers from even reading safety instructions printed in their own language. A clear theme which emerges from this study is that the "side-effects" of pesticide use, human poisoning, environmental pollution, and food contamination, are at their most damaging in the underdeveloped world. As these costs have become apparent, the view that international trade in pesticides needs to be controlled has developed. Acceptance of this norm has been influenced by the realization in the West that trading in deadly toxins ultimately hurts them too. Pesticides profitably dumped on the Third World market can return to Western consumers in their food imports from the same countries, a process which has been labeled the "circle of poison" (Weir and Schapiro 1981).

3 Limiting Agrochemical Use: Integrated Pest Management

3.1 The Rise of Integrated Pest Management

In light of the damage that can be done to the environment and human health by the misuse of chemical pesticides, many people have called for a more limited use of these substances in general, going beyond trade restrictions. A body of opinion has steadily emerged which would like to see all uses of manufactured pesticides ended, in favor of alternative practices of pest control. Even more conservative voices within the world of agrochemicals have come to aspire toward a situation in which reliance on chemicals is replaced by a multifaceted approach to the problem of crop protection in agriculture—integrated pest management. This middle ground, of maintaining agrochemical use, but in a much more limited and sustainable manner, represents a clear expression of agroecology and has gathered momentum in parts of the world where principles of environmental sustainability have taken root.

Several governments have implemented legislation reducing pesticide use in this way. In 1972 President Richard Nixon, riding the wave of public concern induced by environmental pollution from DDT and Agent Orange, gave rhetorical support for IPM schemes in the United States. The governments of Denmark, the Netherlands, and Sweden in the late 1980s launched schemes to cut pesticide use by 50 % before the end of the century. The Dutch government has continued to advocate IPM in a series of initiatives since then (Boorma 2008), and the United States in 2004 launched the National Road Map for IPM, promoting the exchange of information on implementing such schemes. In possibly the world's first binding legal IPM provision, the 2008 German Plant Protection Law insists that IPM procedures are followed in plant protection (IITA 2008). IPM has also received advocacy from the European Union 2009 Sustainable Use Directive.

The inclusion in the FAO's Pesticide Code of Conduct of Article 3.8 stating "Governments and the pesticide industry should develop and promote integrated pest management" (FAO 1986) signified that the principle that agrochemical usage be kept to a minimum has developed the status of an international norm. This was reaffirmed in 1992 when IPM was cited as good practice at the United Nations Conference on the Environment and Development (UNCED) spawning the Consultative Group on International Agriculture's "Research Programme on IPM" in 1996 and a Global IPM Facility, jointly sponsored by the FAO, UNDP, and World Bank the following year.

The agrochemicals industry has noted this and made efforts not to appear out of line with such opinion. As far back as 1983, a report from Shell Chemicals on their agrochemical business acknowledged that:

> Environmental and economic arguments as well as sound biological principles support a trend to integrated pest management (IPM), by which is meant the coordination of agricultural practices and biological and chemical control of pests (Shell Chemicals 1983).

The report goes on to stress that IPM ultimately must still be dependent on chemical applications. The acceptance of the role of other methods of pest control, however, indicates a tacit acknowledgement of the norm for minimizing chemical use. The agrochemical industry's international mouthpiece, the Global Crop Protection Federation, for example, has a working group dealing specifically with IPM implementation.

The development of this norm of limiting agrochemical use has its roots not only in the problems of environmental and human poisoning referred to earlier but also in the growing realization that overreliance on chemicals in agriculture has its own pitfalls. While crop yields undoubtedly improve with the initial application of pesticides, these yields are difficult to sustain because pests often develop resistance to a particular toxin after prolonged exposure to it. By the end of the twentieth century, the number of insects known to be resistant to pesticides rose and has increased tenfold since the 1950s to over 500, and 124 species of weeds were known to be resistant to herbicides (Cox 2004: 85; Heap 1997). The physiological adaptation of insects to a pesticide can take on a number of forms. Some insects have been known to evolve a layer of their body which is impenetrable to a pesticide, while others develop systems which can store insecticides and then detoxify them. In Malaysia, the mosquito *Aedes aegypti* (L.) has developed the capacity to excrete an insecticide which was once fatal to it, before it can be absorbed. Research in Malaysia has also revealed that pests can sometimes develop resistance to types of insecticides other than the one which has actually been used against it. The "diamondback" moth [*Plutella xylostella* (L.)] became immune to the effects of both organophosphate and carbamate pesticides, despite never having been exposed to the latter form of chemicals (Sahabat Alam Malaysia 1984: 35).

In addition to this problem of pest resistance is the phenomenon of pest resurgence in the face of continued pesticide exposure. Pesticides often eliminate natural predators of the targeted pest, which can lead to the pest actually flourishing after a while. The response of farmers to pest resistance and resurgence is often to increase the dosages of pesticides, which merely serves to exacerbate the problems of pollution, poisoning, and food contamination, while ultimately not improving yields. The effect of increasing pest resistance has been to make the issue of minimizing the use of pesticides and fertilizers salient to the industries that manufacture them. The realization from the agrochemical industries that it is in their best interests to discourage the overuse of their products is, of course, a position far removed from that of the environmentalists, some of whom call for an outright end to pesticide use, but some consensus has been able to emerge among them.

3.2 The Alternatives to Chemical Pesticides

3.2.1 Biological Control

The most widely used alternative to chemical pesticides in agriculture is the practice of mobilizing the natural predators of a pest in order to control it. This usually involves the introduction of a natural enemy somewhere where it does not naturally occur. For such predators to become established in their new habitat, however, a small pest population must be maintained in order for them to continue suppressing the pest. Careful research is required before such action is taken in order not to upset the ecosystem and create new, unforeseen problems. If a predator is introduced which also attacks crops or beneficial insects, it can become a pest in its own right, as happened when Sri Lankan crows (also known as Indian house crows; *Corvus splendens* Vieillot) were introduced to Malaysia by British colonialists in the early twentieth century with the intention of controlling coffee caterpillars (Sahabat Alam Malaysia 1984: 40). An alternative to introducing new species to a habitat is to augment an existing pest predator by providing it with food and facilities for breeding.

The most common form of biological control is the use of insects to control other insects. This technique has been employed successfully in the protection of cassava crops in Central Africa by the International Institute of Tropical Agriculture (IITA), an internationally funded center based in Ibadan, Nigeria. IITA research discovered a number of predators to the mealybug [*Phenacoccus manihoti* Mat.-Ferr. (Horn., Pseudococcidae)], the cause of considerable depletion in cassava yields, and launched, in the 1980s, the world's largest biological control program based around the parasitic wasp *Epidinocarsis lopezi* (De Santis). The parasite quickly became established in much of the "cassava belt," which stretches from Senegal to Mozambique, and helped reverse a crisis which was costing around $2 billion annually in losses. The mealybug was brought under control in all nineteen countries in which the wasp was released and crop losses fell from 50 % to below 20 % (Gikaru and Ajayi 1990: 33).

Biological control can also include the use of microbes as pathogens against a variety of pests. Some well-known examples of this include *Bacillus thuringiensis*, used by organic gardeners to control caterpillars, and *Trichoderma viride* Pers., which attacks silver leaf fungus on fruit trees. The advantage of microbes over insects in biological control is that they are usually more specific predators and are less prone to infest beneficial crops or insects. The field of biopesticides has been boosted by the development of techniques to genetically increase the capacity of microbes to kill their insect hosts, such as implanting genetic fragments for the venom of scorpions and mites into the genome of insect-specific baculoviruses, greatly increasing their deadliness when infecting insect hosts. Biopesticide sales in the United States grew by 20 % per year in the 2000s (HighBeam 2012).

3.2.2 Resistant Plants

Another means of reducing dependence on pesticides in agriculture is to breed strains of crops which are inherently resistant to their normal predators. Many voices within agriculture have come to advocate a switch from the traditional practice of breeding plants for maximizing yields, as the "Green Revolution" had taught the Third World, to focusing on producing hybrid species requiring less chemical protection. Once again, economic arguments have been critical in altering perspectives within the agricultural community. The risks to human health and the environment from excessive pesticide use have been well documented, but the appeal of this form of crop protection lies in the fact that it reduces production costs and offers better guarantees of regular, albeit smaller yields.

Probably the most significant research in developing resistant strains of plants is being carried out by the IITA on the banana and its close relative the plantain. These fruits, which represent a staple food for over 60 million Africans, have increasingly fallen victim to a fungal disease known as Black Sigatoka [*Mycosphaerella fijiensis* (Morelet)], first discovered in 1973 in Zambia. The natural resistance of bananas to disease is negligible, owing to a continual history of selective breeding which has produced extremely low levels of genetic variability between fruits. Large plantations, responsible for providing the West's supply of bananas, have overcome this problem with the aid of chemicals, but this is an option not open to Africa's many subsistence farmers. Hence, the IITA has developed resistant genotypes from wild bananas being propagated in the laboratory to produce new hybrid strains of banana. A process of evaluation is now being implemented to determine which new strain of banana/plantain is most appropriate to be bred for agricultural use (IITA 2012).

Much research in the field of plant resistance has concentrated on isolating the genetic traits responsible for resistance, so that they can then be bred into other plants not possessing such a capacity. The pioneer in this new era of genetically engineered crops was a strain of tomato which was interbred with a gene from the bacterium *Bacillus thuringiensis*. This bacterium kills caterpillars and its toxin, if introduced into a plants genetic architecture, can make the plant resistant to caterpillars and other common pests. As in the domain of hormone residues in food, a clear difference in attitudes to genetically modified crops has emerged between Europe and North America. They have been embraced in the United States, but not in more risk-aversive Europe through fears of the potential health and pollution consequences of meddling with nature in this way.

3.2.3 Semiochemicals

There exist a number of ways to help protect crops from pests involving chemicals, but which fall short of directly killing the pest. The chemicals used are less toxic and consequently less hazardous to man and the environment than traditional pesticides.

Probably the best researched of these chemical control methods involves the use of insect sex pheromones which can be applied so as to disrupt the mating of insects or lure them into traps. Such methods are now commonly used in orchards (Chandler et al. 2011). A different method of controlling insects by disrupting their reproductive activities is to use chemicals known as chemosterilants of males of a pest species. These chemicals, though, can have the disadvantage of being mutagenic to the pest, permitting the target organism to genetically develop resistance in the same manner as many have to conventional pesticides.

3.2.4 Cultural Controls

Not all of the nonchemical forms of crop protection are procedures rooted in technology, however. During the latter part of the twentieth century, cultural controls (limiting pests by affecting their habitats) have reemerged as general techniques employed by farmers to protect their crops before dependence on pesticides sets in.

Returning to the age-old practice of crop rotation is one such form of cultural control. With the advent of the Green Revolution, crop rotation was largely abandoned in favor of monoculture, which allows for more economical harvesting and sowing, but at the same time permits pests to flourish. Multi-cropping, on the other hand, provides pests with only small areas of host crops to inhabit, while the practice of having fallow seasons within the cycle breaks up any pattern of gradual pest proliferation.

Another traditional farming practice which has been rediscovered as a means of culturally controlling pests is the destruction of crop residues after harvesting. Burning or plowing fields after they have been harvested removes any remaining pest habitats and eggs that may otherwise flourish when the next growing season begins. Interplanting a cash crop with plants or flowers which deter its pests is another old-fashioned agricultural technique which is beginning to find favor again, especially with the rise in consumer demand for organic produce in the West. Planting orange marigolds (also known as French or Aztec marigolds; *Tagetes erecta* L.) among crops of cayenne peppers (*Capsicum annuum* L.), for example, attracts pollinating insects to the flowers while simultaneously repelling other potentially harmful insects with their scent. Similarly, the application of natural products such as lemon rind, tobacco plant stems, and ash is effective in killing some insects or at least in deterring them.

The use of physical controls against pests can sometimes be an effective means of limiting their damage without resorting to chemicals. Placing metal barriers in the ground around a crop field is a way of deterring termites or rodents, for example, while utilizing yellow boards covered in glue can serve as a means of trapping whiteflies (Hemiptera: Aleyrodidae). Projects in the United Kingdom, Norway, and Sweden in the early 1990s explored the benefits of creating banks of grass in the middle of crop fields, providing habitats for spiders and beetles which are the natural predators of aphid pests (Hawkes 1992). The premise behind this simple procedure, created by exempting field tracts from plowing, is to reverse the effects of a gradual increase in the size of crop fields which has resulted in fewer hedgerows and with it fewer aphid predators.

3.2.5 Integrated Pest Management

Integrated pest management (IPM) utilizes the various pest control techniques mentioned previously, in line with the norm that chemical pesticide use should be optimized. The FAO/UNEP Panel of Experts have defined the concept as follows:

> A pest management system that in the context of the associated environment and the population dynamics of the pest species, utilizes all suitable techniques and methods in as compatible a manner as possible and maintains the pest population at levels below those causing them injury. (FAO 1967)

This represents a very holistic approach to pest control, as the entire ecosystem of which the plant and pest form a part is always considered. This is a total change in approach to traditional pest control, where each pest is treated as a separate problem and any interrelationships are not considered. Thus, for instance, a fundamental principle behind IPM is the idea that the targeted pest should never be completely eliminated, but rather maintained at an acceptable level whereby damage to the crop is not economically significant.

The conception of this economic threshold indicates that IPM is rooted in more than merely the desire to restrict pesticide use for the good of the environment and human health. It becomes apparent that what are at first seemingly contradictory norms form the framework on which the system is operated. The value on which traditional agrochemical use is guided, namely, the optimization of profit by increasing yields and decreasing damage, is still influential under IPM, but is reconceptualized. By operating a system in which the aim is to satisfy all of these norms, the idea of an optimum yield becomes understood both in terms of economic profit and the human and environmental costs. Balancing these disparate aspirations requires that systematic research be undertaken before the appropriate remedies are integrated into the economically deficient ecosystem in question. At a simple level, this may just mean taking time to estimate levels of pest infestation in a region prior to applying appropriate crop protection techniques, rather than applying pesticides immediately as a preventative measure. This sort of action will be likely to cut the farmers' input costs, while simultaneously lowering the risk to the environment. The ultimate projection of this idea is to refine the deduction of the optimal yield with the aid of computer technology. Computer models can be made of the complex ecological interactions making up the system under consideration, to determine which measures of pest control represent the most appropriate long-term methods of obtaining an optimal yield.

3.3 Problems Associated with IPM

While the attraction of a scheme in which the environmental and human hazards of agrochemical use are reduced at the same time as economic profits are maximized is obvious, IPM is not without its drawbacks as a pest control scheme. The proposed alternatives to pesticides for use in crop protection also possess flaws which can become apparent if they are not carefully operated. Intensive research is required before biological control schemes can be enacted to ensure that the ecosystem is not undesirably disrupted by the introduction of a pest predator. It needs to be ensured that the predator is specific to the pest it is intended to control, or else it may become a pest in its own right by attacking crops or beneficial insects. The introduction of cane toads [*Bufo marinus* (L.)] to Australia and of crows to Malaysia to control coffee caterpillars are cases in point. In both instances the introduced species are accepted as having caused more harm than good to the crops they were intended to protect (Sahabat Alam Malaysia 1984).

The augmentation of advances in genetic engineering to the field of biological control, creating what are known as biopesticides, has created great excitement in the scientific world, but has not taken off as much as many anticipated in the 1980s. Biopesticides by 2011 had only secured around 2.5 % of the pesticide market since they are highly selective, less straightforward to utilize and still comparatively unfamiliar to most farmers (Chandler et al. 2011).

Developing a means of pest control without resorting to chemicals or pest predators, by breeding pest resistant crops, also has its weaknesses. For a start, it is possible that the crop variety with the best resistance may have a yield that is too low to make it economically viable, or that its quality may be below what is expected by consumers. Only a limited number of resistant crops will be able to match these essential criteria. It is also known that a side-effect of increasing a crop's resistance to a particular pathogen can be to reduce its resistance to another. Great concern has also been aired regarding the ramifications of manufacturing genetically engineered crops that are resistant to pests. Evidence that some insects have become resistant to *Bacillus thuringiensis*, the toxic genes of which have been incorporated into cotton plants, suggests that this form of pest control is prone to the same Achilles heel that has basically called pesticide use into question (Tabashnik et al. 2008).

Perhaps the biggest fear concerning this technology, however, is that ultimately it may actually provide a new and bigger stage for pesticides to act on and thrive. It should be remembered that it is agrochemical businesses that own the vast majority of plant breeding companies, and the concern of many is that, far from using resistant crops as an alternative to chemicals, they are exploited as a means of allowing more intensive pesticide use. Crops have been developed which are resistant to particular herbicides rather than weeds, allowing greater quantities of such herbicides to be used against the weeds without harming the crop. An empirical study by organic farming lobbyists in the United States, but based on agriculture department statistics, found that national levels of herbicide use had significantly increased since the augmentation of GM crops in the country (Benbrook 2009). The potential environmental consequences of this trend do not need to be spelled out, suggesting that the technology of inducing greater crop resistance is in the wrong hands and could exacerbate a problem it was hoped it could help solve.

The mutagenic effects of chemicals used to sterilize male pests have already been discussed, and it is clear that all forms of "indirect" pesticides are still in their infancy as crop protection alternatives. At the same time, it is a common delusion that natural chemicals are inherently safer than their synthesized counterparts and so more preferable for use as pesticides. The use of tobacco-based solutions is frequently cited as a traditional pest control agent which can be rediscovered as an alternative to modern insecticides, but nicotine is as equally hazardous as most synthetic chemicals owing to its high mammalian toxicity.

The use of IPM as a package of pest control measures has had its successes, as has been illustrated, and it has been enhanced through the application of information technology. Extensive national pesticide reduction schemes have thus been implemented in many developed countries, but its impact in the Global South has been much more limited (Cuba and Indonesia are notable exceptions). IPM's applicability as an antidote to all the ill effects associated with pesticide use does, therefore, need to be qualified. The bulk of environmental and human tragedies occur in the Global South, where the application of such substances is comparatively unregulated. IPM does not always represent a viable alternative in these states because it is more complicated and, ultimately, rooted in advanced technology. An extensive empirical study by proponents of such measures, for example, concluded that "introducing IPM in South East Asia through the conventional transfer of technology oriented transfers simply does not work" (Chowdhury and Ray 2008: 226). Returning to age-old methods of pest control may be less hazardous for Global South workers, but it should be remembered that it was the inadequacy of such measures to protect crops that led to the Green Revolution and chemical control in the first place. An economically viable IPM system requires sophisticated technology and a well-trained workforce able to analyze the ecology, geology, and agronomy of a region and prescribe the appropriate solution. These prerequisites are clearly not to be found in most Global South countries. This problem is recognized by the epistemic community who continues to advance IPM principles to developing countries with some successes, but progress is slow.

4 The Politics of Agrochemicals

4.1 The Emergence of Agrochemical Politics

The production and use of agrochemicals thrived from the late 1940s to the 1960s, when food yields soared and many tropical diseases appeared to be being brought under control through their use, but then the rise of political ecology brought numerous side-effects into focus. The issue of pesticide-induced environmental pollution was, in many ways, the catalyst for the emergence of the whole issue of environmental change on the international political agenda in the 1960s. The publication in 1962 of *Silent Spring* by Marine Biologist Rachel Carson from the United States, despite concerted corporate attacks on its scientific authenticity, is widely recognized as having helped fuel the takeoff of environmental politics. The book's title alludes to a future world in which birdsong could no longer be heard, drawing on evidence that organochlorine pesticide use was damaging eggshells. It was this ecocentric message which prompted a backlash in the United States and much of the West against what was undoubtedly a profitable and, in some cases, life-saving technology, although the book did also highlight human health hazards associated with organochlorine pesticide use (Carson 1962). The controversial use of the jungle defoliant "Agent Orange" (a trade name of the herbicide 2,4,5-T) by the United States during the Vietnam war also served to heighten anxieties about pesticides. At that point the use of such chemicals even entered the world of "high politics" when Swedish Prime Minister Olaf Palme denounced the applications of Agent Orange by the United States as "ecocide" at the 1972 United Nations Stockholm Conference on the Human Environment, prompting a diplomatic spat between the two countries. As with other environmental issues, the 1960s and early 1970s saw the entire arena of agrochemical production, trade, and use at the international level move from being a relatively unchallenged and heralded technological development to a highly politicized set of issues.

The rise in concern at the effects of organochlorine insecticides on wildlife since the 1960s has contributed to the banning of, or severe restrictions on, the use of DDT, dieldrin, and other notorious chemicals in most developed countries. The US government enacted legislation restricting DDT use in 1969 and then outlawed its use altogether in 1972. Pesticides continue to arouse a certain amount of political controversy in the domestic political arenas of the developed world, but the phasing out of the most carcinogenic and polluting chemicals and their replacement with less toxic formulations, alongside the establishment of stringent consumer standards and health and safety regulations, have significantly reduced environmental and health concerns. There have been some notable environmental benefits from these domestic legal changes, such as the return of sparrow hawks in the United Kingdom since the 1970s after coming close to disappearing. However, as the United States figures referred to earlier indicate, there continue to be some significant pesticidal impacts on wildlife.

Since the 1960s, however, it has been transnational issues of pesticide use, production, and trade that have commanded most social, environmental, and political significance. The "Green Revolution" saw many chemicals, withdrawn from domestic use in the developed world, continue to be marketed to the Global South where regulatory standards tend to be more lax. The monocrotophos used in Argentina, referred to earlier, was imported from the United States, where its use is prohibited. The response of many agrochemical firms to greater scrutiny of their produce by health and environmental groups in the North has been to redirect their goods to much less restrictive markets in an "industrial flight" or "race to the bottom."

Chemicals were first legally restricted in a number of developed countries in the late 1960s and 1970s chiefly because of their proven effects on birds and other wildlife, but this, in itself, has never proved a sufficient basis for global rules to develop. Global regimes which have emerged in the governance of pesticides have only crystallized once vested industrial and governmental interests have also come to see some advantage in regulation due to the consequent harmonization of trading standards.

It was the 1984 Bhopal disaster that served as the catalyst for a campaign involving numerous environmental and consumer activists aiming to regulate the global production, trade, and use of pesticides led by the purpose-built global pressure group Pesticides Action Network (PAN) formed 2 years earlier. The Bhopal disaster served to highlight concerns over pesticide toxicity beyond that which had been possible in the countless smaller-scale disasters that had occurred before 1984. Bhopal also served to expose a clear International Political Economy dimension to the pesticide industry since safety standards at the plant were found to be much more lax than those at the home base in Virginia.

Crucially, self-interest as well as compassion in the Global North came to favor the regulation of the pesticide trade in the 1980s and 1990s as governments came to see that domestic legislation was insufficient for protecting their citizens. Pesticides profitably dumped on the Global South market can return to Northern consumers in their food imports from the same countries, or through long-range atmospheric pollution due to the "grasshopper effect." Additionally, chemical firms needed to improve their reputations after Bhopal and came to see that global standards would be less costly than further domestic legal restraints on their industry and even advantageous in the long run. Thus, the powerful players in pesticide politics, the chemical companies, and Northern governments have gradually been persuaded of the need for regulation, paving the way for the development of international law in the 1990s.

Contemporary global governance with regard to agrochemicals is focused on four areas: (1) regulating permissible amounts of residual chemicals in traded food, (2) regulating the export of certain pesticides, (3) outlawing the use and production of the most toxic chemicals, and (4) targeting a specific pesticide as part of the ozone regime.

4.2 *The Politics of Agrochemical Residues in Traded Food*

The origins of global policy on agrochemicals can be traced back as far as 1963 when the Food and Agricultural Organization and World Health Organization co-launched a body intended to "protect the health of consumers and to ensure fair practices in the food trade" (Codex 1989: 31). The Codex Alimentarius Commission, the implementing machinery of the FAO/World Health Organization Food Standards Programme, has a Committee on Pesticide Residues (CCPR) which sets global standards for recommended maximum levels of pesticide traces in traded foodstuffs, initially intended to be no more than voluntary guidelines. A Codex Committee on Additives similarly deals with traces of veterinary drugs or fertilizers.

Environmental and consumer groups have long suggested that Codex standards are more informed by the latter of its two stated aims and cannot be relied upon to guarantee consumer safety since the body is not impartial in its judgments and is chiefly motivated by the desire to harmonize national food standards to an agreed minimum in order to facilitate international trade. The membership of Codex is open to any member state or associate member of the FAO and WHO who can then vote on a majority basis for the adoption of draft standards for food quality issues. The commission has always been far closer to the FAO than the WHO, owing to the latter's broader portfolio of responsibilities, and has attracted similar sorts of criticism to its closer parent of being over-influenced by multinational corporations linked to the food industry (Avery et al. 1993). For example, of the 23 "international non-governmental organizations" listed as participants at the 39th CCPR meeting in July 2007, all were business representatives (Codex 2007).

This concern at excessive corporate influence was heightened with the creation of the World Trade Organization (WTO) and the sudden elevation of Codex's technical standards to quasi-international law. The 1995 WTO Agreements on the Application of Sanitary and Phytosanitary Measures (SPS) and Technical Barriers to Trade (TBT) cite Codex standards as the benchmark for determining whether state food standards are being used by members as an unfair barrier to free trade. The United States and Canada have accused the European Union of this in relation to hormone residues in beef, but a leveling down of international residue standards has not yet happened. Food in the Global North generally still continues to be produced in accordance with national pesticide residue standards since lowering consumer safety standards in democracies with active civil societies and a press is politically infeasible.

Codex standards for agrochemicals, though less stringent than the domestic standards of many developed states, are presently almost certainly sufficient to safeguard against significant pesticide risks to human health. Despite high levels of corporate influence, the CCPR's standards are drawn largely from the findings of the Joint Meeting on Pesticide Residues (JMPR), a respected WHO/FAO forum of scientists and academics without any corporate representation. JMPR recommendations on acceptable residue limits in foodstuffs, though less stringent than some domestic standards, are very much informed by the precautionary principle with levels set much lower than are known to be dangerous to health.

As with many other environmental and health issues, there has been some breaking of the ranks on the appropriateness of the precautionary principle in spite of its apparent legitimization by all governments at UNCED in 1992. This was most notable in 2001 when the US delegation at the 16th session of the Codex Commission on General Principles led a walkout in protest at attempts to develop further use of the principle in Codex standards, arguing that this would represent a "nonscientific" trade barrier. The US government and global chemical industry representatives have since focused on lobbying for a global harmonization of Codex

Maximum Residue Limits (MRLs), but to date the right of states to fix their own—even more precautionary—MRLs has remained. Where Codex pesticide residue limits have been most influential is in providing a standard for developing countries lacking any MRLs of their own. Hence, Codex standards have not leveled down standards with regard to pesticide residues in traded food and, despite extensive corporate lobbying and being co-opted by the WTO, have instead leveled up standards and served to enhance public safety around the world. The precautionary principle has so far held sway and, at the moment, the pesticide residues regime represents something of a "bootlegger and Baptist coalition"[2] (Yandle 1983) with its rules developed from principles emerging from an epistemic community committed to safeguarding human health, with the economic interests of industry brought on board.

Significant national differences can be seen with regard to traces of growth hormones in traded meats. The European Union has banned the use of such products since 1985 in contrast to the United States and Canada, leading to a series of trans-Atlantic trade disputes once import restrictions were introduced in 1989.

4.3 The Methyl Bromide Regime

An international regime has emerged since the early 1990s, regulating releases into the atmosphere of the soil-fumigant methyl bromide which is used extensively in the farming of tomatoes and strawberries, particularly in the United States. Concerns had been voiced about the environmental effects of methyl bromide for years (the Netherlands government phased out its use in 1992), but it took the realization that the chemical posed a threat to human life for it to be made subject to any international regulation. The discovery that methyl bromide was a significant ozone-depleting agent saw a global agreement concerning methyl bromide use and production reached in November 1992 in Copenhagen as part of the *Montreal Protocol on Substances that Deplete the Ozone Layer*, the key treaty dealing with the issue of ozone depletion.

The Copenhagen meeting decreed that methyl bromide production and consumption levels should be frozen at 1991 levels from the start of 1995. In September 1997, the 9th Meeting of the Parties to the Montreal Protocol committed 160 governments to a timetable for a complete phaseout of methyl bromide production and use. In line with the "common but differentiated responsibilities" principle agreed upon at UNCED, developed countries agreed to end the use of the chemical by 2005 after a series of intermediate cuts, while developing countries agreed to a deadline of 2015 to eliminate its use following a freeze in 2002. As with other areas of environmental and humanitarian global governance, however, the US position backtracked under

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[2] The term is derived from the days of alcohol prohibition in the United States when both the church and the illegal "black market" gained in different ways from the law.

the Bush Junior administration from seeming to support a complete phaseout, and they have maintained a significant level of methyl bromide use since 2005 by exploiting a “critical use exemptions” clause to the agreement far more than had been anticipated. The California strawberry industry, mindful of the costs of switching to alternative soil fumigants, lobbied hard for US delegates to argue that previously agreed upon alternative fumigants were not adequate for the West Coast climate, much to the irritation of most other Montreal Protocol parties (Gareau 2008). Hence, methyl bromide continues to be used, principally in the United States but also in several other countries. A global phaseout is still proceeding, albeit more slowly than was originally envisaged.

4.4 Prior Informed Consent in Trading Chemicals

Probably the most significant development in the global governance of chemical pollutants was the 1998 *Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade* which came into force in 2004. The Rotterdam Convention sets out legally binding commitments constraining governments attempting to export chemicals banned in their own countries through the Prior Informed Consent procedure (PIC). The chemicals’ PIC regime stands as an example of how private governance can form the basis of more stringent consumer-focused regulation. The Rotterdam Convention made legally binding Article 9 of the FAO’s (1986) *International Code of Conduct on the Distribution and Use of Pesticides*, a voluntary set of safety standards for the handling and transport of pesticides.

The PIC was initially resisted by displays of corporate power, but eventually was able to overcome such vested interests. The relevant PIC provision in Article 9 was withdrawn during the lead-up to the FAO Code’s ratification in 1985 despite appearing on seven of its eight drafts in the face of strong persuasion from the United Kingdom and United States, motivated by a chemical industry lobby alarmed at the prospect of restrictions on their trade. No national delegation officially requested the deletion of the PIC provision, and 30 countries protested its removal, but it appears that covert pressure convinced delegates at the ratifying conference that the Code as a whole would be at risk if a compromise over Article 9 was not accepted (Hough 1998: 113–120). Led by the Pesticides Action Network (PAN) and OXFAM, a campaign to reincorporate PIC into Article 9 of the FAO Code and advance the principle carried on, regardless of the 1985 ratification. The Netherlands became the first country to formally embrace PIC into domestic legislation in 1985 and the European Community made moves toward adopting the procedure for all its member states before eventually absorbing the whole FAO Code of Conduct, including PIC, into European law in the 1990s.[3]

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[3] EC Directive EEC2455/92

The establishment of the principle of PIC as a binding international rule was sealed by eventually gaining the support of the chemical industry in the early 1990s. The agrochemical industry's global political mouthpiece at that time, the *Groupement International Des Associations de Fabricants de Produits Agrochimiques* (GIFAP), announced in its annual report for 1991 that one of its aims for 1992 would be to "continue to cooperate with FAO/UNEP on the implementation of PIC" (GIFAP 1991: 11). The reason for this apparent "U-turn" on PIC appeared to be a fear of the alternatives, such as an outright prohibition of the export of certain pesticides. The drafting of a bill in the United States during 1991–1992 proposing the introduction of export controls for pesticides raised alarm in the agrochemical industry and prompted GIFAP to take the extraordinary step of criticizing the bill on the grounds that it was contrary to the very article of the FAO Code of Conduct it had so vehemently opposed:

> A major concern ... is the appearance of a draft Bill on pesticide export control in the USA which is very much at variance with PIC in the FAO Code, namely that this draft legislation is export rather than import control orientated. (GIFAP 1991: 13)

GIFAP here saw an opportunity to ensure that any chemical trade regulations that did emerge would be based only on import rather than export restrictions. In a choice between PIC and export restrictions of the sort discussed in the US Congress, the chemical industry came to accept the principle because it represented the lesser of two evils in the pursuit of their main goal of maintaining free trade. Thus, again, an agrochemical regime came to be formed through a "bootlegger and Baptist coalition" of actors agreeing to cooperate to enforce norms in the name of differing values: safeguarding human health and maximizing economic returns, with the former the primary influence.

The Rotterdam Convention obliges parties exporting any chemical restricted by their own domestic legislation to send Decision Guidance Documents (DGD) to importing authorities detailing the basis of such restrictions. The process also ensures DGDs are automatically circulated to all parties for chemicals listed under Annex III of the Convention. A Chemical Review Committee (CRC) considers proposals from parties for including new chemicals in the automatically triggered PIC list (Annex III). By 2012, there were 43 chemicals, including 32 pesticides, contained in Annex III.[4] The CRC considers the reliability of the evidence provided and the significance of reported effects in comparison to the quantities used and then discerns whether any reported ill effects could be prevented by proper application

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[4] List of pesticides subject to PIC procedure: 2,4,5-T; alachlor; aldicarb; aldrin (HHDN); binapacryl (Endosan); captafol; dustable powder formulations containing a combination of at least 7 % benomyl, 10 % carbofuran, and 15 % thiram; chlordane; chlordimeform; chlorobenzilate; DDT; dieldrin (HEOD); DNOC and its salts; dinoseb and dinoseb salts; 1,2-dibromoethane (EDB; ethylene dibromide); endosulfan; ethylene dichloride; ethylene oxide; fluoroacetamide; HCH; heptachlor; hexachlorobenzene; lindane; mercury compounds; pentachlorophenol; monocrotophos; methamidophos; phosphamidon; methyl parathion; parathion; toxaphene (camphechlor); tributyltin compounds.

of the chemical. The secretariat is able to take up reports from NGOs in addition to those from governments. This practice was established under the voluntary scheme due to PAN pressure in highlighting health problems peculiar to developing countries resulting from the use of some pesticides. The contentious issue of whether the rules of the Convention could be overruled by World Trade Organization provisions on free trade in the event of any clash was fudged by removing a get-out clause to this effect, which was supported by the US government (who has not ratified the Convention). In its place a number of governments were permitted to include in the preamble a statement that the Convention will not "prejudice their respective positions in other international forums and negotiations addressing issues related to the environment and trade." There was some opposition to including the word "environmental" in the negotiating of the Convention, but it was eventually agreed that PIC would be extended to any:

> . . . chemical formulated for pesticidal use that produces severe health or environmental effects observable within a short period of time after single or multiple exposures, under conditions of use.
> (Rotterdam Convention, Article 2d)

Even for those chemicals able to make Annex III, whether PIC does lessen the problems associated with their trade is, though, open to debate. The procedure provides for information to be provided to importers, but does not actually prohibit the trade in hazardous chemicals. Further, some have expressed concern that, far from empowering Global South importing countries, the PIC procedure has actually served to reinforce dependency since the scientific assessments used are from the Global North (Barrios 2004; Karlsson 2004). The enshrining of PIC as a rule for the trading of hazardous chemicals is an important step forward for global governance but does not, in itself, represent the realization of environmental- and consumer-focused safety standards comparable to those that have become established in many countries of the developed world since the 1960s.

4.5 The Politics of Persistent Organic Pollutants (POPs)

Inspired by the progress achieved with the PIC regime, but also by its practical limitations, a global campaign aiming to eliminate the use and production of the most toxic and persistent chemicals worldwide emerged following the formulation of the Rotterdam Convention. UNCED (Chapter 19, Agenda 21) (United Nations 1993) raised the profile of a pressure group campaign, supported by a WHO-based epistemic community, culminating in a treaty similar to the methyl bromide convention, but for a range of chemicals including notoriously hazardous pesticides like DDT, aldrin, and dieldrin. After endorsement by UNEP's Governing Council in 1997, the Intergovernmental Forum on Chemical Safety (IFCS), set up by UNCED, was charged specifically with the task of implementing the proposal which it duly adopted as the chief of its "Priorities for Action" at its first meeting.

Table 1 Pesticides subject to the Stockholm Convention

Intentionally produced	
Aldrin	*Use and production banned apart from laboratory-scale research*
Chlordane	
Chlordecone	
Dieldrin	
Endosulfan	
Endrin	
Heptachlor	
Hexachlorobenzene (HCB)	
Lindane	
Mirex	
Pentachlorobenzene	
Toxaphene	
Dichlorodiphenyltrichloroethane (DDT)	*Use restricted to disease vector control*
Unintentionally produced	
Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD "dioxins"/PCDF "furans")	*Use and production minimized with aim of elimination*
Hexachlorobenzene (HCB)	
Pentachlorobenzene	

Once again the development of a new regime can be seen to have emerged from a lengthy process of pressure group campaigning and United Nations agency-led epistemic cooperation. WHO Expert Committees have been at the forefront of developing global standards for measuring chemical toxicity since the 1950s, and their "Classification by Hazard Scheme," launched in 1975, is the key reference point for the FAO's "Code of Conduct on the Use and Distribution of Pesticides" and the Rotterdam Convention. On the back of their success in getting the FAO Code ready for signature, PAN in 1985 launched their "Dirty Dozen" campaign calling for the outright prohibition of many of the same chemicals which subsequently formed the basis of the POPs. Sixteen years later many of the dirty dozen formed the basis of the International Legally Binding Instrument for Implementing International Action on Certain Persistent Organic Pollutants (POPs Treaty) which was signed by 127 governments at a diplomatic conference in Stockholm in May 2001 and entered into force in 2004 (Table 1).

Under Article 8 of the Convention, a Persistent Organic Pollutants Review Committee appraises proposals to add new chemicals to the list.[5] The Stockholm Convention is explicitly linked to its UNEP sibling the Basel Convention on Control of Transboundary Movements of Hazardous Wastes and their Disposal with measures calling on parties to minimize the generation and movement of waste

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[5] For example, among chemicals proposed for inclusion by the parties are Hexabromobiphenyl (HBB) and Polycyclic Aromatic Hydrocarbons (PAHs) which have been banned in Europe by the UNECE Protocol on Long-Range Transboundary Air Pollution since 2003.

POPs. The Convention is an example of "soft international law" in that it is legally binding, but contains no enforcement measures.

The production and use of the outlawed chemicals has long ceased in most developed countries, but their properties ensure that they remain a domestic hazard to their populations. Due to their slowness to break down and propensity to travel, the sterility, neural disorders, and cancer in peoples of the developed world can be attributed to the use of POPs in other parts of the planet. The political significance of this is such that even President George W. Bush, shortly after his government's revocation of the Kyoto Protocol on Climate Change in 2001, declared the United States would support international environmental cooperation on POPs. That the POPs regime is not fundamentally driven by ecocentric values is evidenced by the fact that the infamously environmentally unfriendly DDT is exempted from prohibition by governments signing on to the POPs regime declaring that they require the use of the chemical to combat mosquitoes in the fight against malaria and other diseases (e.g., dengue) borne by this group of insect vectors. This qualification follows a concerted campaign by public health specialists. Again, the value of safeguarding human health and the coincidental satisfaction of corporate interests have been the driving force for political action rather than environmental values.

The chemical industry, represented at Stockholm by GIFAP's successor the Global Crop Protection Federation (GCPF) and other global lobby groups, again gave their backing to an agreement which constrains their freedom of action in order to prevent something more restrictive from emerging. The chemical industry presence at the Stockholm negotiations was more low-key than at other conferences on global chemical trade issues, and they were largely receptive to environmental/consumer group demands. The POPs pesticides were not worth fighting for as they were by now rarely produced by the big agrochemical companies of the Global North since their patent protection had mostly expired and cheaper generic versions were being produced by small companies in the Global South. Hence, a global ban on POPs could even serve the interests of the agrochemical giants since it would give them an opportunity to corner the market in new, alternative and patent-protected pesticides. Hence, at Stockholm the chemical lobby concentrated on ensuring that the list of chemicals making up the POPs list be limited to the older organochlorine pesticides (Clapp 2003). The chemical industry and the US delegation at the negotiations of the Stockholm Convention fought hard to ensure that the term "precautionary principle" did not appear in the final text, and it was eventually replaced with the more ambiguous compromise phrase "precautionary approach," which the industrialists hoped would open the door to less expansive "scientific" toxicity assessments (Olsen 2003: 99–100). The significance of such semantics is clear from considering the Bush administration's pronouncements on the principle previously accepted by the US government at UNCED; "the US government supports precautionary approaches to risk management but we do not recognize any precautionary principle" (Graham 2002). By 2012, the United States still had not ratified Stockholm with Washington's initial enthusiasm curbed by the inclusion of furans and dioxins on the list which are significant by-products of the large chlorine industry in the United States.

5 Conclusions

The advent of agrochemicals epitomizes the dilemmas that industrialization and economic development present to humanity; progress, but at a price. They have contributed greatly to the invaluable task of increasing the world's food supply, helping avert environmentalist fears of overpopulation in the 1960s and 1970s through the "Green Revolution" and could still prove crucial in averting future food shortages. In the 1940s and 1950s, the use, production and trade in pesticides and fertilizers were essentially uncontroversial, and they appeared to vindicate the view that human ingenuity and scientific progress could defeat global problems like poverty and disease. The emergence, from the 1960s, of evidence that agrochemicals—particularly pesticides—also affected the world negatively through human poisoning and environmental pollution has, though, made their use more contentious and very political. Since then, principles of agroecology have taken root with the growth of stringent, precautionary domestic legislation in most industrialized countries leaving the greatest political dilemmas for the Global South where agrochemicals are most needed but, at the same time, are most dangerous.

Global rules have emerged dialectically from a dialogue between rival interests, led by chemical corporations and environmental pressure groups with governments somewhere in between and often divided themselves.[6] The regulation of pesticides became part of the global agenda due to the action of pressure groups and epistemic communities, promoting agroecology, coordinated by UNEP and the WHO. Powerful governments and business interests tried to resist but were eventually persuaded, through fear of being exposed as immoral to their electorates/consumers to come to the negotiating table. Pressure groups, led by PAN, have successfully helped put agrochemical issues on the global agenda and advanced the values of environmental conservation and safeguarding human health. The rules that have emerged from this process are not, however, driven purely by social and environmental concerns and are "tempered" by competing interests of the chemical industry who generally have greater influence on the governments signing and ratifying the international agreements. Governments in international politics are still more likely to be driven by economic national interests than by domestic affairs, where consumer rights and ecocentric policies can hold them to account (at least in developed democracies). Global governance in the area of agrochemicals is as yet, therefore, limited in comparison to domestic, environmental, and health policy in much of the Global North and insufficient in providing hope for the eradication of the occurrences of environmental pollution and human poisonings which still blight much of the Global South in particular.

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[6] The US government represents a classic case of "transgovernmental relations" when dealing with global pesticide issues with the position of delegates at the Codex, PIC, and POPs regime meetings promoting international harmonization and less precautionary approaches to classifying chemical toxicity which are often at odds with the standards of the Environmental Protection Agency.

The first steps taken in global pesticide governance may be small ones, but they are still significant. Norms once established cannot easily be erased. Unraveling agreements clearly made with regard to human and environmental interests is more difficult than preventing them in the first place since the selfish pursuit of profit is more clearly exposed as such and reputation does count for something in the contemporary interdependent world. The precautionary principle cannot be wished away by the United States or the chemical industry. Methyl bromide is still going to be phased out despite the increasingly desperate rear-guard action fought by the US government. Codex standards are still based on precautionary calculations of human toxicity even if they are being exploited by big business as a means of circumventing more stringent domestic standards. The POPs regime is currently limited in what it can do, but now in force, it can only broaden and deepen. The Stockholm Convention Conferences of the Parties have discussed a working compliance mechanism to improve implementation, and new chemicals have been added to the original POPs list, thanks to concerted lobbying by PAN and many other groups present as observers at the Review Committee meetings and independent assessments by an epistemic community representing no vested interests.

The chemical industry has no direct interest in curbing its freedom to trade in pesticides as it chooses, but the Bhopal disaster and public fears of continued exposure to presumed obsolete chemicals brought them to a negotiating table laid by civil society actors. Once at the table, the industry has been able to negotiate from a position of strength and further their own interests, but the fact that they have had to come to the table is still an important breakthrough in the development of global governance. Ultimately, the global governance of agrochemicals is in the interests of both sides at the table, even if their motivations for being there are different. Actors driven by different values can, nevertheless, reach mutually beneficial agreements. Just as “bootleggers and Baptists” supported alcohol prohibition in the United States, environmentalists and the chemical industry have found themselves seeing global pesticide regulatory measures as means to very different ends.

Agrochemicals are here to stay as their benefits are still apparent to food producers and the side-effects tolerated by most farmers and consumers. Agroecology informs agrochemical use in much of the developed world, but the application of more sustainable strategies remains limited in the industrializing world. The demand in the West for organic food continues to grow, but so does the global demand for food. However, the side effects of agrochemical use are sufficiently apparent that their production, use and trade will also continue to be brought under tighter scrutiny and regulation. As with ecological principles in general, many farmers, citizens, and regulators in industrializing countries need to be convinced that sustainable agrochemical use does not compromise their economic development. This is the challenge for proponents of agroecology.

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Critical Evaluation of Genetic Manipulation for Improved Productivity: Is This a Sustainable Agenda?

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Abstract Despite brilliant successes that have been achieved with the applications of genetic improvement in food production to sustain large monocultures and to compete in a global market economy, the chronic crises affecting agriculture have not been resolved. An expansion of mechanized, modern agriculture with intensive chemical use has contributed to the reduction in the farming population worldwide, thus destabilizing local economies and food security. Nevertheless, the emerging bioeconomy is supporting the cultivation of genetically modified (GM) crops as the most advanced approach to improve the quality of life for all while successfully resolving the foreseeable, global challenges of providing adequate food, fiber, and renewable energy for a growing human population. The global area planted with GM crops has more than doubled worldwide in the last decade, especially in developing countries, and resulted in a reduction of cultivated germplasm due to the diffusion of a limited number of genetically improved varieties whose products are mainly

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directed toward the global market. Research foci for GM crops are purposefully oriented to make crops withstand harsh environmental conditions as the effects of global climate change rapidly alter the attributes of agricultural landscapes. Also, crops are genetically modified to yield more food, fiber, and renewable energy and to withstand the effects of pests and disease. These are additional, desirable goals of the GM research agenda, yet they can be meaningless if they are not delivered to local farmers with all the advice and integration which are the basis for achieving sustainable agriculture.

This review presents a critical assessment of GM crops, their potentialities, and drawbacks based on a comprehensive evaluation of current literature reporting both positive and negative aspects of GM agriculture. The debate on this topic is extremely relevant. Recent findings on possible risks for human health about the most diffused genetically engineered traits suggest that an application of GM technology in agriculture should not be overestimated.

Without denying the value that genetic engineering in agriculture may possess for certain agrarian contexts, we also discuss the possibility of applying sustainable crop management approaches to food production practices as a much needed alternative to increase biodiversity within cultivated fields. This and similar efforts recreate farming conditions that could make agriculture more sustainable, thus restoring ecological services useful for the entire ecosphere, while returning the added value of agricultural products to farmers.

Keywords Agroecology • Bioeconomy • Biodiversity • Biofuels • Biotechnology • Ecological services • Ethics • Food safety • Food security • Genetic engineering • Genetically modified organisms • Germplasm • Recombinant DNA • Soil • Sustainability • Transgene

1 Introduction: Agricultural Paradigms

Improving edible crops through selection and breeding has been practiced since the dawn of agriculture, allowing human communities to settle down and prosper, despite ongoing struggles they had to endure against pests, disease (Gliessman 2007; Altieri 1995), and, in more recent times, the whims of unpredictable weather patterns. Insects, weeds, fungi, and the physical factors involved in any kind of agricultural production (weather conditions, soil, water, air quality) have always challenged growers to achieve abundant crop yields from one growing season to the next. Prior to the Industrial Revolution, farmers were aware of the connections between living beings and the environment, especially for those that contributed directly to the production of human foods. This knowledge that was passed from generation to generation for millennia preserved a culture of agriculture that changed when the successes of the first agro-industrial paradigm began to emerge on the belief that with specific technological tools the principles of agriculture could become applicable anywhere in the world (Gliessman 2007), at any time.

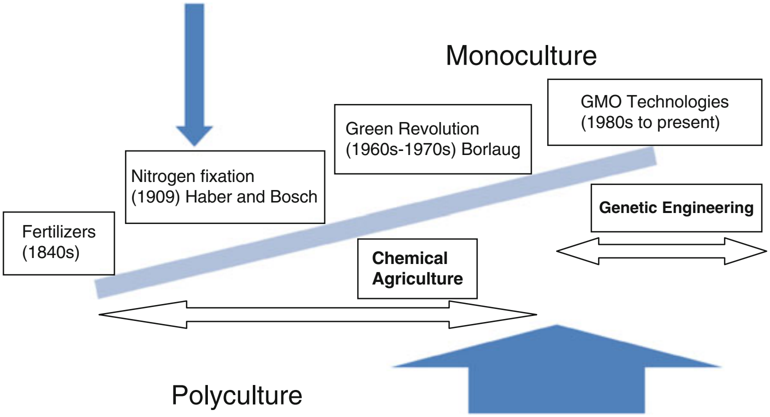

Fig. 1 Evolution of agricultural paradigms in relation to crop diversity

This agricultural revolution coincided in Europe with the invention of the first mechanized implements that operated through the combustion of nonrenewable fossil fuels and the discovery of synthetic fertilizers. These technologies triggered a culture of food production over large scales and for higher levels of specialization in agriculture. The first employment of fertilizers, for example, soon began to erode the indigenous cultures of practicing ecological agriculture (Altieri 2003; Altieri and Merrick 1987) as the new chemical paradigm of food production achieved its impressive successes with much higher crop yields (Borsari 2011). The need to increase the amount of food production, the reduction of farmer labor, together with the lack of information on possible drawbacks of indiscriminate application of newly developed chemical fertilizers and pesticides, led to a fast expansion of modern agriculture.

At the same time, agricultural research was channeled toward a very pragmatic and goal-oriented approach aimed at increasing agricultural output to insure food security for a growing human population (Tilman et al. 2002). Within this framework, agriculture in the northern hemisphere targeted the pursuit of farming practices that greatly supported emerging technologies since the years of the Industrial Revolution. As a result, the first synthetic fertilizers came about and their application to fields showed remarkable crop yields and superb economic returns for those who embraced the chemical agriculture model. Later, more chemical products (e.g., herbicides, insecticides, fungicides, and miticides) became available to farmers in order to control the proliferation of competing organisms (Borsari 2011; Raeburn 1995). These initial successes reinforced the idea that chemistry was the technological tool needed to enhance food production and an important support to farm size expansion. As a consequence, in less than a century, farms became large monocultures in the industrialized world as new tools of production (improved varieties, new machinery, and agrochemicals) and technologies (molecular breeding) were developed (Fig. 1).

In a few decades, however, this approach showed its limits since the struggle against crop pathogens was only attenuated temporarily by this new model of food production (Borsari 2011; Gliessman 2007). Rather, it became more challenging to maintain crop yields as noxious organisms became naturally selected to withstand chemical treatments, thus demanding new poisons be synthesized and used to keep the populations of these organisms under control. Also, the threats to the environment and to animal and human health have provided substantial evidence that abuses of chemical usage within our food system can have grave consequences (Kalevitch and Kefeli 2007; Raeburn 1995). In fact, at the beginning of the 1980s in Europe and in the United States, the organic movement grew and diffused an agricultural model that could represent an alternative to intensive industrial agriculture in order to produce quality foods having little or no chemical residues. At the same time, a significant segment of the fruit production sector began to transition from the conventional use of chemicals toward an integrated management of orchards, which is based on bringing together a variety of production techniques (agronomic, biological, and ecological), to help increase yields and fruit quality, while limiting the use of chemicals as much as possible. Chemical applications could even be avoided completely if an economic threshold of damage was not reached, allowing for greater emphasis on banning from the market all chemicals with high pollution risk and toxic effects on humans and the environment.

The discovery of DNA structure and a better understanding of its functions in regulating keystone biological processes such as protein synthesis and gene expression launched (approximately 30 years ago) agriculture into a new era of productivity and innovation. The immediate challenges in controlling pests through chemical warfare led the research focus of the chemical industry to invest resources in biotechnologies and their applications in agriculture (Mikulas 2004). In this context genetic engineering can be considered as the most advanced biotechnological application to genetic improvement in agriculture. In fact, genetic engineering is a biotechnology application based on DNA manipulation and gene transfer among species in order to obtain "new" organisms with desired characteristics. Research on genetically modified (GM) crops has allowed, for example, the insertion of genes from certain organisms into cells of unrelated species and to develop crops more resistant to pathogens in order to maintain, or potentially increase their yields, prolong food shelf life, or simply make food more attractive to consumers.

A sincere interest in the development and cultivation of GM crops in many countries of the world has been growing since GM soybeans [*Glycine max* (L.) Merr.] were first commercialized in 1996. According to James (2010), GM crops are cultivated on about 148 million hectares, and this area has been increasing continuously since the beginning of the twenty-first century. There is a current trend among farmers to grow more GM crops around the world, increasing this value by about 15.4 million hectares across 29 different countries. The United States has the highest level of GM cultivation in the world, followed by Argentina, Brazil, Canada, India, and China, and together these six countries cultivate 92 % of all GM crops worldwide (James 2010). Countries with emerging economies have experienced variable gains in productivity by adopting GM technology. In India, for example, the introduction of GM cotton resulted in a major economic failure (Buiatti 2004), even though in traditional cotton cultivation areas of the United States GM cotton reduced the use of chemical insecticides significantly compared to non-GM cotton (NRC 2010). However, the rate at which GM plants are being employed in developing countries is faster compared to their adoption in the industrialized world, and traits for which GM crops are particularly desired include tolerance to high levels of herbicide application and resistance to pests and other pathogens (James 2010). The most widely cultivated, bioengineered crop in 2010 was soybean, and this covered more than 50 % of the total GM crop area worldwide, followed by maize (*Zea mays* L.) at 31 %, cotton (*Gossypium hirsutum* L.) at 14 %, and canola (*Brassica napus* L.) at 5 % (James 2010).

Despite the support that many agricultural scientists and their research institutions give to biotechnology, a skeptical attitude remains among a majority of small-scale farmers, other scientists, and consumers that genetic breakthroughs offer positive, long-term solutions to the challenges affecting modern farming. Criticism toward agricultural biotechnology stems from the linear, simplistic mode of applying knowledge to a living world, which instead is biologically diverse, complex, dynamic, and only partially known (i.e., largely nonlinear) (Altieri 2004; Carman 2004).

Moreover, rapid changes continue to occur as terrestrial ecosystems become converted into farm land or larger cities expand their suburbia, amplifying present pressures and stresses to increase food production for a growing human population. These are exacerbating habitat conservation efforts, while biodiversity is lost at an alarming rate in the conversion of ecosystems through ongoing efforts to continue to fulfill increasing human needs for food, fiber, and energy (e.g., Doyle 2013). New knowledge is often applied to rapidly solve one problem without considering that simplistic decision-making may only contribute to the generation of new, more challenging problems. Current and increasing pressures for producing more food and fulfilling the high demands of energy could threaten environmental homeostasis and jeopardize the livelihoods of millions of small-scale farmers worldwide and, ultimately, humanity.

On the other hand, supporters of genetic engineering in agriculture claim that biotechnology is leading the way in food production and that GM crops have positive environmental effects in reducing the input needs of agrochemicals into the environment (Macek et al. 2007). However, genetic engineering still cannot answer many questions related to the safety and sustainability of the form of agriculture it proposes since this has been designed to solve specific, agronomic problems within an agricultural system that is not always integrated with the environment and ecosystem where farming is practiced. Therefore, a renovated ethic for modern farming needs to be developed, as well as new approaches aimed at enhancing the sustainability of agricultural practices. These goals could be achieved by increasingly integrating them within the ecosystem to which they belong, thus overcoming all the drawbacks of intensive agricultural practices that have been experienced until present times.

Supporters of GM crops continue to argue that the need for genetic engineering is driven by the necessity of feeding a more populated world and for improved nutrition and quality of life on a global scale. However, the employment of new technologies in the developing world has not always been capable of emancipating tropical countries from their chronic relapses of food crises. The Green Revolution and more recently GM crops have not succeeded in defeating world famine; rather they sometimes contributed to disrupting small-scale farming systems whose resilience against environmental adversity has always been successful (Shiva 1991). The high diversity of crops and services that these systems have been able to maintain over centuries has been vital for insuring food at low environmental cost by the valorization of native animal and plant ecotypes that sustained local communities for centuries (Commissione Internazionale per il Futuro Dell'Alimentazione e dell'Agricoltura 2009). Instead, genetic engineering in agriculture has contributed to the silent demise of a majority of small-scale farming systems, which are much better examples of agricultural sustainability, and to massive losses of local genetic resources (Borsari 2011). At present, an additional important issue which is strongly debated at various levels of the global food production industry is the labeling of foods derived from genetically manipulated organisms and its ecological, economic, health, energy implications for maintaining food yields and quality of life for all human beings.

The purpose of our review is to critically analyze the value of the most recent breakthroughs in GM technology in agriculture to highlight its benefits but also its limitations. Some applications of biotech agriculture may be valuable in certain agricultural contexts such as those of industrial countries for biofuels or phytoremediation purposes (Macek et al. 2007), yet they may remain unfeasible for low-input agricultural systems, which are typical in the majority of underdeveloped and developing countries and their economies.

2 Agriculture, Biotechnology, and Biodiversity

Twenty-first-century agriculture is predicated on the need for insuring food security, improving nutrition, and reducing poverty worldwide. Biotechnology companies claim that genetically modified organisms are the much needed tools to achieve these goals (Altieri 2004). Two assumptions support the view of the genetic engineering paradigm: the first being that hunger is due to a large break in continuity between food production and human population density, whereas the second is that biotechnology is the vehicle for insuring the highest agricultural outputs (Altieri and Rosset 1999). However, there is no relationship between hunger and population level, because for every densely populated and hungry nation like Nigeria or Bangladesh, for example, there is a scarcely populated and hungry nation like Mozambique or Bolivia. Moreover, despite the potential that GM crops may have for improving food quality and quantity, the relationship between food production in the industrialized world versus developing countries remains skewed and vulnerable

Table 1 Contrasting attributes of organic and GM agriculture (Modified after Altieri 2005)

Attribute	GM agriculture	Organic
Oil dependency	High	Medium
Labor requirements	Low, hired	Medium, family, or hired
Management intensity	High	Low to medium
Mechanization	High	Low to medium
Plant diversity	Low	Medium to high
Crop variety	One or few GE crops	Medium to high
Integration of crops and livestock	None	Little
Insect pests	Very unpredictable	Unpredictable
Insect management	Insect-resistant crops	IPM, biological control
Weed management	Herbicide-resistant crops	Cultural control, rotations
Disease management	Chemical, vertical resistance	Antagonists, horizontal resistance
Plant nutrition	Chemical	Organic fertilizers, manure
Water management	Large-scale irrigation	Water-saving systems
Information-based	High	Low to medium
Knowledge-based	Low	High
Costly off-farm inputs	High	Low to medium

(Shiva 1991). The modification of plants and animals through genetic engineering is the biotechnological context that from the 1980s to present times has generated the most controversy. Several arguments are at the center of the diatribe between supporters and antagonists of GM technology, with the primary argument being that transgenic plants and animals are employed for human nutrition and are grown in direct contact with other species, thus posing serious risks to environmental and human health. Therefore, it is imperative to verify what developments may occur in the near future with GM technologies in agriculture and for what kinds of markets GM foods could be addressed while assessing the advantages and disadvantages of this modern approach to agriculture. Buiatti (2004) conceded that the GM products available on the market are limited to a handful of herbaceous plant species, conceived primarily to withstand insect infestations (*Bt* crops) and/or to survive treatments with high dosages of herbicides (HT crops); thus, their true value in agriculture remains debatable. However, GM crops have quickly affected agriculture in Africa (Paarlberg 2006) and achieved outstanding cotton yields in China (Huang et al. 2004). Their potential for further improvement of drought tolerance and to compete successfully against pathogens so as to reduce the need for pesticides (Macek et al. 2007) has enhanced the enthusiasm for GM crops.

It may be necessary then to delve more into the philosophical framework which has emerged since the early 1980s in support of genetic engineering in order to understand its immediate traction in the agricultural scenario of the industrialized world. The philosophical and technical attributes of genetic engineering (GM) in agriculture versus organic farming are literally at opposite extremes on a conceptual scale of the modern food production system (Table 1).

Another fundamental difference between GM and traditional agriculture is related to seed supply. Seed is patented and always purchased by farmers from multinational corporations in GM agriculture. However, it is often saved from previous crops or purchased from small local seed distributors in traditional farming systems (Mikulas 2004).

According to Altieri (2004), the crop yields that GM agriculture claims to achieve should not even become an issue to justify its promotion and further expansion as sufficient grain is produced to support a population of eight billion people if it is not fed to animals. An increasing affluence (based on per capita meat and animal product consumption) in densely populated countries like China and India has diverted most grain production to feed livestock, thus generating a new set of health, agricultural, and environmental challenges for all. Other challenges affecting food production like water availability, land depletion, and increased resistance by pathogens often give even more support to biotechnology in modern agriculture (Huang et al. 2002). In contrast with the high-technology paradigm of food production, Altieri and Rosset (1999) presented an eloquent rationale in ten theses to explain why biotechnology in modern farming cannot provide for the ambitious promises of ensuring food security and conserving environmental integrity and ecological services on a global scale, thus constructing a very strong case to make all stakeholders in agriculture reflect on the vulnerability of the GM agriculture paradigm. A schematic summary of the above-mentioned theses is presented in Table 2.

In temperate climates, an increase in soil fertility is related to the accumulation of humified organic matter; the creation of vegetal soil (Zucconi 2003) is the primary means of expanding biomass production per unit area. Nature accomplishes this process efficiently, through the humification of organic matter, although this process is somewhat neglected in agriculture, leading inevitably to an impoverishment of soil quality. The humification process is also a key component in the natural suppressive ability of soils upon soil pests (Zucconi 2003). Organic residues are used by microorganisms as sources of energy and nutrients. Simple molecules are easily and rapidly metabolized so that microorganism populations can grow more rapidly than when more complex and stable polymers are degraded. The accumulation of residues from a single crop disrupts the humification process, inducing odd decompositions that delay the stabilization and release of toxic metabolites (Zucconi 2003; Zucconi et al. 1984). These in turn may induce specific allelopathic effects (dispathy) accounting for “soil sickness” (Zucconi and de Bertoldi 1987). Root absorption, in particular, may be hindered by these toxins (Giorgi et al. 2008; Neri et al. 2005; Zucconi 1993, 2003), promoting dystrophies, root dieback, and eventually disease (Bonanomi et al. 2006; Neri et al. 1996) in the crop, or crops, being cultivated.

The sustainability of an agricultural system can be significantly improved through better control of soil organic matter evolution, by mimicking the natural process of humification, a process needing biodiversity, crop rotations, use of organic amendments, and reduction of pesticides, fertilizers, and soil tillage practices, to become truly effective. A restoration of the humification process within soils

Table 2 Claims of biotech agriculture benefits contrasted by the agroecological approach to food production and security

Thesis	Biotech agriculture claim	Agroecological viewpoint
1	Biotech agriculture can supply sufficient food for the world and thus defeat hunger	There is no relationship between population size and hunger in a certain country. Rather, hunger stems from inequality and lack of easy access to food and land
2	Biotech agriculture can alleviate poverty in the developing world by increasing agricultural output	The interest of biotech agriculture is focused on increasing lucrative opportunities for food corporations by controlling germplasm
3	Biotech agriculture can decrease the cost of seed-weed management per acre with herbicide-resistant crops	This advantage may be short-lived as more herbicide-tolerant super-weeds adapt and evolve
4	Engineered crops in biotech agriculture produce higher yields	Studies conducted by the United States Department of Agriculture in 1998 and 1999 disproved this claim
5	Many scientists in favor of biotech agriculture claim that the ingestion of genetically engineered foods is safe	There are potential risks in consuming genetically engineered foods as the new proteins produced in such foods could: (a) Act as allergens or toxins (b) Alter the metabolism of the food causing it to produce allergens or toxins (c) Reduce its nutritional quality or value
6	Biotech agriculture can more successfully control the damage caused by insects with insecticide resistant crops using its approach "one pest-one gene"	Pest species rapidly adapt to the insecticide present in the plant and consequently develop resistance
7	Biotech agriculture is safe and free from environmental risks	Biotech agriculture threatens the sustainability of agriculture through homogeneity of the landscape leading to genetic erosion
8	Biotech agriculture has expanded through marketing and distribution agreements without regulations in developing countries by simply assuming that biotech crops are safe	There are very limited funds even in the United States to assess the safety of genetically engineered crops
9	Biotech agriculture is supported by funds derived from the private sector	These funds should be devoted to enhance research in ecologically based agriculture
10	Biotech agriculture is technology-centered and this is its approach to achieve success in food production	The ecological services provided by biodiverse agroecosystems sustain and maintain the productivity of food systems

also enhances a natural suppressive ability against soilborne diseases, maintaining strong, healthy plants that are less vulnerable to pathogens and parasites, thus reducing, or even eliminating, the need for pesticide applications.

The inevitable loss of biodiversity caused by intensive agriculture and the significant changes to the landscape constitute additional issues that deserve much attention (e.g., Storkey et al. 2012; Power 2010; Kremen 2005), as agriculture continues to extend crop cultivations onto less suitable, marginal lands. The surging rationale explaining this trend is linked to the increasing needs of securing more food for a growing human population and to produce crop biomass for use as renewable biofuels. A major drawback of intensive agriculture consists of the demise of native pollinators including honeybees, which remain vital for efficient and productive farming operations. In the upper Midwest region of the United States and in other regions of the world, the homogeneity of agricultural landscapes based on monocultures of maize and soybeans are biological deserts to bees, while canola and alfalfa fields provide only a narrow window of opportunity for bees to collect nectar and pollen consistently and throughout the growing season (M. Spivak, personal communication; April 7, 2011). Additionally, the widespread and heavy use of pesticides (especially on HT soybeans and cotton) has weakened pollinators' abilities to withstand disease, thus contributing to the massive losses of honeybee colonies through a new pathology identified as "colony collapse disorder" (CCD). The future of food security can be seriously jeopardized with irreversible declines in bee populations worldwide (Spivak et al. 2011). Unfortunately, the typical agricultural landscape designed for the cultivation of GM crops remains homogeneous and often laden with toxic chemicals, despite recognizing the need for reconstructing refugia within farms (Vidrine and Borsari 1999) or designing more biodiverse landscapes through farmscaping (Pickett and Bugg 1998) to retain the necessary pollination and biological control services.

Although notable studies have confirmed the higher productivity of biodiverse grassland (Tilman et al. 1996) and forest (Iverson et al. 1997) ecosystems when compared to agricultural systems, the relentless loss of natural habitats remains ubiquitous and apparently unstoppable. Even in cultivated fields it has been demonstrated that simultaneous cultivation of more than one crop benefits nutrient uptake, enhances resilience against environmental stresses (Gliessman 2007), and attracts pollinators and beneficial insects (Spivak et al. 2011; Pickett and Bugg 1998; Vidrine and Borsari 1999). These findings suggest the need to develop more sustainable models of food production and to establish better dialogue links with farmers and their organizations while seeking more opportunities to enhance the approaches and practices of agroecology. Employing the synergies and interactions within farming systems, living organisms and the environment could provide valuable opportunities to solve problems and challenges in present, as well as in future food production systems (Borsari 2011).

At the same time, the emerging bioeconomy is stressing the cultivation of GM crops to produce a variety of nonfood products such as biomass for biofuels (Chapotin and Wolt 2007), in order to assist with an increasing need for renewable energy in the United States (Tilman et al. 2002) and abroad. Thus, the cultivation of energy crops legitimizes research focused on the genetic improvement of these and similar commodities, supporting an aggressive employment of biotechnology to resolve as expeditiously as possible the energy issues affecting a growing society, on a global scale.

3 Genetically Modified Crops, Biofuels, and Sustainable Agriculture in the United States

3.1 Present Approach to Renewable Biofuel Production

Agriculture remains an energy-intensive and energy-expensive human enterprise, requiring, in the United States alone, the consumption of about 40 % nonrenewable oil (W. Jackson, personal communication; August 8, 2008). At the same time, continuous threats to small-scale farming due to an expansion of monocultures that are better suited to the biotechnology paradigm in agriculture have been accentuated by an amplification of maize production to supply ethanol as a form of renewable fuel (Wilson et al. 2012). Together with maize, more plant species are of considerable interest as biomass crops, including switchgrass (*Panicum virgatum* L.) and poplar (*Populus* spp.) already at the top of the list, followed by canola (*Brassica napus*), soybeans (*Glycine max*), sorghum (*Sorghum* spp.), and sugarcane (*Saccharum* spp.) (Chapotin and Wolt 2007). These taxa are being studied genetically to assist with the enormous energy demand in the United States with the expectation of lessening its dependence on foreign oil.

Recent fluctuations in the price of fossil fuels sharply increased food costs, thus amplifying the symptoms of a global agricultural crisis that primarily affects family farms (Borsari et al. 2009). The economic crisis of 2008, which produced riots about rising food prices in the developing world, indicated how society is strongly dependent on nonrenewable oil. Consequently, to counteract unpredictable price surges in nonrenewable fossil fuels, farmers in the United States have been growing more maize with GM seed in partnership with the emerging ethanol industry. The decision for intensifying the cultivation of maize has spurred a significant rise in price for this commodity, and unavoidably for food costs.

Notable are the environmental implications for this recent agricultural political shift. For example, maize farming has accentuated soil erosion and reduced soil and water quality (Reicosky et al. 1995) because crop rotations have been neglected. This, and similar situations, have accelerated the collapse of agrobiodiversity (Altieri 1999, 2004; Vidrine and Borsari 1999; Pickett and Bugg 1998), posing serious threats to the extirpation of beneficial species and jeopardizing valuable ecological services linking pollination to food production.

Producing maize for ethanol requires massive amounts of capital investment and land resources to develop the needed infrastructure necessary for the processing, transformation, and delivery of this new commodity. Such a venture has been responsible for tremendous conversions of land into maize monocultures, which increased from 31.9 million hectares in 2002 to 37.6 million hectares in 2007, hijacking interests among land owners for land conservation projects and programs (Wilson et al. 2012). Paradoxically, ethanol from maize does not even appear to possess the advantageous characteristics capable of aiding in the quest for fulfilling the enormous energy needs of the United States. A comparative analysis of ethanol from maize and biodiesel from soybeans, for example, showed that ethanol yields

25 % more energy than the energy invested in its production, whereas biodiesel yields 93 % more energy. Compared with ethanol, biodiesel releases just 1.0, 8.3, and 13 % of the agricultural nitrogen, phosphorus, and pesticide pollutants, respectively, per net energy gain (Hill et al. 2006). Relative to the fossil fuels they displace, greenhouse gas emissions are reduced 12 % by the production and combustion of ethanol and 41 % by biodiesel, which also releases less air pollutants per net energy gain than ethanol and requires less input. As well, biofuel cannot replace oil without impacting food supplies and, even if all United States maize and soybean production were dedicated to biofuels, it would only provide a limited amount of energy (12 % of gasoline and 6 % of diesel demand). Hill et al. (2006) concluded that biodiesel provides sufficient environmental advantages, and together with other biofuels such as "synfuel hydrocarbons" or "cellulosic ethanol," if produced from low-input biomass grown on agriculturally marginal land or from waste biomass, could provide more viable supplies and environmental benefits than food-based (maize) biofuels.

Regardless of these findings, enthusiasm for ethanol from maize has led to an increasing use of marginal farmland for growing this plant species, which has exacerbated soil loss one step further, while stretching even more the resources needed to achieve the required yields. This effort has been far from achieving agricultural sustainability and has seriously damaged soil and water sources and destabilized many farming communities. Maize cropping remains in chronic need of agrochemical products and several other off-farm inputs to retain the expected yields, with soil erosion at the top of a scale of threats to the long-term productivity of agricultural systems. According to Hill et al. (2006), a biofuel should provide a net energy gain, have environmental benefits, be economically competitive, and be producible in large quantities without affecting food supplies in order to be a viable alternative to nonrenewable energy sources.

3.2 *Prairies for a Sustainable Bioenergy Production System*

We remain dubious that the emerging biofuel model of production can truly become successful if constructed with the similar approaches that led to the design of annual monoculture systems, although opportunities for the growth of GM crops to be employed in the bioenergy industry are available at present. On the contrary, farms of native and perennial polycultures as feasible forms of agroecosystems for the growth of food and biomass for biofuels possess outstanding potential to develop an agriculture less dependent on oil (Jackson 2010) and be resilient and truly sustainable (Glover et al. 2010). The prairie ecosystem was, before agriculture, the largest ecological unit in the North American continent and the fertility of its soil constituted the outstanding attribute that European settlers inherited for the development of one of the most productive farming systems in the world (Borsari and Onwueme 2008; Jackson 2002; Smith 1998). Native grasslands had almost disappeared within the last century due to the fast conversion process of prairies into large monocultures. However, through modest restoration efforts, several prairie patches have been reconstructed in the last 30 years across the North American plains (Smith 1998), as scientists better understand their functioning and potential to develop more sustainable landscapes (Borsari et al. 2010) and agriculture (Jackson 2002). The interest in prairie biomass as a potential valuable source of renewable biofuel can be pursued by pelletizing the dry stalks and leaves of native grasses and forbs at the end of the growing season to be employed as a renewable energy source for heating purposes.

The higher productivity of low-input, prairie polyculture systems has been known for some time (Tilman et al. 1996). As a result of this research outcome and an ever-increasing public desire and need for sustainability in modern agricultural systems, an interest in prairie restoration has been rapidly rising in the upper Midwest region of the United States (Smith 1998) to design and manage pastures that mimic the functioning of prairies (Jackson 1999). This emerging trend is persuading the farming industry and community to rethink many agricultural practices and encourage innovative small-scale ventures that are more focused and committed to sustainability (Wilson et al. 2012). To this end, farmers in southeastern Minnesota (United States), for example, have started to subsidize their heating bills in winter by employing maize stover, although this method has shown that fields with 40 % or more of the maize stover removed may incur topsoil losses of about 560 kg ha^{-1} per year (Comis and Perry 2009). On the other hand, and more specifically for this particular bioregion of the United States, patches of native prairie mixtures can be pelletized and employed as a feasible and renewable source of energy, and this approach seems much more sustainable than maize stover for several reasons. The use of prairie grasses for burning does not require any removal of maize stover from the field, which decreases soil erosion rates significantly (Montgomery 2007). Furthermore, restored prairie patches have been producing 51 % more usable energy per hectare on degraded land than ethanol from maize produced from fertile, agricultural soils (Tilman et al. 2006). The massive root systems of prairie perennials (Fig. 2) grown in polycultures improve water and soil quality while adding to the overall ecological diversity of the farm (Tilman et al. 2006; Jackson and Jackson 2002).

Therefore, prairie reconstruction effort enhances the stability and resiliency of an ecosystem upon which agricultural land is better preserved while at the same time helping to reduce the operating costs of production. Also, the extensive root systems of native prairie plant communities increase the amount of soil organic carbon while sequestering even more carbon in the form of carbon dioxide (CO_2) from the atmosphere, which is a major contributor to global climate change (Omonode and Vyn 2006). Prairie reestablishment enables farms to sequester as much carbon as they would produce with the use of fossil-fuel-based machinery (Tilman et al. 2006), suggesting that this type of carbon neutrality empowers farming systems to further wean themselves from nonrenewable oil (Wilson et al. 2012; Jackson 2010). Reconstructed prairie plant communities have also been proven to provide habitat for pollinators (Vidrine and Borsari 1999), abundant nectar sources for honeybees (Spivak et al. 2011), and natural enemies of crop pests and to increase on-farm

Fig. 2 Model of the root system of a perennial prairie grass at the Manitoba Museum in Winnipeg, Manitoba, Canada

biodiversity (Bianchi et al. 2006; Landis et al. 2000; Pickett and Bugg 1998; Altieri 1995). More ecological functions and services are ensured by prairie grasses planted around agronomic crops by keeping pesticides, soil, nitrogen, and phosphorus from leaching away (Lovell and Sullivan 2006), in addition to sequestering more carbon compared to agricultural lands (Kucharik 2007), while reducing the amount of atmospheric carbon and contributing to soil fertility.

An agriculture paradigm that relies on native perennials was proposed by Jackson (2010) as an imperative provision to his "50-Year Farm Bill." Planting native perennial species marks the desire to rethink the agricultural practices of the last 150 years while implementing a vision to conceive farms as a natural habitat (Jackson and Jackson 2002), where biodiversity is valued and enhanced.

Reconstructing prairie on agricultural land not only aids in the restoration of vanishing agrobiodiversity but is extremely valuable to the maintenance, resilience, and productivity of farms (Altieri 1999). Conspicuous capital investments have been made to develop the tools and technology to convert perennial plants into biofuels instead of employing annual species (Glover et al. 2010) like maize. The challenge remains to continue studying the potential of prairie plants, without affecting land and resources, to continue producing food crops. In the meantime, additional research could determine which diverse composition of native prairie species produces maximal biomass yields and this knowledge could benefit farmers interested in employing prairie pellets as a renewable source of energy. Prairie pellets produce a comparable amount of biomass to maize stover, encouraging the conversion of agricultural fields into prairies one step further in the vast plains of North America (Table 2) without affecting prime agricultural soils, as prairie reestablishment can be achieved successfully on marginal land. With the recognition of the tangible financial benefits and intangible, yet priceless ecological benefits that ecosystems provide to society (Altieri 1995, 1999), the need for responsibly managing and conserving the few remaining prairie ecosystems remains critical to the well-being of all. This work exhibits the necessary combination of sustainable agricultural practices, effective financial management, and sound stewardship and shows a tangible example of an innovative, “grass-roots” approach that is necessary to lead agriculture in the United States and beyond into a new, sustainable era. It is prudent to encourage the cultivation of native, perennial polycultures rather than other nonnative biofuel crops (Glover et al. 2010). The future condition of our agricultural systems will be dependent on individual farmers who are willing and able to recognize the importance of developing agricultural systems that can produce useable energy while also preserving the integrity of the ecosystems that preceded them. The burden of the transition to a more sustainable system is dependent on our body of knowledge. It also hinges directly on farmers’ abilities to put into practice projects that can be feasibly employed using current agriculture practices, bypassing lengthy legislative processes, while adding significant benefits to the environment. To this end, we support the vision of prairie farming to be embraced by more farmers in the United States and in several other grassland regions of the world and advocate a vision for twenty-first-century agriculture that is restorative (Borsari 2011) and strongly committed to enhancing agrobiodiversity (Table 3).

4 The Ethical, Socioeconomic, and Political Issues of Biotechnology in Agriculture

The evolution of agricultural biotechnology is often driven by decisions made by company investors, with most agricultural innovations being profit-driven rather than need-driven (Altieri and Rosset 1999). The root of such a lucrative attitude derives from the industrial revolution and its mechanistic and reductionistic approaches, supporting the idea that the world is simply a deposit of goods and

Table 3 Summary statistics for biomass yields for pellet production, crop species, and plot type in a family farm in southeastern Minnesota, United States (From Wilson et al. 2012)

Plot	Year harvested	Mean yield (kg ha^{-1})	Crop type	Land type (agricultural vs. marginal)	Timing of harvests
Grasses and forbs	2008	1,140 ± 780	Polyculture	Marginal	Autumn
	2009	2,450 ± 740			
Prairie grasses	2008	2,170 ± 870	Polyculture	Marginal	Summer, autumn
	2009	2,930 ± 990			Autumn
Maize	2008	3,150 ± 680	Corn	Agricultural	Autumn
	2009	N/A			

N/A data not available

resources to be harvested and manipulated, as these have the sole scope of creating wealth. Within the principles of this ethic, problems of poverty, food scarcity, and economic development remain of marginal or no interest at all to the genetic engineering industry whose real thrust is to continuously generate higher profits.

The Commissione Internazionale per il Futuro Dell'Alimentazione e dell'Agricoltura (2009) shared similar views describing in its manifesto "[Genetically Modified Organisms] GMOs as a perfect example of privatization and commercialization of scientific knowledge by a handful of powerful corporations that control GM crops in a global market" (p. 32). According to Mandel (2004), a dysfunctional regulatory system needs to be fixed in order to promote the development of genetically engineered crops in a transparent manner and with solid scientific information. However, a much nebulous topic is the ethical issue of genetic engineering science and its applications to agriculture because its knowledge is no longer finalized toward a better understanding of nature, but rather to the production of patented items and processes aimed at increasing corporate profits (Mikulas 2004). This antagonistic (and often inimical) approach to more traditional forms of agriculture originated with the alliance between private corporations and public scientific institutions such as agricultural universities, thus diverting the knowledge of farming to the servicing of private interests (Altieri 2003, 2004, 2005). The intellectual property rights of GM seed have also legitimized an appropriation of traditional knowledge by the same corporations that have patented manipulated germplasm as an innovative breakthrough (Borsari 2011) while impeding its use by those farmers who first developed it and preserved it from generation to generation (Shiva 1991). Consequently, the philosophical disparity between food production in traditional farming systems and biotechnological agriculture has grown deeper over the late nineteenth and twentieth centuries (Fig. 3).

Giampietro (2002) argued that it is difficult to evaluate the real benefits of genetic engineering without embracing a process of social learning to enable agriculturists to evaluate the tradeoff of biotechnology in agriculture, with scientists being the facilitators of this process, if they are willing to serve in this capacity. The applications of biotechnology in agriculture are subverting the diversity and natural resilience of the agricultural world while also homogenizing the knowledge

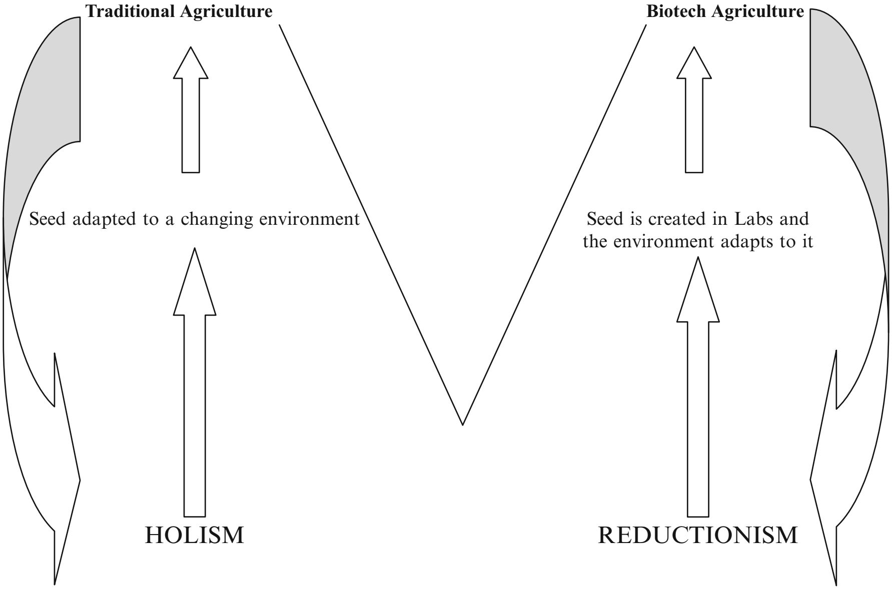

Fig. 3 The paradigmatic gap of modern agriculture

and practices of producing food that diverse human communities have been passing to their descendants for millennia. A reductionist type of agriculture may offer simplistic solutions to short-term challenges, but it should also realize its limitations due to the complexity, adaptability, and resilience of the living world.

A highly centralized food system like the one we have put in place for food production and distribution is very fragile and often vulnerable to the fluctuations of oil prices and availability. Although the ongoing effort to educate consumers to eat locally is notable for fostering support for local family farms and agriculture and for the maintenance of local economies, it remains imperative that the "eat local" movement assist ever more with a decentralization of the present food system. This effort could lessen the need for further expansion of GM crop growth and cultivation on the large production scale for which they have been designed. A new ethic for agriculture in the third millennium is needed, and to this end Aldo Leopold's *land ethic* (1949) already exists to provide a solid foundation that could inspire all agriculturalists and managers to embrace stewardship in agriculture with passion and commitment if they wish their land to remain productive for future generations.

4.1 Consumers and the Demand-Side Viewpoints

The socioeconomic impact of agricultural biotechnology varies greatly between industrial and developing countries. This dichotomy stems from the differing values consumers place on food depending on their income. According to the law of demand, consumers buy more when a product is cheap and buy less when a product is expensive. For low-income consumers, mostly in developing countries, a healthy life may be jeopardized by a lack of food due to income constraint. Therefore, reduced food prices through biotechnology in such nations are beneficial for improving food consumption and nutrition and, consequently, life expectancy and productivity. For example, Anderson and Jackson (2005) provided evidence of the welfare gains resulting from the health-enhancing attributes of golden rice, which boosted the productivity of unskilled workers among Asia's poor. However, for higher-income consumers in industrialized countries, food expenses take up only a small proportion of income, and as a result people do not have a nutrition deficit from insufficient food availability. Even for those who live below the poverty line, government transfer programs, such as food stamps, ensure that basic nutritional needs are fulfilled for economically disadvantaged groups. Therefore, the reduced prices and enhanced nutrition that biotechnology provides is not crucial to consumers' welfare in industrial countries. In fact, there is a disproportionally detrimental impact of reduced food prices from biotechnology innovation in agriculture.

According to economics theory, when incomes rise, consumers increase their consumption of goods. In contrast, when incomes decline, consumers decrease their goods consumption, but increase their consumption of similar goods having inferior quality. McCluskey et al. (2003) reported that favorable attitudes toward food safety and the environment, self-reported knowledge about biotechnology, and self-reported risk perceptions toward GM foods, income, and education all significantly discouraged the willingness of Japanese consumers to purchase GM foods. Noussair et al. (2004) suggested that 35 % of French consumers were unwilling to purchase GM foods and 42 % were willing to buy them only if GM foods remained relatively inexpensive. This evidence could imply that GM foods are inferior goods, whereas non-GM foods are goods of superior quality. Consequently, a declining income could lead to increased consumption and wider acceptance of GM foods among consumers. For a long time, continually enhanced crop productivity through the employment of machinery, chemicals, plant breeding and, recently, genetic engineering has been able to reduce food prices substantially, so affordability has ceased to be an issue for consumers in developed countries.

However, this type of development also created an unwanted consequence that few have fully comprehended: lower prices of maize, soybeans, wheat, and other crops provide a boost for downstream food processing industries to develop a variety of processed inferior food products. This trend induces excess demand and consequently affects human health, especially for those low-income consumers who are usually with limited information and knowledge, despite their increased consumption of inferior foods. For instance, Drewnowski and Darmon (2005) argued that good taste, high convenience, and the low cost of energy-dense foods with added sugars and fats, in conjunction with large portions and low satiating power, may be the principal reasons for overeating and weight gain, especially for those low-income households who are financially constrained from having healthier and more balanced diets.

Table 4 Percent variation of costs and yields of GM and non-GM crops (From Buiatti 2004)

	Cost (seeds ha^{-1})		Cost (weeds ha^{-1})		Yield	
Crop	Min.	Max.	Min.	Max.	Min.	Max.
Soya (HT)	13.5	15.0	−33.0	−35.0	−12.0	4.0
Corn *Bt*	3.0	11.0	6.0	6.0	3.0	9.0
Canola (HT)	11.0	25.0	−8.0	−54.0	−11.0	79.0

HT herbicide tolerance, *Bt* insect resistance. Minimum and maximum data refer to those collected from different studies that were carried out in various sites and under different environmental conditions. Negative values indicate percent below standard

4.2 Producers and the Supply-Side Viewpoints

Regarding the economics of GM crops, it appears that its current beneficiaries are countries that can devote large tracts of land for this model of agricultural production, such as the United States and Canada in North America. Although the economic benefits to growers in the United States vary from year to year and from model to model, they range from $16.3 to $161.3 million, indicating that economic returns are positive when farmers choose to grow *Bt* cotton (Shelton et al. 2002). However, the cultivation of *Bt* cotton in India resulted in a dramatic economic disaster for local farmers and the causes of this failure have to do with lower yields and a reduced quality for a product that was marketed locally (Shiva 1991). Economic analyses have indicated an overall economic benefit to growers of $65.4 million (field corn), $45.9 million (cotton), $0.2 million (sweet corn), and $0.5 million (potatoes), for a total economic benefit of $111.9 million in the United States. An analysis conducted by the Environmental Protection Agency (EPA) also indicated a reduction for chemical treatments of 7.5 million acres of cotton, 0.127 million for sweet maize, and 0.089 million for potatoes, but it did not calculate a figure for field maize because of variable insect pressure, although other studies have documented declines in insecticide use in field corn (Shelton et al. 2002). Data from a study conducted by the European Union in several countries on the cultivation of GM maize, soybeans, and canola revealed that industrialized countries may not necessarily reap all the benefits of GM agriculture as professed by the biotechnology companies. Buiatti (2004) reported, for example, that the cost of seed per hectare is higher for GM crops, whereas the cost for managing weeds remains higher in non-GM crops. Yields varied significantly and not always in favor of GM crops; however, GM canola was superior to all other crops under study (Table 4).

In summary, the primary problem for developed countries is not that they cannot afford enough food to sustain people's livelihoods, but rather it is an excessive intake of lower-quality foods which leads to an unhealthy life. Therefore, it is unwise for governments to underestimate this cheap-food saturation problem (Caraher and Coveney 2004).

Governments may justify the maintenance of a "laissez-faire" approach to GM policy as well as other agriculture subsidies by arguing that lower food prices are important and beneficial for low-income people. However, the likelihood that low-income people will experience negative health effects from processed food (and even GM foods) remains high. Eventually, governments will have to bear health-related costs through a socialized health-care system. In other words, it is possible that all the cost savings that biotechnology progress in production agriculture provides will be obliterated by the rising long-term health problems and costs incurred by society. If we include the potential safety risk of GM crops to human health (Dona and Arvanitoyannis 2009; Bakshi 2003) and to the environment as mentioned earlier (Lovei and Arpaia 2005; Giampietro 2002), the benefit of GM agriculture would be further discounted. Looking to the risk-averse principle, the utility of social benefit and return of GM foods are much lower than we thought they were, and if we internalize the long-term externality costs that we often neglect, the social cost of GM crops is probably high. Therefore, we suggest that the net benefit of GM foods for developed countries in terms of their short-term reduced cost and enhanced yield productivity is overstated at best, erroneous and negative at worst.

Our argument is not aimed at discouraging efforts to increase agricultural output while reducing food prices. We contend that we should scrutinize any new innovation in agricultural technology because from the experiences of the recent financial crises, for example, we have realized that not all financial innovations aimed at technological enhancement are good for human welfare, or economies. The same and more can be said for agricultural innovations as food is not a commodity we simply produce, sell, buy, and consume; it is what we ingest and digest within our bodies every day and is thus much more important for our livelihood and well-being than any other economic good. The safety and quality of food have tremendous implications for human health and thus labeling foods is a legitimate and foreseeable need.

Another anxiety of today's modern economy is that GM crops affect employment. The technology and mechanization that have increased productivity have also replaced a majority of laborers in the agriculture sector over the past two centuries and a larger proportion of laborers in the manufacturing sector over the past three decades. What we have been neglecting to consider is the possibility that improved food quality might not be achievable through the discovery and progress of biotechnological and genetic engineering. A better option may be sustainable agriculture, or an agriculture which supports integrated farming systems, that incorporates an appropriate combined employment of labor, agrobiodiversity, knowledge, and management to improve food quality and human health and thus achieve agricultural sustainability.

5 Genetically Engineered Crops, Food Security, and Safety

5.1 From Classical Plant Breeding to Genetic Engineering

Developing genetically improved varieties has been and will be a constant feature that will accompany and probably guide the worldwide evolution and growth of agriculture into the future. The imperative goal for addressing all plant breeding efforts to increase yield was heralded by the tenets of the "Green Revolution" that, after the end of World War II, reverberated in developed as well as in developing countries (Khush 2001). Thus, a strong emphasis was fostered to promote breeding programs working on the genetic improvement of traits that directly, or indirectly, enhanced higher food production, with particular attention being directed to the most important cereal crops: rice, wheat, and maize. For inbreeding or autogamous species, plant breeders aimed at the selection of improved pure lines to identify superior monogenotypic and homozygous varieties. For outbreeding species the best results were achieved through a development of single-cross hybrid varieties which exploit both heterosis, due to their high level of heterozygosity, and genetic uniformity since hybrids are normally obtained by crossing two homozygous, inbred lines. Cloning achieved similar results for species that could be vegetatively propagated. Significant, although slower improvement has also been pursued through the use of open-pollinated and synthetic varieties for species where hybrid seed production was hampered by specific characteristics of their reproductive system such as the inability to obtain inbred lines, absence of effective male-sterility systems for hybrid seed production, or polysomic inheritance (Hallauer and Miranda 1988; Simmonds 1979; Allard 1960). Breeding methods based on Mendelian inheritance (mono- or oligogenic traits), statistics, and quantitative genetics (polygenic traits) were strongly supported through the development of molecular genetics and, in particular, with a wide introduction of molecular markers, in both basic and applied agricultural research. Molecular markers also improved the efficiency of germplasm collection, evaluation, and conservation programs that were conceived to support further improvements and to ensure the ability to store and preserve genetic variability (Tanskley and McCouch 1997). Moreover, advancements in cell and tissue culture allowed for more efficient plant vegetative propagation for both commercial and research purposes and also improved classical methods of selection through applications such as the production of doubled haploids to speed progress toward homozygosity. DNA sequencing led to increased knowledge about genome structure and function, thus furnishing a powerful tool in the development of new approaches to crop improvement (Feuillet et al. 2011).

At this point, "reverse genetics" (from DNA to the trait) began flanking "forward genetics" (from trait to the gene), the latter being strengthened mainly by a diffusion of DNA markers introduced into plant breeding programs (Schneeberg and Weigel 2011). In this way, classical and advanced breeding strategies were perfectly integrated with each other and their synergistic application gave significant validation to the genetic improvement of new varieties for a wide range of crops, not only cereals (Varshney et al. 2010). Consequently, a general public acceptance of innovations in plant breeding methods and strategies was achieved. However, genetic uniformity, which has always been a key factor for the success of genetically improved varieties, remained responsible for satisfying the needs of a high input agriculture model in terms of fertilizers and pesticides due to increased public concern about issues related to environmental protection and human health. Biodynamic, organic, and sustainable agriculture developed as alternatives to high-input, biotechnological agriculture, with plant breeding objectives that were addressed toward the needs of a more environmentally sustainable agricultural approach to food production (CSSA 1991). Advances in molecular research applied to plant genetics uncovered more refined details of many biochemical pathways (Raines 2011; DellaPenna 2001), and the highest expression of molecular technology was represented by gene cloning and gene characterization. Gene technology opened a new horizon to both basic and applied research through the application of recombinant DNA methods, bringing about the development of genetic engineering. The possibility of manipulating and transferring genes across species, from viruses to animals, allowed for the breakthrough of the most important limit to plant breeding, finding effective sources of new genes to obtain prolonged progress in plant breeding programs.

With genetic engineering, every species could potentially become a source of germplasm to identify genes, or even biochemical pathways for genetic improvement of a specific crop. Moreover, genetic engineering information at molecular and physiological levels could be transferred to plant breeding programs to improve elite varieties without disrupting their genotypes, but rather enriching them through the insertion of one or few genes that were not present in the original germplasm. Therefore, genetic engineering could rely on genetic selections previously carried out by breeders and could improve them by accessing traits that were impossible to ameliorate using classical plant breeding methods. As a consequence, a surprisingly wide range of plant species and agriculturally important traits have been subjected to both public and private research, with the goal of obtaining new varieties, improved by the genetic engineering approach. This strategy seemed very attractive since it represented the most advanced contribution of science to solving the needs of a changing agricultural mainstream (James 2010). A strong attraction for the diffusion of genetic engineering was also provided by the possibility of patenting biotechnological inventions that offered the inventor a stronger monopoly right than the plant breeder's right in protecting plant varieties obtained using traditional and molecular breeding methods (Fleck and Baldock 2003; Kowalsky et al. 2002). However, the debate concerning the diffusion of GM crops and the wide acceptance of GM foods is still open at both scientific and public levels. Numerous points of view indicate that methods of food production should change, especially with regard to the:

(a) Current trend of global human population growth followed by the corresponding increase in food needs
(b) Environmental and health concerns resulting from the application of intensive agricultural systems
(c) Loss of biodiversity due to the introduction of monogenotypic improved varieties followed by extremely simplified agricultural systems
(d) Expansion of farm land through the destruction of forests and increased greenhouse gas emissions from agricultural practices

5.2 Legitimizing a Wider Acceptance of Genetic Engineering in Agriculture

Even though there is general agreement on accepting that the future target in crop science will be the development of agricultural systems able to produce sufficient food of high quality using production strategies characterized by a reduced impact on environmental resources, not all agree with considering genetic engineering as a potential, or sole strategy to achieve this objective (Foley et al. 2011; Tilman et al. 2011; Tester and Langridge 2010; Takeda and Matsuoka 2008). These goals are strongly debated when genetic engineering is applied to agriculture and whenever genetically modified organisms leave laboratories and are released into the environment as GM microorganisms, crops, insects, or animals (Butler and Reichardt 1999). Previous experience from environmental pollution and human health disasters due to the uncontrolled use of chemicals such as DDT, PCBs, dioxin, and asbestos suggests caution toward an indiscriminate diffusion of new technologies, especially when they are applied to living organisms.

Moreover, breaking the barrier that prevented gene exchange among sexually isolated species, the risks related to an uncontrolled diffusion of transgenes in the environment, the chance of horizontal gene transfer, possible risks for human health, uncontrolled use of chemicals and pesticides on GM crops, and side effects on nontarget species from GM toxins are the main reasons for skepticism toward the biotechnology approach to food production.

In discussing applications of genetic engineering in agriculture, risk assessment concerning the effects of GM feed and food on animal and human health is the topic that gathers most attention regarding both public and scientific opinions, as confirmed by review articles recently published on this topic (Snell et al. 2012; Séralini et al. 2011; Trabalza-Marinucci et al. 2008; Sandermann 2006; Sharma et al. 2006). Human health and safety is a very delicate issue that has exacerbated the acceptability of agricultural biotechnology among large segments of society in various parts of the world. Notable in this context, for example, has been the refusal of GM foods by consumers in the European Union since the early 1990s (Lappé and Bailey 1998), or even rejection of the same by some African countries like Zimbabwe and Zambia, even when affected by a food crisis in 2002. The unusual, unnatural methods of breeding GM crops have triggered the fear of the potential risk of introducing into the food supply new proteins that could have harmful effects on human health through violent allergic reactions (Altieri 2004). A thorough assessment of potential allergenicity for a new protein is very difficult to achieve when the gene or genes coding that protein have been transferred from an organism that has never been eaten before. In the 1990s, Aventis™ marketed StarLink® maize, which contains the *cry9C* protein and is approved only for animal feed and ethanol production, although its registration was canceled in the United States in October 2000 because of its erroneous introduction into human food supplies (Shelton et al. 2002).

Therefore, the principle of equivalence between GM and non-GM feed or food due to genetic modification itself has been applied to evaluate the safety of GM products for animal and human health (EFSA 2008, 2011). To this end, Domingo (2007) showed the absence of clear evidence of potential toxicity from GM plants even though several levels of incompleteness in the tests, mainly short experimental periods and lack of toxicity tests, were generally evidenced in most of the cited studies. Domingo and Bordonaba (2011) further showed that information about the topic increased significantly over a few years, but only for a limited number of crops, mainly maize and soybeans, and that an equal amount of research results reported nutritional equivalence or concerns between GM and non-GM crops. Moreover, Snell et al. (2012) analyzed long-term and multigenerational animal feeding trials based on OECD guidelines as the main focus for critical evaluation of the applied research methods. Authors of this review expressed an evident criticism against research showing negative effects from GM soybeans and maize (Kilic and Akay 2008; Trabalza-Marinucci et al. 2008; Vecchio et al. 2004; Malatesta et al. 2002a, b, 2003, 2008) since the data from these studies were distorted by clear methodological errors. Snell et al. (2012) therefore concluded that GM plants can be safely used as feed or food and that a long-term or multigenerational study would be necessary only after 90-day feeding trials evidenced the need for further investigations, based on a case-by-case approach. The toxicity of *Bt* maize as revealed by Séralini et al. (2007), although initially denied by Doull et al. (2007), was subsequently confirmed by a further comparative analysis conducted using a larger number of genetically modified maize (de Vendômois et al. 2009).

Subsequently, Séralini et al. (2011) reevaluated data that were criticized by Snell et al. (2012) and showed that they could still represent evidence for liver and kidney toxicity in mammals, due to both herbicide-tolerant and insect-resistant transgenic maize and/or soybeans. Moreover, they suggested that long-term and transgenerational evaluations are fundamental for testing chronic toxicity in GM crops together with improved statistical analyses. The two most common GM plant groups (glyphosate and insect-resistant GM crops) were related to possible confounding effects that researchers should consider when planning experiments aimed at the evaluation of GM crop toxicity (Séralini et al. 2011).

5.3 *Herbicide Tolerance-Resistance*

Herbicide-resistant (HR) plants are genetically engineered to resist or tolerate glyphosate herbicide applications as plant tissues accumulate a modified form of 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) that is not degraded by glyphosate after herbicide application. As a consequence, glyphosate could accumulate in plant tissues together with other molecules included in the herbicide formulation. Therefore, effects from genetic transformation combine with toxicity related to the presence of herbicide residues in GM-containing feed or food. However, for herbicide tolerance, these two effects could be separated by using

GM soybeans or maize that has not been sprayed with herbicides involved in the genetically engineered trait. As a result, the production of GM and non-GM raw material used to carry out any experimental trial should be considered as a crucial step in the design of experiments aimed at comparing feeds that were identical in genetic composition and nutritional characteristics and the presence of pesticide residues differing only for the transgene construct present in the GM raw material. The toxic effect of the herbicide itself could be evaluated with separate experiments and eventually combined with the effects of the transformation event. However, in real operational situations the presence of herbicide residues in feed or food containing GM raw materials is not unreasonable. This aspect is important since most research articles that detected possible toxic effects due to herbicide (glyphosate-based)-tolerant GM feeds explained their results as also due to the possible presence of glyphosate and/or its metabolite residues in the GM feed: thus, one reason for the criticism toward these articles. The presence of pesticide residues in experimental feeds, both GM and non-GM, should be carefully evaluated in order to avoid confounding effects and to assure a fair comparison among experimental feeds. This suggests that close collaboration between agronomists and plant geneticists would be useful in the planning of experiments for GM toxicity testing, especially during the preliminary phase of experimental raw material production. Although glyphosate has been considered toxicologically and environmentally safe (World Health Organization 2011; Duke and Powles 2008), recent data have been obtained regarding human toxicity and safety concerns about glyphosate and its metabolites (Antoniou et al. 2011; Aris and Leblanc 2011; Paganelli et al. 2010; Benachour and Séralini 2009; Gasnier et al. 2009; Benachour et al. 2007; Richard et al. 2005; Yum et al. 2005; Marc et al. 2004).

The results of the studies refuted by Snell et al. (2012) still maintain their relevance, even though the toxicity effect could be assigned to residuals of the glyphosate-based herbicide in the raw material used for GM feed preparation, instead of the transgenic gene or products (Séralini et al. 2011).

Additional investigations revealed that an increased, instead of a decreased, herbicide use was observed in the United States together with a progressive increase of HR cultivated crops, mainly HR soybeans (NRC 2010; Benbrook 2009). Also, the appearance of glyphosate-resistant weeds raised new problems in the weed management of HR genetically modified crops (Sanchís et al. 2011; Duke and Cerdeira 2010; Powles 2008; Sandermann 2006) due to the repeated use of the same extremely efficient wide-spectrum herbicide. As a consequence, higher doses of herbicide had to be applied to keep weeds under control, a feature that could partly explain the increased consumption of herbicides where HR crops are widely cultivated (Benbrook 2009). Concerns also have been raised regarding GM crops engineered to tolerate glufosinate-based herbicides since Aris and Leblanc (2011) found that a glufosinate metabolite was detected in all blood samples of pregnant women and their fetuses and in most nonpregnant women's samples analyzed. Previous investigations also suggested potential toxicity for humans and mammals (Garcia et al. 1998; Watanabe and Iwase 1996). Overall, current research has enhanced public concern on possible toxic health effects due not only to the transgenic DNA itself but also to an increased potential risk of detecting herbicide residues in GM feed and food.

5.4 *Bt* Insect Resistance

Transgenic crops engineered to acquire insect resistance are designed to accumulate various forms of toxins derived from *Bacillus thuringiensis* (*Bt*) within tissues of the whole plant due to the constitutive expression of the transgene. Insects feeding on GM plants ingest the toxin and, if susceptible to the toxin, are destined to die. Therefore, the GM plant is characterized as having acquired a strong genetic resistance against specific insects and receives negligible damage due to insect attack. The efficacy of *Bt* technology led to its wide diffusion in countries where cultivation of GM crops is allowed (James 2010), and it was proposed also as an effective approach for both developed and developing countries because of increased crop yields, decreased use of insecticides, decreased mycotoxin contamination, reduced labor, and increased income (Huesing and English 2004). These aspects have different importance depending on the crop that is considered since *Bt* crops are used both as nonfood crops and in feed or food crops.

Two main positive effects can be attributed to *Bt* GM crops: reduction of mycotoxin contamination and decreased need for insecticide use. The major effect of *Bt* maize consists of reduced feed and food contamination by mycotoxins, which deserve particular attention due to the extreme human and animal toxicity of these dangerous contaminants. However, debate on mycotoxin contamination also raises questions about the responsibility of cropping systems based on monogenotypic varieties and monocultures in generating secondary effects such as mycotoxin accumulation in crop products. Moreover, a general reduction of insecticide use on *Bt* crops has been observed for all the species where *Bt* technology has been applied on a large scale (NRC 2010; Benbrook 2009). Nonetheless, insect resistance management programs should be applied across the scope of *Bt* crop cultivation to prevent the resistance mechanism of *Bt* crops leading to selection for *Bt* toxin resistance within populations of target insects (Gassmann et al. 2011; Hutchinson et al. 2010). Examples of *Bt* insect resistance originated in laboratories or evolved in cultivated fields and possible strategies to delay insect resistance together with the impact of *Bt* crops on nontarget insects have been recently discussed (Tabashnik et al. 2011; Carrière et al. 2010). All of these studies indicate that an accurate management plan is necessary to avoid insect resistance leading to significant reductions in *Bt* efficiency in specific insect disease control systems.

Avoidance of crop insect resistance is one of the main objectives of all *Bt*-based plant breeding plans and two main strategies are applied to prevent this from happening: refuge crops and gene pyramiding (Carrière et al. 2010). Much concern about insect resistance to *Bt* toxins is expressed by farmers that do not use transgenic insect-resistant varieties, but instead use *Bt* toxin-based insecticides, such as those in use at organic farms, or farms that follow non-GM production protocols. An appearance of insect strains tolerating *Bt* toxin would make *Bt* insecticide treatments useless and expose non-GM crops to unpredictable yield losses, forcing farmers to return to using those pesticides that were replaced by *Bt* insecticides. Effective information on appropriate strategies for managing the coexistence between GM (using *Bt* crops) and non-GM cropping systems (using *Bt*-based insecticides) is still lacking, posing severe limitations to an expansion of GM crops, mainly in areas where GM and non-GM farms could be present side by side. Under these and similar circumstances, both insect resistance and *Bt* crop management programs could be better prepared for an adaptive approach to GM technology in agriculture.

A diffusion of *Bt* crops on a large scale can also affect populations of nontarget species. Several studies and reviews have reported different evaluations of the scientific results on this topic, especially after the initial debate regarding effects on the monarch butterfly (Sears et al. 2001; Losey et al. 1999). Similarly, Schmidt et al. (2009) demonstrated higher mortality in the coccinellid *Adalia bipunctata* (L.), when fed microbially with trypsin-activated *cry1Ab* and *cry3Bb* toxins, by using an ecotoxicity testing protocol for laboratory use. It has been suggested that the increased mortality of the larvae in the toxin feeding trials was caused directly by the activated *Bt* toxins, thus raising questions regarding their commonly postulated specificity and their mode of action on *A. bipunctata*. Thus, Narajo (2009) concluded that *Bt* technology had a lower impact on nontarget species than non-*Bt* crops treated with insecticides, even though untreated non-*Bt* fields showed higher abundance of nontarget species when compared to *Bt* fields. Also, high levels of *cry1Ab* endotoxin were found in nontarget herbivores and arthropod predators feeding on transgenic plants, suggesting that long-term exposure to insecticidal toxins should always be considered in evaluating *Bt* crop risk assessment (Harwood et al. 2005). Detection and persistence of *cry1Ab* toxin in the maize rhizosphere was also reported by Baumgarte and Tebbe (2005), but no evidence of effects on bacterial communities was observed.

Overall, reviews of the literature show no significant harmful effects of *Bt* crops on nontarget species. These claims can be evinced based on the scientific investigations available, even though the high variability of species, interactions with target insects, and environmental conditions were recognized as factors making the studies of transgenic crops and their effects on nontarget species quite challenging to ascertain. Different interpretations were given to these data by Lovei and Arpaia (2005) and Lovei et al. (2009), who included in their evaluations insect resistance due to proteinase inhibitors together with *Bt* crops. These reviews concluded that in field experiments negative effects of transgenic crops on nontarget species were more common than positive ones, although these results were criticized by Shelton et al. (2009).

In the debate on nontarget effects, it is interesting to note that discordance has been common among the data from laboratory and field experiments (Narajo 2009). Laboratory studies using transgenic plant tissues or pure transgenic protein revealed significant toxicity effects on several nontarget species despite a lack of detection of the same in field experiments.

5.5 Effects of Bt Toxins in the Soil

Large quantities of *Bacillus thuringiensis* (*Bt*) toxins derived from maize plant residues left in the field after harvest may have implications for the biological interactions occurring in the soil ecosystem. Potential impacts on soil organisms depend on the persistence of the *Bt* toxin in plant residues, as demonstrated by the longevity and insecticidal activity of the toxins in the soil. To this end, Zwahlen et al. (2003a) investigated how long the toxin persisted in plant residues in two field studies in the temperate maize-growing region of Switzerland. The study of degradation of the *cry1Ab* toxin in transgenic *Bt* maize leaves during autumn, winter, and spring using an enzyme-linked immunosorbent assay (ELISA) showed no degradation of the toxin during the first month. During the second month, *cry1Ab* toxin concentrations decreased to approximately 20 % of their initial values. There was no further degradation during winter. When temperatures increased again in spring, the toxin continued to degrade slowly. In the second field trial, representing a no-tillage system, *cry1Ab* toxin concentrations decreased without initial delay, as with soil-incorporated *Bt* plants, to 38 % of the initial concentration during the first 40 days. They continued to decrease until the end of the trial, 200 days later in June, when 0.3 % of the initial amount of *cry1Ab* toxin was detected. In addition, the impact of transgenic *Bt* maize on immature and adult earthworms (*Lumbricus terrestris* L.) in the field and in the laboratory was investigated by Zwahlen et al. (2003b) and showed that no lethal effects of transgenic *Bt* maize on immature and adult earthworms were observed during the first 160 days of the laboratory trial. However, after 200 days, adult earthworms displayed a significant weight loss of 18 % of their initial weight when fed (*Bt*+) maize litter compared to a weight gain of 4 % of the initial weight for (*Bt*-) maize-fed earthworms. Degradation of *cry1Ab* toxin in maize residues was significantly slower in the field than at 10 °C in the laboratory.

More recently, Douville et al. (2007) investigated the occurrence and persistence of the *cry1Ab* gene from *Btk* and *Bt* maize in aquatic environments near fields where *Bt* maize was cultivated. Field surveys revealed that the *cry1Ab* gene from transgenic maize and from naturally occurring *Bt* was more abundant in the sediment than in the surface water. The *cry1Ab* transgene was detected as far away as the Richelieu and St. Lawrence rivers (about 82 km downstream from the maize cultivation plot), suggesting that there were multiple sources of this gene and/or that it undergoes transport in the water column. Sediment concentrations of the *cry1Ab* gene were significantly correlated with those of the *cry1Ab* gene in surface water ($r = 0.83$, $P = 0.04$), indicating that DNA from *Bt* corn and *Bt* were persistent in aquatic environments and could be detected in rivers draining farming areas. Without a doubt, *Bt* commercial products inevitably contain residues of the *Bt* toxins. Since *Bt* toxins accumulate in plant tissues, any side effect from the genetic transformation process itself (Rosati et al. 2008) appears together with possible effects from the accumulated toxin. Therefore, aspects related to human health from *Bt* technology should also be considered in the overall evaluation of *Bt* effectiveness in future studies. Evidence of hepatorenal toxicity in rats due to *Bt* toxin effects and/or unintended direct or indirect metabolic consequences was reported for maize (de Vendômois et al. 2009). As well, Aris and LeBlanc (2011) showed a correlation between maternal and fetal exposure to *cry1Ab* protein (a *Bt* toxin) and also that *cry1Ab* was detected in pregnant women, in their fetuses, and in nonpregnant women. These reports suggest that, in addition to previous research, the traces of *Bt* toxin in livestock gastrointestinal contents should continue to raise concerns about the safety of *Bt* crops used as feed or food.

5.6 Fate of Transgenes

Once GM feed or foods have been ingested by animals or humans, the transgenic DNA and gene products should behave like other nutrients. DNA and proteins are mainly digested in the gastrointestinal tract. Most of their digestion products are absorbed, and residual partially digested DNA and/or proteins are excreted. In ruminants, transgenic DNA and proteins start their degradation in the rumen due to the extremely active bacterial population operating in the pre-stomach. Safety assessment of GM feed and food has been focused on studying the fate of transgenic DNA sequences or proteins to test for possible toxicity of GM toxins that usually are not present in non-GM products. Evaluating the risk of horizontal gene transfer of transgenes has been another important research emphasis for the biotechnology industry in the last decade. Moreover, GM DNA and proteins could be absorbed and transferred by the blood flow to animal tissues. Concerning livestock, degraded portions of GM DNA or proteins could finally be recovered in the commercial products (meat or milk), thus raising the question of whether animal products obtained using GM feeding systems should be considered as containing or not containing genetically modified residues. Different levels of DNA and protein degradation from GM feed in the gastrointestinal tract of livestock have been reported in a wide range of animal species (Paul et al. 2010; Alexander et al. 2007; Flachowsky et al. 2007; Sharma et al. 2006; Chowdhury et al. 2003a, b; Duggan et al. 2003). Alexander et al. (2007) reviewed the literature and concluded that DNA fragments could pass through the intestinal wall and considered this as a natural physiological event. Transgenic DNA or proteins within organs and tissues have been detected in several animals at different levels (Ran et al. 2009; Chainark et al. 2008; Sharma et al. 2006; Mazza et al. 2005). However, other studies did not find transgenic DNA in organs or tissues (Walsh et al. 2011; Flachowsky et al. 2007; Chowdhury et al. 2003b; Jennings et al. 2003). Concerning milk, several studies did not detect milk contaminated with transgenic DNA (Guertler et al. 2010; Phipps et al. 2002). Rizzi et al. (2008) detected multicopy chloroplast-specific gene fragments, but did not recover a single copy of DNA from maize *zein* and *cry1Ab* genes in goat milk. The presence of GM DNA in samples of commercial cow milk was assumed to come from fecal or airborne contamination (Agodi et al. 2006). However, presence of transgenic DNA fragments was detected in milk and blood and also in the liver, kidney, heart, and muscle of goats fed with Roundup Ready® soybean meal (Tudisco et al. 2010). Moreover, these DNA fragments were also detected in the liver, kidney, and blood of kids fed with milk from the GM group, which also showed a change in lactic dehydrogenase-1 isoenzyme when compared to the control non-GM group (Tudisco et al. 2010).

It is noteworthy to point out that transgenic DNA was not found in 100 % of the animals analyzed. This research confirmed that multicopy chloroplast DNA was detected in almost all milk samples of both GM and non-GM treated dams. Also, single copy lectin gene fragments were found in milk samples, although at a lower frequency than multicopy chloroplast DNA. These results reflect those of Alexander et al. (2007) that plant DNA derived from feeds could be detected in blood and organs and multicopy DNA is easier to detect than single copy DNA sequences (Tudisco et al. 2006a; Klotz et al. 2002). The changes occurring in enzyme activity as determined by GM transgenic feed and as already found in previous research on rabbits (Tudisco et al. 2006b) are interesting and will need further evaluation in more animal species.

6 Conclusions and Perspectives: Supporting Sustainable Agriculture and Development

Although many challenges still affect the acceptability and feasibility of genetic engineering in agriculture, its potential to yield positive results cannot be denied. It remains certain that an employment of biotechnology involves certain unavoidable risks because living beings reproduce, passing on to their offspring the gene or genes that have been introduced from other species (Table 5). Therefore, a

Table 5 Concerns posed by selected traits of GM crops (From Ervin et al. 2003)

Genotype	Environmental concern
Herbicide tolerance	Increased weed-like characteristics of wild relatives of crops through gene flow
	Development of herbicide-tolerant weed populations through avoidance and selection
	Development of herbicide-tolerant "volunteer" crop populations
	Negative impact on wildlife populations through reduction of food supplies
Virus resistance	Increased weed-like characteristics of wild relatives of crops through gene flow
	High risk for disease among neighboring plants of virus-resistant crops through plant alteration
	Development of more virulent viruses that are difficult to control through virus alteration
Insect resistance	Increased weed-like characteristics of wild relatives of crops through gene flow
	Development of resistant insect populations
	Toxicity to populations of nontarget and beneficial insects and soil microorganisms

skeptical attitude is necessary with the clear understanding by all parties involved in biotechnological agriculture that such an approach is not necessarily inimical to GM crops but rather necessary, as research is still needed to better understand what makes up genes and what regulates their expression.

In addition, more interactions could involve the transgenes with transgenic organisms and these also could occur between genetically modified organisms and their environment, determining effects on human health (Altieri 1995, 2000; Altieri and Rosset 1999). As a direct consequence of these new relationships, more effects could reverberate within agricultural markets and economies, affecting societal rules and shaking the values that ultimately form the foundations of human socioeconomic systems (Shiva 1991).

Therefore, it is imperative to learn more about the secondary effects of introducing a gene into an organism because its interaction with other, preexisting genes will be inevitable and unavoidable. To this end, it is necessary to invest even more capital in research and to embrace patience and humility as the necessary attitudes to study life when transgenic manipulations are made. In addition, pursuing a genetic engineering agenda for food production remains a gigantic, multidisciplinary effort, which should not be limited to biologists or geneticists. Including physicists, mathematicians, chemists, computer scientists, agricultural scientists, and farmers, who must apply what is being discovered by biologists and geneticists, is a necessary effort for developing research programs in GM agriculture.

The mechanistic approach of genetic engineering cannot control the unpredictability of gene transfer as genes are inherited from generation to generation nor insure whether or not the same will remain unaltered through time (Buiatti 2004). This factor and the limited knowledge about genomes and metabolic networks are presently additional limitations to an expansion and broader appreciation of GM technologies in agriculture. It is not simply a matter of approving or rejecting GM foods and feeds, but rather assessing every single product in complete transparency, eliminating unfounded optimism, yet fostering knowledge for this new, rapidly emerging field of studies in the biological sciences. Farmers, in particular, should be at the top of the list of stakeholders in discussing and deciding whether GM crops should be employable or not. Additional connections with other scholars in other disciplines like sociology, economics, philosophy, and ethics also are necessary to pursue a variety of diverse perspectives that will more accurately guide the decision-making process for an employment of GM technologies in food production. This need is justified given that the subject is highly complex, thus requiring the most inclusive quorum of stakeholders to resolve issues and to answer questions from the broadest variety of viewpoints. In fact, living beings are unpredictable in how they adapt or fail to adapt to specific environmental conditions. Genetically modified crops can behave similarly, especially if the species among which the transfer of genes takes place are more distant, and as more of the transferred genes interact with the host's genome.

We refer to sustainable development as a series of research, political, and economic choices that are compatible with the conservation of natural resources and with the well-being of humans and all other living organisms. From this definition,

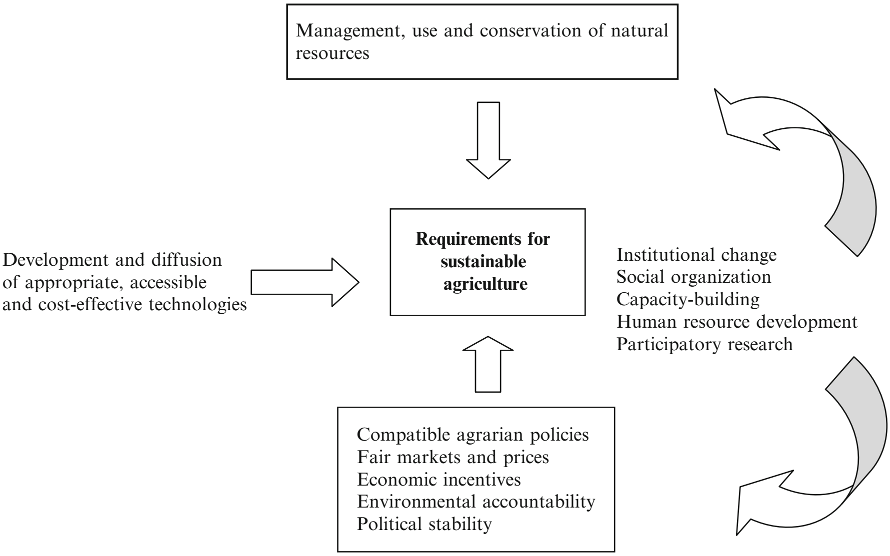

Fig. 4 Needed elements for achieving sustainable agriculture (From Altieri 1995)

no antagonizing concepts emerge whether we support a biotechnological view for future agriculture or whether we support a more agroecological perspective. Sustainable development for human beings means achieving a level of quality of life which includes the freedom of individuals and their communities to make their own choices about using and consuming GM crops autonomously while respecting the choices of others. The coexistence of biotechnology and traditional agriculture is challenged by all the issues we have presented. If genetic engineering in agriculture is to persist, it will have to be with respect for biodiversity, natural and cultural, thus avoiding past mistakes of imposing the cultivation of a few species on a global scale with the simplistic assumption that such a *modus operandi* can function equally well in any other agrarian context or be economically feasible for all farmers.

Existing laws to protect consumers will have to be strengthened so that everyone will have the opportunity to choose genetically manipulated food or otherwise, in transparency and without risk of being penalized. The achievement of sustainable agriculture should become a priority value in the operational ethic of every agriculturist, and the model proposed by the agroecological approach to food production (Fig. 4) should be embraced by all forms of agriculture (traditional, sustainable, biotechnological, or organic) in the years to come.

There is a compelling need to employ and amplify the potential of biodiversity in the development of a new paradigm for sustainable agriculture, which cannot be achieved with a sole emphasis on GM crops and technologies. The biodiversity model for agriculture is based on the concept of suppressiveness and is supported by two simple principles:

1. Natural equilibrium of agroecosystems achieved through the management of more diverse plant communities (both agronomic crops and non-cultivated plants)
2. Humification and organic matter cycling (which regenerates the natural fertility of soils through an accumulation and recycling of diverse, organic residues)

An application of the proposed paradigm enhances agricultural sustainability because it fosters the capability of agrarian systems to regenerate some consumable resources. It also better ensures food quantity and quality, while soil fertility management emerges as a priority feature of this philosophy. Only through a respect of such guidelines can GM crops be introduced more responsibly into modern farming systems.

Finally, the pathway leading to a systemic change that has the power to revolutionize the present food system and achieve agricultural sustainability focuses on three focal concepts that have been already discussed: ethics, energy, and economics. A renovated ethic is necessary to develop a sustainable agriculture whether genetic engineering and its applications in food production will play a pivotal role or not. Agriculture remains a very costly human activity whose dependence on nonrenewable fossil fuels is presently impeding an achievement of sustainability. Its reliance on oil is quickly eroding the knowledge and culture of practicing agriculture, which should not be obliterated by biotechnological agriculture on the simplistic assumption that the “old way” of farming has become valueless and obsolete. The lucrative economic gains of food corporations should not be achieved at the cost of extirpating entire rural communities of small farmers worldwide, as these remain vital to the future of food production. Neither should it be at the cost of extirpating species and destroying habitats that are so valuable for the preservation of biodiversity and ultimately for the long-term successes of any food production system.

Education, research, and extension in agriculture remain the vehicles to achieve sustainability in modern food systems. The preparedness of future agriculturists requires a more holistic approach and this can be achieved through education reform in a college of agriculture through a promotion of innovative thinking and leadership (Borsari 2012; Onwueme et al. 2008; Borsari and Vidrine 2005), which is most attentive at reconciling food production with resource manipulation (both natural and human). Within this context, research plays a very important role as the time has come to liberate this vital human activity from the mandates and constraints of the agricultural industry which has aggressively imposed which priorities are to be predominantly pursued (Jordan et al. 2007).

Education also serves to accentuate the need for policy change in the current management of our extremely centralized food systems and to foster transparency concerning information and regulation for anything concerned with food production and its distribution to markets and consumers. Preservation of agrobiodiversity remains fundamental to any form of agriculture, while the mandate of lessening the dependence on nonrenewable fossil fuels to maintain production needs to shift toward more renewable energy sources. Ultimately, the challenges of food production and distribution in the years to come will be better approached and hopefully overcome by looking at technology in a more realistic manner. New and relatively rapid breakthroughs in genetic engineering may assist in this effort, but will not fully succeed without the simultaneous, complementing effort, knowledge, and wisdom of traditional farming methods and crops that have adapted through long-term selective pressure.

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Organic Farming and Organic Food Quality: Prospects and Limitations

Sabine Zikeli, Ewa Rembiałkowska, Aneta Załęcka, and Maciej Badowski

Abstract This review provides an introduction to organic farming, its history and concepts, organic certification systems and governmental support, impacts to the environment and food security, the quality of organic food, and the impact of organic farming on human health. Organic farming is a holistic approach to agriculture and food systems that is based on agroecosystem health, soil fertility, reduction of inputs, and locally to regionally adapted farming systems. The first organic ideas were developed after World War I in Europe as an alternative to the existing conventional farming systems which induced rapid and crucial social and environmental changes in rural areas. Today, organic farming is growing rapidly on a global scale, with around 370 million hectares currently under certified organic management and a turnover of organic products amounting to 60 billion US dollars. Given that organic farming has environmental benefits, some governments are subsidizing organic farmers, while others establish legally valid organic standards that must be followed to enhance consumer trust in organic labeling.

Many recent studies comparing organic and conventional farming have been performed, although almost exclusively in North America and Europe. These studies show that environmental impacts of organic farming are less than those from conventional farming, but the conclusions depend on the different farming systems used for comparison and on the parameters that were assessed. For soil parameters such as organic matter or aggregate stability, the effect from organic farming systems was positive compared to conventional farming systems, although contrary results exist

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in some cases. For nitrate leaching, study results are diverse and depend on production systems (animal husbandry, crop production, proportion of legumes). For greenhouse gas emissions, organic farming provides lower emissions on a per hectare basis compared to conventional farming, but the same or higher emissions on a product basis because of lower yields. If the yield gap between organic and conventional farming systems could be reduced, the potential for a reduction of greenhouse gas emissions would rise. Organic farming performed better with regard to biodiversity compared to conventional farming for most taxa assessed. The impact of organic farming on food security cannot be clearly assessed because studies on the performance of organic farming in developing countries are lacking. Currently, some authors argue that organic farmers in developing countries profit from organic production if they can realize a price premium for the products and reduce input costs.

One of the most important consumer motivations for the purchase of organic products is their health benefits. Organic products performed better than conventional products for different food compounds by containing less pesticide residues that are harmful to human health, having more desirable bioactive substances, and in the case of organic meat and milk, having more desirable fatty-acid composition. Animal experiments have shown positive health impacts from organic food. Several studies conducted on rats have indicated higher immune system reactivity in organically fed rats compared to conventionally fed animals. Similar results have been obtained for chickens and cows.

The rapid growth of organic farming also can be a threat to future development if the organic sector cannot maintain its integrity and credibility. Organic products are available not only in farmer markets but in on-farm shops and organic food stores and are becoming increasingly present in conventional supermarkets. This involves long supply-chains, large suppliers, as well as processing, distribution, and trade *via* conventional processors and wholesalers. This *conventionalization* of organic food-chains may challenge the credibility of the organic sector as an environmentally friendly and socially fair form of agriculture. As the organic sector depends very much on this credibility, the question of how to retain this authenticity will be a major concern for the future.

Keywords Organic farming development • Organic farming history • Organic farming and food security • Organic food • Organic plant products • Human and animal health • Greenhouse gas emissions • Biodiversity • Conventionalization • Participatory Guarantee Systems • Environmental impact • Energy use • Life-cycle analysis • Yield levels in organic farming • Quality

1 Organic Farming

1.1 Introduction

Twenty years after the Rio Summit and more than 40 years after the publication of the Club of Rome's book "The Limits to Growth" (Meadows et al. 1972), the major questions for modern agriculture remain unchanged and are becoming more pressing: How to feed a growing global population, particularly the poor in rural areas? How to do this by using natural resources such as water and soil in a sustainable manner? How to transform fossil-fuel-dependent processes in a world where these sources of energy will be less available and more expensive than in previous years? How to stop the loss of biodiversity? How to ensure that the food we eat is sufficient and healthy?

In addition to these problems, further challenges have arisen over recent years: How to adapt agricultural practices to climate change while at the same time mitigating greenhouse gas emissions from agriculture? How to deal with the demands of a *bioeconomy* that claims agricultural land and resources not only for food and feed but also for fuel and fiber?

Some progress in food security has been made in regions such as Asia and Latin America which have managed to reduce the number of undernourished people, but at high environmental costs. The International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD 2009) stated “Business as usual is no longer an option.” But what is the option? Is organic farming one option or even THE option for a sustainable intensification of agriculture? Many studies have shown that organic farming offers a wide set of environmental benefits while improving farmer incomes in industrialized countries (Sanders et al. 2011) as well as the livelihoods of small-holders in the Global South (Pretty et al. 2003). Nevertheless, some problems with organic farming practices persist, such as the use of copper as a fungicide or the difficulties in developing organic zero-tillage systems. In addition, the current debate on organic farming and food security is based on the question of whether yields from organic farming can compete with yields using conventional farming practices. In this context, the following discussion provides a historical overview of the development of organic farming on a global scale. We explore the current status and discuss the ecological and environmental benefits, current limits and food security aspects of organic farming while addressing aspects of organic food quality and the effects of organic food on human health.

1.2 What Is Organic Farming?

1.2.1 Definition of Terms

The terms *organic*, *biological*, and *ecological* farming are used in different languages and in different contexts to describe farming systems that are considered *sustainable*, *alternative*, or *low input*. Different standards exist, but all are based on a similar set of principles and refer to the same concept of low external inputs to agriculture. Within the Codex Alimentarius Guidelines for the Production,

Table 1 IFOAM Principles of Organic Agriculture: overview (IFOAM 2005)

Principle of health	Organic agriculture should sustain and enhance the health of soil, plant, animal, human, and planet as one and indivisible
Principle of ecology	Organic agriculture should be based on living ecological systems and cycles, work with them, emulate them, and help sustain them
Principle of fairness	Organic agriculture should build on relationships that ensure fairness with regard to the common environment and life opportunities
Principle of care	Organic agriculture should be managed in a precautionary and responsible manner to protect the health and well-being of current and future generations and the environment

Processing, Marketing and Labelling of Organically Produced Foods (FAO/WHO 1999), organic agriculture is defined as:

> a holistic production management system which promotes and enhances agroecosystem health, including biodiversity, biological cycles, and soil biological activity. It emphasizes the use of management practices in preference to the use of off-farm inputs, taking into account that regional conditions require locally adapted systems. This is accomplished by using, where possible, cultural, biological and mechanical methods, as opposed to using synthetic materials, to fulfill any specific function within the system.

The Codex Alimentarius Guidelines have been developed closely along the lines of the organic principles set by the International Federation of Organic Agriculture Movements (IFOAM) that were founded in 1972. IFOAM is the world umbrella organization of organic farming that today unites nearly 870 member organizations, supporters, and associates in 120 countries. In 2005, IFOAM published the newest version of its norms focusing on four main principles: health, ecology, fairness, and care (Table 1). The principles were developed in an open consultation process from 2003 to 2005 such that they should be universal and create a sense of identity for the organic sector. Against this background, all more detailed standards and guidelines of IFOAM are set.

When connected to farming methods or food production, the use of the term *organic* or related terms in other languages is restricted by legally implemented rules and standards. Therefore, the terms *certified* and *noncertified* organic agriculture have been introduced. *Certified* organic farming refers to organic farming practices which are based on the standards or guidelines of either an organic association or standards defined by governmental bodies, such as the standards of the National Organic Program (NOP) in the United States which is administered by the US Department of Agriculture. Organic certification includes the control of farming practices by a third party, normally a certification body. *Noncertified* organic agriculture, or similar farming systems, refers to agricultural systems that operate in accordance with the principles of organic agriculture, but which are not regulated by third-party certification which requires detailed documentation of farming practices and certification costs. Both are difficult to achieve for many small-scale farmers, particularly in countries of the Global South. Nevertheless, such systems are a very important part of organic farming in these regions (Altieri 2002). The IFOAM has

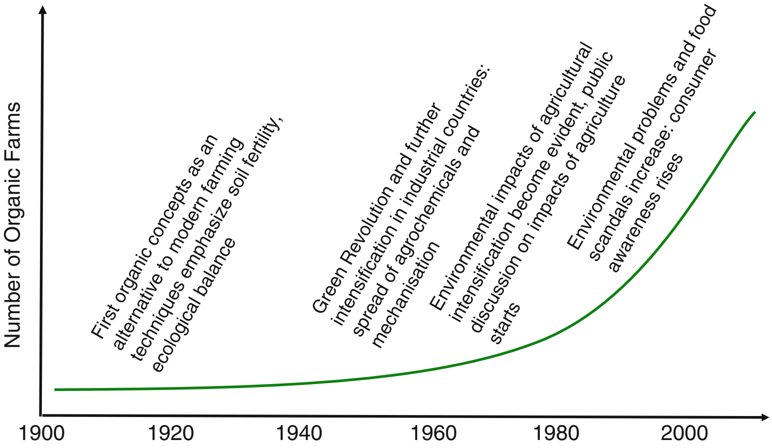

Fig. 1 Historical development of organic farming (Modified from Eyhorn et al. 2003)

also recognized this importance and has introduced standards for the development of Participatory Guarantee Systems (PGS) (IFOAM 2008) which try to formalize such practices without the full documentation requirements of third-party certification (see Sect. 1.3.2).

1.2.2 Historic Development and Perceptions

Organic farming has not only been a specific way to produce food and to nourish the population, but it was – and often is – also a lifestyle. The early protagonists of organic farming discussed social, philosophical, and political issues in their literary works which strongly influenced the lifestyles and attitudes of their followers. The organic movement was largely and originally driven by individual pioneers and farmer associations, supported by consumers and civic organizations. Historically, organic farming has its roots in the different *alternative movements* which developed before and after World War I in Europe as a reaction to the rapidly changing situation of farmers and rural communities due to the mechanization of agricultural practices and globalization of markets before 1914 and to the disastrous living conditions of a large proportion of the urban population. Further momentum was gained by a growing influence of new scientific approaches such as the use of synthetic fertilizers and pesticides in agriculture which required greater inputs than previous farming systems and which began the *industrialization* of agriculture (Conford 2001). These initial topics were overlain on a growing environmental awareness of large proportions of the population in Europe and in the United States from the 1970s onward which led to organic farming being perceived as a more environmentally friendly form of agriculture (see Fig. 1).

All early organic movements were united in their criticism of the western lifestyle, specialization and mechanization of farms, disappearance of small-scale farmers, globalization, and use of artificial fertilizers. Almost all protagonists also expressed visions of an ideal society which could ensure long-term soil productivity. Most of the early protagonists were also advocates of family farms, while a few others called for new forms of ownership and human interactions within society (Conford 2001; Vogt 1999).

When tracing back the organic movement to its roots, the inspiration of the early organic pioneers was often derived from different sources which were closely linked to the social and cultural environments of the countries of origin of the pioneers. In some cases, these roots still determine the current organic sector. For example, biodynamic agriculture was first established by Rudolf Steiner and his followers in the German-speaking countries, and today biodynamic farms are comparatively widespread in Austria, Germany, and Switzerland.

The early organic movement in Great Britain during the 1930s and 1940s was inspired by farming practices in the Orient, either by experiences of pioneers such as Sir Albert Howard in India or by connecting to works of others such as Franklin Hiram King's book "Farmers of Forty Centuries" (King 1911). In particular, Howard's work was entirely based on natural scientific findings deduced from the practices of Indian farmers which Howard came to know during his stay in India when he served as the director of the Institute of Plant Industry in the Indian State of Indore. The most important figure of the early organic movement in Great Britain, Lady Eve Balfour, the founder of the "Soil Association" – still the most important organic association in the United Kingdom today – was herself a disciple of Howard.

For the organic movement in the United States, the catastrophe of the "Dust Bowl" in the 1930s triggered its birth with Jerome Rodale, Louis Bromfield, and Edward Faulkner as the leading figures. The pioneers in the United States strongly expressed the need for more adapted agricultural practices because they perceived the occurrence of floods and heavy wind erosion leading to the dust storms of the 1930s as a "soil crisis" (Beeman 1993). In particular, Faulkner's approach was based on the maintenance of agricultural productivity by using appropriate tillage practices without mouldboard plows and by incorporating organic material into the soil (Conford 2001).

Even though each group of pioneers was strongly influenced by their own social and cultural backgrounds, a lot of dialogue existed between them. Conford (2001), for example, documents that Howard read and commented on the manuscript of Jerome Rodale's book "Pay Dirt" (1945) and wrote a foreword for it, while Ehrenfried Pfeiffer, a disciple of Rudolf Steiner, was heavily involved in the foundation of Eve Balfour's Haughley Experiment. The Haughley Experiment was established in 1939 by dividing a 100 ha site in Suffolk, East Anglia, United Kingdom, into three sections large enough to maintain different farming systems and rotations adjacent to each other. The farming systems included (1) an organic farming system with animal husbandry and a 10-year crop rotation, (2) a conventional farming system with animal husbandry, and (3) a conventional stockless farming system. The goal of the experiment was to study the effects of various farming systems on soil fertility, crop growth, and plant and animal health, to maintain a nearly closed nutrient cycle between animal husbandry and crop production, and to apply “real-world” farming techniques in the experiment (Balfour 1949).

The informal, personal relationships between the pioneers of organic farming were formalized much later in the beginning of the 1970s when IFOAM was founded, which gave the organic movement a consolidated voice. During this period, organic farming practices were defined, and the representation of organic ideas in public shifted from individual pioneers to organic farming associations representing groups of farmers who adhered to certain farming principles.

Organic farming has always been seen as a farming system that delivers high-quality, healthy food (e.g., Balfour 1949). In Germany, Austria, and Switzerland, the first organic protagonists in the 1920s and 1930s, even before biodynamic farming was more widely established, were members of the so-called Lebensreformbewegung. This movement propagated small-scale, horticulture-based farming with vegetarian diets on stockless organic farms or farming with very low stocking densities and very strong foci on product quality and their impact on human health (Vogt 1999). The close connection between food quality and organic farming is also reflected in current consumer expectations. Zanoli et al. (2004) studied consumer motives for buying organic food in different European countries and showed that consumer health and/or the health of their children played a central role in purchase decisions independent of nationality. The participants in the study perceived organic food as healthier than conventional food, while altruistic aspects of organic food production, such as environmental protection, were less important. In this regard, the ambitions of the early organic farming protagonists are still present in current social perceptions of organic farming and organic products. Further details on the topic of organic food quality are discussed in Sect. 2.

The educational backgrounds of the organic farming pioneers were very different and ranged from experienced farmers to agricultural scientists (like Howard), to artists, and to founders of a more philosophical or spiritual approach, such as Rudolf Steiner. Steiner was the founder of anthroposophy which is a philosophy that maintains, by virtue of a prescribed method of self-discipline, cognitive experience of the spiritual world can be achieved. Anthroposophy covers all aspects of life from education to medicine.

Despite the different approaches and ideologies, some basic ideas were very similar and can still be found in all definitions of organic farming and in all standards and guidelines in use today. The first and central paradigm is the emphasis on the maintenance and improvement of soil fertility in organic farming systems. Whether the *pioneer* approach was influenced more by science such as Sir Howard’s “Rule of Return” stressing the closing of nutrient cycles as much as possible with sophisticated systems of manure use and composting (Howard 1943) or by spiritual ideas such as Rudolf Steiner’s (1924) biodynamic compost preparations (traditional medicinal plants such as oak bark, dandelion, and common yarrow are mixed with animal organs, buried in the soil, and later added in small quantities to the compost) and horn preparations (cow horns are filled with silica powder and cow dung and buried in the ground during summer and winter, respectively, then dissolved in water and sprayed on the field), in all cases soil fertility was a central feature of organic farming. Holistic approaches seeing the farm as an *organism* (e.g., Rudolf Steiner) and the importance of animal husbandry are also common features of the early organic farming mind-set. Additionally, the use of external inputs such as pesticides and synthetic fertilizers was banned by all early protagonists.

Some of the early British protagonists of organic farming were firmly rooted in Christian beliefs (Conford 2001), and in other European countries similar tendencies within the organic movement were present. During the 1940s and 1950s, the Swiss couple Hans and Maria Müller, together with the German microbiologist Hans Peter Rusch, founded the *organic-biological* movement, as opposed to biodynamic farming. Hans Müller was strongly engaged in Swiss agricultural politics, while his wife dedicated herself to the education of rural women. The couple was strongly influenced by their Protestant religion and put the independence of family farms and healthy high-quality production at the center of their activities. Together with Hans Peter Rusch, the couple created the basis for the majority of the current Swiss organic farming associations and the largest organic association in Germany, Bioland, which was founded in the 1970s (Vogt 1999).

Politically, the early phase of the organic movement was very diverse; the followers of organic ideas could be found from the far right to the far left. This is in contrast to the current more homogenous structure which is still very much determined by the *alternative movements* of the 1960s and 1970s and, therefore, rather oriented to the left and generally associated with socialist ideas. Conford (2001) documents political activities on the radical right for British protagonists such as Jorian Jenks and Henry Williamson as does Vogt (1999) for early German organic activists.

In the 1960s and 1970s, organic farming became very much linked to the emerging environmental protection movement in Europe and the United States. During this stage of development, the organic movement in both geographical regions occurred at almost the same pace. Rachel Carson's book "Silent Spring" (Carson 1962) triggered a hot debate on the use of pesticides in conventional agriculture because of their role in the decline of biodiversity and their harmful effects on human health. In this context, organic agriculture was perceived as an alternative to the current form of conventional agriculture. In the 1960s and 1970s, structural change in agriculture accelerated among developed countries, leading to a reduction of small family farms, while at the same time the promotion of "all back to nature" philosophies (realized as a simple agrarian lifestyle) became prominent (Treadwell and McKinney 2003). Some of these "counter urbanites" in the United Kingdom were strongly influenced by the cultural revolution of the 1960s and started out as members of rural communes before becoming successful organic farmers or other players in the organic sector (Conford 2008); similar developments took place in other European countries and in the United States. In the

1970s, the importance of individuals declined, while new organic associations were founded (e.g., Germany, United Kingdom, and France) or older ones such as the Soil Association or Demeter were strengthened. The organic movement finally became united on a global scale with the foundation of IFOAM in 1972. The very diverse associations in the different countries for the first time started to speak with one voice on an international level. Due to the growing environmental awareness of consumers, organic foods became much more important than in previous years, resulting in a call for government action during the 1980s. However, *organic production methods* were not clearly defined, as competing definitions between different associations existed. Moreover, the term was not protected legally; this opened the door to fraud and free-rider usage. As consumer interest rose along with the complexity of organic food-chains, it became more imperative to protect consumers and producers from fraud. In addition to the growing success of organic foods on the market, the European Union in the beginning of the 1990s saw organic farming as a tool to reduce agricultural surpluses while improving environmental quality. For this reason, the European Union started to participate in the development of the organic sector by implementing subsidies and regulation of farming practices (see Sect. 1.3.3). These activities served to further enhance market development and acceptance of organic farming as an alternative to conventional agriculture within civil society.

Despite the success of the movement, the organic sector in developed countries often critically discusses current developments, frequently using the phrase "*conventionalization of organic farming*" in the debate (e.g., Darnhofer et al. 2010; Guthman 2004). Among many stakeholders, a feeling of unease exists because of the current rapid growth of the sector together with government engagement that may disconnect current organic farming practices from the original ideas of a holistic farming system. In this context, some current protagonists criticize government engagement in the organic sector, because it is believed that government engagement led to a situation in which fast development of the organic movement occurred at the price of weakening organic ideas and values (Tovey 1997).

Today, in addition to the developments discussed above, other aspects of organic farming have become more important, specifically the increasing importance of countries in the Global South as a source of further development of the organic sector. These countries currently have a much stronger voice than they did previously. The globalization of organic food-chains links countries in the Global South more closely to developed countries in the Global North, and the needs of organic farmers in the Global South have become more prominent. In addition, individuals who are, in the broadest sense, protagonists of a global alternative movement (such as Vandana Shiva) transport new ideas into the organic sector, specifically ideas much less focused in western-world views, than in previous years. These ideas include the role of traditional farming methods, the role of indigenous knowledge, and the empowerment of small-scale farmers. How this development will shape the future of the organic movement on a global scale is still unresolved.

1.3 Current Status of Organic Farming Worldwide

1.3.1 Facts and Figures

This section provides an overview of the current status of organic farming globally, in particular the development of land under organic management and global organic markets. In addition, the primary drivers of growth in the organic sector during recent years will be identified.

Generally, available data on organic farming on a global scale is scarce, particularly for countries in the Global South, because organic production is usually not recorded separately in agricultural databases. In some regions, such as the European Union, large and well-maintained data sets are accessible online, but this is more the exception than the rule. Most data on organic farming on a global scale is presented in FIBL/IFOAM annual publications based on government statistics, surveys, data from organic certifiers, and nongovernmental organizations (NGOs). Willer and Lernoud (2012) provide detailed information for data collected on a per country basis.

Globally, only 0.9 % (37 million ha) of the total agricultural land in use is under organic management, with large differences between countries and regions. An additional 43 million hectares is managed for other organic land uses, primarily for wild collection and organic beekeeping (Willer and Lernoud 2012). Despite significant growth in the organic agriculture sector during the last several decades, the overall share of organic farmland compared to the area which is farmed using modern conventional methods or within traditional agricultural systems is still very small.

Since 1999, when data collection on organic farming by FIBL/IFOAM began, the area under organic management has quadrupled (Willer 2008). Compared to rapid development in previous years, the growth of organic farmland worldwide today is modest but constant. This growth is primarily derived from the organic sector in Europe, which has annual growth rates as high as 20 % in some countries of the European Union (European Commission Directorate-General for Agriculture and Rural Development 2011), and is defined as the agricultural area utilized under organic management. However, the organic area cultivated in India and China has slightly declined because many farmers have dropped out of certification schemes. These farmers have not been able to realize market access for their organic produce and certification schemes have been implemented in a more restrictive manner compared to previous years (Wai 2012), thus showing how important market development and a reliable and transparent certification system are for developing the organic sector. Similar development took place in a few new member states of the European Union (such as Bulgaria) where the organic market is still in its infancy and lacks the size to process large amounts of organic produce at premium prices (European Commission Directorate-General for Agriculture and Rural Development 2011). Figure 2 shows the development of organic farming on a global scale over the last 6 years.

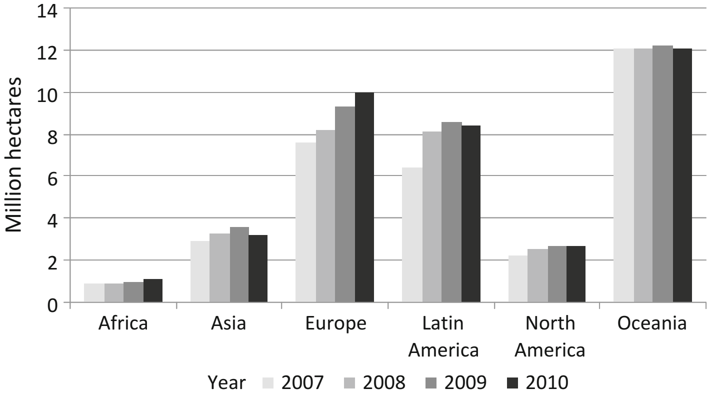

Fig. 2 Development of agricultural area under organic management (certified organic) worldwide for the years 2007–2012 (Willer and Lernoud 2010)

Currently, Australia has 33 % of all agricultural land under organic management, and Europe has 27 %, providing the highest combined shares among world regions (Willer and Lernoud 2012). Countries with major agricultural exports like Argentina, Brazil, China, and India converted significant amounts of land to organic agriculture, with the primary focus on Latin America (8 million ha), followed by Asia (2.7 million ha) and Africa (1.1 million ha) (Willer and Lernoud 2012).

As organic farming systems reflect environmental conditions for agriculture, area-based comparisons among countries or regions on a global scale may be skewed. For example, organic farmland in Australia is primarily dominated by extensive grazing systems, while arable farming plays a major role in Europe (Willer and Lernoud 2012).

Individual country statistics usually display a similar production structure for organic agriculture as for conventional agriculture. This is particularly so in countries of the Global South where most certified organic production is for export cash crops such as coffee, tea, cocoa, cotton, spices, and fruits (Willer and Lernoud 2012). Latin American countries such as Argentina, Uruguay, and Mexico participate in global organic food distribution due to the high amount of land under organic management in these countries and the high number of organic farmers compared to other world regions. In European countries, the cultivation of crops differs between conventional and organic farming systems. In Germany, for instance, leguminous crops for biological nitrogen fixation are more often used in organic farming, while in conventional farming, grain legumes almost disappeared from crop rotations (Agrarbericht 2004).

Current data reveal that three quarters of all organic producers are located in countries of the Global South, including a large number of small-holder farmers. Globally, about 1.6 million farmers work according to organic standards (Willer and Lernoud 2012). Personal motives of farmers for conversion to organic systems are manifold and well-researched for developed countries, while for countries of the Global South such data is scarce. Four major drivers for conversion to organic farming have been determined for the European Union:

1. Using subsidies as governmental support for organic farming.
2. Positive market development.
3. Facilitating environment such as well-established extension services, vocational training for organic farming and agronomic research (European Commission 2010).
4. Personal motives such as ecological perspectives on pesticide use and consumer protection also may be important (Rahmann et al. 2004).

As described above, the market for organic products is one of the major drivers of the development of the organic sector. On a global scale, the organic food market grew from 17.9 billion US$ in 2000 to 59.1 billion US$ in 2010 (Sahota 2012) with the concentration of revenue in the United States (50 %) and Europe (47 %) and the remaining revenue in Oceania, Japan, and South Korea (Sahota 2012). This distribution has not changed over recent years, and most consumption of certified organic products is concentrated in the developed world, while regional organic markets in the Global South are still in their infancy. According to Sahota (2012), the concentration in only two markets is a major weakness of the global organic sector. This situation makes global organic production very vulnerable to reduced demand in the United States and Europe, a situation very likely to occur in the near future due to the economic crisis in both the United States and the European Union. Thus, one major challenge in the years to come is the development of regional markets for organic products produced in the Global South. In some countries such as Thailand, India, and China, a stronger growth of local markets is visible, driven mainly by growing consumer awareness which is triggered by food scandals and the development of a more affluent middle class (Panyakul 2012; Sahota 2012; Wai 2012). The existence of well-functioning markets for organic products including transparent certification systems is a major driver for growth of the organic sector. If the above-mentioned countries pursue this opportunity in the coming decades, improved growth of organic farming could be realized.

1.3.2 Role of Standards in Organic Farming

A crucial issue for a working organic sector is the development of organic standards and the implementation of a functional certification system (Albersmeier et al. 2009). The organic nature of a product is based on standards which are applied during production and processing of the product; these standards are mainly process standards. It is therefore a quality which a consumer cannot assess directly when buying a product. As organic products are sold at premium prices that reflect the added value of the products (e.g., sustainable production, fairness, and animal welfare), consumers as well as organic producers must be protected from fraud. Consumer and producer trust in the labels used for differentiating organic products from conventional ones is the backbone of a working organic sector. To ensure this trust in organic certification systems, documentation of the adherence of the producers and processors to organic standards is indispensable. On a global scale, the United States, the European Union, and the Japanese standards are prevailing, all of which are developed and implemented by governments (Zorn et al. 2011). Currently, 84 countries possess fully implemented national organic regulations, and 24 are in the process of drafting such regulations (Huber et al. 2012).

If organic standards are lacking, or only implemented on a voluntary basis, and/or certification systems are not working properly, this undermines consumer trust, hampers the development of local organic markets, and can seriously damage the organic sector in a country. Even though standards and regulatory systems are central to the development of the organic sector, they may interfere with and manipulate further development of organic agriculture in a manner seen as inconsistent with the philosophy of the organic movement. In particular, the role of governments in the design and implementation of organic standards is criticized by some stakeholders in the organic sector. As the organic market grows, governments become more interested in it (Courville 2006), leading to a shift in normative power from the organic and grassroots associations and organizations to governmental bodies. This is contrary to the attitudes of a movement that was and still is driven mainly by the activities of farmers and processors, much more than conventional agriculture.

Historically, the first organic standards were developed by organic farming associations during the 1950s (e.g., Demeter in Germany) and 1960s (e.g., Soil Association in the United Kingdom). These standards can be seen as blueprints for other regulatory frameworks developed later by governments and nongovernmental organizations (NGOs). A further important step was the implementation of the European (European Union) Regulation ECC 2092/91 – which heavily influenced the design of the Codex Alimentarius Guidelines (implemented in 1999) as well as many other governmental and private regulations (Courville 2006). Today, implementation of organic regulations by governments deeply changes the role of organic associations from being those who defined organic farming to those acting as lobbyists, marketing organizations, and consultants for their members.

A second criticism refers to the complexity of organic standards. For example, the current European Union Regulation No. 834/2007 (the revised version of European Union Regulation ECC 2092/91 since 2008) consists of a main body of 23 pages that is supplemented by EC Regulation No. 889/2008, which has 84 pages of detailed rules on organic production, processing, labeling, and control; further regulations on third-country imports, wine-making, and aquaculture exist (European Commission 2007, 2008a, b, 2009, 2012). Other organic regulations are equally extensive and difficult to handle, particularly for small-scale farmers. Fulfilling such requirements includes a high amount of bureaucratic paperwork and poses great obstacles for small-holder farmers in the Global South who often are illiterate and possess only small amounts of agricultural land (Courville 2006). In addition, certification costs become prohibitively high for such producers. Excluding small-scale farmers due to complex certification procedures is obviously in contrast to all basic organic principles. In addition, small-holder producers are very important for the organic market as they produce a high share of the organic commodities such as cocoa, coffee, herbs, and spices. To tackle the problem, two different approaches exist: Internal Control Systems (ICS) to facilitate organic exports from small-holder farmers and Participatory Guarantee Systems (PGS) particularly for local markets.

The Internal Control Systems is a meta-regulatory system developed by IFOAM and the International Organic Accreditation Service (IOAS). Farmers who are organized into farmer groups, cooperatives, and producer associations or who are contracted by an exporter can implement ICS systems. This includes the establishment of an internal inspection system with internal inspectors (e.g., members of the farmer group). These inspectors check all member farms for compliance with the organic standards. In addition, an external inspector tests the functioning of the ICS by inspecting a certain subsample of all farms in the farmer groups and by checking the documentation of the internal inspectors and farmers. This procedure reduces certification costs significantly (van Elzakker and Rieks 2003) and can simultaneously serve as a tool for capacity-building among the farmer groups.

Initially, the reception of ICS systems by government authorities was quite critical; it was strongly doubted that such systems could be properly verified. Presently, however, ICS systems are more widely accepted by government authorities (e.g., in the European Union) (Courville 2006). Nevertheless, the basic criticism of the ICS remains unsolved. The internal inspectors are economically and often personally linked to the other members of the farmer groups, making internal inspections potentially biased and leading to favoritism and lax internal controls. Even though these risks are known, no better alternatives are currently available.

Besides the ICS, PGS is emerging as an alternative option in the certification process for organic farmers. IFOAM defines PGS as:

> Participatory Guarantee Systems are locally focused quality assurance systems. They certify producers based on active participation of stakeholders and are built on a foundation of trust, social networks and knowledge exchange. (IFOAM 2008)

In developed countries, PGS systems developed partly from a growing frustration by organic farmers who felt restricted by the current costly third-party certification systems and who take the surveillance of certification bodies as an affront to their own deeply grounded understanding and commitment to organic principles. Therefore, PGS systems can be seen as a farewell to the established *conventionalized* organic sector which may no longer reflect the basic holistic ideals of organic farming. A further reason for the establishment of PGS systems is that the requirements for third-party certification are too demanding, particularly for small-scale farmers in the Global South. Yet, even in industrialized countries small-scale farmers drop out of certification because handling the documentation for third-party certification has become too laborious for them (IFOAM 2008).

IFOAM offers a PGS logo for initiatives that receive approval from the IFOAM PGS Committee. In order to create a common ground for PGS systems, IFOAM defines a Shared Vision and Shared Ideals. In contrast to ICS, PGS is not recognized by third-party organic certification body. PGS systems are, in most cases, strongly rooted in a local or regional context and are based on a close relationship between organic farmers and consumers of organic products. In a way, PGS is a route back to the early days of the organic movement when food-chains were short, and no need for elaborate certification schemes existed because consumers were close enough to the farms to personally control the actions of the producers.

PGS schemes can also give financially less sustainable communities access to organic food, strengthen local organic markets, and contribute to food security (IFOAM 2008; Courville 2006). The direct connections between consumers and producers are also an important means of fostering consumer trust in organic produce in developing countries. For this reason, countries such as India and Brazil designed a legal framework that allows for accreditation by PGS for internal markets (Fonseca et al. 2008; Sligh and Christmann 2007). In this context IFOAM also promotes the inclusion of PGS systems into organic guidelines particularly to strengthen the role of small-holder farmers (IFOAM 2008).

PGS systems place themselves deliberately out of the regular third-party certification system, either out of a lack of financial or organizational resources or because farmers refuse to comply with the demands for documentation and costs for certification and have a general distrust for an organic sector that has left the niche. For consumers and farmers in countries of the Global South, PGS may be a very successful tool for the establishment of local markets as documented by several case studies (e.g., Fonseca et al. 2008; Nelson et al. 2008). Nevertheless, problems may arise from the coexistence of certified and noncertified organic farming, such as when price premiums are paid for certified products while PGS producers have to go without them. PGS in developed countries may serve as a viable option for local markets and alternative distribution channels like local farmer markets, box schemes, or community-supported agriculture (IFOAM 2008), but as food-chains become longer and more complicated, it is difficult to imagine that PGS-certified products can be included in larger supply-chains.

Both systems, ICS and PGS, offer new ways to empower small-holder farmers by enabling them to access international or local markets. On the other hand, both systems also create new challenges for the organic sector. The ICS with all of its power for capacity-building has several drawbacks. Even though it involves much lower bureaucratic hurdles than regular third-party certification, large efforts are still required from farmers such as documentation of inputs or production plans. This implies that access to longer organic food-chains is only possible for farmers that are already organized and possess a certain level of training and education or have access to help from NGOs. Such prerequisites exclude many poor farmers from ICS schemes, those who have the strongest need for support.

A third major challenge connected to certification and setting standards is the problem of international harmonization of standards. In this regard, again the two sides must be balanced. Consumer trust must be ensured by confirming that similar organic standards are applied worldwide while also taking into account different production systems and regional characteristics. In recent years, international organic trade has been dominated by standards developed by the major importing countries such as the United States, the European Union and Japan. Meanwhile, many other countries have also implemented their own national guidelines. As mutual recognition between the standards continues to be scarce, double and even triple sets of standards have had to be followed by producers who export to different countries. This situation has threatened to become a major obstacle in the development of the organic sector. In order to avoid tedious and costly certification and import procedures and to harmonize organic standards for successful organic trade on a global scale, assessing the equivalence of standards becomes crucial. By recognizing a national organic standard of the exporting country as equivalent to that of the importing country, a complicated process for organic imports can be considerably shortened and facilitated. To achieve this goal and ensure access by developing countries to international markets, the International Task Force on Harmonization and Equivalence in Organic Agriculture was initiated in 2003 (Crucefix 2007).

At the moment, there is considerable progress in the global harmonization of organic standards. To foster worldwide harmonization, IFOAM published, in its revised version of the *Norm Book*, a new strategy for standards harmonization called “The IFOAM Family of Standards” within the IFOAM Organic Guarantee System (IFOAM 2012). For “The IFOAM Family of Standards,” the Common Objectives and Requirements of Organic Standards (COROS) were developed as an internationally valid baseline for equivalence assessments of national or private standards that are based on the IFOAM Principles of Organic Agriculture (see Sect. 1.2). The COROS were established by an IFOAM working group, the Food and Agriculture Organization of the United Nations (FAO), and the United Nations Conference on Trade and Development (UNCTAD). The COROS is based on IFOAM Basic Standards and on the Codex Alimentarius Guidelines for the Production, Processing, Marketing and Labeling of Organic Foods and other internationally important standards (IFOAM 2012). Governments are encouraged to use COROS for equivalence assessment or for bilateral or multilateral decisions on standards recognition. In the future, this new instrument may successfully facilitate organic trade by using a universal and transparent procedure for equivalence assessment.

In addition to COROS, important bilateral agreements among countries were recently signed. In 2012, after 10 years of discussion, the mutual recognition of organic standards of the United States (NOP) and the European Union was achieved, leading to a simplification of trade (Huber et al. 2012).

Despite the importance of standards and their harmonization, some proponents of organic agriculture have voiced growing concern about the focus on standards that shifts the core of organic farming from holistic principles and systems approaches to following prescriptions on how to farm and how to use inputs or processing aids. Ikerd (2006), for example, fears that the harmonization of standards initiates a development similar to conventional agriculture where further “industrialization” of organic farming is driven by price pressure and specialization of production systems at the cost of diversity, holism, and local roots. Nevertheless, as the organic sector has left its niche, harmonizing standards will be a key issue for enabling organic trade on a global scale and for continued growth of the organic sector.

1.3.3 Role of Government Support

During the early stages of development, when organic farming was perceived as an alternative to conventional mainstream farming methods, governments showed no interest in supporting such endeavors. Organic farming associations, individual farmers, and organic consumers perceived themselves as opponents to the conventional food system (see Sect. 1.2.2). Therefore, early support for organic farming was provided mostly by civic groups and individuals interested in organic farming practices. Profit was generated from production and private donations, or the work was performed without any remuneration from on-farm research by organic farmers. This status changed toward the end of the twentieth century when different national funding schemes were developed, particularly in Europe (e.g., Germany, Austria, Denmark), to acknowledge the positive effects of this farming method (Lampkin et al. 1999). Today, the presence or absence of government support for organic farming can significantly influence the growth and stability of the organic sector within a country. As discussed by Stolze and Lampkin (2009) regarding the situation in the European Union, policy instruments support organic farming through supply, demand, or both and can be legal regulations and financial or communicative instruments. The implementation of legal instruments such as organic regulations has positive impacts on supply and demand. Financial instruments, such as producer support *via* area payments or inspection cost support, enhance supply while supporting marketing initiatives and investment grants target demand. Communicative instruments such as vocational training programs, consumer information campaigns, or the introduction of state logos for organic products are also important measures. Depending on the focus, government support can take very different forms, including the implementation of organic regulations, increasing organic sales *via* marketing programs for organic products and direct area-based subsidies for organic farming. To be successful, an integrated strategy that simultaneously strengthens supply and demand is necessary; otherwise, oversupply may lead to marketing problems (Stolze and Lampkin 2009).

In developed countries, government support *via* direct area-based payments is a successful tool for increasing the area under organic management and has been followed by the European Union and other European countries such as Switzerland and Norway. Since 1994, conversion to and maintenance of organic farming are supported in most European Union member states (Häring et al. 2004). Support for organic farming in these countries is embedded in the overall agricultural policy and focuses on different goals. Currently, the most important political goal is the reduction of negative effects from conventional farming on the environment and on biodiversity. To achieve this goal, area-based payments for conversion and maintenance of organic farming have been introduced within rural development programs and agri-environmental measures of the Common Agricultural Policy (CAP) in the European Union (Schwarz et al. 2010; Stolze and Lampkin 2009). Initially, reducing production surpluses was the primary target of policy-makers when organic farming support was introduced across the European Union at the beginning of the 1990s. The lower yields in organic production systems were seen as a strategy to reduce overproduction and to minimize related costs (Dabbert et al. 2002). Since the end of the 1990s, the two primary goals (environmental protection and reduction of agricultural production surplus) changed and organic farming became, in itself, a policy goal. Today, organic farming is seen as a strategy for sustainable development, in particular for environmental protection and animal welfare, and is therefore supported by the CAP (Sanders et al. 2011).

If considered as an *infant industry* (an industry that is not yet fully developed, where production costs are still too high to permit achievement of a competitive market status independently), a government can also temporarily support organic farming at an early stage of development in order to set up infrastructures that allow further growth until the organic market is large and mature enough to function without further government interference (Dabbert and Häring 2003). Such temporary support may be vital for the establishment of local markets such as in China or Brazil. The aforementioned authors also discuss the support of organic farming as a sustainable alternative farming method that relies less on risky technologies (e.g., the strong reduction in pesticide use or the ban on using genetically modified organisms) compared to mainstream conventional agriculture. Organic farming in this context is considered as a backup method to produce food in case conventional agriculture and its technologies might prove to be harmful. This aspect is also discussed by the IAASTD (2008) which sees organic farming exactly as such an alternative. The question arises as to whether organic farming is still considered as such an alternative farming method or whether it already has left its niche. For some countries such as Austria (with 20 % of the agriculturally usable area under organic management in 2011) or Switzerland (with 12 % of the agriculturally usable area under organic management in 2011), organic farming practices cover a considerable amount of the arable land (Willer et al. 2013). In these countries, organic farming is more of a mainstream production method than an alternative. In addition to organic farming, other farming practices were also developed, such as "integrated farming," which focuses on maintaining ecosystem services. Triggered by books such as *Silent Spring* (Carson 1962), citizens in industrialized countries called for more environmentally friendly and agroecologically oriented farming methods. This demand was subsequently promoted by scientists and agroindustry. In the 1990s, the term "integrated farming systems" was used by different authors such as Edwards et al. (1993) and Vereijken (1992) to introduce agricultural practices which were considered to be sustainable and oriented toward ecological principles such as nutrient cycling, use of rotations, and maintenance of biodiversity. Often, integrated farming was very closely linked to integrated pest management (Vereijken 1989). On one hand, this approach allows for the use of all available means of pest control, but tries to keep pesticide input to levels as low as possible in order to be economically viable and with as little damage as possible to the environment (FAO 2013). In addition to environmental aspects, integrated farming systems should also include social and economic aspects of sustainability. Morris and Winter (1999) argued that integrated farming systems could be a third manner of operation, lying between conventional and organic agriculture. In Europe, integrated farming approaches have, up to now, lacked a clear legal definition of accepted agricultural practices; therefore, they never enjoyed the same attention as organic products from a consumer perspective. In China, on the contrary, the label “Green Food” for products from integrated management systems exists; it is widely known and accepted among consumers and may even serve as a basis for the development of organic farming in the country (Paull 2008; IFAD 2005). As a countermovement to industrialized conventional agriculture, agroecologically sound farming methods have spread worldwide, primarily driven by consumer demands.

The efficiency of government support for organic cultivation is documented by the rapid increase in organic acreage and in the number of organic farms in European Union member states after 1991 when subsidies for organic farming as a part of the agri-environmental measures of the CAP were introduced (Sanders et al. 2011). However, subsidies are never the only driving force for conversion to organic farming; other important drivers are market demand, a supportive public and economic viability of organic enterprises (Sanders et al. 2011; Padel et al. 1999). The development stage of organic farming within a country is reflected not only in the area under organic management, but also in the *per capita* consumption of organic products. A country with a well-developed organic sector is characterized by a high number of producers, but also a high number of processors and a functioning trade in organic products which are easily accessible by many consumers. In addition, consumer trust in organic certification and labeling is vital to ensure the long-term function of the sector. If the above-mentioned conditions are not provided, the stability of organic farming may be threatened in the long-term.

As described previously, the economic viability of organic enterprises plays a vital role in the development of organic farming. Whether or not organic farming is an economically sound means of production for a farmer depends not only on governmental support, but also on whether price premiums can be realized for organic products. This is the case for the majority of European organic farmers; when combined with governmental support, their returns are as high as or higher than those of conventional farmers (Schwarz et al. 2010).

In the United States, national organic regulations are in place, similar to the European Union, but the government took a different free-market policy approach to facilitate the development of an organic market (Dimitri and Oberholtzer 2005). Organic farming research and extension is provided by universities; certification cost reimbursement programs and different market grant programs open to organic farmers exist, but no subsidies based on the various public and environmental benefits from organic farming exist in the United States (Dimitri and Oberholtzer 2005). The differences in funding schemes have led to slower growth of the certified organic farmland in the United States compared to the European Union, but have led to a faster, consumer-driven development of the organic market in the United States. Recent research (Uematsu and Mishra 2012) shows that household incomes of organic farmers in the United States are not significantly higher than those of conventional farmers, which is a further impediment to the growth of the sector.

Apart from European countries and the United States, government support for organic farming is scarce in most countries. Nonexistent policies for the organic sector in Australia may even hamper or delay growth as described by Wheeler (2012).

Despite the large area under organic management there (primarily extensive rangeland of around 12 million ha as of 2010) (Willer and Lernoud 2012), no mandatory national standards exist, organic farming research is scarce and currently declining, special extension services for organic farmers are often missing, and the positive environmental externalities of organic farming are not taken into account. Consequently, these conditions are slowing development of the Australian organic sector.

For developing countries, reasons for implementing special organic farming policies differ from those of developed countries. Today, some governments are beginning to see the opportunities of organic farming and are reinforcing their support, although rarely in the form of direct payments. UNEP-UNCTAD (2008) published a set of policy recommendations for developing countries based on the assumption that organic farming systems are particularly well-suited for resource-poor, small-holder farmers because external inputs are reduced, soil fertility is increased, yields become more stable and food security is enhanced while traditional farming methods and traditional varieties and breeds are conserved. In addition, organic farming can be a useful tool in capacity-building. Besides protecting public goods, the production of export commodities for an ever-growing international market can be an important strategy for improving farmer incomes. As the use of synthetic pesticides is banned in organic systems, health risks for farmers, farm workers and consumers are reduced.

The UNEP-UNCTAD particularly emphasizes the close interaction between government organizations and the private sector in order to develop organic action plans and the importance of incorporating organic farming policies in a country's overall agricultural policy. Further important steps include the development of national organic regulations for the local organic market, access to certification services, examining the feasibility of PGS systems, and the implementation of ICS. Demand for organic products should be enhanced by consumer information and the implementation of organic trademarks. On the supply side, farmer organizations should be supported and export promotion activities should be introduced. In order to strengthen organic production, all measures regarding information and education of farmers are central.

Recently, governments from countries in the Global South have started to support organic farming more strongly than before. For example, Patil et al. (2012) report that the Indian central government, as well as the federal states, such as Karnataka, offers subsidies, loan waivers and training for farmers willing to convert to organic farming. The policy in Karnataka aims at reducing inputs for farmers affected by crop failure and indebtedness. Similarly, in 2003, the Brazilian Ministry of Agrarian Development launched programs to support organic farming in order to support small-scale farmers (Blanc 2009). Prior to these activities, Brazil started to introduce organic regulations in 1994, which were driven not only by the insistence of NGOs and activists, but also by larger companies interested in economic possibilities within the organic sector (Blanc and Kledal 2012). Developing countries with a well-established organic sector (such as Costa Rica) have developed similar to Europe or the United States, with a strong commitment by private sector organizations that was backed up later by governmental activities such as the implementation of organic regulations and organic action plans (UNEP-UNCTAD 2008). Government involvement becomes particularly important when aspects of international trade are concerned because only state institutions are able to perform negotiations to facilitate market access to and from other countries. Costa Rica is a good example as it is one of the few countries on the “third-country list” of the European Union. This means that Costa Rican organic regulations are recognized as equivalent to European Union regulations for organic food and farming. This equivalency implies that organic products from Costa Rica can be imported into the European Union without additional certification according to European Union standards, thus facilitating trade in organic products between the two economies.

The above-mentioned examples show that government support can be very favorable for the development of organic farming. On the other hand, strong government involvement also can be dangerous as reported by several authors (e.g., Stolze and Lampkin 2009; Ikerd 2006). Organic farming as a concept is created by producers, civic associations, and other concerned persons; governments should not interfere by changing the concept at will. The success of organic farming policies is ensured by the involvement of all stakeholders, otherwise the organic idea will deteriorate over time.

A further critical point related to government support, and particularly referring to direct payments as practiced in the European Union, is whether organic farmers become dependent on such financial measures, resulting in negative consequences for the development of the entire sector. Offermann et al. (2009) intensively discussed this question and came to the conclusion that even though direct payments are important for the economic viability of organic enterprises in the European Union, the level of support is of minor relevance when compared to other support measures and market returns. When asked directly, some farmers in Austria and Denmark have even suggested a complete cancelation of subsidies for organic farming.

It is difficult to assess whether government support in developing countries has any significant influence on the development of the organic sector, as research and published material are almost exclusively centered on the situation in Europe and the United States. Further research is needed in developing regions because expectations within the organic sector are high and organic farming is seen as one method of alleviating poverty. If so, suitable policy measures for increasing organic farming should be identified.

1.4 Ecological and Environmental Benefits and Limits of Organic Farming

1.4.1 Methodological Approaches

Organic farming is perceived as more environmentally friendly than conventional farming. As discussed in Sect. 1.3.3, this assumption is the basis for payments to organic farmers for the protection of environmental goods and services such as groundwater, soil, and biodiversity. Many studies have been performed to assess the benefits of organic farming to the environment. Various scientific approaches have been used including long-term field trials for comparisons between organic and conventional farming systems, farm-pair comparisons of existing conventional and organic farms, case studies, modeling approaches on a farm or regional scale, indicator-based studies, and life-cycle analyses (LCA). The latter usually describes the environmental impacts of farming systems on a per product basis, while the other methods refer to area-related impacts. For local problems such as nitrate leaching, area-related assessments are appropriate, while for pollutants with global impacts such as greenhouse gases, assessments that are allocated per product unit may be more appropriate (Mondelaers et al. 2009).

Currently available studies primarily cover farming systems in temperate regions, particularly in North America and in Europe. Evidence for the performance of organic farming systems in the tropics and subtropics is scarce; case studies exist, but peer-reviewed literature is very often not available. Therefore, the following sections mostly refer to evidence of the performance of organic farming systems in temperate regions. Fortunately, the Swiss Research Institute of Organic Agriculture (FIBL) initiated three systems-oriented field trials in India (semiarid, cotton based), Kenya (subhumid tropics, maize- and vegetable-based), and Bolivia (humid tropics, agroforestry-based using cacao) to assess the performance of organic agriculture with regard to environmental impacts and economic feasibility for farmers (Zundel et al. 2008). Additional scientific studies and field trials on farming system comparisons can be expected with the rising interest of governments in the Global South toward organic farming. Therefore, in the near future, data availability will hopefully increase and some of the conclusions from currently available meta-analyses may have to be reconsidered.

1.4.1.1 Soil

Soil protection and maintenance of soil quality are central to the long-term sustainability of agricultural systems, because soil is the basis for agricultural production. Today, agricultural soils on a global scale are affected by salinization, nutrient depletion, erosion, topsoil compaction, and loss of soil organic matter. These features of land degradation have received considerable attention in research and agricultural practices and different approaches for the protection of soils (e.g., no-tillage or reduced-tillage systems) have been developed, however the rate of soil deterioration around the world continues to increase (Bai et al. 2008).

Soil fertility enhancement is central to the concepts of organic agriculture. Today, IFOAM (2005) in their “Principle of Health” perceive organic farming as “a production system that sustains the health of soils, ecosystems and people.” Organic crop production systems must “conserve or improve the soil’s structure, organic matter, fertility and biodiversity” (IFOAM 2012). As described in Sect. 1.2.2, the early protagonists of organic farming were very concerned with all aspects of soil fertility and focused on the recycling of nutrients and organic matter (e.g., Howard's "Rule of Return") (Howard 1943). Today soil fertility management in organic farming systems is determined by managing soil organic matter to ensure crop production by optimizing soil biological, chemical, and physical processes (Watson et al. 2002).

To evaluate soil fertility within a farming system, different parameters can be used as indicators. To compare organic and conventional farming systems, soil organic matter, soil structure, soil erosion, and soil biological activity are the most appropriate measures (Stolze et al. 2000). In addition, to assess the long-term sustainability of a farming system, the long-term development of nutrient levels, such as plant available P, can provide important insights. Many studies have been performed to compare soil fertility between organic and conventional farming systems using these parameters, the results of which are discussed in the following subsections.

Soil Organic Matter – The turnover of soil organic matter (SOM) is central to organic farming systems because it determines the availability of nutrients for crop yield; many studies use this parameter when comparing farming systems. One of the first systematic reviews of the available literature is provided by Stolze et al. (2000) who deduced that organic farming in many cases leads to increased levels of SOM compared to conventional farming, although some studies have found no differences or lower amounts of SOM compared to conventional farms. These results have been confirmed by more recent meta-analyses and reviews (e.g., Gattinger et al. 2012; Tuomisto et al. 2012a; Gomiero et al. 2008, 2011; Mondelaers et al. 2009). The primary reasons for the higher amount of SOM in organic farming systems are due to higher inputs of organic matter from farmyard manure, green manures, and external organic matter inputs into organic farming systems (e.g., Bakken et al. 2006; Pimentel et al. 2005; Clark et al. 1998).

Similar amounts of SOM under organic and conventional management have been described in farm-pair comparisons by Gosling and Shepherd (2005) who attributed their findings to lower yields and, therefore, lower biomass input under organic management and the fast turnover of organic matter in grass-clover mixtures due to the narrow C to N ratio of this plant material. Similarly, Wander et al. (2007) links insignificant differences in SOM between organic and conventional fields to fast C turnover, despite high levels of manure fertilization.

Differing results among studies result from SOM not only being determined by management practices, but also by soil parameters such as texture, composition of clay minerals, climate, and water regime. In addition, total SOM is a comparably inert parameter and may need several years to show changes after conversion. In some studies, the new equilibrium of SOM after conversion to organic farming may not have been achieved yet.

Soil Physical Parameters – Compared to research on differences between SOM of conventional versus organically managed sites, research on the impact of organic farming on soil physical parameters is scarce. Only a few studies measured aggregate stability, soil structure, and water infiltration as soil physical parameters that can be influenced by different management systems.

In a field trial, Mäder et al. (2002) documented a 60 % stronger aggregate stability in organic compared to conventional systems. Jordahl and Karlen (1993) reported similar, but less pronounced results. Bakken et al. (2006) found greater numbers of biopores in some sites, which may lead to faster water infiltration and less erosion. Gerhardt (1997) describes, using a farm-pair comparison, organic sites as having more pores and better developed soil aggregates. These positive effects are usually coupled with higher amounts of SOM in organically managed soils and higher earthworm and soil microorganism activity (Bakken et al. 2006; Mäder et al. 2002; Siegrist et al. 1998; Jordahl and Karlen 1993).

Such positive effects also may lead to reduced levels of erosion in organic farming systems. Reganold et al. (1987) was one of the first to assess the impact of organic farming on soil erosion by comparing two sites under long-term organic versus conventional management. In this comparison, the organic site showed better performance with less soil loss and a deeper A-horizon; similar findings were presented by Liebig and Doran (1999) for organic and conventional farms in Nebraska and North Dakota in the United States. Nevertheless, Stolze et al. (2000) discussed more critical features of organic farming systems. Intensive tillage might lead to aggregate destruction, slow development of plants in early growth stages resulting from restricted N availability may reduce soil cover, and wider row distances in organic farming may increase exposure of the soil surface to heavy rains, leading to more erosion under organic farming conditions.

Reduced Tillage and No-Tillage Systems in Organic Farming – No-tillage systems are widely recognized as an appropriate tool for the protection of cultivated soils because erosion is reduced, soil structure is improved, water infiltration is enhanced, soil biological activity is preserved, and reduced labor and fuel costs can be realized. To date, the United States is the pioneer with nearly 20 % of the total cropland under no-tillage practices (Triplett and Warren 2008).

Unfortunately, despite the strong focus on soil fertility, organic farming systems are very difficult to adapt to no-tillage or reduced-tillage practices as these systems strongly rely on herbicides to combat weeds and volunteer plants from the preceding crop. Despite the completely different approach to weeding from organic farming, research and development of no-tillage or reduced-tillage systems are becoming increasingly important. When tillage operations are reduced in organic farming systems, plowing is usually substituted by shallower tillage or no tillage at all. This practice results in increased weed pressure and reduced yields (e.g., Vakali et al. 2011; Gruber and Claupein 2009). Often the incorporation of grass-clover leys in the soil is difficult to achieve by shallow tillage operations; the same is true for other plant residues and organic manure. In addition, in cooler climates, N mineralization is slower in spring which also depresses yields (Mäder and Berner 2011). However, research on reduced tillage in organic farming systems has gained new impetus; the core of the new approaches is the development of adapted rotations and appropriate tillage techniques. Some of the results are very promising as they show lower yield reduction compared to inversion tillage (14 % for wheat, 8 % for barley, and slightly higher yields for sunflowers) as in previous studies (Berner et al. 2008). Such results are stimulating for further research and transfer to practice. Notably, for stockless arable organic farming systems that become more widespread, no-tillage or reduced-tillage systems would be feasible options for maintaining or increasing soil fertility. Two different strategies exist that differ between Europe and the United States (Mäder and Berner 2011). While farmers and researchers in the United States are focused on no-tillage systems with high cover crop residues, European researchers and farmers are moving toward conservation tillage by reducing tillage depth or practicing non-inversion tillage. The systems practiced in the United States are based on high-residue cover crops as a means to suppress weeds. Whether such systems are applicable or not depends on the possibility of establishing the cover crops and combining them with suitable cash crops (large seeds or transplants). This is the case in climates that have long growing seasons, when late planting is possible and soils are fertile well-drained and prone to erosion (Morse and Creamer 2006).

No-tillage or reduced-tillage systems in organic farming may also include the use of companion crops and mixed cropping systems as well as new approaches for land use in space and time. Because plowing is very energy-intensive, but the reduction of energy costs and the prevention of greenhouse gas emissions are high on the organic farming agenda, the development of reduced-tillage and no-tillage systems will gain importance in the future.

1.4.2 Ground and Surface Water

The protection of ground and surface waters is a major issue because drinking water contamination leads to human health risks. Agriculture affects both ground and surface water through erosion, leaching, and surface runoff of fertilizers and pesticides. Regarding organic and synthetic fertilizers, the most important compound leached from agricultural soils is nitrate. Phosphorous is much less mobile, making the leaching risk comparatively low. Phosphorous contamination of water primarily occurs *via* erosion and surface runoff. Phosphorous translocation is usually tied to the transport of soil particles and only a minor amount to leaching; for highly P-saturated soils, leaching is a relevant pathway. As soils under long-term organic management tend to have lower amounts of P compared to conventionally managed soils (Gosling and Shepherd 2005; Løes and Øgaard 2001) and P contamination of ground and surface water from organic farmland is not very likely, the next section discusses nitrate leaching, but excludes phosphorous.

1.4.2.1 Nitrate Leaching

Humans have influenced the global nitrogen (N) cycle to a significant degree through the release of nitrous oxides by burning fossil fuels, producing N-based fertilizers, and by cultivating plants that perform biological nitrogen fixation (BNF). Rockström et al. (2009) developed the concept of *planet boundaries* as a framework to introduce indicator thresholds that describe different earth system processes. Within this concept, two boundaries have been transgressed by humanity: biodiversity loss and the N cycle. In recent decades, humans have produced more reactive N than all terrestrial ecosystems combined. Currently, about 75 % of the reactive N released by humans is related to food production, 70 % originates from the Haber-Bosch process (technical synthesis of NH_3 from N_2 and H_2 for the production of N fertilizers), and 30 % from BNF (Galloway et al. 2003). Unfortunately, agriculture is currently not very efficient in using N; the more N is added to an agroecosystem, the more is lost. Only 10–20 % of the reactive N used in agriculture is consumed by humans; the remainder is transferred to different environmental compartments (Galloway et al. 2004). A major effect of N leached from agroecosystems is the contamination of groundwater in regions with intensive agriculture (Stoate et al. 2001). Nitrogen from agricultural sources accounts for 50–80 % of nitrates entering European waters (Brunori et al. 2008). From groundwater, N is transported through the watershed to rivers, lakes, and finally to the ocean. Excess N can cause eutrophication and anoxic or hypoxic waters in coastal areas, the *dead zones* which exist, for example, in the Gulf of Mexico and the Baltic Sea. Many agroecosystems are N limited; as soon as N levels increase, the species composition in the ecosystem changes. This is one of the primary routes for accelerated loss of biodiversity in intensively used agroecosystems in developed countries (Stoate et al. 2001).

On a global scale, differences in N budgets in agriculture are huge. Across wide regions of the developing world, cropping systems are N deficient, while at the same time developed countries produce large surpluses of nitrogen. In Europe, N surpluses range from 262 kg ha^{-1} $year^{-1}$ in the Netherlands to less than 40 kg ha^{-1} $year^{-1}$ in Poland; most of the N is derived from mineral fertilizers (Galloway et al. 2004). Regional N deposition resulting from intensive livestock husbandry in central Europe is severe, altering ecosystem characteristics completely and resulting in loss of biodiversity. Groundwater contamination with nitrates is frequently encountered (UNEP-DEWA Europe 2004), and transfers of nitrates to rivers and coastal areas are prevalent. European agricultural policy tries to tackle the problem using directives (e.g., European Union Nitrates Directive) and incentives for N reduction within the agri-environmental programs of the CAP. These strategies are partly successful, but more efforts must be made. For North America, the picture is similar, with large differences between regions, such as with the high amounts of N inputs into the Mississippi River basin, accompanied by large N exports for animal feed and human food (Galloway et al. 2004).

Due to the importance of nitrate leaching into drinking water, large numbers of studies on the influence of agricultural management practices on nitrate leaching have been published in recent years. Compared to conventional farming, organic agriculture is theoretically supposed to reduce nitrate leaching because of lower animal stocking densities and lower N inputs from restricted fertilizer use. The validity of this assumption was assessed in many studies, mostly in European countries. Two recent meta-studies addressed the topic and collected a considerable set of studies for their works: Mondelaers et al. (2009) included 59 peer-reviewed studies in their meta-analysis, and Tuomisto et al. (2012a) included 47 studies. The studies covered field experiments as well as nitrate leaching models. According to both working groups, the nitrate leaching per unit area was significantly lower in organic sites than in conventional sites. Tuomisto et al. (2012a) calculated a reduction of 31 % in nitrate leaching in organically managed versus conventionally managed systems, but this large reduction resulted mainly from the inclusion of modeling studies which might overestimate the reduction potential of organic farming. In field trials, differences between both farming systems were not significant. Mondelaers et al. (2009) described a wide variance in their studies and indicated effects of soil type (sand versus clay), region, farming type (arable versus mixed), research method, and time of measurements on study outcomes. When nitrate leaching is related to product units, organic farming performs similar or even worse than conventional farming (Tuomisto et al. 2012a; Stolze et al. 2000). Reasons for reduced leaching per unit area are lower overall fertilization levels due to lower stocking densities and lower use of external N-fertilizer inputs (Korsaeth 2008; Stolze et al. 2000), application of farmyard manure which is less prone to leaching (Stolze et al. 2000), and more frequent use of cover crops, intercropping and leys (Gomiero et al. 2011; Stolze et al. 2000).

Critical nitrate loads in the leachate from organic farms are detected after tillage of legumes, in particular after perennial leys (Gomiero et al. 2011; Eriksen et al. 1999), cultivation of crops like vegetables that receive high amounts of fertilizers, but have low efficiency in N uptake (Østergaard et al. 1995), and the delayed release of N from manure and plant materials which result in a lack of synchronicity of availability for and uptake of N by crops (Torstensson et al. 2006). Another source of nitrogen leaching is organic husbandry systems for pigs and poultry. In free-range systems, hot spots with high nutrient loads are created over time at highly frequented areas in the paddocks such as water and feeding troughs and shade/sleeping huts (Quintern and Sundrum 2012).

As farming systems are very diverse and climatic and soil conditions for the studies differ, it is difficult to come to a universally valid conclusion on the comparison of organic and conventional farming systems with regard to nitrate leaching. Despite some weak points, the potential for the reduction in nitrate leaching exists with organic farming, but the weaknesses must be taken into account and cropping systems must be improved accordingly. Even for nitrate leaching hot spots in free-range pig and poultry management, solutions exist that satisfy the high demands for animal welfare. Huts and troughs can be designed as movable units so that nutrient concentration in specific areas is reduced (Quintern and Sundrum 2012).

The higher quantity of nitrate leached per product unit in organic farming as documented by Tuomisto et al. (2012a) is related to the lower yields in organic farming compared to conventional farming. Here the issue will be to research methods for reducing yield losses in organic agriculture.

From a local, practical point of view for drinking water management, organic farming can be applied as a suitable tool to prevent nitrate and pesticide leaching. In countries such as Germany, the water management committees of large cities such as Munich encourage farmers who work in relevant watersheds to convert to organic farming. The farmers receive financial support for conversion to and maintenance of organic farming (in addition to governmental support for organic farming), and these committees also help in marketing the organic products with premium prices for organic and regional production and drinking water protection (Stadtwerke München 2012). Consumers seem to be willing to pay a price premium for this type of value-added product. Similar systems have been implemented successfully in other German cities for several years, so water management committees can efficiently reduce the risk for ground and surface water contamination, a cheaper alternative than treating contaminated water.

1.4.3 Energy Efficiency and Greenhouse Gas Emissions

Agriculture is a major driver of greenhouse gas (GHG) emissions on a global scale. In 2005, around 10–12 % of the total global anthropogenic greenhouse gas emissions were derived from agricultural systems (5.1–6.1 gigatons CO_2 eq year^{-1}) (Smith et al. 2007). Currently, agriculture is the largest emitter of nitrous oxide (N_2O) (emissions from soils related to N fertilization) and methane (CH_4) (enteric fermentation of ruminants, wet rice cultivation, manure storage, and land use change, the latter not included in the emission figures stated above), emitting about 60 and 50 %, respectively, of all global anthropogenic emissions of these gases (Smith et al. 2007). Methane has a global warming potential (GWP) 21 times larger than carbon dioxide (CO_2), and for N_2O the GWP is 310 times higher (IPCC 1995). For CO_2 emissions, fuel use for motorized vehicles and for the production of electricity and inputs like pesticides and fertilizers are the largest sources. Greenhouse gas releases from deforestation related to land use change make up another 12 % of global GHG emissions and can be connected to agriculture (El-Hage Scialabba and Müller-Lindenlauf 2010). When all direct and indirect GHG emissions from agriculture are taken into account, the agricultural share of the global anthropogenic GHG emissions rises to one third (FAO 2011). Agricultural systems are in a precarious situation as both victim and initiator of climate change. Agriculture emits GHGs and is simultaneously very vulnerable to rising temperatures and extreme weather events.

Within agricultural systems, mitigation potentials for GHG emissions exist. For example, agriculture is a source and a sink for CO_2. Soil organic carbon temporarily stores CO_2 and serves as a major sink; therefore, carbon sequestration in soils is one way to mitigate GHG emissions. Naturally, agricultural ecosystems turn over large amounts of CO_2, and these processes are almost balanced. Enhancing the potential of agroecosystems to sequester carbon may contribute to the mitigation of greenhouse gases. Using legumes instead of synthetic N fertilizers minimizes the dependency on external energy-intensive fertilizers (Crews and Peoples 2004; Peoples et al. 1995). Improved N-use efficiency may contribute to reduced N_2O emissions. As ruminants are the major sources of CH_4, improved husbandry systems for cattle, including improved feeding practices, dietary additives and breeding for longevity are further options.

In organic farming systems, some strategies for the reduction of GHG emissions are already being applied, such as breeding for longevity in ruminants and the substitution of synthetic, easily soluble N fertilizers through biological N fixation, while others, such as the use of synthetic feed additives, are not accepted. Many studies at different scales exist on the connection between the performance of organic farming and GHG emissions, energy efficiency and carbon sequestration. Greenhouse gas emissions in organic farming systems have been assessed in field trials (e.g., Ball et al. 2007; Flessa et al. 2002), modeling studies (e.g., Halberg et al. 2008; Küstermann et al. 2008; Foreid and Høgh-Jensen 2004) and life-cycle assessments (e.g., Cooper et al. 2011; Nemecek et al. 2011; Casey and Holden 2006). Based on these studies, several meta-analyses (Gattinger et al. 2012; Tuomisto et al. 2012a; Mondelaers et al. 2009; Gomiero et al. 2008; Stolze et al. 2000) have been compiled in recent years leading to contrasting results in the comparison of organic and conventional systems. The following section discusses the outcome of these studies.

1.4.3.1 Energy Use and Efficiency

Energy use in organic farming is related to GHG emissions from production systems, but also to the goals of careful and sustainable use of nonrenewable energy sources as stated in organic production standards and guidelines (e.g., IFOAM 2005). The energy consumption in organic farming systems has been frequently evaluated (e.g., Gomiero et al. 2008; Stolze et al. 2000) (Table 2). Depending on the production systems, energy use varies considerably even for the same crop (Table 2). In the majority of studies, organic farming had a considerably lower energy use per unit area, but also per product unit compared to conventional farming (Table 2). The lower use results from reduced inputs for the production and transport of agricultural products, particularly fertilizers, pesticides, and fossil fuels for energy-consumptive foodstuffs compared to conventional systems (Tuomisto et al. 2012a; Deike et al. 2008; Gomiero et al. 2008). A further option to reduce energy use in highly mechanized arable cropping systems is adoption of reduced- or no-tillage systems, but this is very difficult to apply in organic farming systems and requires further research (Tuomisto et al. 2012b).

1.4.3.2 GHG Emissions

The sources of GHG emissions between organic and conventional farming are basically the same, except for emissions derived from producing and transporting agricultural inputs such as synthetic fertilizers or pesticides. The production of synthetic N fertilizers is very energy-intensive; 0.4–0.6 gigatons of CO_2 are released, amounting to 10 % of the direct emissions from agriculture, and is equivalent to 1 % of the total anthropogenic GHG emissions (El-Hage Scialabba and Müller-Lindenlauf 2010). Nitrous oxide emissions, which are closely linked to the level of

Table 2 Selected results of studies on energy use in organic and conventional production systems (system borders not identical between studies)

	Energy consumption (GJ ha^{-1})			Energy consumption (GJ t^{-1})		
Product and reference	Conventional	Organic	Difference in % between organic and conventional	Conventional	Organic	Difference in % between organic and conventional
Winter wheat						
Haas and Köpke (1994)	17.2	6.1	−65	2.70	1.52	−43
Reitmayr (1995)	16.5	8.2	−51	2.38	1.89	−21
Deike et al. (2008)	11.5–11.8	5.7–6.5	−52 to −43	nd	nd	nd
Average of complete rotation						
Deike et al. (2008)	12.4–12.9	8.2–8.0	−36 to −35	nd	nd	nd
Nemecek et al. (2011)	17.0–21.0	12.6–14.5	−25 to −30	1.88–1.97	1.64–1.75	−12 to −6
Orange juice						
Knudsen et al. (2011)	nd	nd	nd	0.76–0.95	1.26	−39 to −25
Milk						
Haas et al. (2001)	19.1	5.9	−69	2.7	1.2	−55
Olives						
Kaltsas et al. (2007)	69.4	40.8	−41	nd	nd	nd

nd Not determined

N fertilization in agricultural systems, are often related to the cultivation of legumes such as grass-clover mixtures or leguminous cover crops in organic farming (Ball et al. 2007; Flessa et al. 2002).

Generally, the current evidence on GHG emissions from different farming systems shows that organic farming almost always performs better per hectare than conventional farming, but if product units are used, the emissions from organic farming systems can be higher due to lower yields (e.g., Mondelaers et al. 2009; Stolze et al. 2000). In addition, the GHG emissions from organic farming are heavily dependent on the products considered in the different assessments. Tuomisto et al. (2012a) reported that olives, beef, and several field crops performed better in organic production systems while organic milk, cereals, and pork produced higher GHG emissions than conventional farming systems. Küstermann et al. (2008) modeled energy inputs and greenhouse gas emissions from 28 farms in Bavaria, with and without livestock, and a research farm. Their results showed remarkably lower GHG emissions from organic farming (106–1,875 CO_2 eq ha^{-1} $year^{-1}$) compared to conventional farming (1,878–3,697 CO_2 eq ha^{-1} $year^{-1}$) on a per hectare basis. The authors stress that system differences (with or without livestock) persist between farming systems, no matter whether they are conventional or organic. When the calculations were performed on a per product basis, the GHG emissions were higher for organic management (376 kg CO_2 eq t^{-1}) versus conventional management (263 kg CO_2 eq t^{-1}).

Studies similar to those by Küstermann et al. (2008), Ball et al. (2007) and Flessa et al. (2002) are often based on assessments of GHGs in the field and are sometimes coupled with modeling approaches. Therefore, these studies provide strong and valid evidence of direct emissions in the field for organic and conventional farming systems and are well-suited to improving our understanding of emission processes and assessing GHG emissions based on area. However, such assessments cannot assess GHG emissions across the entire food-chain, an approach which is absolutely necessary for comparisons on a product basis. In addition, indirect emissions of GHGs, such as those from construction of housing and machinery or the N_2O emissions derived from the deposition of ammonia and nitrogen oxides (NO_X), must be included as well. In addition, it is important how and where system borders are defined, such as whether or not changes in land use for agriculture are included as sources of GHGs within an assessment. If so, comparing organic to conventional production systems may deliver completely different results. If the CO_2 emissions from a system are only related to on-farm processes (e.g., motor vehicle use and direct energy use to heat stables), then emissions related to the production of fertilizers may be underestimated. To assess GHG emissions along the food-chain, life-cycle analysis (LCA) is often used as an appropriate tool. Again, the outcomes of comparative studies between conventional and organic systems vary according to the product analyzed, but also on the unit of allocation used (product unit versus area). Table 3 provides an overview of selected publications on LCAs of organic and conventional products and production systems. In most cases, the differences between organic and conventional farming were expressed in favor of organic farming when calculated on an area basis, but were quite similar to conventional

Table 3 Selected results of the global warming potential (GWP) of organic farming compared to conventional farming systems based on life-cycle analysis

	GHG emissions org./GWP		GHG emissions conv./GWP		
Product	Area-related CO_2 eq ha^{-1} $year^{-1}$	Product-related t CO_2 eq t^{-1} product	Area-related t CO_2 eq ha^{-1} $year^{-1}$	Product-related t CO_2 eq t^{-1} product	Source
Dairy[a] (Germany)	6.3[c]	1.3[c]	9.4[c] (intensive) 7.0[c] (extensive)	1.3[c] (intensive) 1.0 (extensive)	Haas et al. (2001)
Arable rotation[b] (Switzerland)	2.2–2.9	0.3–0.4 (dry matter)	2.9–4.5	0.3–0.4 (dry matter)	Nemecek et al. (2011)
Wheat bread (United States)	n.a.	0.3	n.a.	0.33	Meisterling et al. (2009)
Oranges (Brazil)	n.a.	0.08–0.11	n.a.	0.12	Knudsen et al. (2011)

n.a. Data not available

[a] Data from farms

[b] Data from research trials

[c] mean

farming when related to product units. In dairy or beef production systems, for instance, the key issue is milk yield per cow. In conventional farming systems in industrialized countries, high milk yields per cow are realized by using grain- and soy-based feed concentrates which reduces CH_4 emissions as they are mainly related to the digestion of roughage (hay, silage, pasturages, and straw). In organic farming, the use of concentrates in ruminant feeding is restricted, and feeding ratios for dairy cows are mainly based on roughage with little or no additional concentrates, leading to lower milk yields. Therefore, organic farming systems are often criticized for their higher or similar emissions of CH_4 per product unit for milk or beef compared to conventional systems (e.g., Haas et al. 2001). What is not taken into account in this critique is that a certain share of grasslands used for dairy or beef production cannot be used for any other agricultural purpose due to climatic conditions or topography. The only way to make use of such agroecosystems is the establishment of extensive grazing systems for ruminants. Only ruminants are able to transform feedstuffs which are low in nutrients, and which cannot be digested by humans, into protein for human consumption. Concentrates, on the other hand can be consumed by humans directly without the loop through cattle or dairy cows. Presently, 34 % of the arable land worldwide is used for the production of feed grains or related products (FAO 2006b). With the current projection of world population growth to 9.3 billion in 2050 (United Nations 2011) and the projected rise in daily calorie intake to 3130 kcal *per capita* per day (FAO 2006a), it is critical to base ruminant feeding on concentrates which could also be used for human nutrition even though this might reduce GHG emissions to a certain degree. In the future, global meat production is expected to rise further, from 229 million t in 1999/2001 to 465 million t in 2050 (FAO 2006b). This trend will put additional pressure on land and water reserves as more land and water are needed to produce meat instead of plant-based products with the same nutritional value (Freibauer et al. 2011).

In addition to the evaluation of agricultural production, the studies of Knudsen et al. (2011) and Meisterling et al. (2009) focused on processed products and included post-harvest processing and transport of the processed goods to the consumer. In the case of organic oranges produced in Brazil and shipped to Denmark (Knudsen et al. 2011), transport to the consumer made up a major part (58 %) of the total global warming potential, and similar numbers also were reported for wheat (Meisterling et al. 2009). These results demonstrate the importance of including associated emissions which are not directly related to the farming systems. The studies of Knudsen et al. (2011) and Meisterling et al. (2009) show that the assessment of GHG emissions occurring during the transport of raw materials and final products and during the processing of the latter are very important for a comprehensive evaluation of product-related GHG emissions. When looking at the complete food-chain from farm to fork on a product level, the issue of food miles becomes much more important compared to the role of transport in primary production. Modes and efficiency of transport such as ship versus airplane or individual traffic of the consumer versus transport in larger vehicles are highly relevant to energy use and emissions of GHGs (Smith et al. 2007). Storage (e.g., for frozen products) and processing also strongly influence GHG emissions as well (Fritsche and Eberle 2007). These effects often overlay differences in emissions derived from the farming system. Furthermore, the GHG emissions of organic farming systems can be improved by using waste materials for bioenergy production. In a LCA for German organic dairy systems and stockless organic farming systems, Michel et al. (2010) conclude that the digestion of farmyard manure, slurry and plant residues in a biogas plant decreases GHG emissions from organic farming systems by substituting for fossil fuels and minimizing storage emissions of GHGs, particularly for farmyard manure. Kavargiris et al. (2009) came to similar conclusions for Greek vineyards and the use of grape pomace for bioethanol production.

When GHG mitigation strategies related to agriculture are discussed, carbon sequestration in agricultural soils is a major topic. According to Lal (2004), agricultural and degraded soils worldwide have the capacity to sequester 0.4–1.2 gigatons of CO_2 year^{-1} if proper management techniques are applied such as the restoration of degraded soils, replanting of woodlands, using no-tillage agriculture, using cover crops, providing manure applications, applying sewage sludge, providing efficient irrigation and water management, conserving water, improving grazing systems, agroforestry, managing nutrients, and cultivating energy crops on unused land.

Hence, the question is whether and how organic farming can contribute to C sequestration? As stated in Sect. 1.4.2, the evidence for more soil organic matter varies, but the tendency is toward higher soil organic matter in soils under organic management. A recent meta-analysis by Gattinger et al. (2012) based on 74 pairwise comparisons of organic versus conventional farms showed clear differences in soil organic carbon concentrations and soil organic carbon stocks in the topsoil of organically managed soils compared to soils under conventional management. For carbon sequestration, the data was less clear but showed a high potential for organic farming practices. Unfortunately, many data sets covered primarily the topmost 20 cm of arable soils, so a considerable amount of soil organic matter in the lower soil horizons was not taken into account. Other authors such as Hülsbergen (2008) and Freibauer et al. (2004) report C sequestration potentials of 0–0.50 t ha^{-1} year^{-1} for organic production. The primary factors that determine sequestration potential are livestock density and the amount of root crops, legumes and corn cultivation in organic farming systems (Hülsbergen 2008). It is also important to note that both farming systems have inherent soil limits for C sequestration. These limits depend on soil texture, clay mineral composition, and water regime, implying that even in organic systems, C sequestration will decrease with the duration of organic farming after conversion. In addition, enrichment of soil organic matter also influences N_2O and CH_4 emissions which might offset a part of the mitigation potential. Nevertheless, mixed farming, recycling of organic materials and the cultivation of fodder legumes are characteristic features of organic farming which are promising tools for C sequestration (Gattinger et al. 2012).

In conclusion, organic farming systems have the potential for a more favorable performance compared to conventional systems with regard to GHG emissions, in particular if organic farming manages to improve yield levels without compromising benefits. The key factors for lower GHG emissions in organic farming are (1) less N fertilization leading to lower emissions of N_2O, (2) no emissions of CO_2 from the production of energy-intensive N fertilizers and pesticides, and (3) the potential for C sequestration in organically managed soils.

1.4.4 Biodiversity

Presently, biodiversity loss is of major concern for the sustainability of ecosystem services to mankind. Species extinction occurs in nature even without human influence. However, species extinction rates for the last 100 years exceed those based on fossil records around 100–10,000 times depending on the estimates (Mace et al. 2007). The effect of species loss is difficult to quantify, but if species loss continues at the current rate, ecosystem resilience will be at risk (Hooper et al. 2012; Rockström et al. 2009). Biodiversity is most seriously affected by land use changes, habitat loss, excess discharges of N and P to freshwater and marine ecosystems, and overexploitation, but climate change is becoming the dominant driver (Rockström et al. 2009; Mace et al. 2007).

In agroecosystems, the term *biodiversity* includes non-domesticated as well as domesticated species (on-farm managed biodiversity) and also refers to measures of biodiversity on different levels (genetic biodiversity, diversity within and among populations, and species diversity) (Mace et al. 2007). In addition, the *functional heterogeneity* of an agricultural landscape may play an important role in the regulation of ecosystem services in agricultural systems in particular for biodiversity (Fahrig et al. 2011). Agroecosystems must be seen as parts of larger landscapes in which nutrient and water fluxes take place and in which wild species move within and among different habitats. According to Fahrig et al. (2011), agricultural landscapes show gradients of intensively used cover types such as crop fields (e.g., monocultures, high external inputs) to less intensively used cover types such as extensively grazed pastures or multi-story cropping. At the other end of the scale, more natural cover types such as hedgerows, forest patches, or wetlands are found which provide resources for different species. By manipulating land use intensity and occurrence of different cover types, farmers can influence biodiversity in agricultural landscapes. Up to now, in modern conventional agriculture, the management of biodiversity has played a minor role and biodiversity was reduced by pesticide use in order to establish crop monocultures and natural habitats were eliminated to ease mechanization or to acquire new cropland.

Compared to conventional farming systems, the increase in biodiversity at all scales (α, β, and γ)[1] and the biodiversity of non-domesticated (associated biodiversity) and domesticated species (planned biodiversity) in organic farming has been documented in many studies and reviewed systematically in several

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[1] α, biodiversity within an ecosystem; β, biodiversity between ecosystems; γ, overall biodiversity of ecosystems within a larger region.

Table 4 Effects of organic farming on phylogenetic groups in comparison to conventional farming

	Number of studies		
Taxon	Positive	Negative	Mixed/no difference
Birds	10	0	4
Mammals	3	0	0
Butterflies	4	0	3
Spiders	8	0	3
Earthworms	8	0	6
Beetles	16	2	5
Other arthropods	10	5	4
Plants	23	1	3
Soil microbes	18	1	11
Total	100	9	39

From Tuomisto et al. (2012a), Hole et al. (2005)

meta-studies (Tuomisto et al. 2012a; Rahmann 2011; Mondelaers et al. 2009; Gomiero et al. 2008; Bengtsson et al. 2005; Fuller et al. 2005; Hole et al. 2005). Rahmann (2011) found 396 literature sources on the assessment of biodiversity in organic farming systems compared to conventional systems; 83 % of these studies documented higher biodiversity in organic farming systems, 14 % could not find any differences, and 3 % found lower biodiversity in organic farming systems. However, research activities are unevenly distributed on a global scale, as the majority of these studies were published for European farming systems and very little for organic farming systems in tropical or subtropical regions.

Yet, the most comprehensive study is that by Hole et al. (2005) who not only reviewed 76 studies across a broad range of taxa, but also evaluated why organic farming systems performed better than conventional systems in a very detailed and balanced approach. Tuomisto et al. (2012a) screened additional peer-reviewed studies for subsequent years and reported similar findings (Table 4).

1.4.4.1 Influence of Farming Practices on Different Taxa

Most studies reviewed by Tuomisto et al. (2012a) and Hole et al. (2005) found positive differences between organic and conventional farming systems, although the magnitude of change in species richness, diversity and abundance varied among the phylogenetic groups studied. As for the methodological approaches, farm-pair comparisons are most widely used followed by observations in field trials.

Particularly for plants, the response is stronger and more consistent than for other species (Fuller et al. 2005). Plants are directly influenced by the use of agrochemicals and fertilizers; the absence or strong reduction of both in organic farming has a direct effect on plant biodiversity. In addition, Gabriel and Tscharnke (2007) found that insect-pollinated plants benefit more from organic farming than noninsect-pollinated plants, a result of the higher abundance and diversity of pollinators in organic farming systems.

For soil microbes and fungi, many studies exist which document higher fungal and/or bacterial diversity in organic farming systems compared to conventional farming systems (e.g., Mäder et al. 2002; Shannon et al. 2002; Fraser et al. 1988). Hole et al. (2005) identify as a key feature in their findings the addition of more biomass as animal and green manure which enhances bacterial populations. In addition, the different fertilizing regimes in organic and conventional farming lead to a higher abundance and diversity of arbuscular mycorrhizal fungi (Oehl et al. 2004; Ryan et al. 1994).

Comparative studies for earthworms show differences in abundance and species richness for arable farming systems (e.g., Pfiffner and Mäder 1997). Hole et al. (2005) report greater abundances, higher species diversities, larger and more active populations, greater densities, more vertical burrowing species and more juvenile animals in arable fields under organic management. The findings could be attributed to the more frequent use of farmyard and green manures in organic farming systems. Scullion et al. (2002) showed that differences in earthworm biomass were connected to the proportion of leys in rotation of the farming systems; whether the farming system was conventional or organic was not significant. Generally, studies on organic and conventionally managed grasslands show varying results with no clear evidence in favor of either system (Hole et al. 2005).

For arthropod species, the results of the studies depend strongly on the taxa involved. While butterflies (e.g., Rundlöf et al. 2008) seem to profit from organic farming regimes, beetle communities show inconsistent results, with some studies reporting higher species richness for carabids and others reporting the opposite (Hole et al. 2005). Specific species needs, different cropping designs and site characteristics might lead to these inconsistencies.

For larger animals, the situation is also less clear. For bats, the species richness between conventional and organic sites was not significantly different, but their foraging activity was 84 % higher on organic farms than on conventional farms (Wickramasinghe et al. 2003). Organic farms appear to provide higher habitat quality in terms of habitat structures and insect abundance. Similar findings exist for birds, stressing the positive effects of more frequent landscape structures, smaller field sizes, and less intensive crop management in organic farming systems (Freemark and Kirk 2001; Chamberlain et al. 1999).

1.4.4.2 Biodiversity of Domesticated Species

The biodiversity of non-domesticated (associated biodiversity) and of domesticated species (planned biodiversity) plays an important role in sustaining agroecosystems. Genetic diversity within one species, for example, ensures the adaptability of the species to environmental changes or to pests and diseases. For cultivars of domestic plants and breeds of domestic livestock, sufficient numbers of individuals are necessary to ensure this adaptability. Presently, the numbers of individuals in animal breeds or plant cultivars are often very low, and their conservation and long-term survival are threatened. Organic farming standards (e.g., IFOAM 2005) stress the importance of local and traditional breeds and cultivars for organic farming systems. Whether organic farmers adhere to these standards or not is difficult to tell as peer-reviewed studies on the use of animal breeds and plant varieties in organic farming do not exist. In any case, some of the high-yielding animal breeds and plant varieties used in conventional farming are not suitable for organic farming systems. It is difficult to feed and maintain the health of high-yielding Holstein-Friesian cows, for example, with high amounts of roughage and little feed concentrate (Sattler et al. 2004). As well, certain lines of broiler chicken production are not acceptable in organic management as they tend to grow very fast and frequently exhibit physical deformation at the end of the fattening period (Hörning et al. 2010). Wheat varieties with short stems are not suitable in organic farming as they are not competitive against weeds (Wolfe et al. 2008). How farmers deal with these problems is rarely documented in research, only a very minor number of publications exist and they are often case studies or nonscientific books.

For example, Bocci et al. (2012) conducted a survey among Italian organic farmers and reported a large amount of on-farm seed-saving for commercial varieties and old or traditional varieties, in particular for wheat and vegetables. For the latter, farmers named special quality features and the use of special brands including geographical indications as reasons for their practice. Depending on the region, the amount of farm-saved seeds made up to 87 % (e.g., in Calabria) of the seeds used. In Germany, a large research project is currently under way to preserve old cultivars and to develop new cultivars of Emmer (*Triticum dicoccon* Schrank ex Schübl.), an old wheat species which has been used since the Neolithic Age (Körber-Grohne 1995). The project is funded within the governmental research scheme on “Organic Farming and Other Forms of Sustainable Agriculture” and is a focused action among research institutions, commercial plant breeders, organic farming associations and the baking industry. The aim is to preserve old varieties, to enhance the diversity of organic farming systems, to provide new products for organic consumers and to create awareness of the value of old crop species and varieties.

Yet, Rahmann et al. (2004) documented for Germany that old animal breeds were of no importance to organic farmers, most of whom kept the same modern breeds as their conventional neighbors. The reason for this pattern is the higher productivity of modern breeds. In a comparison between old and modern sheep breeds in Germany, Rahmann (2006) showed that from an economical point of view the use of old breeds is only feasible if special marketing channels, with additional price premiums, can be achieved or government payments for the conservation of old breeds are available.

Whether or not organic farming helps in the conservation of plant and animal genetic resources is an open question. On one hand, economic necessities may drive organic farmers to use the same breeds and varieties as conventional farmers, yet organic farming systems may offer opportunities for the conservation of old breeds and traditional crop varieties. Old breeds tend to have lower productivity and may be better adapted to extensive management systems like organic farming which have lower nutrient levels and less feed import. In addition, use of traditional varieties and breeds may enable farmers to develop special brands to arouse consumer interest. By creating such added value, consumers can be tied to a special region or a traditional product, thus serving the economic needs of farmers while conserving genetic resources of domesticated plants and animals.

1.4.4.3 Effects of Farming Practices on a Landscape Scale

The previous sections have primarily dealt with the effects of organic farming on a field scale. When organic and conventional farming are compared on a landscape scale, recent studies have reported interesting effects. Rundlöf et al. (2010), for example, found higher plant species diversity in conventional field margins when situated in landscapes with a higher share of organic area than in conventional field margins when less surrounding land was organically farmed. Plants were dispersed from organic fields to conventional fields leading to higher diversity. Norton et al. (2009) found that organic farms were associated with inherently diverse landscape types, less intensively managed hedgerows, longer and more diverse rotations including leys and were more often mixed farms. On the other hand, interactions among higher degrees of landscape complexity, species richness and abundance could not be detected despite clear positive effects of organic farming at the landscape scale for almost all observed taxa (Winquist et al. 2011). Particularly for organic farming, a strong positive effect of landscape complexity and predation on aphids was observed; in homogenous landscapes predation in organic fields was lower than in conventional fields. Biological control, organic management practices and landscape complexity are strongly interrelated as predators may be differently affected by each factor or by combinations of factors. More research is needed for better understanding and management of predator-prey relations in organic farming systems.

Few reports focus on the impact of organic farming on landscape elements (e.g., structural elements, non-crop habitats, trees, arable fields, pastures, greenhouses, or field margins) and they often do not take human beings with their visual perception and cultural backgrounds into account (e.g., Steiner and Pohl 2009). A study undertaken in Norway included several stakeholders in an assessment of the impact from two organic farms (one with traditional farming methods focusing on goats and goat cheese production and a farm focusing on sheep production, but extending to cattle breeding and tourist rentals) on overall landscape quality in an area where farming has been abandoned yet was needed for nature conservation and tourism (Clemetsen and van Laar 2000). Both farms, despite their differences, were evaluated as having a positive impact on landscape quality by the stakeholder group who assessed the impact as positive for the community by preserving traditional farming methods, establishing new farming methods and increasing cohesion in the community. This result was independent from the different approaches of the farms toward organic farming.

1.4.4.4 Reasons for Higher Biodiversity in Organic Farming

Even if the results of the studies mentioned in the previous sections vary to some extent, most of them arrive at similar conclusions regarding higher biodiversity in organic farming systems (Hole et al. 2005):

(A) The reduction/prohibition of pesticide and synthetic fertilizer use has a beneficial effect on biodiversity because direct and indirect negative effects on diverse organisms are removed.
(B) Careful management of structural elements, field borders, and non-crop habitats favors biodiversity and abundance of arable plants, invertebrates, birds and mammals.
(C) Mixed farming is practiced more often in organic farming leading to higher habitat heterogeneity over space and time.

Particularly in very homogenous landscapes, biodiversity benefits from organic farming (Winquist et al. 2011). Hole et al. (2005) report that organic farmers are probably more sympathetic toward the conservation of biodiversity than conventional farmers. Yet, organic farmers may have been more strongly influenced over time by organic principles such as the protection of agroecosystems and therefore acted more sympathetically toward biodiversity conservation. To explore this issue, more detailed sociological studies on the motives behind conversion to organic farming and particularly on the attitudes of farmers before and after several years of conversion would be helpful.

Given the weight of the reported evidence, it is more than likely that organic farming practices contribute to farmland biodiversity in intensively managed agroecosystems such as in Europe or Canada. On the other hand, because land use efficiency is lower in organic farming systems, more land is required to produce the same amount of food. Tuomisto et al. (2012a) state that organic farming needs 84 % more land than conventional farming in Europe due to reduced crop and livestock yields and land requirements for biological N fixation. The need for additional land to achieve 100 % organic farming is probably much lower than calculated by Tuomisto et al. (2012a), but the question remains as to whether an increased need for land for organic farming would counteract all efforts to conserve biodiversity, as more farmland means less space for other ecosystems such as forests. In the current debate connected to population growth and agricultural intensification ("Growing More from Less"; Syngenta 2009), the conservation of biodiversity while increasing food, fiber and fuel production from agricultural land is a central issue. Two approaches to achieve this goal exist:

1. Segregation of natural habitats and intensively used agricultural land (land-sparing, wildlife-friendly farming)
2. Integration of both in the same area (land-sharing)

Tscharnke et al. (2012) strongly advocate for land-sharing combined with wildlife-friendly farming, as the long-term functioning of ecosystem services such as biocontrol, pollination and soil fertility can only be provided in this way. Based on the studies cited in this section, organic farming would be a viable option for a land-sharing, wildlife-friendly farming approach based on agroecological intensification.

1.5 Organic Farming and Food Security

Since the food crisis of 2008, the question of feeding a world population of more than 9 billion in 2050 has received much political and scientific attention. After years of public neglect, agriculture is again on center stage for politicians and investors. Despite some efforts, the aim of reducing hunger as stated in the UN Millennium Goals was not achieved in 2012 as nearly 870 million people remain hungry (FAO 2012). How to combat hunger while at the same time providing feed for animals to serve a continuously growing demand for meat on a global scale, producing fuel from agricultural products, and delivering natural materials for technical use in the future bioeconomy is highly debated. One pathway leads to a growing intensification of agriculture *via* a second "Green Revolution" based on the genetic engineering of agricultural plants and animals, improved access to fertilizers and pesticides for poor farmers, and technological and infrastructural investments where both are lacking. The major challenge in this case is to increase production and minimize environmental impact at the same time. The other path follows "sustainable crop production intensification" (FAO 2010) based on adequate utilization of ecosystem services, minimization of negative external effects from agriculture, intensification of knowledge and the reduction of external inputs. Here, minimizing environmental impacts and maintaining ecosystem services are emphasized. The IAASTD (2008) stated that "business as usual is not an option" and named organic farming as a valid alternative to current conventional farming systems, pushing the discussion regarding the 2008 food crisis.

As the global area under organic management continuously increases, with some developing countries discovering organic farming as a means of entering global market-chains, the question of whether organic farming can feed the world or not has gained a lot of attention, especially in reference to a more environmentally friendly way of agricultural production. When referring to food security and organic farming, two central questions must be differentiated. The first question is whether organic farming as it is practiced today can produce enough food, feed, and fiber to serve the needs of a growing global population, and more so, in a way that is superior to conventional practices associated with negative environmental effects. The second question is whether small-holder farmers who are threatened by food insecurity become more food-secure when they convert to organic farming, thereby producing more diverse products for their own consumption, but also for sale, thus entering new marketing channels on regional scales (e.g., within PGS systems) or even gaining access to international markets *via* certified organic production. The latter is a very important issue because current hunger and food insecurity are not problems of mere food availability (except in emergency situations), but are results of insufficient economic access to sufficient high-quality food.

Based on recent reviews of this topic, an assessment of the question "Can organic farming feed the world?" must be made. Organic production methods, as described in the previous sections, have many positive environmental effects. In some cases the performance is very clear in comparison to conventional farming, while in others the differences are less clearly expressed. Benefits of organic farming practices can be expected by providing and maintaining ecosystem services which then enable the long-term productivity of agricultural systems. Despite these benefits, the land use efficiency and yield level of organic farming systems are critical issues when the impact of organic farming on food security is discussed. Some argue that organic yields and/or land use efficiency is lower than in conventional agriculture (e.g., Tuomisto et al. 2012a; Connor 2008; Trewavas 2001). This implies that organic farming needs more agricultural land in order to produce the same amount of food as conventional agriculture. This would lead to accelerated land use including deforestation and the destruction of other natural habitats, thereby offsetting all positive external effects of organic agriculture.

Based on the discussion above, several studies have been published that compare yields from conventional and organic farming, often in relation to long-term trials on the comparison of different farming systems, mostly in temperate regions. For example, Badgley et al. (2007) modeled the global food supply that could be achieved by organic farming practices and found that organic farming could provide sufficient calories for the current world population on a *per capita* basis without increasing the amount of agricultural land. This study was criticized by different experts because of improper comparisons between the two systems and excessively optimistic assumptions on nutrient availability (Connor 2008; Cassman 2007). Seufert et al. (2012) performed a meta-analysis of 62 studies comparing the yields of conventional and organic farming based on peer-reviewed literature involving 34 different agricultural crops. On average, organic crops had 25 % lower yields, but this result depends strongly on location, site conditions, and agricultural system (yields differed from 5 to 34 %). Similar results were also found by De Ponti et al. (2012). Seufert et al. (2012) primarily used studies from developed countries for their meta-analysis. Only a few studies with critical data sets were available for developing countries which described yield reductions of 43 % in organic systems on average, contrary to the findings of many other case studies that reported higher yields for organic farming or similar practices (e.g., IFAD 2005; El-Hage Scialabba and Hattam 2002). The discrepancy arises from different intensities in the systems compared. Most case studies refer to low-input systems that experience an increase in intensity when converted to organic farming, while in the peer-reviewed reports used by Seufert et al. (2012), yield levels of conventional systems were much higher on average than on-farm yields because the data sources were usually field experiments. De Ponti et al. (2012) performed a similar meta-analysis but separated the studies on crop level and on the level among regions of the world. This approach reflects differences in production intensities and therefore also yield differences between conventional and organic systems. As soon as a farming system comes close to the potential yield or the water-limited yield, the yield difference increases to the maximum. The results of De Ponti et al. (2012) showed the lowest relative yield for organic systems in Europe with 70 % and the highest relative yield in Asia with 89 %. For tropical countries, the yield difference was rather small, yet these authors could use only a very few studies from tropical and subtropical regions.

As the majority of food-insecure people live in developing and underdeveloped countries, the lack of scientific information on the productivity of organic farming systems in the tropics and subtropics makes it difficult to deduce any valid conclusions. Many case studies show a high positive impact from conversion to organic farming, but often the initial production system is not clearly described and statistical data evaluation is not performed. The case studies represent only single events, but it is not clear whether they can be transferred to a larger scale. The field trials initiated by the Research Institute of Organic Agriculture (FIBL), Switzerland (Zundel et al. 2008) may provide interesting information, but many more system comparisons are needed to come up with sound conclusions. In addition, yield level is not the only determinant factor as to whether a farming system is functioning well or not, although it is an important one. Some authors argue that the reduction of input costs and the availability of premium prices for organic products significantly contribute to increased food security of small-holder farmers (Ramesh et al. 2010; El-Hage Scialabba and Hattam 2002).

As far as the improvement of livelihoods of small-holder farmers by certified organic farming practices is concerned, the price premiums achieved by accessing world markets with their products might offset yield reductions, but naturally the number of farmers who are able to profit from such food-chains is small (Halberg et al. 2006). Nevertheless, besides this pathway, the option of applying agroecological methods mostly exists for small-scale farmers in the developing world. Parrot et al. (2006) stress the multifunctional aspects of organic farming systems, certified or uncertified, that provide benefits to farmers:

- Risk aversion: Organic farming practices often perform better under stress (e.g., drought) than conventional systems, thus minimizing risk.
- Health: Organic farming reduces the exposure of farmers to pesticides, as well as their families and farm workers; organic food with high nutritional value is relevant for food-insecure persons and persons with life-threatening illnesses.
- Environmental resilience: Organic farming practices increase soil organic matter and result in higher water retention capacities, thereby reducing runoff, erosion, and drought stress; additional water and soil conservation measures further reduce erosion.
- Biodiversity (non-domesticated and on-farm managed biodiversity): Higher biodiversity under organic farming increases soil fertility and resilience to diseases and pests; crop diversity minimizes the risks of crop failure, increases the length of the growing season, and improves diets.

When all these aspects are taken into account, a mere focus on yields between organic and conventional farming seems to be a very narrow approach in evaluating the feasibility of organic farming systems when food security is concerned. The question also arises as to whether the potential yield of a certain crop should be the target value for such comparisons. To achieve the potential yield, high amounts of inputs are necessary which will have environmental trade-offs which are usually not accounted for in yield comparisons. Nevertheless, organic crop yields have room for improvement. Organic farming systems are far from perfect, rotational designs can be optimized, the use of legumes and the timing of N availability can be improved, and varietal breeding for organic systems could improve yield because conventional varieties or animal breeds are not always suitable for organic systems. Last, organic farming is knowledge-intensive, and increased extension services for organic production and participatory approaches might be helpful. Previously, organic farming research received only a fraction of the funding of conventional research. Thus, it could be argued that with greater funding organic yields may significantly improve.

2 Food Quality

2.1 Concept of Food Quality

Food quality is complex because there are numerous definitions of this expression. Evans and Lindsay (1996) presented a specific model addressing the *quality viewpoints* that comprise five different groups of quality criteria. The model includes:

1. Food assessment (characteristics and comparisons of foods)
2. Product-based criteria (demonstration of qualitative correlations between measurable properties or functions of measurable characteristics)
3. User-based criteria (defined by consumer needs)
4. Value-based criteria (ratio between price and the level of satisfaction obtained)
5. Production-based criteria (in accordance with norms and production practices)

Based on this model of *quality viewpoints*, internal and external quality parameters can be specified (Luning et al. 2005). Internal features comprise those measurable characteristics which are directly related to the food product and are defined by chemical and physical parameters (i.e., sensory properties such as durability, safety- and health-related aspects, and the comfort of use and reliability). Among external features, there are production characteristics (i.e., method-related aspects such as conventional versus organic), environmental matters, and marketing-related issues.

2.2 Ecological Criteria of Food Quality: The Analytical and Holistic Methods of Food Evaluation

According to Meier-Ploeger and Vogtmann (1991), the ecological criteria for food quality can be divided into two basic groups – analytical and holistic. The first set is

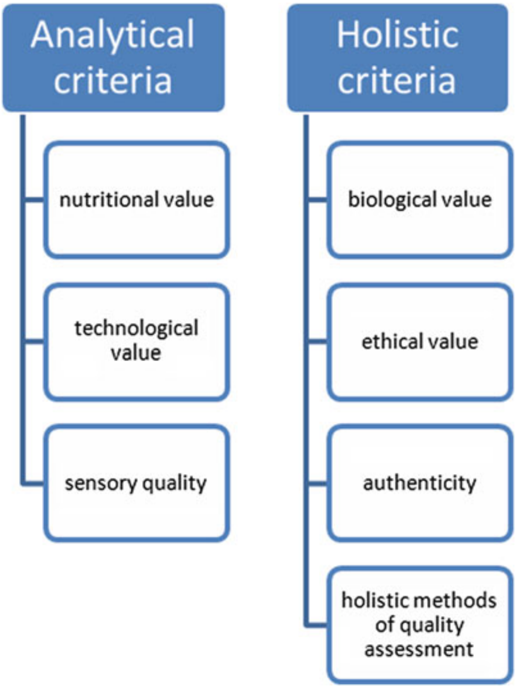

Fig. 3 Ecological criteria for food quality

nothing more than those features analyzed from nutritional, technological, or health perspectives. The second is more innovative and involves new technologies and is also based on environmental awareness; both groups are shown in Fig. 3.

Technological value is an important aspect for specific participants in the food production chain. This aspect comprises a number of properties and parameters defined by producers, processors, distributors, and consumers. Among these characteristics are storage quality (shelf life), cooking use, and dry matter content. Apart from these characteristics, the content of specific compounds can determine technological value, such as the content of gluten needed for baking.

Another group of analytical criteria involve sensory quality, which is represented by a set of properties related to the appearance of the food product (e.g., size, color, freshness, cleanliness, and firmness), as well as the human organoleptic characteristics of smell, taste, touch, and hearing. These criteria play fundamental roles with regard to consumer preferences, which are assessed by two methods:

1. *Consumer testing* – showing the level of preference, acceptance, and desirability. This assessment involves a non-trained group of people who define their preferences related to a certain food product. It is a common way to assess the level of satisfaction provided by organic versus conventional foodstuffs.
2. *Sensory assessment application* – involves a qualified panel of experts who can define measurable properties which are further submitted to statistical analysis.

One of the numerous methods based on this procedure is a *triangle test* which enables the panelists to differentiate between three food samples to indicate that which is most preferred. In both assessments, organic fruits and vegetables are more commonly preferred with regard to sensory features (Rembiałkowska 2000).

Nutritional value can be defined by the content of desirable and undesirable compounds. A minimum level of impurities and an optimum level of favorable substances make up an ideal profile of a nutritionally valuable food product. There are numerous desirable compounds defining nutritional value, such as antioxidants, vitamins, polyphenols, and secondary substances. Among undesirable components are nitrates, nitrites, pesticide residues, heavy metals, and mycotoxins. Another component is the proportion of substances such as fatty-acids; the higher the level of unsaturated fatty-acids, the more nutritionally valuable the product.

The *holistic criteria*, apart from the assessment procedures, comprise three principles:

1. *Authenticity* – has potential for food product traceability and is a method enabling an assessment of whether or not a product is organic and originates from organic farming. Authenticity may also be understood as a counterbalance to the rising phenomenon of food globalization. This concept was a basis for the "slow food" movement and established as an objection against the dominant tendencies in food production. Such understanding of the notion *authenticity* is strictly related to the idea of local food. Some studies indicate that the consumers are committed to eating locally (Hu et al. 2012; Bingen et al. 2011). Modern consumers are intensively searching for minimally processed products, from known and safe sources, such as purchased locally and directly from the farm. In the United States, the distance of food transportation from production site to the area of consumption is approximately 2,000 km (Wilkins and Gussow 1997). At the same time, there are scientific studies confirming that it is possible to satisfy nutritional needs of consumers, such as from New York State, using food produced locally. Although local farming was nearly terminated, most New York consumers assessed local varieties of vegetables and fruit as best looking and having better taste and smell (Wilkins and Gussow 1997).
2. *Biological value* – are the beneficial effects, on animal and human health, from food consumption. It is defined by the occurrence of diseases and features such as fertility, immune status, vitality and welfare. This principle is difficult to quantify because the assessment results never give unambiguous answers, as products affect the human organism as a whole. As well, it is not possible to predict and describe the interactions between substances that occur in different proportions and that may differ with regard to bioavailability.
3. *Ethical value* – comprises animal welfare, environmental impacts and social and economic aspects. The balance between these viewpoints is an important indicator for consumers with developed ecological awareness.

Several holistic methods are used to determine food quality. At the current stage of development, these methods enable us to distinguish product origins, but do not allow for assessment of the potential health impacts of organic food. The methods include:

1. Copper chloride biocrystallization (Kahl 2006)
2. Imaging chromatography (Załęcka 2006)
3. Circular paper chromatography (Pfeiffer 1984)
4. The drop picture method (Schwenk 1991)
5. Kirlian photography (Kononenko and Zrimec 2000; Jessel-Kenyon et al. 1998)
6. *P*-value measurement (Hoffman 1991), and
7. Biophoton emission measurement (Popp 1991)

Biocrystallization is the only validated and standardized method, so it can be applied in every laboratory used for food quality assessment. Biocrystallograms are created as a result of submitting a mix of the examined sample and copper chloride to the crystallization process, and as in every imaging method case, they are characteristic of each sample examined. Biocrystallograms are traditionally assessed, based on different morphological features and with the use of such techniques as indexing or ranking, which are submitted to standardization under ISO standards applied in sensory analysis. The use of this biocrystallogram assessment technique enables the information provided in images to be analyzed statistically (Busscher et al. 2010).

2.3 Harmful Components in Conventional Food

There are numerous types of impurities present in commonly available food products. Their prevalence is not always a result of human activities, as some of them occur in raw materials naturally. Nevertheless, they pose a high risk for consumer health. Generally, the harmful components of food comprise three basic groups of chemicals: pesticides, mycotoxins, and nitrates and nitrites.

Pesticides are present in the environment because they are deliberately introduced into ecosystems to protect crops and improve their quality. Pesticides enable farmers to increase their profitability; yet, these chemicals tend to accumulate and move up the food-chain (through the food-web), posing a risk for human consumption.

There are millions of acute pesticide poisonings every year in the world, and thousands of which result in death (Richter 2002). This problem is especially serious in developing regions such as Asia, where awareness of the risk is low and exposure is high.

Children are a specific group of consumers, as their vulnerability to poisoning is higher compared to adults. Their immune systems have not completely developed, nor their defense mechanisms against xenobiotics (e.g., organophosphorus or organochlorine compounds); therefore, children are the subject of many studies related to pesticide exposure.

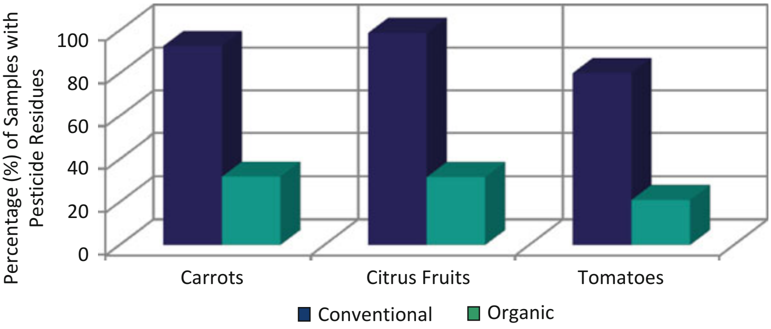

Fig. 4 Percentage of samples of food groups with pesticide residues from organic and conventional farms (Ökomonitoring Gesamtbericht 2002–2006 (2007))

One such investigation was carried out by Pennycook et al. (2004) who studied the pesticide poisoning risk to children in the United Kingdom from eating apples and pears. Three different chemicals (dithiocarbamate, phosmet, and carbendazim) were analyzed in children from 1.5 to 4.5 years who were exposed daily to a pesticide impurity that exceeded the acute reference dose. The number of children exposed to the consumption of more than the maximum permissible level of pesticides varied from 10 to 226 a day (depending on the type of the chemical).

Every human body contains a certain quantity of chemical substances. This fact has been confirmed by Van Oostdam et al. (1999) who conducted a comparative investigation of persistent organochlorine fat-soluble pesticides in the milk of women from the subarctic. Although DDT has been banned since the 1970s, the study examined DDT derivatives and showed that considerable quantities of these substances were present.

Pesticides are also considered as factors that influence hormone balance, as many of them have similar chemical structures to substances naturally occurring in the human body. This may contribute to a decrease in fertility rates and was confirmed by the effect of nonylphenol which was used as an active compound in a number of pesticides. Its chemical structure is very similar to estrogen, the female reproductive hormone, resulting in a disrupted reproductive cycle (Odum et al. 1997).

According to basic organic farming principles, the use of pesticides and other chemicals is banned. Since only natural plant protection methods are allowed, such as allelopathy and natural pest enemies, the prevalence of pesticide residues in organic plant foods is much lower compared to conventional. This trend has been confirmed by many authors around the world (e.g., Gnusowski et al. 2006, 2007, 2008, 2009; Benbrook 2004; Baker et al. 2002).

Germany is one of the countries where monitoring of pesticide contamination is performed (Ökomonitoring Gesamtbericht 2002–2006 (2007)). According to the results, the percentage of organic fruits and vegetables with pesticide residues was considerably lower in comparison to conventional foods (Fig. 4). However, organic products are not completely free of pesticide residues, and it is impossible to avoid certain levels of chemicals in these crops.

Nitrates are used by farmers, and even though they are considered irrelevant to human health, they do pose a serious risk to consumers when reduced to nitrites. This reduction makes the chemical much more harmful to human health. According to Szponar and Kierzkowska (1990), nitrites are 6–10 times more toxic than their oxidized form. The cause of this reduction is usually the inappropriate storage and transportation conditions of raw materials and the influence of intestinal microflora after consumption.

The primary effect of nitrites in humans is methemoglobinemia, the oxidation of fetal hemoglobin to methemoglobin, which is not able to transport oxygen within the blood. The risk is particularly high with regard to infants and toddlers as they exhibit an elevated vulnerability to the process of oxidation (Duchań and Hady 1992; Dreisbach 1982). Moreover, their food and liquid absorption is considered higher compared to older children and adults, including nitrates and nitrites. Furthermore, the acidity of gastric juice in children is slightly lower in comparison to adults, resulting in increased activity of intestinal microorganisms responsible for the process of nitrate reduction (Kasjanowicz et al. 1998). In the 1980s and 1990s, several cases of nutritional methemoglobinemia in children were reported (Stolarczyk and Socha 1992; Świątkowski 1980). The harmful compounds were identified in some parts of spinach and carrots.

Another adverse effect from the intake of nitrates is the presence of nitrosamines. Both nitrates and nitrites are the precursors of these compounds, which have mutagenic and carcinogenic properties (Rejmer 1997; Singer and Lijinsky 1976). In most cases, the effects were stomach and liver tumors (Szponar and Kierzkowska 1990). The harmful properties were confirmed in many different countries, in regions where population exposure to nitrates in food and water was relatively high (Janicki 1991).

According to some reports, nitrates can play a favorable role in human physiology, as they provide protective properties against circulatory diseases and hypertension (Hord et al. 2009). However, it is uncertain if nitrates contribute to methemoglobinemia as much as it appears. These issues are still under discussion and require more human dietary studies (Katan 2009).

There are a number of factors influencing the concentration of nitrates in crops. According to Cieślik (1995), the content depends on species and crop variety, harvest time and climate and soil conditions. However, the most important factor is the level of nitrogen fertilization, commonly used as easily dissolvable chemicals in conventional farming. Plants do not use any mechanisms to reduce the level of uptake from soil; therefore, the compounds enter plant roots easily. There are certain methods for minimizing the accumulation of nitrates in plant leaves, stems and roots, such as using several small doses of fertilizer at different stages of plant development instead of a single large dose. However, these techniques are not sufficiently effective and are rarely applied in conventional farming. Organic farming is based on strict principles and does not allow the use of mineral fertilizers. Therefore, the content of nitrates and nitrites in organic plant products is usually lower compared to conventional products (Rembiałkowska 2000; Rutkowska 1999;

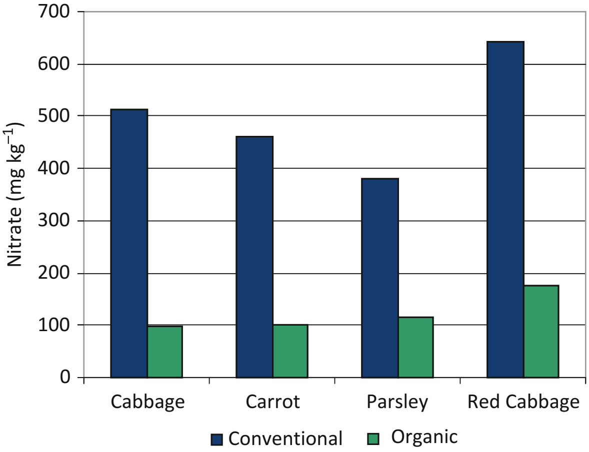

Fig. 5 Nitrate content in conventionally and organically cultivated vegetables (Rutkowska 1999)

Leszczyńska 1996) (Fig. 5). Generally, leafy vegetables accumulate the highest amounts of nitrates, followed by root vegetables and potatoes, with the risk of nitrate consumption associated mostly with cabbage and spinach.

Mycotoxins are the other group of harmful compounds present in food products. As secondary metabolites of fungi, mycotoxins naturally occur in the environment, especially under favorable conditions. Their presence depends on high temperature, high humidity, and sufficient organic matter. Mycotoxins are produced by particular species of fungi, primarily in the genera *Aspergillus*, *Fusarium*, and *Penicillium*. Presently, hundreds of different mycotoxins have been identified, most during the 1960s, when a number of diseases could not be explained. It was possible to identify these compounds through the development of analytical technology. Particularly useful for the identification of mycotoxins are high-performance liquid chromatography (HPLC) and gas chromatography (GC) (Desjardins 2006). Prevalence of mycotoxins is closely associated with harvest diseases of vegetables, fruits, cereal grains and oilseeds. Inappropriate storage conditions after harvesting are another factor contributing to the formation of these substances. Among numerous diseases related to this problem is *Fusarium ear rot*. Occurring in Europe for several years, it affects wheat, maize and barley, reducing yield and grain quality.

The mycotoxins commonly occurring in crops and posing a human health risk are ochratoxins, aflatoxins, patulin, trichothecenes and fumonisins. It is equivocal if organic farming contributes to an increased level of mycotoxins in food products. Their prevalence in the environment is natural and not caused by any chemicals or technologies. Since the use of fungicides in organic production is banned, the risk of mycotoxin exposure seems to be higher and has been confirmed by a number of studies (Czerwiecki et al. 2002a, b). However, numerous investigations provide a different answer, confirming elevated mycotoxins in conventional crops (Spadaro et al. 2007; Versari 2007), indicating this issue is still unresolved. Figure 6 shows

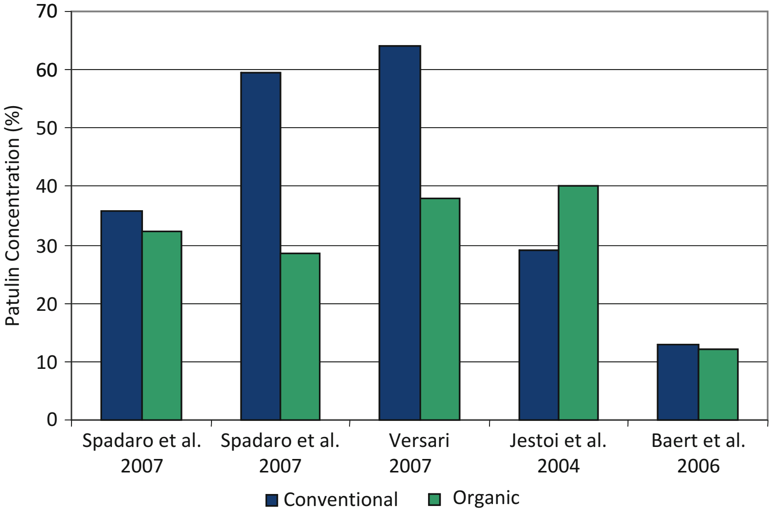

Fig. 6 Comparison of patulin concentrations in conventional and organic apple juice

the percentage of apple juice samples from conventional and organic production containing patulin. This mycotoxin is often found in apples, pears and grapes and is not destroyed by pasteurization or sterilization.

2.4 Quality of Organic Versus Conventional Plant Products

Demand for organically produced food is still growing, as consumers become more educated and aware of food-related concerns. One aspect favoring this sector of production is food safety. As stated in the previous sections, organic farming generates less contaminated food. The second reason for the rising interest in organic food is that it contains more desirable and favorable components from a health perspective. In other words, their nutritional quality is higher. There are at least three new meta-analyses showing significantly higher concentrations of desirable compounds in organically versus conventionally produced foods (Palupi et al. 2012; Brandt et al. 2011; Hunter et al. 2011).

Plant products are particularly valuable due to the presence of plant secondary metabolites, crucial for appropriate nutritional value. They are synthesized naturally by plants, but do not participate directly in cell formation. Plants generate them because of external variables, resulting in the regulation of physiological reactions to pests and other stress factors. Plant secondary metabolites include phenolic compounds, well known for their antioxidant activities and anticarcinogenic protective properties (Brandt and Mølgaard 2001). This group of substances includes flavonoids (anthocyanins, flavonols, flavonoids, isoflavones, flavanones, and

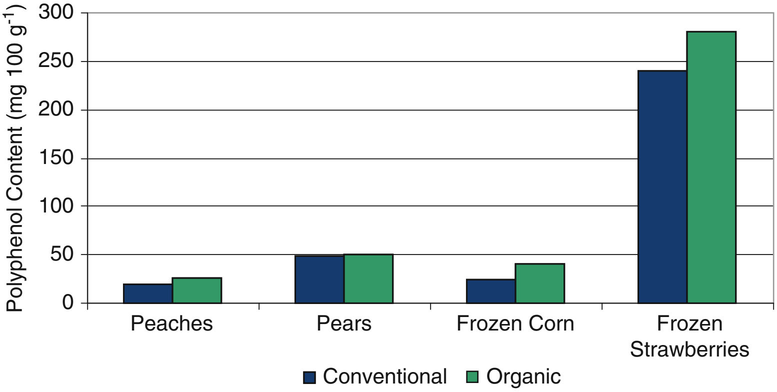

Fig. 7 Polyphenol content in fruits from organic and conventional production (Asami et al. 2003; Carbonaro and Mattera 2001)

flavones), terpenoids (carotenoids and xanthophylls) and nitrogen-containing compounds (glycosides, amines, alkaloids, glucosinolates and nonprotein amino-acids). Among the substances mentioned above, flavonoids play especially important roles in human nutrition. Apart from having antioxidant properties, they help protect against cancer development and atherosclerosis and reduce the risk of stroke. Moreover, flavonoids stimulate the immune system.

Due to their valuable properties, plant secondary metabolites are the subject of numerous analytical studies. Usually, researchers focus on the total quantity of polyphenols. Results from several comparative investigations related to the nutritional quality of fruits and vegetables regarding these substances are shown in Fig. 7. Most of the studies confirmed a higher level of total polyphenols in organically compared to conventionally managed crops.

Carotenoids are another group of secondary plant metabolites which have good health properties. They protect the heart and cardiovascular system by decreasing blood cholesterol content. The immune system is stimulated by carotenoids as they contribute to an increased number of lymphocytes, and they have anticarcinogenic properties (Stracke et al. 2008). Among numerous substances belonging to this group, the valuable and well-known compounds are beta-carotene (present in oranges, carrots, other yellow fruits, and green leafy vegetables), lycopene (found in tomatoes), lutein (present in pepper and corn) and zeaxanthin (found in corn).

There is a discrepancy with regard to the comparison of carotenoid content between organically and conventionally grown crops. According to Toor et al. (2006) and Warman and Havard (1997), conventionally cultivated vegetables contain more carotenoids (lycopene, beta-carotene) than organically cultivated vegetables. However, Pérez-López et al. (2007) and Caris-Veyrat et al. (2004) obtained completely opposite results. Figure 8 shows the results of some comparative studies related to carotenoid levels in pepper (*Capsicum annuum* L.).

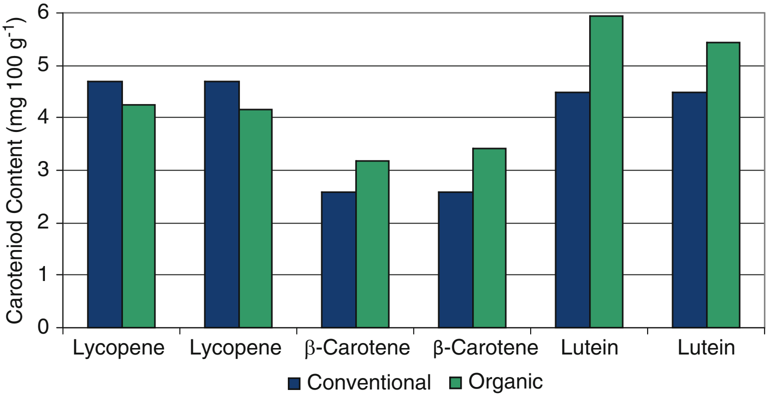

Fig. 8 Comparison of the carotenoid content in organically versus conventionally grown pepper (*Capsicum annuum* L.). Data in first column of each pair for all compounds is from 2005, and data in the second column of each pair is from 2007 (Hallmann et al. 2005, 2007)

Table 5 Comparison of vitamin C content in organically versus conventionally grown raw produce

References	Vitamin C content (mg 100 g^{-1}) Organic	Conventional	Type of raw material
Vogtmann et al. (1984)	76.30	55.50	Spinach
Leclerc et al. (1991)	8.10	7.30	Celery
Rembiałkowska (2000)	47.02	40.87	White cabbage
Schuphan (1974)	15.40	9.70	Lettuce
Termine et al. (1987)	97.80	76.10	Leeks
Hajslova et al. (2005)	9.66	8.94	Potatoes
Hallmann and Rembiałkowska (2006)	28.14	12.24	Onions
Rembiałkowska et al. (2005)	16.84	12.47	Tomatoes
Hallmann and Rembiałkowska (2007)	136.03	119.99	Peppers
Rembiałkowska et al. (2003)	7.27	5.47	Apples
Rapisarda et al. (2005)	65.73	58.71	Oranges

Apart from the substances mentioned above, vitamin C is another compound often analyzed. It is a strong antioxidant and a stimulator of the immune system. Regarding nitrite exposure, vitamin C also inhibits nitrosamine generation (Mirvish 1993). Most of the comparative studies conducted have confirmed an increased level of this compound in raw organic materials (Table 5).

Regarding minerals in organic crops, Worthington (2001) confirmed elevated iron, magnesium and phosphorus in organically grown vegetables. The investigation involved potatoes, spinach, lettuce, carrots and cabbage. Results were explained by the presence of microorganisms in organically cultivated soil that stimulated the absorption and availability of these elements.

Technological crop value is mostly associated with dry matter content which affects storage quality (Rembiałkowska 2000). According to Bulling (1987), organic plant products had lower storage losses because they absorbed less water during cultivation. Mineral fertilizers, banned in organic production, tend to increase the quantity of water absorbed with soluble mineral compounds. The average storage loss related to conventional crops amounted to 38 % of the initial mass, while organic crops exhibited approximately 28 % storage loss of initial mass (Bulling 1987).

2.5 Quality of Organic Versus Conventional Animal Products

Apart from regulations related to plant production, organic farming also defines specific guidelines concerning livestock production. Feeding (organic origin of fodder, no artificial additives), animal welfare (outdoor run, natural bedding, indoor space – possibility of free movement), and maintenance and breeding conditions (breed selection, compliance with weaning, and slaughter age) are discussed within organic guidelines. Except situations when the life of an animal is endangered, the use of antibiotics in organic farming is banned, as well as the use of genetically modified products and hormones. Fodder must consist of raw materials of organic origin.

All the factors mentioned above relate to meat quality. The sex and age of animals and post-slaughter activities (bleeding out, steaming and cooling of carcasses) have an impact on meat nutritional value and technological properties (Kerry et al. 2000).

The primary feature analyzed in comparative studies of organically versus conventionally produced meat is total fat content. According to numerous studies, organic meat contains less fat than conventional meat, regardless of the kind of meat. Fisher et al. (2000) and Hansson et al. (2000) confirmed that fat-free body mass of organically produced beef was higher than that for conventionally produced beef. However, Walshe et al. (2006) obtained different results, showing higher fat content in organic beef. Bee et al. (2004) reported a lower fat-free body mass in pork carcasses derived from organic husbandry. Similar results were obtained by Combes et al. (2003a) and Castellini et al. (2002) who analyzed the quality of organically versus conventionally raised poultry and Pla (2008) and Lebas et al. (2002) who focused on properties of rabbit meat.

A number of investigations confirm a lower fat content in organically produced meat; animals under organic husbandry have more everyday movement outside and higher quality fat, as reflected by intramuscular fat content (marbling). High marbling is considered a favorable sensory feature, making organic beef (Woodward and Fernandez 1999) and organic pork (Hansen et al. 2006; Millet et al. 2004; Olsson et al. 2003; Sundrum et al. 2000; Fernandez et al. 1999) more tender and juicy.

Another feature determining meat quality is fatty-acid composition, defined by saturated and unsaturated fatty-acid proportions. One of the key indicators is the n-6

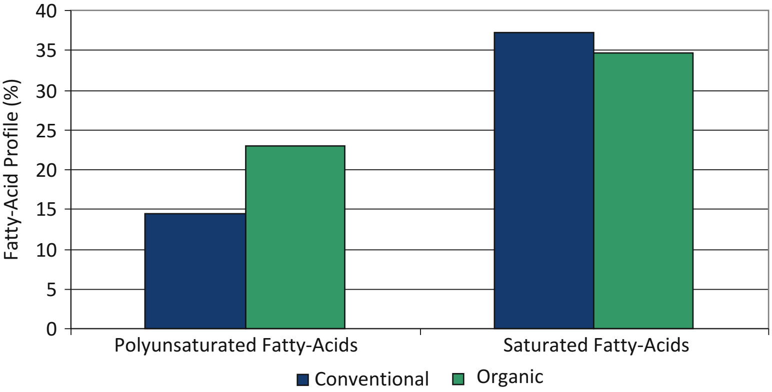

Fig. 9 Comparison of fatty-acid profiles (%) between organically and conventionally raised pork (Kim et al. 2009)

to n-3 ratio; the lower the ratio, the more nutritionally desirable the meat. The n-3 acids have anticarcinogenic properties (Augustsson et al. 2003; De Deckere 1999), protect the cardiovascular system and reduce the risk of inflammation (Bucher et al. 2002). According to Marmer et al. (1984), Wood et al. (2003, 1999) and Matthes and Pastushenko (1999), organically raised beef exhibits a significantly lower n-6 to n-3 ratio in comparison to conventionally raised beef; similar results were observed by Nilzen et al. (2001) and Hansen et al. (2000) in organically raised pork. Kim et al. (2009) confirmed that meat derived from organically raised pigs contained less saturated fatty-acids and more polyunsaturated fatty-acids, making the meat nutritionally more desirable (Fig. 9).

The same conclusion was drawn by Combes et al. (2003a) and Castellini et al. (2002) who analyzed the fatty-acid composition of organically raised poultry from organic and conventional farms. The level of docosahexaenoic acid (n-3) was two times higher in organic meat and was explained by the presence of grass in an organic diet.

Pla (2008) and Pla et al. (2007) conducted a number of studies with regard to rabbit meat quality. Their results indicated that meat from organically reared rabbits contained less saturated and monounsaturated fatty-acids than meat from conventionally reared rabbits. Moreover, the studies revealed higher quantities of polyunsaturated fatty-acids, promoting greater nutritional favorability.

Studies related to the sensory properties of organically versus conventionally produced meat are not as numerous as with fruits and vegetables. Angood et al. (2008) analyzed British lamb meat that was commonly offered in the market. Organic samples scored higher in terms of taste and juiciness. The latter factor was a result of the increased level of intramuscular fat in organic lamb chops. Danielsen et al. (1999) compared the sensory quality of organically produced pork to that of conventionally produced pork and found the latter to be more tender, most likely an effect of the higher daily weight gain in conventionally raised pigs. A similar sensory assessment was conducted on poultry meat (Combes et al. 2003b; Castellini et al. 2002), with organic samples generally scoring higher because organic chicken breast meat was juicier. Studies conducted by Pla et al. (2007) and Pla (2008) indicated that organic rabbit meat had better sensory properties. A triangle test was applied to distinguish organic samples of rabbit meat from conventionally produced samples, and more than 83 % of those tested answered correctly, indicating organic rabbit meat was more tender. In terms of flavor, a higher intensity of anise and grassy flavors was identified in conventionally produced rabbit meat, while organically produced meat was more hepatic in flavor.

Meat storage quality can be defined by the content of thiobarbituric acid-reactive substances (TBARS). Their concentration is an indicator of the intensity of fat oxidation processes. An increased level of TBARS in organic beef was confirmed by Walshe et al. (2006), while Lopez-Bote et al. (1998), Warnants et al. (1999) and Nilzen et al. (2001) obtained similar results with organic pork.

Organic milk production represents a small but stable percentage of global milk production. Milk is a valuable source of numerous bioactive substances that determine its nutritional quality, many of which are subjects of comparative studies between organic and conventional milk production. The fatty-acid profile is the primary feature analyzed, and most investigations confirm a more favorable n-6 to n-3 ratio for organically produced milk (Butler and Leifert 2009; Ellis et al. 2006). Butler and Leifert (2009) confirmed that their ratio in organic milk did not exceed 1.25, whereas in conventionally produced milk it was more than 2.5.

Another important feature of milk is the conjugated linoleic acid (CLA) content. CLA is particularly beneficial to human health, as it protects against cancer and heart disease and enhances the immune system (Whigham et al. 2000). Organic breeding can contribute to an increase of CLA in milk (Butler et al. 2008); up to 60 % more was explained by higher proportions of grazing and roughage in feed ratios for organically reared animals (Collomb et al. 2008).

Fat-soluble vitamins are also a subject of study related to organically produced milk and organic dairy products. According to Bergamo et al. (2003), organic dairy products contained higher levels of tocopherol and beta-carotene; however, differences in retinol content were not confirmed.

Studies on mineral compounds in milk have not provided a clear picture. As mineral supplementation of soils and fodder is banned in organic systems, higher concentrations of selenium, copper, iodine, zinc and molybdenum have been found in conventional milk (Coonan et al. 2002). Antioxidants (vitamin E, carotenoids) are higher in organic milk (Butler et al. 2008; Nielsen et al. 2004).

Microbiological indicators are also among the parameters that can help to distinguish between organic and conventional milk. For example, when the somatic cell count (SCC) is high, udder inflammation occurs and milk quality declines. Unfortunately, comparative study results are equivocal. Bennedsgaard et al. (2003) showed no significant differences between conventional and organically produced milk with relation to SCC, but the longer the cows were maintained in organic husbandry, the lower the SCC in their milk. Hardeng and Edge (2001) confirmed that organically maintained cows suffered udder inflammations less frequently, although the SCC was not lower in comparison to conventionally raised animals.

Certain bacterial concentrations are important indicators of milk quality as well. Karwowska (1999) reported on Polish cow milk with regard to the bacteria of greatest concern to human health. Results showed that conventional milk contains more *Streptococcus agalactiae* and *Staphylococcus aureus*, both of which cause mastitis. The odor of raw milk is not commonly accepted by consumers. The odor is not present in milk from conventionally raised cows. Consumers preferred this milk more than milk from organically raised cows (Zadoks 1989).

2.6 Impact of Organic Feed on Animal Health

Investigations involving human beings are usually very expensive and difficult to carry out. Therefore, laboratory animals are often used as models for humans. However, strictly established conditions must be provided if the impact of certain feed types is being investigated. The only factor differing among the study groups should be the fodder provided to the animals. The raw materials used as experimental input must originate from precisely defined farming systems, comprising the same or similar soil and climate conditions.

A number of parameters can be investigated using animal studies that include reproduction and fertility, newborn condition, physiological rates, and food preferences. Such investigations have previously been performed on mice, rats, rabbits, and chickens.

Fertility rates can have a genetic basis, but are more often associated with environmental factors; therefore, the relation between fodder and fertility parameters is a common subject of study. Scott et al. (1960) investigated the ability of mice to become pregnant and found that mice provided organic feed became pregnant significantly more often in comparison to those on a conventional diet. As well, less degenerative changes in the ovaries of mice provided organic food were observed.

Similar studies have been performed on rabbits, showing positive changes in reproductive organs as a result of consuming organic food (Staiger 1986; Aehnelt and Hahn 1973). Staiger (1986) indicated that rabbits fed conventionally grown food exhibited diminished fertility and higher mortality of newborns compared to rabbits fed organically produced food.

According to Velimirov et al. (1992), organic food contributed to an increased number of live-born rats and resulted in significant weight gains in female rats. The same conclusions were drawn by Gottschewski (1975) who confirmed a lower mortality of young rabbits provided organic food compared to those fed conventionally grown food (27 % versus 51 %, respectively). There also were fewer perinatal deaths and more weaned pups for rabbits provided organically grown feed.

Paci et al. (2003) analyzed the reproductive performance of rabbits from organic and conventional rearing systems. They found that the number born per litter was lower for organically reared females in comparison to conventionally raised animals

(7.5 versus 8.9, respectively). However, the birth mortality of conventionally reared rabbits was significantly higher compared to that of organically reared rabbits (23.53 versus 9.1, respectively). The organic system also significantly reduced the gestation length of rabbit females (31.1 days *versus* 31.7 days). Plochberger (1989) studied hens fed organic *versus* conventionally grown food. Organic feed reduced morbidity, enhanced weight gain and increased egg weight.

Apart from reproductive parameters, immune status also is an important subject of numerous comparative investigations. According to Finamore et al. (2004), organically produced food given to rats stimulated lymphocyte proliferation, an indicator of improved health by the body when reacting properly to stress. Similar research performed by Lauridsen et al. (2005) confirmed enhanced immunological reactivity of rats fed organically produced food. This reactivity was a secondary immune response to a given antigen. Rats provided conventionally produced food were characterized by having lower immunoglobulin G and alpha-tocopherol concentrations in the blood. Moreover, rats provided organically produced food exhibited elevated amounts of body fat and had a more relaxed behavior.

According to Barańska et al. (2007), organically produced fodder contributed to enhanced splenocyte proliferation in male rats, whereas splenocyte proliferation was reduced in females. In addition, increased antioxidative properties of blood plasma were found in rats fed on materials grown without herbicides or chemical soil fertilizers. The primary conclusion is that animals consuming fodder produced without any artificial compounds are better prepared to survive diseases.

Huber et al. (2009) investigated the performance of chickens fed organic versus conventionally produced diets. Animals provided organic diets exhibited enhanced immune reactivity and more intensive “catch-up growth” (ability to manage after a challenge), whereas chickens fed conventionally produced diets showed an increased weight gain.

It is important to emphasize that not all studies reflected higher weight gains in animals provided organically produced foods. In a study conducted within the Quality Low Input Food (QLIF) program, the final body mass of rats provided organically produced diets was lower than those provided conventionally produced diets (Średnicka-Tober et al. 2013). However, in the controlled experiments, the experimental animals provided organic food *versus* conventionally produced food had very similar diets and levels of movement; the only difference was the production system of the food components. To summarize, the lower final body mass of the animals under organic husbandry is not surprising as they have more movement, while the weight gain of experimental animals is only due to the production system of their food, thus making the results difficult to interpret.

Only a few studies related to food preferences have been conducted. According to Pfeiffer (1969), organic foods were significantly more preferred by mice. The ability to distinguish between organically and conventionally produced foods was confirmed by Plochberger (1989) and Edelmüller (1984) who analyzed the behavior of chickens and rabbits. The animals chose organic potatoes, cereals and common beans significantly more frequently compared to conventionally produced foods.

2.7 Impact of Organic Food on Human Health

The relationship between organic food consumption and health status is a subject of great importance. However, such studies are very expensive and difficult to perform. The primary concern is bioavailability, which cannot be precisely determined. Each organism has a different health status and responds differently to food products; thus, few attempts have been made.

There are three types of investigations related to human health responses to organic food. The first is an *intervention study*, involving a number of people fed a defined diet. The food is the only factor differing in both experimental groups. The other factors are the same or as similar as possible; persons leading the same lifestyle are particularly selected (e.g., in orphanages, prisons, or cloisters). Furthermore, it must be a blind study such that the participants are not aware to which group they belong and what kind of food is provided to them.

The second type of investigation is a *crossover* study, including different short test periods, conducted one after another. The experimental group is always the same, but their diet changes with each test phase. Conclusions can be drawn based on biomarker analysis, reflecting health responses.

The third kind of study is an *observational* investigation, involving a larger number of people. The participants note all of observations related to their health and well-being by answering survey questionnaires, which are reviewed by researchers. However, in such studies, a number of aspects other than diet (e.g., lifestyle, physical activity) can affect the results. Therefore, it is necessary to study large groups of consumers and to look for the correlations between diet and health parameters.

Although studies on humans are not as numerous as investigations performed on laboratory animals, they are the most interesting and reliable sources of information. Fuchs et al. (2005) analyzed the physical and mental status of nuns provided a biodynamic (very similar to organic) or a conventionally produced diet. The nuns on a biodynamic diet had lower blood pressure and better immunological parameters. Furthermore, their mental and physical conditions as well as general well-being were better during the study. According to information obtained from the “biodynamic group” prior to the experiment, individuals used to have more headaches. Starting from the moment of organic diet application, their ability to deal with stress increased; however, the investigation was not a blind study, so a “placebo effect” (the respondents knew about better nutrition, and it could positively influence their well-being) cannot be excluded.

A more complex investigation was carried out by Stracke et al. (2008) and was based on an addition of conventionally and organically grown carrots to a normal diet for volunteers. During and after the study, numerous parameters were measured including vitamins C and E, LDL oxidation, and antioxidative properties of blood. The only significant observation was elevated plasma lutein obtained from persons eating organic carrots.

An effort to provide fully controlled study conditions was made by Di Renzo et al. (2007) in Italy. Ten healthy men consumed organically and conventionally grown products for 2 weeks. After the first "organic phase," an elevated antioxidative activity of their blood plasma was reported, but due to incomplete statistical analysis, no significant difference could be confirmed.

A more developed crossover study was conducted by Grinder-Pedersen et al. (2003). Sixteen people were involved in the investigation and were fed organically produced food for 3 weeks and conventionally produced food for 2 weeks. During both phases, the excreted flavonoid content and several oxidative defense markers in their blood were measured. According to the results, the organic diet positively affected the urinary excretion of quercetin and kaempherol, as well as protein oxidation and plasma antioxidative capacities. The level of selected markers did not vary during either phase. Although the raw materials used in the study were from the same geographical region, variations were present. Thus, the reason for the final results is not precisely known.

A study named "Prevention of Allergy – Risk Factors for Sensitisation in Children Related to Farming and Anthroposophic Lifestyle" (PARSIFAL) was carried out in five European countries on approximately 14,000 children who were divided into two groups. The first group consumed organic and biodynamic food, whereas the second group was provided conventionally produced foodstuffs commonly available in the market. Children in the first group exhibited fewer allergies and lower body weight than participants on the conventional diet (Alfven et al. 2006).

Mothers with newborns were a subject of a project named "Kind, Ouders en gezondheid: Aandacht voor Leefstijl en Aanleg" (KOALA) Birth Cohort Study conducted in the Netherlands where 2,700 newborns were involved in an investigation based on organic dairy product intake. A decreased risk of eczema was reported as a result of consumption of organic dairy products (Kummeling et al. 2008). Moreover, an increased CLA level in the breast milk of mothers was identified, which is also associated with organic food intake (Rist et al. 2007).

A number of observational studies have been made, usually related to the lifestyle comparison of people consuming organic and conventional foods. Human health is also affected by living conditions, eating habits, nutritional pattern, and physical activity. There are assumptions that a preference for organically produced food is associated with the above-mentioned factors. Several authors have confirmed that consumers of organic products assess their health condition more sensitively than others (Rembiałkowska et al. 2008). However, these results cannot provide a clear answer as to whether the cause is solely based on diet.

3 Conclusions and Outlook

Organic farming is an economically viable option for many farmers today because the organic market is growing continuously on a global scale. Most developed countries have large and well-functioning organic sectors, and organic products are easily available to most consumers. As the consumption of sustainable and fairly produced goods has increased, so has interest in personal health and fitness. This interest developed further into the Lifestyle of Health and Sustainability (LOHAS), where the consumption of organic products is firmly rooted in many western countries, particularly in those with more access to resources and education. Yet, even in many emerging economies such as China, Brazil, and India, organic markets are developing. Certification and labeling systems such as Internal Control Systems or Participatory Guarantee Systems allow organic farming to serve as a tool for small-scale farmers in the Global South to gain access to international markets to increase their income, reduce inputs and costs and increase crop diversification and price premia for organic products. Nevertheless, and particularly for certified organic farming, this is in most cases no solution for those who are most strongly affected by food insecurity as these population groups in many cases lack the degree of organization and education that is necessary to enter the organic market, at least not without the help of NGOs.

The largest advantage of organic farming systems lies in their reduced impact on the environment compared to conventional agriculture. This is also the reason why many governments in industrialized countries subsidize organic farming. Research is frequently performed comparing environmental impacts from conventional and organic farming, with a strong focus of this work in Europe and North America. Most of the studies focus on soil quality, soil fertility and related topics such as enrichment of soil organic matter and erosion, nitrate leaching, GHG emissions and mitigation options, energy efficiency and biodiversity. As both conventional and organic agricultural systems are very heterogeneous, study results often differ. Not all studies show organic farming to have better performance compared to conventional farming, and in some cases, the systems perform similarly. Nevertheless, when a systems approach is taken into account and more than one parameter is evaluated, organic farming has a large potential to provide food, feed, fiber, and fuel with less impact on the environment than conventional agriculture. Especially for biodiversity, there is little doubt that organic farming systems show clear benefits for most species of wild organisms.

For N leaching, the evidence is mixed; some conventional farming systems perform better than organic systems, while some do not. This difference depends on the timing of fertilization, the overall N status in the system and the use of grain legumes and perennial leys. Here, a clear research need can be identified that is related to increases in N efficiency and better timing of N availability. In organic farming, as less soluble natural fertilizers are used, it is more difficult to define the most effective timing for fertilizer application.

The evidence is strong for more soil organic matter and greater diversity of soil organisms in organic farming systems. Nevertheless, to improve these systems even more by adapting no-tillage or reduced tillage to them remains a challenge for years to come. The organic concept of agriculture is also based strongly on resource use efficiency; this refers also to energy use. By adopting no-tillage or reduced-tillage systems, organic farming could reduce the use of fossil fuels for energy-intensive tillage measures such as plowing and could improve soil fertility by reducing erosion and further enhancing the soil fauna and flora. Unfortunately, plowing is still the most important tool for weed control in most organic farming systems. The substitution of its use by implementing adapted rotations and new shallow tillage strategies remains a challenge.

Whether or not organic farming is a more climate-friendly way of farming than conventional farming is currently being debated. The scientific results are diverse, no matter whether the comparison is performed using LCAs or on a field-study basis. There are many hints that organic farming systems have the potential for a more favorable performance compared to conventional systems with regard to GHG emissions, in particular if organic farming manages to optimize yields compared to their current status. The key issues are the lower levels of N fertilization and lower emissions of N_2O, no emissions of CO_2 from the production of energy-intensive N fertilizers and the potential of C sequestration in organically managed soils. Nevertheless, when comparisons are performed on a product level, the lower yields per area remain a critical issue that lead to similar or even higher GHG emissions in organic farming. If organic farming could improve yield levels, it could further reduce GHG emissions.

In recent years, much effort has been put into comparing studies between organic and conventional farming, but from a higher level of observation, a central question remains unanswered: Which systems and which parameters are we comparing in the end? Usually the comparisons are performed between systems which either represent the “state of the art” in field trials for the management systems or which refer to “real-world” practices in farm-pair comparisons. The studies necessarily must focus on one or only a few parameters such as nitrates in leachate, the number of butterflies along a transect, or the SOM content of a given set of fields. Meta-studies then assess the impacts by collectively examining several studies to arrive at a conclusion. This approach neglects the fact that agricultural management refers to an agricultural system where many interactions exist between different environmental compartments. If a single parameter such as nitrate in the soil is measured, other effects from agricultural activities such as effects on biodiversity are not included in the research for very practical reasons such as the disciplinary knowledge of the researchers, financial constraints and different statistical requirements. To really assess which of the farming systems, organic or conventional, is more appropriate, a more systems-oriented approach in research is necessary. Of course, studies on individual parameters are necessary to assess the performances of farming systems for very specific aspects; they are also important for locating weaknesses of farming systems in terms of environmental damages. Yet, such studies are not viable for truly assessing whether one farming system is better than another.

Whether organic farming can feed the world or not remains an open question. Too little research has been performed in developing countries on the performance of organic systems. Organic farming in developed countries has an approximately 25 % lower yield than conventional farming, but in many cases a more reduced environmental impact. Whether the results from developed countries can be transferred to developing countries with much lower inputs into agricultural systems remains doubtful. In addition, again the question "What are we comparing?" arises. Organic farming may produce lower yields, but at the same time it has many environmental benefits; the lower yields are even connected to environmental benefits. An increased richness of wild plant species on arable fields (and therefore a higher number of insects) is closely related to weed pressure, one of the major factors behind yield reduction. Pest pressure is a problem in organic systems, but the costs of contamination of groundwater by pesticides do not occur in the comparison studies. Again, the comparison of both systems calls for a more systems-oriented approach. There are many hints that organic farming (certified or not) can be a valid option for small-scale farmers in developing countries to increase their household income and to improve their food security, simply because organic farming creates market access. As organic farming is growing on a global scale, there is potential for farmers in developing countries to improve their livelihoods by converting to organic farming.

A further issue in organic farming is the use of adapted and diverse crop and animal breeds, another aspect of agro-biodiversity. As the concept of organic farming strongly favors the use of adapted animal breeds and plant varieties, organic farmers, consumers and researchers should put a stronger focus on breeding for organic farming purposes. Today, the same breeds and varieties are often used in both systems, mostly because no organic breeds or varieties are available. This may create problems in the long-term, as breeding goals strongly differ between conventional and organic systems. Here the risk is great that further concentration of commercial breeding activities for crops and domestic animals will ignore the needs of organic farmers completely, as the organic market for seeds and animals is still very small compared to conventional farming. Particularly for large international players, it may not be advantageous to invest in breeding programs for plants or animals if the return on investment is not secured due to a small number of consumers. In addition, the focus on genetically modified (GM) crops and hybrids by plant breeding companies strongly affects the availability of varieties required by organic principles. For some crops such as soybeans or cotton, the availability of non-GM seeds may reach a critical point for organic farmers in the near future, as it becomes difficult to find non-GM seeds for organic cultivation (e.g., for organic cotton growers in India). On the other hand, traditional varieties or breeds may also not be suitable for the needs of current organic farmers. Traditional open pollinating varieties of many vegetables may not fulfill the requirements of retailers in terms of size or may be very susceptible to diseases such as late blight. These varieties have not been modified by breeding efforts during recent years. The use of such varieties benefits the conservation of biodiversity of agricultural crops, but not necessarily the production process on organic farms. Relying on traditional breeds, even though they might be very successful in some cases, is no option for organic farming systems. Therefore, an urgent need exists within the organic sector to implement its own breeding schemes, either together with small and medium breeding companies or by public or private funding. As the number of breeding companies decreases, this need becomes ever more pressing.

One of the most important reasons for the growing demand of organically produced food was the finding that most human diseases result from inappropriate diets and poor food quality. It has been continually proven that many substances prevalent in marketed conventional foodstuffs are responsible for poisonings, diseases and malformations. Fruits and vegetables contain certain levels of pesticide residues that are harmful to human health (e.g., due to their carcinogenic and mutagenic properties). Soil fertilization leading to elevated N levels in the soil results in nitrite generation in raw materials and consequently poses a risk to children. Mycotoxins are especially harmful substances which are very difficult to avoid.

Organic farming is the most adequate mitigation measure related to most of the aforementioned issues. According to numerous studies that compare safety and nutritional quality between conventional and organic foods, the following conclusions can be drawn:

1. Organically grown fruits and vegetables significantly decrease human exposure to pesticide residues, which are much more prevalent in conventionally grown crops.
2. Organic plants for human consumption are considered safer for children with regard to nitrite poisoning.
3. Mycotoxins contaminate both conventional and organic raw materials, and there is no clear answer as to whether organic farming reduces human exposure to mycotoxins.
4. Organically grown crops exhibit lower yields than conventionally grown crops, but exhibit higher levels of desirable bioactive substances, such as polyphenols, carotenoids and vitamins.
5. Carcasses of organically reared animals exhibit lower total mass and lower total fat content, whereas they have much more favorable fatty-acid composition. However, the storage quality of organic meat is lower in comparison to conventionally produced meat.
6. Organically produced milk exhibits a more beneficial fatty-acid profile and higher CLA content, but its sensory quality is lower due to an undesirable odor.
7. Animal experiments confirm a positive impact of organic food on the survival rate of newborns, as well as immunological parameters and physiological features of living organisms.
8. There are assumptions that diet based on organic products may contribute to better physical and mental condition and enhance the immune system of humans. More developed and specific investigations are needed, however, to draw reliable and accurate conclusions.

The largest threat to the development of organic farming arises from its success. The organic sector continues to grow at a fast pace without any serious drawbacks and is as yet unaffected by the current financial crisis. This rapid growth poses new challenges to all involved in organic production, beginning with institutional issues such as the establishment of functional certification systems to preserve the bottom-up organic approaches while large international players enter the market. Up until now, the organic sector has been resilient to these new demands and has adapted itself by including new strategies such as PGS on a grassroots level. Currently, new trends such as regional food production are also taken into account which opens up new pathways for smaller-scale farmers.

Nevertheless, the threat remains that as soon as organic farming leaves its niche (in many countries this already has happened), the organic sector is confronted with the fact that it may become more difficult to remain a social movement driven by the concept of "being an alternative" to current conventional systems in farming, trade and society.

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Veterinary Medicine: The Value of Plant Secondary Compounds and Diversity in Balancing Consumer and Ecological Health

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Abstract Foods have a significant impact on health. Certain dietary components such as plant secondary compounds (PSCs) are increasingly recognized as important in the prevention and treatment of disease. Nevertheless, the low-diversity approach of high-producing plants with high concentrations of energy and protein has necessitated reducing concentrations of PSCs because they limit how much forage herbivores can consume in monocultures. In contrast to monocultures, silvopastoral systems emulate ecologically basic interactions among trees, shrubs, and herbaceous species with herbivores, making them more productive and resilient to environmental and market changes. In addition to enhanced productivity, plant diversity offers herbivores multiple arrays of PSCs which may improve animal nutrition, health, and welfare. Thus, an ideal feeding system should focus on harvesting the benefits of plant diversity, from productivity, resilience, and health to economic and biological sustainability on ranches.

Keywords Herbivores • Parasitic infections • Food selection • Self-medication • Intake • Feedback mechanisms • Feed-forward mechanisms • Diet • Foraging • Grazing • Self-selection • Nutrients • Well-being • Taste • Silvopastoral systems • Sustainability

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1 Plant Diversity in Ecosystems

Plant diversity on grazing lands provides a number of ecosystem services and economic benefits to society. However, such diversity seems to be a part of history (Stypinski 2011), when wild herds would graze natural plant communities across vast landscapes, using the great variety of plants available along temporal and spatial gradients (Hofman 1989; Mack and Thomson 1982). Today, large areas sustaining different types of vegetation around the world have been converted to grazing lands by reducing herbaceous vegetation or by introducing exotic grass species, thus simplifying plant diversity and structure in these systems (Niedrist et al. 2009; Provenza et al. 2007; World Conservation Monitoring Centre 1992). However, plant diversity is a necessary attribute for the maintenance of ecosystem homeostasis at different landscape scales (Hector et al. 1999, 2010; Pardini 2009) and an important variable for increasing primary and secondary productivity at the ranch scale (Galvánek and Leps 2008; Isselstein et al. 2007).

Many ecosystems around the world are naturally highly diverse, sustaining a great variety of plant species with distinct life forms, life spans, phenologies, and chemical characteristics (Hector et al. 2010; Bakker et al. 2006; Singh and Upadhyaya 2001; World Conservation Monitoring Centre 1992), where vegetation as a whole is a key element for forage production (Stypinski 2011; Isselstein et al. 2007; Bakker et al. 2006). Yet, plant cover has been largely modified to introduce graminoid vegetation, practices known to provide initial increases in primary production. However, it is also known that such productivity decreases over time as soil fertility declines (Humphreys 1991). Under management systems where forage production is based only on graminoid vegetation, the system has less capacity for self-organization, leading to reduced productivity and compromised system stability.

As such, livestock performance under production systems based on grass monocultures for forage is maintained based on external energy sources that provide water, fertilizers, herbicides, pesticides, and supplemental feeds. These systems are far different from those where most herbivores evolved. Historically, herbivores evolved interacting with a great variety of plant species as forage (Provenza et al. 2007; Nai-Bregaglio et al. 2002; Hofman 1989), and despite domestication, animal nutritional needs and basic herbivore behaviors related to diet selection have not changed over time, while the diversity and complexity of ecosystems have been largely modified through management.

2 Plant Diversity and Secondary Compounds

Human health is linked to the soil through plants that nurture herbivores and people (Provenza 2008). Plants are nutrition centers and pharmacies with vast arrays of primary (nutrients) and secondary (pharmaceuticals) compounds (PSCs) which provide multiple services vital for agroecosystems (Crozier et al. 2006; Engel 2002; Craig 1999). Despite these benefits, livestock production systems have not valued diversity to the full extent of its potential, as evidenced by the persistent attempts to simplify ecological systems to maximize yields of crops and pastures (Provenza et al. 2007). The low-diversity approach of high-production forages has necessitated reducing concentrations of PSCs because they limit how much forage livestock can consume in monocultures (Provenza 2008; Provenza et al. 2003). The outcome is energy- and protein-rich monocultures of plants low in PSCs (Johns 1994).

This monoculture approach severely restricts the potential for grazing animals to take advantage of the nutritive and pharmaceutical effects of PSCs. Low concentrations of PSCs make plants, animals, and people more susceptible to environmental hardships (Crozier et al. 2006; Asay et al. 2001). In their stead, producers have resorted to costly fossil-fuel-based fertilizers, pesticides, and insecticides to grow and protect plants in monocultures; antibiotics and anthelmintics to maintain the health of herbivores grazing those monocultures; and nutritional supplements and pharmaceuticals to sustain the well-being of humans (Provenza 2008). Secondary compounds represent plant defense systems. Relying on PSCs, rather than pesticides, virtually eliminates dietary risks due to pesticides (Halweil 2007).

Plant secondary compounds are partitioned into three broad classes – phenolics, terpenes, and alkaloids – each with thousands of compounds (Engel 2002). Tannins (phenolics) and saponins (glycosides of terpenes and steroids) at appropriate concentrations reduce internal parasites (Hocquemiller et al. 1991) and affect ruminal bacteria and digestion processes which reduce greenhouse gas emissions and improve nutrient utilization (Waghorn 2008; Hu et al. 2005) and meat quality in ruminants (Priolo et al. 2005). In addition, PSCs can negatively impact the viability of *Escherichia coli* O157:H7 (Wells et al. 2005) which causes severe intestinal disease and can lead to life-threatening kidney problems. Thus, bioactive compounds in plants have the potential to enhance the health of herbivores and people through direct and indirect effects.

3 Plant Secondary Compounds as Medicines: Feedback Mechanisms

Plant secondary compounds cause postingestive consequences in herbivores typically through their negative actions on several cellular and metabolic processes (Cheeke 1988; Cheeke and Shull 1985). In turn, these negative actions impact several trophic levels (Lozano 1998), including herbivores and the bacteria, parasites, and fungi that inhabit herbivore bodies.

Internal parasites are one of the greatest disease problems in grazing livestock worldwide (Jackson et al. 2012). Endoparasite control through chemotherapy is becoming less effective due to the rise in anthelmintic resistance (Jackson and Miller 2006). Resistance is the consequence of underdosing, mass therapy, and use of the same class of anthelmintics for prolonged periods of time (Huffman et al. 1998; Geerts et al. 1997). Thus, considerable attention has been given recently to alternative approaches of control such as the use of bioactive plants that adversely affect internal parasite populations. In this context, the strategic use of PSC-containing forages in grazing management emerges as a promising solution for the control of parasitism in conventional and organic farming systems (Barrau et al. 2005).

Several *in vitro* and *in vivo* studies suggest condensed tannins can adversely affect ruminant nematode parasites. The mode of action of tannins is mainly a direct anthelmintic effect, inhibiting mobility of nematode larvae and impacting reproduction (Paolini et al. 2004; Athanasiadou et al. 2000; Molan et al. 2000). Additionally, tannins increase the supply of bypass proteins (Foley et al. 1999; Reed 1995) that enhance immune responses to intestinal parasites (Min and Hart 2003; Niezen et al. 2002). Livestock feeding on plants with tannins such as sulla (*Hedysarum coronarium* L.) and sericea lespedeza (*Lespedeza cuneata* [Dum. Cours.] G. Don) have lower nematode burdens, lower fecal egg counts, and higher body gains than those consuming plants of similar quality without tannins (Min et al. 2004; Min and Hart 2003; Coop and Kyriazakis 2001; Niezen et al. 1998).

In addition to tannins, other PSCs have antiparasitic effects. Wild chimpanzees suffering from parasite-related diseases consume the bitter pith of the plant *Vernonia amygdalina* Delile (Huffman and Seifu 1989), which contains sesquiterpene lactones and steroid glucosides which have antiparasitic activity at the doses consumed by the animals (Koshimizu et al. 1994). The PSCs in *V. amygdalina* also have been effective at killing nematodes that cause significant losses of livestock in the tropics (Plotkin 2000). Other plants selected by chimpanzees have medicinal effects at the doses consumed, such as with the limonoids in *Trichilia rubescens* Oliv. which have antimalarial activity (Krief et al. 2004) and methoxypsoralen in *Ficus exasperata* Vahl which is a strong antibiotic (Rodriguez and Wrangham 1993). Chicory (*Cichorium intybus* L.) contains an array of condensed tannins and other phenolic compounds including sesquiterpene lactones, coumarin, and caffeic acid derivatives that reduce the need for commercial anthelmintics in young farmed deer (Hoskin et al. 1999). Plant-derived alkaloids and terpenes also have antiparasitic properties (Kayser et al. 2003; Hocquemiller et al. 1991).

Nonetheless, the use of PSCs as antiparasitic agents has been overshadowed by the inherent negative effects of PSCs at high doses in herbivores. Some propose that the potential benefits associated with PSCs should be traded off against their negative consequences (Athanasiadou and Kyriazakis 2004; Hutchings et al. 2003). For instance, one management practice could involve forcing animals to forage on PSC-rich pastures and then moving them to nutritious forages low in PSCs. Nevertheless, a more efficient approach that may improve animal nutrition and welfare involves allowing animals to select their own doses of PSCs as a function of need. This practice may be possible if animals are able to associate the ingestion of a specific food with the postingestive effects (i.e., antiparasitic) that those foods provide to the herbivore.

Traditionally, palatability (what individuals like) and nutritional needs (what individuals must consume) have been defined independently as separate constructs rooted in different mechanisms. It is typically not considered that foods taste good *when* they meet nutritional needs and that they taste bad *when* they do not. The "wisdom body" functions at a noncognitive level to change the liking of foods based on postingestive feedback from nutrients and PSCs (Provenza and Villalba 2006; Provenza 1995).

Research over the past 30 years has redefined palatability as a process, not an event. Palatability involves dynamic ongoing interrelationships among cells and organs that feedback to the palate to change the liking of a food as a function of the needs of the animal relative to the assortment of foods available (Provenza and Villalba 2006; Provenza 1995). These relationships, mediated by neurotransmitters, hormones, and peptides, are the basis for the nutritional wisdom of the body. This wisdom is manifested through the ability to meet needs for energy, protein, amino acids, various minerals, and to self-medicate. Flavor-feedback relationships enable animals to discriminate among foods, each with a distinct utility for the body at given points in space and time (Provenza and Villalba 2006). In this process, from insects to mammals, the body learns to like what it needs including medicines (Villalba and Provenza 2007; Bernays and Singer 2005).

Consistent with this hypothesis, parasitized sheep self-medicate with tannin-containing foods to reduce helminthoses, even when those foods are of low nutritional quality (Lisonbee et al. 2009). Sheep with high parasite burdens have increased preference for tannin-containing foods compared to non-parasitized sheep until their parasite infection is terminated by chemotherapy (Villalba et al. 2010). As parasite loads increase, sheep eat more tannin-containing foods which are effective at reducing parasite burdens (Juhnke et al. 2012). Parasitized goats in Spain increased the percentage of tannin-containing heather (*Erica* spp., *Calluna vulgaris* [L.] Hull) in their diet relative to anthelmintic-treated goats (Osoro et al. 2007), and in Uganda, parasitized goats tended to selectively browse *Albizia anthelmintica* (A. Rich.) (a bitter plant) that leads to declines in fecal egg counts (Gradé et al. 2007). Sheep with adult populations of *Haemonchus contortus* (Rudolphi) Cobb ate more of the Mexican tannin-rich plant *Lysiloma latisiliquum* (L.) Benth. than noninfected animals (Martinez Ortiz de Montellano et al. 2010).

There is growing evidence that parasitized herbivores learn to self-medicate. If so, producers may not need to give fixed or average doses of chemicals to all the animals of a herd which likely have different parasite burdens. Nor will it be necessary to *force* parasitized animals to graze monocultures of PSC-rich pastures. On the contrary, forage mixes could be sown, enhancing the antiparasitic and nutritional characteristics of the forage offered. If parasitized animals learn to self-medicate on PSC-containing plants, this could aid in the development of management programs geared at seeding and distributing strategically specific "medicinal" plant species in the environment to allow herbivores to combat disease by themselves. These programs can be used in combination with traditional disease prevention and treatment practices which typically use commercial chemicals.

4 Plant Secondary Compounds as Preventive Agents: Feed-Forward Mechanisms

Preventive strategies that help individuals resist disease are more effective long-term healthcare strategies than treating disease (Schepetkin and Quinn 2006). Johns (1999) argues that herbal medicines and pharmaceuticals used by humans today have replaced the health-promoting phytochemicals commonly present in primate and early hominid diets. Thus, a reduction in the availability of those preventive and naturally occurring chemicals in foods inevitably led to an increase in the use of other chemicals that treated or acted upon, instead of preventing, disease. As an example, there is a fine line between medicine and food in primates and indigenous peoples in different parts of the world. In mountain gorillas, 30 % of their daily herbaceous diet contains PSCs with antibacterial properties. Of the 172 plant species consumed by Mahale chimpanzees, 22 % are used to treat gastrointestinal-related illnesses in humans. In addition, 89 % of the species used to treat symptoms of malaria among the Hausa of Nigeria are also used in a dietary context (Huffman 1997).

Besides the effects of PSCs on infective vectors, the involvement of PSCs as preventive agents in chronic disease is significant. For instance, when an overload of free radicals or reactive oxygen species (ROS), produced either from normal cell metabolism or from external sources, cannot be neutralized, their accumulation in the body generates a phenomenon called oxidative stress. This process plays a major role in developing chronic and degenerative illnesses such as cancer, autoimmune disorders, aging, rheumatoid arthritis, and cardiovascular and neurodegenerative diseases (Pham-Huy et al. 2008; Valko et al. 2007). The body has several mechanisms to counteract oxidative stress: (a) physiological, through *in situ* production of antioxidants, and (b) behavioral, by ingesting antioxidants in foods and/or supplements. Vitamins (E, C), beta carotene, lycopene, selenium, and omega-3 and omega-6 fatty-acids are all examples of antioxidants in foods (Pham-Huy et al. 2008). Flavonoids are well known for their antioxidant capacities (Middleton et al. 2000). The flavones and catechins seem to be the most powerful flavonoids for protecting the body against ROS (Nijveldt et al. 2001). Phenols, flavonoids, isoflavones, terpenes, and glucosinolates also have immunomodulatory and anticarcinogenic properties and a wide spectrum of tumor-blocking activities (Drewnowski and Gomez-Carneros 2000; Craig 1999; Potter 1997). Stilbenes such as resveratrol and pterostilbene, which also occur in a wide variety of plants such as grapes and blueberries, have antioxidant, anti-inflammation, and anticancer activities (Bhat and Pezzuto 2002). Antioxidants like flavonoids reduce the negative impacts of ROS in the body. Interestingly, birds preferentially select flavonoids in their diets which lead to lower oxidative stress and enhanced immunity (Catoni et al. 2008). This feed-forward behavior has also been suggested as "nutraceutical" self-medicative (Catoni et al. 2008).

Changes in populations of commensal bacteria in the gastrointestinal tract may stimulate gut-associated myeloid tissues which modulate cell-mediated immune responses and consequently influence resistance against disease (Provenza and Villalba 2010). Condensed tannins have bactericidal effects (e.g., Min et al. 2002; Robbins et al. 1987) and thus have the potential to impact intestinal bacteria. Through this mechanism tannins may have probiotic effects that indirectly impact the immune system. For instance, calves treated with green tea polyphenols had more beneficial commensal species of *Bifidobacterium* and *Lactobacillus* and fewer harmful *Clostridium perfringens* (Ishihara and Akachi 1997). Moreover, the selective effects of tannins on bacteria, both in the rumen and in the intestines, may be an important avenue for research regarding the impact of tannins on intestinal immune responses. For instance, condensed tannins in *Onobrychis viciifolia* Scop. (sainfoin) appear to enhance immune cell development in sheep which may contribute to improving both resistance and resilience to endoparasite infections (Ríos-de Alvarez et al. 2008).

In addition to PSCs, certain plant biochemicals considered to be "primary" also act as preventive agents. For instance, certain polysaccharide polymers of glucose (glucans) and mannose (mannans) provide immune-stimulating and antineoplastic activity (Tizard et al. 1989). These complex carbohydrates, common in fungi and yeasts, are also present in vascular plants (Schepetkin and Quinn 2006). Galactomannans, copolymers of galactose and mannose, are in seeds of soybeans, glucans are in oats, and arabinogalactans are in juniper (Schepetkin and Quinn 2006; Tizard et al. 1989). All of these compounds stimulate macrophage function, from phagocytosis to nitric oxide and cytokine production. Likewise, plants in the genus *Echinacea* contain arabinogalactans, fructofuranosides, and heteroxylans that increase mouse, rat, and human macrophage activity (Barrett 2003). These immunomodulatory carbohydrates may also act as adjuvants, improving phagocytosis and enhancing immune responses (Franklin et al. 2005).

5 Feedback (Treatment) vs. Feed-Forward (Prevention)

Within the realm of self-medicative behavior or of ingesting substances for the curative treatment of a disease, postingestive feedback after ingestion of a medicine (e.g., relief or reduction in discomfort) primes an animal to develop a preference for such beneficial compounds. In contrast, ingestion of PSCs as preventive agents does not necessarily involve learning about the beneficial effects of the chemical. In addition, ingestion of preventive chemicals does not involve a feedback mechanism because disease or discomfort is most likely absent when those chemicals are ingested – typically on a daily basis with diet – and the benefits involve reducing the likelihood of disease in the near or distant future. Thus, this preventive process is thought to function as a feed-forward (i.e., anticipatory) mechanism (Billing and Sherman 1998). As an example, humans ingest bitter or spicy foods spontaneously, irrespective of whether they feel ill or not.

To maintain these behaviors in the short term, the consequences of ingesting foods rich in phytochemicals must be positive, a result of the many combinations of mechanisms the body uses to integrate cellular responses with the utility of foods. Some of the more important mechanisms cause animals to eat small amounts of a variety of foods, thus exposing their bodies to vast arrays of secondary compounds (Provenza et al. 2003; Provenza 1996). The long-term benefit is that this behavior provides multiple health benefits as well as chemoprophylaxis against food-borne pathogens (Nilius and Appendino 2011). As culture or food availability in a certain environment may prime individuals to consume bitter and/or spicy foods, the long-term (and unintended) consequence will be protection against pathogens or against chronic diseases.

Recent research suggests that eating spicy foods may not only be related to protecting against food-borne pathogens but to reducing inflammation, an ingestive behavior which has been selected through evolution since ligands that signal pungency are potent anti-inflammatory agents (Nilius and Appendino 2011). Consumption of spicy foods, due to their many benefits, may have meant a higher level of evolutionary fitness among ancient peoples, and thus a greater selection for liking spicy foods (Nilius and Appendino 2011). Olive oil, a large component of the Mediterranean diet associated with many cardioprotective and neurological benefits, contains oleocanthal, a major anti-inflammatory phenolic which causes oral pungency and acts on the same receptors as do spicy foods (Nilius and Appendino 2011).

Collectively, preventive PSCs are more likely to be ingested routinely with food than PSCs used to treat illness. Individuals may ingest appropriate concentrations and proportions of preventive PSCs and other natural products simply as a consequence of consuming varied diets. Diets will reflect food alternatives present in a certain environment and ultimately are manifested through tradition and culture in humans and other animals.

6 Impacts of PSCs on Food Products

There is increasing concern about the emergence of diet-related illnesses (Pollan 2008). For instance, diets high in saturated fats are correlated with an increased incidence of cardiovascular disease and cancer (Xu et al. 2006; Tucker et al. 2005; Boyd et al. 2003), although recent meta-analyses suggest more research is needed on the topic (Siri-Tarino et al. 2010).

An alternative to restricting or suppressing consumption of animal fats involves producing animals with a healthier profile of fatty-acids. For instance, nutritionally essential n-3 fatty-acids (omega-3 fatty-acids) have antioxidant properties and reduce coronary disease and cancer risks (Allport 2006).

Animal diets can significantly modify the composition of fat in muscle (Van Soest 1994) and milk (Dhiman et al. 1999). As opposed to grain-based diets, plant-based diets create animal cell walls with much higher ratios of omega-3 to omega-6 fatty-acids. Higher levels of omega-3 fatty-acids in human diets are thought to calm inflammation, thus reducing incidence of cardiovascular disease and cancer. Beyond nutrients in ruminant diets, other phytochemicals in their diets modify fatty-acid composition in their bodies. Plant secondary compounds alter fatty-acid composition in milk and muscle. Condensed tannins reduce ruminal biohydrogenation by inhibiting the activity of ruminal microorganisms and increasing the proportion of vaccenic acid (Vasta et al. 2008, 2009), a trans-fat that reduces cholesterol in plasma and also has anticarcinogenic effects (Lock et al. 2004).

The selective effect of tannins on bacteria, both in the rumen and in the intestines, is an important avenue for research. Compounds such as terpenes and alkaloids also have bacteriostatic and bactericidal properties (Nagy and Regelin 1977), with selective effects on ruminal bacteria (Villalba et al. 2006), and thus with the potential to affect fatty-acid profiles.

Beyond fatty-acid profiles, PSCs which are absorbed and stored in milk and muscle can confer health benefits to people. For instance, tannin intake produces a meat lighter in color with a longer shelf life (Priolo et al. 2005, 2009), which is likely attributable to its higher concentration of antioxidants. A number of terpenes and terpenoid compounds (e.g., limonoid triterpenes, artemisinin, limonene, farnesol) in plants have biological actions in mammals. Some terpenoids are cytotoxic to tumor cells and display anticancer activity (Mo and Elson 2004). Sesquiterpene lactones have antitumorigenic, anti-amoebic, antibacterial, antifungal, and cardiotonic properties (Huffman et al. 1998; Robles et al. 1995; Picman 1986). Saponins have anticancer and immunomodulatory properties, and they can lower cholesterol levels in plasma (Guçlu-Ustundag and Mazza 2007). Thus, it is important to assess the degree to which the meat of animals grazing plants with terpenoids and saponins specifically, and other PSCs generally, is enriched when animals graze diverse pastures rich in PSCs.

7 Plant Diversity, PSCs, Productivity, and Health

It was shown over 50 years ago that increased plant species richness leads to increased production (De Wit 1960). More recent research shows that even the best chosen monocultures cannot achieve greater productivity or carbon stores than higher-diversity assemblages (Tilman et al. 2001). In addition, plant diversity also impacts food intake and animal productivity. For instance, all plants contain PSCs that limit how much of a particular plant an herbivore can eat. Herbivores are able to meet their needs for nutrients by ingesting a variety of plants with different PSCs that complement one another (Provenza et al. 2003; Freeland and Janzen 1974). Large doses of single PSCs may overload specific detoxification mechanisms in herbivores. Thus, PSCs that affect different organs or detoxification pathways are likely to be less toxic as a diluted mixture than as a larger dose of one PSC (Freeland and Janzen 1974). In addition to being less toxic, a variety of PSCs may deliver a higher total antiparasitic dose than ingesting a single plant, thus providing a stronger antiparasitic effect.

Providing a variety of plants with different PSC profiles has the potential to allow herbivores meet needs for nutrients and reduce internal parasite loads simultaneously. Diverse pastures offer ruminants multiple arrays of PSCs which may improve their nutrition and welfare, as complementary relationships among multiple food resources in nature may improve the fitness of consumers (Tilman 1982). Unfortunately, this integrative concept is in direct opposition to reductionist science, particularly the principle of parsimony – Ockham's Razor – which holds that the preferred theory is the one with the fewest assumptions. This principle has guided the quest for "silver bullets" or single causes for food benefits (Spelman et al. 2006). Thus, research efforts are typically focused on single nutrients over whole foods (Jacobs and Tapsell 2007) or on specific chemicals over synergies among multiple bioactive components (Spelman et al. 2006). The impacts of diverse arrays of PSCs in various plant species and their complementarities on animal nutrition and health are still, for the most part, unknown.

8 Grazing and Spatial and Temporal Biodiversity

Wild herbivores forage in spatially complex environments having patchy resource distributions (Ritchie 1998). Spatial variability is also present in grazed pastures (Chapman et al. 2007). This variability has an impact on how animals utilize nutrients and medicinal and/or preventive PSCs.

Foraging animals are continuously making choices about where and what they graze within a diverse plant community. They make multiple decisions regarding their location in a landscape, patch selection, and even which plants and plant parts to eat within a selected patch (Senft et al. 1987). Time is lost while animals search for and handle preferred food items in a diverse community. These activities inevitably reduce harvest efficiency (Chapman et al. 2007). Studies offering animals the choice of alternative forage species such as ryegrass and white clover growing side by side, rather than sown as a conventional intermingled mixture, have provided evidence that animal performance benefits from having such a choice (Cosgrove et al. 2001). When grass and clover are planted in strips, as opposed to homogeneous mixtures, intake of forage by sheep increased by 25 % (265 g sheep^{-1} day^{-1}), and milk production by dairy cows increased by 11 % (2.4 kg cow^{-1} day^{-1}) (Cosgrove et al. 2001). Separation of species minimizes the time needed to select and handle desired amounts of different forages. In addition, planting forages in strips overcomes many difficulties inherent in establishing and maintaining mixed pastures and also mimics what happens naturally as different plant species aggregate in response to environmental conditions (Chapman et al. 2007). Diverse patches of forage monocultures influence the temporal sequence at which different forages are consumed. Temporal allocation of different plant species may influence the efficiency of nutrient use, as well as the kinetics of interactions among PSCs which in turn will influence the medicinal and preventive effectiveness of PSCs. A supplement of either alfalfa (saponins) or birdsfoot trefoil (tannins) prior to consuming endophyte-infected tall fescue (alkaloids) caused lambs to ingest more total dry matter and nutrients than lambs fed only tall fescue (Owens et al. 2012). Heifers that first grazed on alfalfa followed by endophyte-infected tall fescue spent considerably more time foraging on tall fescue than heifers that grazed in the reverse sequence (Lyman et al. 2011).

9 Plant Diversity, Prevention, and Food Interactions

When varied diets are consumed, there is potential for multiple interactions among all the different chemicals present in foods. The idea that one compound can influence another and increase its potential health benefit, once consumed, is termed "food synergy" (Jacobs and Tapsell 2007). This idea exists in the context of foods as well as medicine. "Chemical synergy" (Spelman et al. 2006) describes the phenomena in medicinal plants. When compounds in medicinal plants are looked at as individual components, they are generally less effective than when used as whole plants.

As explored by Jacobs and Tapsell (2007), "food, not nutrients, is the fundamental unit in nutrition." When focus is taken at the single compound level, rather than the whole food, we oversimplify a series of complex interactions between compounds themselves as well as the breakdown, digestion, and adsorption of these chemicals (Jacobs and Tapsell 2007).

Resources are complementary or synergistic when the average benefit of the combination exceeds the benefit of each component in isolation. Resources are antagonistic when the average benefit of the combination inhibits the benefit of each component in isolation (Tilman 1982). Synergistic pharmaceuticals have proven to be more effective in treatment of hypertension as well as various cancers. Using multiple types of medications at low dosages has increased success and effectiveness compared to a single medication at a high dosage (Spelman et al. 2006). Many of these "Medicinal Cocktails" are found occurring naturally together in the whole plant (Spelman et al. 2006). Not only are these medical cocktails often more effective, they also have significantly fewer side effects and are safer (Spelman et al. 2006). The use of whole plant herbal medications instead of synthetically produced single compounds has multiple advantages and has great potential to be increasingly utilized in modern medicine.

Chemical interactions can also occur when individuals consume an array of different foods with contrasting chemical properties leading to enhanced protection or availability of the chemical compound ingested. Synergy can be observed in the benefits of resveratrol, a phenolic compound found in grapes and berries. Calcium increases the bioavailability of resveratrol (Liang et al. 2008). In addition, resveratrol has low water solubility and must be carried by a protein to remain bioavailable (Liang et al. 2008). Bioavailability of resveratrol is likely increased with consumption of dairy products, allowing resveratrol to use β-Lactoglobulin (a major protein in dairy products) to increase its solubility in water. These synergies could perhaps explain the pairing of red wine (source of resveratrol) with cheeses (source of calcium and β-Lactoglobulin) in French cuisine.

In contrast to beneficial effects, some interactions may reduce the activity or bioavailability of preventive chemicals. In this scenario, the effects of consuming an array of different foods may lower the preventive effects of single chemicals. For instance, resveratrol and phenolic compounds have been shown to have antagonistic affects, making resveratrol much less bioavailable when phenols are present (Pinelo et al. 2004).

There are still many interactions we need to identify, from food patterns to chemical interactions in order to enhance the preventive effects of foods on chronic diseases. One of the benefits of understanding specific chemical interactions is that once the particular interaction is known (i.e., beneficial or antagonistic), we may be able to make generalizations about foods that contain those chemicals.

10 Plant Diversity and the Value of Silvopastoral Systems

Some ecosystems currently used for livestock grazing still support herbaceous vegetation mixed with forb/herb, shrub, and tree species (Niedrist et al. 2009; Pardini 2009; World Conservation Monitoring Centre 1992). Even when such systems might be considered of lesser importance for current high-input agricultural systems, they collectively display a greater capacity for sustainable production. At the same time, the interest in diversifying forage sources in pastures around the world is guiding people toward cultivating shrub and tree species associated with herbaceous vegetation to form silvopastoral systems (Papanastasis et al. 2008; Devendra and Ibrahim 2004; Torres 1983).

A silvopastoral system (SPS) is a form of land management where woody species are intentionally allowed to grow in the same land unit with agricultural crops including grasses and livestock. The temporal association can be simultaneous or sequential, and some associations can surge as a result of spontaneous vegetation modified through management (Huxley 1983; Torres 1983; Anonymous 1982). Such systems are intended to emulate basic ecological interactions among trees, shrubs and herbaceous species, and livestock to improve their resilience to environmental and market changes (Huxley 1983; Anonymous 1982). Silvopastoral land management systems have greater species diversity and vegetation strata to promote greater ecological stability and more sustainable productivity (Hector et al. 2010; Pardini 2009; Devendra and Ibrahim 2004).

Silvopastoral systems represent an alternative to grass monocultures to improve livestock productivity by increasing forage quality and availability over time, enhancing livestock comfort and improving soil conditions among other direct and indirect benefits to the system (Alonso 2011). The grass-tree arrangements in the same unit of land are planned to more efficiently use aboveground space having at least two strata that produce forage (Mahecha and Angulo 2012; Torres 1983) and one providing shade; herbaceous species occupy the lower vertical stratum, shrubs use the intermediate stratum, and trees form the higher stratum. These arrangements are intended to be more productive and beneficial than single-species plantations (Calle et al. 2012; Mahecha et al. 2007b).

Many plant species in any given ecosystem are potentially useful for introduction into silvopastoral systems. Diverse studies of natural plant communities have identified a variety of plants well adapted to soils and prevailing climate conditions which should make them a primary choice when searching for plants to initiate intensive silvopastoral systems. Velázquez-Martínez et al. (2010), in a species-rich tropical region of Mexico, observed that heifers included 56 non-grass species in their diet yielding 48.9 % forb/herbs, 36.8 % grasses, 12.4 % woody perennials, and 5.4 % browse species. In this study, forb/herbs associated with grasses in the understory became a major source of forage, while browses and other woody species played important roles during different seasons of the year. Important species used as forage included *Phyla dulcis* (Trevir.) Moldenke, *Ruellia brownei* L., and *Lantana achyranthifolia* Desf., which are unknown as sources of forage. Similarly, Carranza-Montaño et al. (2002) found 19 plant species (from herbaceous to woody) in the diet of goats grazing in tropical dry forest sites, and the nutritive value of several species exceeded that of grasses; species such as *Leucaena esculenta* (Sessé and Moc. ex DC.) Benth. and *Verbesina greenmanii* Urb. had up to 26 and 27 % crude protein, respectively. In Europe, Isselstein et al. (2007) studied mesotrophic and seminatural grasslands grazed by cows and sheep and also found a high plant diversity in their diets; crude protein in those species ranged from 121 to 156 g kg^{-1} DM (dry matter) and Neutral Detergent Fiber (NDF) from 494 to 609 g kg^{-1} DM.

These and many other studies show that a great variety of plant species in different ecosystems are potential sources of forage if present in the grazing areas. Spontaneous or cultivated forage species differing in phenology and nutritive value become very important sources of forage at different times of the year and become even more important during the dryer seasons when herbaceous vegetation is scarce (Tamayo-Chim et al. 2012; Velázquez-Martínez et al. 2010; Carranza-Montaño et al. 2002). Thus, plant biodiversity can be integrated into extensive livestock production systems.

However, interest has been placed on only a few species when designing richer foraging areas than grass monocultures or when supplementing livestock with fodder forage. Species such as *Leucaena leucocephala* (Lam.) de Wit, *Sesbania sesban* (L.) Merr., *Gliricidia sepium* (Jacq.) Kunth, and *Morus alba* L. have been recommended as prime options to produce forage (García and Medina 2006; Roothaert 1999). However, there are other species known to have potential in different areas of the world such as *Albizia julibrissin* Durazz., a highly nutritious legume that grows throughout the southern United States and is being deliberately used as forage for livestock (Hopkins-Shoemaker 2006); *Cecropia obtusifolia* Bertol., a tropical tree containing up to 24 % crude protein and having great potential as a supplement (Sosa-Rubio et al. 2004); the leguminous shrub *Cratylia argentea* (Desv.) Kuntze is native to South America and has good nutritive value and is highly resistant to drought (Martínez and Lascano 1998); the tree *Acacia karroo* Hayne is indigenous to southern Africa and was once considered a weed, but now is known to have great potential as fodder (Mapiye et al. 2011); and *Moringa oleifera* Lam., a highly nutritive species adapted to a wide range of environmental conditions in tropical areas (Mendieta-Araica et al. 2011; Makkar and Becker 1997). Also, there are other promising species in the genus *Leucaena* such as *L. diversifolia* (Schltdl.) Benth. (Roothaert 1999) and *L. lanceolata* S. Watson (Villa-Herrera et al. 2009) that have been overlooked.

Even though deliberate current grass-tree associations are based on two or three species in the same land unit (to provide shade, forage, or other products or services), in silvopastoral systems where trees provide fodder, enhanced weight gain and milk production and quality have been shown when compared to monocultures. Beef cattle in an SPS based on *L. leucocephala* and native grasses gained from 600 to 800 g day^{-1} (Cinco et al. 2006), providing a better benefit-cost relationship in the system compared to that based only on grasses. As well, lactating cows grazing *Brachiaria* sp. and *Ixophorus unisetus* (J. Presl) Schltdl. associated with *L. leucocephala* or *G. sepium* maintained a positive daily weight gain (DWG) of 130 g day^{-1} compared to those grazing only grasses (−0.45 g day^{-1}) (Davila et al. 1997). Manríquez-Mendoza et al. (2011) reported 444 kg ha^{-1} weight gain (equivalent to DWG from 0.333 to 0.512 kg day^{-1} throughout the year) in Criollo Lechero Tropical heifers utilizing an intensive SPS with tropical grasses (*Digitaria eriantha* Steud., *Megathyrsus maximus* [Jacq.] B.K. Simon and S.W.L. Jacobs, and *Urochloa brizantha* [Hochst. ex A. Rich.] R.D. Webster) and the tree *Guazuma ulmifolia* Lam.

Even though data exists on livestock performance in SPS where livestock directly graze, the potential of fodder trees has been widely assessed in the so-called cut and carry system in which fodder is offered as a supplement fresh, cured, as silage, or in fodder banks used for direct browsing. Grazing lambs supplemented with different levels of tropical fodder trees gained from 90 to 130 g day^{-1} achieving the highest DWG with higher amounts of fodder (75 and 100 %) in the diet (Sosa-Rubio et al. 2004). These authors also found *L. leucocephala* and *C. obtusifolia* as the best fodder trees among six evaluated species. Weaned lambs fed chopped hay were supplemented with fresh *G. sepium* or *Pachecoa venezuelensis* Burkart fodder and gained from 63 to 69 g day^{-1} which was higher than for lambs supplemented with polished rice, showing that fodder from some species can replace conventional supplements of higher cost and still achieve the same weight gain (Diaz et al. 1995). Similarly, Ayala-Monter (2013) achieved a similar DWG (0.369 g day^{-1}) for lambs fed a balanced diet that included fodder from *G. ulmifolia* than for lambs fed a diet based on other conventional feeds such as soya cake. It is known that feeding fodder forage can potentially fulfill animal nitrogen needs leading to better forage digestibility and enhanced food intake (Roothaert 1999; Nherera et al. 1998). However, some fodder trees might have limited potential because they contain secondary compounds that limit intake or nutrient assimilation.

On the other hand, meat quality has been improved when livestock feed on shrubs and trees by browsing or in the cut and carry system (Stypinski 2011). Hopkins-Shoemaker (2006) observed that goat kids fed *A. julibrissin* stored similar amounts of fat and fatty-acids to goats grazing bahiagrass (*Paspalum notatum* Alain ex Flüggé), but lower than goats fed a concentrated feed, with no negative effects on meat quality or organoleptic characteristics.

Most of the research on the effect of fodder trees has been performed in tropical regions, and the benefits are not definitive. Apparently, milk yield by unit of agricultural land is benefited over yield per cow. Davila et al. (1997) did not find differences between cows grazing in monocultures based on grasses and silvopastoral systems that included *G. sepium* and *L. leucocephala*. Neither did Bacab-Pérez and Solorio-Sánchez (2011) for cows grazing silvopastoral systems with *Megathyrsus maximus* and *L. leucocephala*. However, Tinoco-Magaña et al. (2012) showed that cows grazing an SPS associating *C. nlemfluensis* with *L. leucocephala* produced the same amount of milk as cows grazing a monoculture and supplemented (0.40 % live weight) with sorghum grain (10.5 vs. 9.5 L day^{-1}). Urbano et al. (2002) observed a 5.8 L ha^{-1} increase with crossbred (Zebu × Carora) cows using an SPS (associating *G. sepium* with *L. leucocephala*) over a grass monoculture and reported an increase in farm income. The same tendency has been reported from non-silvopastoral systems, but with species-rich pastures where livestock diets are more diverse than in monocultures (Soder et al. 2007). These studies were performed under tropical conditions, and milk yield ranged between 7 and 14 L cow^{-1} day^{-1}. Managing silvopastoral systems seems to be advantageous for increasing milk yield per agricultural unit area (Davila et al. 1997). As for weight gain, most research has been performed within the cut and carry system, in which forage from fodder trees has shown potential for milk production. Evidence suggests that while some fodder tree species will not enhance milk yield and quality (Khalili and Varvikko 1992), other tree species have good potential as supplements to do so. Grazing cows supplemented with *C. argentea* fodder (1.5 % of body weight) slightly increased their milk yield over cows supplemented with sugarcane (Martínez and Lascano 1998). Lobo and Acuña (1998) supplemented cows with the same fodder species mixed with sugarcane and maintained the same milk production as that from other tested supplements, but improved the benefit/cost ratio on the farm. On the other hand, supplementing grazing cows with 2.0 kg DM per day of *G. sepium* fodder increased yield by 1.7 L cow^{-1} day^{-1}. Mahecha et al. (2007a) offered *Tithonia diversifolia* (Hemsl.) A. Gray fodder as a supplement to grazing cows, substituting for 35 % of the concentrated feed, and found milk yield was comparable to those supplemented with a concentrated feed (about 12 L cow^{-1} day^{-1}). Similarly, Mendieta-Araica et al. (2011) found no yield differences between cows offered a concentrate or *Moringa oleifera* Lam. fodder (silage vs. fresh), as the fodder enhanced dry matter intake, although fresh fodder conferred an off-flavor to the milk. *Leucaena leucocephala* has also been reported as good forage for milk production compared to other fodder trees in the cut and carry system. Maasdorp et al. (1999) increased milk yield by feeding *L. leucocephala* (13.19 kg day^{-1}) and *Acacia boliviana* Rusby (11.24 kg day^{-1}), 0.58 kg day^{-1} more than those fed grass hay, but also using the fodder-bank system where cows are allowed to browse for a period of time during the day. Faria-Mármol et al. (2007) substituted up to 2 kg cow^{-1} day^{-1} of a concentrated feed allowing 2 h browsing in *L. leucocephala* fodder banks while maintaining the same milk yield (10–8 L day^{-1}). Also, cows allowed to browse in *L. leucocephala* fodder banks for 1–3 h per day increased their milk yield by 25 % with 3 h of browsing (9.6 L cow^{-1} day^{-1}), but this system can have detrimental effects on cow body condition (Razz et al. 2004). It is likely that the supplementation level was not high enough to maintain the achieved levels of milk production, leading to the mobilization of body reserves that negatively impacted body condition. A general conclusion regarding fodder supplementation is that although some fodder trees can be used as forage for dairy cattle (Milera et al. 2004; Maasdorp et al. 1999; Vázquez-Hernández 1997), these forages do not have enough digestible energy highly demanded by cows (Milera et al. 2004; Roothaert 1999), and other trees might not have enough digestible protein (Khalili and Varvikko 1992). However, food variety is considered an asset for conferring higher nutritional and organoleptic qualities to milk, such as higher fatty-acid concentration and antioxidant compounds that are beneficial to human health (Stypinski 2011). Bobadilla-Hernández et al. (2007) reported 12–14 g L^{-1} of fat, 92.2–94.8 g L^{-1} total solids, and 27.5 g L^{-1} of crude protein in grazing cows supplemented with *Brosimum alicastrum* Sw., *L. leucocephala*, *G. ulmifolia,* and *Psidia piscipula* (L.) Sarg. fodder. Some fodder species such as *T. diversifolia* containing 16 % crude protein and 37.5 % FDN have been found to maintain milk quality similar to cows supplemented with concentrated feed (Mahecha et al. 2007a). Tinoco-Magaña et al. (2012) obtained similar milk composition between cows grazing an SPS (*C. nlemfluensis* and *L. leucocephala*) and those supplemented with 0.4 % of their live weight as sorghum grain. Hernández-Rodríguez and Ponce-Ceballo (2004) substituted up to 2 kg DM of concentrated feed with *L. leucocephala* fodder for grazing cows and observed higher concentrations of fat (1.25 %), protein (0.8 %), nonfat solids (0.2 %), and total solids (0.5 %), except lactose (4.6 %), in a silvopastoral system.

In systems where trees occupy the highest strata, shade provides direct and indirect benefits. Shade improves the microenvironment through ambient temperature reduction, helping to reduce heat stress in livestock (Pérez-Hernández 2012; Kendall et al. 2006; Ominski et al. 2002). Trees also can improve nutrient availability in pastures that, together with the effect of shade on the physiology of herbaceous vegetation, improves or maintains plant nutritive value (Medinilla-Salinas et al. 2013; Mahecha et al. 2007b), and this can positively affect meat production (Kallenbach et al. 2006; Lehmkuhler et al. 1999). Heifers grazing under *Pinus rigida* Mill., *P. taeda* L., and *Juglans nigra* L. trees and fed cereal rye and annual ryegrass gained 675 and 456 kg in weight ha^{-1} (Kallenbach et al. 2006), with the authors concluding that shade did not negatively affect livestock production. Lehmkuhler et al. (1999) reported DWG from 550 to 675 g in steers under rotational and continuous grazing in walnut stands, with slight differences in forage quality among the grazing systems. Similarly, Mahecha et al. (2007b) assessed the performance of steers grazing under *Eucalyptus tereticornis* Sm. at two tree heights and found acceptable DWG under younger shorter trees where canopy allowed more suitable forage quantity and quality. Shade is also important to milk production, as milk yield can be depressed by heat stress in both tropical (Davidson et al. 1988) and temperate climates (Ominski et al. 2002). Under tropical conditions, heat stress can reduce milk yield up to 15 % (Souza de Abreu et al. 1999). Providing shade from trees in a silvopastoral system, Davidson et al. (1988) reported a 2 kg cow^{-1} day^{-1} increase in yield; shade decreased the rectal temperature of cows by 0.6 °C.

A great concern in this type of system is the negative effect that shade might exert on the herbaceous vegetation to reduce yield, and although this effect depends on the canopy type and degree of shading, shade reduces around 20 % of forage production (Medinilla-Salinas et al. 2013; Kallenbach et al. 2006). However, this reduction should not be a concern if other benefits are being provided by the trees that improve the overall productivity of the system.

11 Current vs. “Ideal” Feeding Systems

Despite the potential benefits of plant diversity described in this review, current systems that deal with harvesting the benefits of primary (plant) and secondary (animal) productivity have not valued diversity to its fullest potential. This is evidenced in the tendency to simplify ecological systems to monocultures or single foods in order to maximize yields of crops, pastures, and animals (Provenza 2008). These choices have caused societies to become increasingly dependent on fertilizers, insecticides, and pesticides to grow and protect plants in monocultures and on supplements and other nutrient inputs, antibiotics, and anthelmintics to maintain the nutrition and health of livestock. At great cost to the health of soil, plants, herbivores, and people, these technological “fixes” treat – instead of preventing – the symptoms of food-related ailments. There is a lack of appreciation on how to work with local and regional knowledge such that grazers, browsers, and humans become locally or regionally adapted to the environments they inhabit.

The belief that health is achieved through physical, mental, and social well-being, referred to as the health triangle, ignores the integration of cells, individuals, and societies with the landscapes they inhabit. The resulting imbalance between integration and self-assertion makes the political-industrial-academic complex, which strongly influences health, rigid and narrowly focused. To appreciate what it means to be healthy, we must realize that health is linked to the soil through the plants that nurture the lives of herbivores and people. These relationships evolve as soil, plants, herbivores, and people become locally or regionally adapted to each other and to the ever-changing social and biophysical environments within which they reside.

The lack of flexibility in modern food production is related to complex issues of energy dependence and concerns over use of fossil fuels and climate change. Chemical fertilizers (made from natural gas), pesticides (made from petroleum), farm machinery, and modern food processing, packaging, and transportation have together transformed a system that in 1940 yielded 2.3 cal of food energy for every 1 cal of fossil fuel energy used into one that presently requires 10 cal of fossil fuel energy to create 1 cal of foodstuff (Pollan 2006, 2008). These food-related issues fuel the costs of healthcare. Spending on healthcare in the United States has increased from 5 % of national income in 1960 to 16 % in 2009 due to obesity and diet-related diseases including cancer, diabetes, stroke, and heart disease (Pollan 2006, 2008).

The availability of fossil fuels is likely to decline dramatically during the first half of the twenty-first century, and the deficits are not expected to be alleviated by alternative sources of energy (Homer-Dixon 2006; Kunstler 2005). This seeming catastrophe will create opportunities for communities to benefit from foods produced locally and regionally in ways that nurture the health of soil, plants, herbivores, and people (Provenza 2008; Provenza et al. 2003). By necessity, food production will not be so dependent on fossil fuels for machinery; fertilizers, pesticides, and insecticides to grow and protect plants in monocultures; antibiotics and anthelmintics to maintain the health of herbivores; or nutritional supplements and pharmaceuticals to sustain humans. Rather, people will relearn what it means to be adapted to the landscapes they inhabit. In the process, plants will become more important as nutrition centers and pharmacies, with their vast arrays of primary and secondary compounds useful in nutrition and health. There will be a need to select plant and animal species adapted to local and regional environments. We will need to manage livestock in ways that match seasonally available forages with production requirements. Silvopastoral systems can certainly help producers accomplish this objective. To nurture our health, we will need farming and grazing practices that nurture healthy soil, plants, and herbivores. Fixing carbon and reducing emissions by growing organically, restoring plant material in the soil, and consuming local to regional and seasonal foods all contribute to resolving the climate change crisis. These practices convert food production into a carbon-absorbing activity, reversing industrial agricultures' current role as a major contributor to global warming.

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Controlling the Introduction and Augmentation of Parasites in and on Domesticated Livestock

Miguel Ángel Alonso-Díaz, Juan Felipe de Jesús Torres-Acosta, Carlos Alfredo Sandoval-Castro, and William Bruce Campbell

Abstract Parasites are one of the most important threats to domesticated livestock worldwide. For several decades, their control has been based only on therapeutic interventions using chemical products at fixed intervals throughout the year. Results have demonstrated that dependence on these chemical products, as a single form of control, is not economically and ecologically sustainable. The problem has been augmented due to the emergence of endoparasite and ectoparasite populations resistant and multiresistant to the primary families of chemical products used to control them. Yet, these chemicals continue to be overused as the primary method for parasite control. Even more, their toxicity to animals, environmental contamination, and economic cost are of increasing concern. This limited approach to parasite control has environmental consequences with likely negative impacts to human and animal health. For example, most endectocides used to control parasites (endoparasites and ectoparasites) in domesticated animals are eliminated in the milk produced by females. Thus, there is strong concern regarding human consumption

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of dairy products containing such chemicals. Currently, market demands focus on healthy livestock production with emphases on the high standards in animal health and welfare based on quality production practices. The sustainable production of domesticated livestock needs strong changes, such as considering agroecologically oriented as well as novel approaches for parasite control. Thus, the use of existing drugs should be more strategically implemented and combined with other nonchemical alternatives for ruminant livestock. New strategies for controlling parasites in ruminant livestock should begin with the premise of not eliminating or eradicating parasitic organisms, but instead basing actions on economic thresholds (similar to IPM strategies for agricultural crops). In this review, we discuss the problem and current situation regarding parasites and their control using ranching operation methods. We discuss regions where the problem of chemical resistance is of strong concern and include the ecological and socioeconomic effects of parasite control (or lack therefore). We present information about novel approaches such as improving the nutritional status of the host and biological control methods for integration with domestic livestock in order to decrease the use of and reliance on chemical products.

Keywords Domesticated livestock • Cattle • Sheep • Goats • Parasites • Ectoparasites • Endoparasites • Chemical control • Antiparasitic resistance • Ecological impact • Good parasiticide practices • Novel approaches • Biological control

1 Introduction

The presence of endoparasites and ectoparasites in domesticated livestock is one of the most important health issues in animal production worldwide (Arnaud and Alonso-Díaz 2012; Alonso-Díaz et al. 2007a). Parasites infect grazing ruminants under all types of climatic and geographical conditions, especially in tropical regions. In general, endoparasites such as gastrointestinal nematodes (GINs) reduce the productivity of susceptible ruminant species because of the negative health symptoms they create (e.g., diarrhea, emaciation), resulting in reduced body condition and shortened lifespans. Ectoparasites cause important economic losses in domesticated livestock due to the diseases they transmit and from the parasitism process itself, leading to lower milk yields and offspring production and resulting in high costs for their control.

Parasite control in most domesticated livestock has been based on the frequent administration of parasiticides at fixed intervals throughout the year with regard to environmental conditions, physiological stages, or traditions lacking a scientific foundation (Arnaud and Alonso-Díaz 2012; Fernández-Salas et al. 2012a). These approaches to parasite control have definitely contributed to improved productivity and welfare in ruminants. Yet, it has also been demonstrated that uses of chemical parasiticides, when applied as sole-source methods for controlling parasites, are not sustainable practices for dealing with the increasing economic and environmental costs of parasites within and on domesticated animals (Krecek and Waller 2006). Veterinary parasiticides are important in ruminant production, but in order to prolong their efficacy and reduce their environmental impacts, other strategies must also be synchronously implemented (Beynon 2012a, b; Hoste and Torres-Acosta 2011). Sustainable parasite control might be accomplished by considering greater preventive measures such as the restrictions against transporting animals with GINs among ranches, knowledge of parasite epidemiology, inherent animal resistance, improving the nutritional status of hosts, natural enemies, and a more controlled use of existing chemical products (Torres-Acosta and Hoste 2008). Therefore, to improve the control of parasites in domesticated ruminants by using fewer chemical treatments, it is essential to first reassess some questions at the ranch level:

1. When is the presence of parasites considered a problem in domesticated livestock?
2. Are the population dynamics of parasites in different ecological niches known?
3. When, how, and why are parasiticides used in ruminant production systems?
4. Are there alternative methods, such as biological control or other more agroecologically oriented measures, with which to perform integrated parasite control?

2 Parasitism in Tropical Domesticated Livestock: Human Interventions and Welfare

Domestic livestock production using grazing systems is a dynamic activity characterized by constant change. The quantity and quality of forage and the different types of plants and fruits available in the forage community are continuously changing throughout the year. In addition, there is a period where forage is abundant and another where it is scarce, periods linked to the annual pattern of rainfall and temperature in each region. As a consequence, people and animals must be adaptive to cope with such changes while maintaining livestock productivity and welfare (Torres-Acosta et al. 2009).

While such environmental changes continually affect the production and health of grazing livestock, another important element of change is the capacity of grazing ruminants to exhibit some aspect of reproductive activity throughout the year in tropical areas. This implies that, at different moments during the year, there are animals needing to satisfy their nutritional requirements for pregnancy, growth, lactation, or combinations thereof, regardless of the availability or quality of forage (native or introduced) (Torres-Acosta et al. 2012a).

An even more complex picture can be constructed if parasitic loads change throughout the year. These changes are essentially dependent on climatic variables such as temperature and humidity, but can be greatly exacerbated by the presence of susceptible individuals (breeds having low resistance, individuals that are undernourished, and those that are newly born to young) (Alonso-Díaz et al. 2007a). In good ranching systems, adult animals will develop resistance to the parasitic challenges, and elderly animals are not normally an issue as they are sold or culled before they become a problem. Therefore, only those animals maintained under poor production or inadequate feeding systems can suffer serious problems that affect their welfare.

Commonly, adult ruminant females (dams) in grazing systems suffer hunger and thirst, which are expressed as low body condition and anemia. If dams suffer nutritional deficiencies, the offspring will have low birth weight, there will be insufficient milk production during lactation, and the weaning weight of the young will be reduced (if the offspring do not die beforehand). Also, young animals during the preweaning stage will suffer hunger and may attempt to cover their nutritional needs by feeding on herbs, shrubs, and grasses that do not satisfy their nutritional needs at the time. Consumption of such materials exposes them to GIN infections as well as ectoparasite infestations at earlier ages than would otherwise be expected.

Therefore, livestock welfare is jeopardized by deficient nutrition and parasitism, which in turn causes reduced growth rate (or even death after weaning). Both influences ultimately result in a performance far from expected, as seen from the ranchers' point of view. The rancher, discouraged by the "unexplainable" poor performance of their animals, blames the "bad breed" of the tropical animals as the true cause of the livestock health problems instead of resolving the basic feeding and sanitary issues. Eventually, such issues promote the greater use of "more productive breeds" which generally have a higher maintenance cost (i.e., a higher price for inputs such as feed).

Given this reflection, we review the importance of proper animal management (husbandry) and the role of the human component and parasite control as crucial elements for animal welfare in grazing systems.

3 Hunger and Parasites: Common Enemies in Grazing Systems

Livestock production based on grazing and browsing systems is directly connected to the use of plant resources and an understanding of the interactions between animals and their environment in order to obtain efficient and profitable production without exhausting the available resources or producing environmental damage. Thus, at small and large scales, there are four main factors in this process:

(a) The rancher, managing the animal and the land
(b) The available vegetation
(c) The animals which use the resources
(d) The environment

Table 1 Human activity and natural causes that promote hunger and/or gastrointestinal infection in ruminants within grazing and browsing systems (Adapted from: Torres-Acosta et al. 2009)

Human activities	*Consequences in the system*
Excessive numbers of animals in paddocks	Reduction of edible forage
Rotational grazing is not properly managed or not established	Inedible weeds increase
	Animals are unable to satisfy their hunger and are weakened
	Weak animals are severely infected with GINs and infectivity within the paddocks increases
Reduced grazing or browsing time	Animals cannot satisfy their nutritional requirements and are weakened
Limiting nutrients are not supplemented	Weak animals are severely infected with GINs and infectivity within the paddocks increases
Animals not accustomed to grazing or browsing, or not tolerant to the climatic conditions	Failure to consume sufficient nutrients (undernourishment)
Reproductive management without considering nutritional status	Reproductive failure, or if reproduction succeeds, then weak offspring are more susceptible to infections
Reproductive management without considering future feed availability and quality at calving or weaning	Increased numbers of animals cause overgrazing, leading to reduced availability of nutrients (undernourishment)
Bad management of AHs favors the occurrence of resistant GIN strains	Parasites are no longer killed by the AHs
Animals carrying resistant GIN strains are bought	The entire herd remains infected and those animals severely infected may die
Animals with chronic diseases are bought	Animals gradually weaken
	Weak animals are severely infected with GINs and infectivity within the paddocks increases
Natural effects	*Consequences in the system*
Prolonged drought depletes the forage resource beyond expectation	Excessive numbers of animals per paddock which are unable to satisfy their hunger and weaken
Fires destroy the property and grazing lands	Weak animals are severely infected with GINs and infectivity within the paddocks increases
Severe rainfall causes paddocks to remain flooded	

AHs Anthelmintic medications

These same factors affect, to different degrees, the presence or absence of phenomena such as hunger and parasitism in the system. The use of vegetation during grazing and browsing must be understood as an herbivory process organized by human managers using herbivores (generally ruminants) within a defined area of land. The latter has a defined amount of forage biomass (affected by season) that sustains a definable number of animals (equal to or greater than what the human manager allocates). As such, the occurrence of hunger or parasitism can result from several scenarios, mainly of anthropogenic origin, although some natural phenomena such as prolonged drought or the presence of hurricanes can also be relevant. Some examples of such situations are presented in Table 1.

4 The Spread of Parasitic Diseases and the Potential Impacts

4.1 Human Migrations and Their Impact on Animal Production Technology

North America was colonized by human groups migrating from Asia during the last ice age. After those first migrations, some European groups (e.g., the Vikings) visited the northeastern portion of North America and settled years before the arrival of the Spaniards in 1492. However, it was more than 520 years ago when the discovery, conquest, and colonization of the "new world" became effective at a large scale across the continent. That quest is one example of how livestock production, a vital human activity, has been adapted across different regions of the world. After the "conquest" stage, and with the arrival of more colonists, the discovery of the "new" and open lands led the colonists to spread out from the first few settlements. To survive, the newly arrived colonists attempted to apply their knowledge and traditions to solve the numerous new problems they faced. They also needed to learn and use new information obtained from the local indigenous populations to improve their capacity for survival. Similarly, they had to adapt their knowledge and traditions to maintain the livestock brought from Europe or Africa. The animals had to adapt rapidly to survive in these new environments (hot, humid, and subhumid), with different types of vegetation, new wildlife, and new levels and types of parasitic infections. In addition, the prevalence and severity of the infections were likely linked to the fact that many of the usual factors that helped animals to naturally control their parasite loads were not present in the new ecosystems. Furthermore, it is very likely that many farm animals brought over on the ships had parasites, thus introducing them to the "new world." Hence, there were no natural factors in the environment to control parasites in and on the introduced livestock. The colonists (often inexperienced farmers and ranchers during the early period of colonization) faced many difficulties even when trying to make traditional dairy products such as cheese and butter from the milk these animals produced; the environmental conditions were not adequate for many of the necessary production processes. The prevailing climatic conditions for the new settlements led to altered production objectives (i.e., less milk and more meat). Even with current technology and knowledge, raising livestock for the purposes of milk production is still difficult in tropical areas (González-Sedano et al. 2010; Rojo-Rubio et al. 2009).

The livestock introduced by the Spaniards had to endure most parasitic problems naturally as there were no medicinal drugs available for treatment and the local flora had never been used previously to treat imported farm animals for such parasites. Thus, the livestock were exposed to harsh environmental conditions where natural selection led to the survival of the fittest (with increased resistance to parasitism under the prevailing conditions). Cattle from the colonization were collectively known as creole or Criollo and were adapted to the environments that ranged from semiarid to wet tropics (O'Neill et al. 2010; Russell et al. 2000). Several other types of livestock adapted to the harsh tropical climates and environment were also called Criollo (including sheep, goats, pigs, and poultry). These types of animals eventually became the main source of animal protein for human consumption. The settlers from Europe, with knowledge from local indigenous populations, learned to continually adapt their knowledge to the available resources so as to improve the survival and production of the available animals. These new production systems (ranches or haciendas) survived and evolved over hundreds of years (Bracamonte and Sosa 1988). Unfortunately, the technology and information generated and used in the older production systems was not recorded and was lost over time due to their replacement by "modern" technologies.

4.2 Sustainability of Animal Production in the Modern Era

In the second half of the twentieth century, the production of goods from agriculture and livestock followed a trend toward maximization (Glaeser 1987). The aim was to increase food production as much as possible so as to help reduce world hunger. Such high productivity was based on the use of specific farm animal breeds that were selected for high productivity. Those breeds required high quantities of nutrients to help control diseases. The majority of commercial production systems in Latin America followed this objective, thus departing from traditional production systems. In a matter of a few decades, ranchers changed from using local resources (e.g., Criollo animals and local vegetation) to new animal breeds that required new food resources that most often were imported or at least were less available to ranchers. These new and more productive animals were often less adapted to the climate, vegetation, and diseases of their new home region. As a consequence, ranchers became accustomed to using antiparasitic medications aimed at achieving near total control of parasites, often resulting in the constant use and frequent abuse of antiparasitic medications on livestock.

Meanwhile, several indigenous subsistence ranchers had continued using the resources that had been traditionally employed for hundreds of years (Pedraza et al. 1992). Yet, in recent years they too have begun to abandon their traditional production systems due to the negative "stigma" of using technology intended for "poor people" that is perceived leads to low quality products. This "stigma" results in negative effects such as:

(a) Reduced ability of ranchers to sell animals or their products and by-products
(b) Selling milk and meat at lower prices

Thus, in many countries the Criollo breeds have almost disappeared (Hoffmann and Scherf 2006). The loss of information on how to use local plant resources and Criollo breeds is a great loss for humanity in technological terms, including the loss of the associated genetic pools (animals showing strong genetic resistance to disease). To make matters worse, many ranchers are trying to introduce more productive animal breeds with the objective of obtaining “greater profit,” but without the ability to purchase the necessary inputs to achieve and sustain higher productivity. Such lack of maintenance results in production failures, economic losses, and, eventually, abandonment of ranching activities.

Current trends toward establishment of “niche markets” that focus on traditional or local production systems and breeds might help to reverse this situation. However, to make this “traditional” production more efficient, a large amount of knowledge would need to be rescued (e.g., ethnoveterinary, ethnobotanical) and rediscovered (e.g., native forage and “ancient/local” animal breed evaluations).

4.3 The Fuel Crisis: The New Challenge for Livestock Production?

After the first decade of the twenty-first century, the likelihood of solving the ever-growing problem of world hunger was compromised by a new paradigm: animal feedstuffs required for livestock production were now facing competition with the need to produce fuel from renewable resources (biofuels) (Banerjee 2011; Murphy et al. 2011). As a consequence, the price of some feedstuffs (e.g., maize) continues to increase, and a price reduction is at present unlikely. In addition, climate change is reducing precipitation and increasing temperatures in many regions of the world, leading to reduced grain production while furthering price-related stresses for these commodities. Reduced availability and higher transportation costs threaten the possibility of importing feedstuffs for animal production into countries or regions where large livestock production enterprises are established. Eventually, local agricultural production will not be able to satisfy the needs for feeding large animal populations, especially in those areas where basic feed inputs (e.g., soybeans or maize) are not produced (e.g., the Yucatan Peninsula of Mexico).

This crisis may lead to a reinvention of production systems, or a return to the basics of livestock production by making use of local resources with more resilient animals, while adapting the market to locally available products. The new global tendency will be towards optimal biological productivity or efficiency rather than the current focus on maximum economic return or productivity. This new perspective might imply a process of rediscovery, the essential reacquisition of local knowledge on the use of local resources and breeds. New sustainable parasite control schemes also will be required (Hoste and Torres-Acosta 2011). The development of new technologies or strategies that lead to more sustainable production systems will require funding and a change in the educational system. For example, the technical information contained in most books written over the last few decades was created for professionals involved in intensive production systems. As well, most of those books are based on research performed in developed countries having temperate climates. New books and information sources will need to be based on more local and regional research that responds to local and regional needs and conditions (Torres-Acosta et al. 2012a). However, this will not be an easy task. The infrastructure needed to achieve this goal has different levels of development in different parts of the world (Torres-Acosta et al. 2012c). For example, internet access is scarce in many parts of Africa, South America, and Southeast Asia, and even when there is such access, libraries find it difficult to buy access to "formal academic" information. Even when conditions are optimum for this task, only a limited amount of research eventually leads to technological advancements over a short time frame. Thus, progress in any given area of livestock science requires time, and this is something that most governments and societies in general are not prepared to afford (Torres-Acosta et al. 2012c). Milk and meat will need to be produced using apparently "less productive" animals that are more adapted to harsh environmental conditions and extensive production systems. The negative stigma of using local animals and technologies will need to be eliminated as a necessary adaptive strategy.

The current fuel crisis also implies that commodities such as milk and meat will be difficult to export and import among different regions of the world. Countries sustained by imports to their national food programs (e.g., Mexico or Venezuela) will need to start increasing their self-dependence (food independence), such that more land and water will need to be used for agriculture and livestock production. Again, this will not be easy for most governments to accept, especially those with large urban populations. Furthermore, this is in striking contradiction to the present trend and large support for not converting more land into agricultural operations and thus using more water, so as to prevent many ecosystems and natural habitats from being permanently lost or irreparably damaged, preventing our current society from traveling further down the path of the "Green Revolution," a path that has been shown not to provide healthy alternatives for human society or the environment (i.e., *Silent Spring*, Carson 1962).

Different production systems around the world serve as examples of alternative ranching. For example, integrated farms have been established in many developing countries (South America and Southeast Asia). In these systems, livestock (cattle, goats, sheep) represent only a small part of the production and coexist with fish, pigs, ducks, poultry, and other smaller livestock along with the production of many different agricultural crops (usually fruits and vegetables) (sometimes referred to as polyculture systems) in small-scale to medium-scale production units. This type of production is currently oriented toward subsistence and is thus small scale, but if properly managed can provide surplus for market sale. These types of systems require very limited inputs for the control of parasites and their diseases at smaller scales because the animals are well maintained and their waste products are often used as fertilizers and to produce biogas.

A cultural and political revolution will need to take place in order to sustain the required change in societal attitude. People will need to perceive themselves as global citizens as well as the proud promoters and users of local to regional resources and sustainable technologies leading to a better quality of life for themselves and the generations to come.

5 Parasiticide Medications Used on Ruminant Livestock

Over the last 50 years, parasiticides have played a crucial role in the control of endoparasites and ectoparasites to sustain ruminant livestock production (Sargison 2012). Since the development of the first broad-spectrum parasiticides, ranchers have used them intensively to eliminate parasites by using economic justifications for the quantities used and their frequencies of application. The anthelmintics (AHs) are defined as a chemical group used to control endoparasites (GINs, lungworms, and/or liver flukes) (Floate et al. 2005). The families of AHs currently available worldwide, their primary targets, and environmental side effects are shown in Table 2. Among them, benzimidazoles, probenzimidazoles, imidazothiazoles, and macrocyclic lactones are used to control GINs (Arnaud and Alonso-Díaz 2012). Those AH families are applied topically, orally, *via* intraruminal boluses, by injection, or in the feed (Beynon 2012a). Over the last 5 years, two new AH families have emerged, monepantel and derquantel (Torres-Acosta et al. 2012b), but they have yet to be introduced in most parts of the ranching world.

Acaricides are the chemical group used to control ectoparasites (ticks, flies, and mites). The primary families of acaricides are macrocyclic lactones, amidines, organophosphates, phenylpyrazole, pyrethroids, and growth regulators (Table 2). These products may be applied topically as a dip or poured or sprayed on an animal (Beynon 2012b). They may also be administrated as an oral drench; an intraruminal bolus, by injection; or as an impregnated ear tag. Among these acaricide families, macrocyclic lactones, amidines, and pyrethroids are most often used to control ectoparasites.

Parasiticide medications, when given at the recommended dose and directed to the proper target, are effective and have wide safety margins for both animals and the people that apply them. However, there are factors such as the presence of parasite resistance or multiresistance and/or incorrect forms of applying existing medications that decrease their effectiveness. In fact, most ranchers worldwide have come to expect, and almost exclusively depend, on broad-spectrum parasiticides to effectively control parasites among their livestock (Waller 1993). The broad-spectrum antiparasitic drugs (either as single broad-spectrum active ingredients or combinations of active ingredients leading to broad-spectrum) help ranchers reduce the labor involved in applying different products with different routes of administration. However, these types of drugs can induce resistance among the parasite populations to the specific drugs contained in the products.

Currently, global results reveal that parasite control schemes based on a rigorous or exclusive use and dependence of chemical applications are not sustainable. Continual propagation of this large-scale problem involves many people in pharmaceutical industries, professionals, ranchers, and those in public health. Table 3 presents information about parasite resistance reported in different domestic animals.

Table 2 Families of parasiticides used on domesticated livestock, their primary target, and environmental side effects

Class	Compounds	Used on	Primary target	Environmental side effects
Imidazothiazoles	Tetramisole	Cattle, sheep, pigs, goats, poultry	Nematodes	Affects beneficial arthropods
	Levamisole			
Benzimidazoles	Mebendazole	Ruminants	Nematodes	Affects beneficial arthropods
	Flubendazole	Horses	Trematodes	
	Fenbendazole	Swine		
	Oxfendazole	Dogs and cats		
	Oxibendazole	Birds		
	Albendazole			
	Albendazole sulfoxide			
	Thiabendazole			
	Thiophanate			
	Febantel			
	Netobimin			
	Triclabendazole			
Macrocyclic lactones	Abamectin	Cattle	Nematodes	Highly toxic to aquatic organisms
	Doramectin	Equines	Ticks	
	Eprinomectin	Small ruminants	Flies	Residues in feces have the potential to affect beneficial arthropods
	Ivermectin	Swine		
	Selamectin	Dogs		
	Moxidectin	Exotic species		
	Milbemycin			
	Oxime			
Diphenylsulphides	Bithionol	Horses	Tapeworms	No effect reported
			Liver flukes	

(continued)

Table 2 (continued)

Class	Compounds	Used on	Primary target	Environmental side effects
Hexahydropyrazines	Praziquantel	Ruminants, horses, poultry, dogs, and cats	Cestodes	Safe for the environment
Salicylanilides	Closantel	Cattle	Nematodes	No effect reported
	Nicloclosamide-bases	Sheep	Liver flukes	
	Oxyclozanide			
	Rafoxanide			
Tetrahydropyrimidines	Morantel	Ruminants, horses, swine, dogs, and cats	Nematodes	No effect reported
	Pyrantel embonate			
Aminoacetonitrile derivatives (AADs)	Monepantel	Sheep	Nematodes	Safe for the environment
Derquantel	Derquantel	Sheep	Nematodes	No effect reported
Organophosphates	Dichlorvos	Ruminants	Nematodes	Relatively toxic to animals
	Trichlorfon	Horses	Ticks	Contamination of the environment through fecal excretion
	Coumaphos	Swine		
	Crufomate	Dogs		
	Haloxon			
	Naftalofos			
	Coumaphos	Cattle	Ticks	Toxic to animals, aquatic organisms, beneficial arthropods and people
	Chlorpyriphos		Flies	
	Diazinon			
	Dichlorvos			

Pyrethroids	Cypermethrin	Cattle	Ticks	Highly toxic to aquatic organisms; moderately toxic to birds; toxic to beneficial arthropods
	Deltamethrin	Flies		
	Flumethrin			
	Permethrin			
Amidines	Amitraz	Cattle	Ticks	Slightly toxic to birds
				Moderately toxic to fish
phenylpyrazole	Fipronil	Cattle	Ticks	Highly toxic to fish and aquatic invertebrates
		Equines	Flies	Toxic to bees and birds
		Dogs		
Growth regulators	Fluazuron	Cattle	Ticks	Toxic to aquatic invertebrates

Compiled from: Beugnet and Franc (2012), Beynon (2012a), Horvat et al. (2012), Torres-Acosta et al. (2012b), The Merck Veterinary Manual (2011), Rodríguez-Vivas et al. (2010), Gupta (2007), McKellar (1997), EXTOXNET (1995), Bowen and Strong (1993), NIOSH (1993), and Thomson (1983)

6 Parasiticide Resistance in Ruminant Livestock

The development of resistance in the parasites of ruminant livestock represents a huge threat to common strategies for their control because it produces greater environmental impact. In ruminant livestock worldwide, two major forms of parasiticide resistance have been reported:

1. The presence of GIN populations resistant or multiresistant to the existing families of AHs
2. The presence of ectoparasites, mainly ticks, resistant or multiresistant toward the existing families of acaricides and endectocides

Nearly 20 years ago, the possibility of parasiticide resistance was pointed out in relation to both the misuse of medical drugs and their indiscriminate use. Today, the problem of resistance is common in livestock systems from all types of climates and regions (Table 3).

6.1 Resistance to Anthelmintic Medications in Ruminant Livestock

Anthelmintic resistance has most often been reported in sheep and goat ranches worldwide (Torres-Acosta et al. 2012b; Kaplan 2004) (Table 3). Although the problem is greatest in the sheep and goat sectors where intensive treatment is routinely practiced (Waller 1993), resistance has expanded to include most ruminant livestock (Torres-Acosta et al. 2012c). On cattle ranches, the AH resistance problem has been increasing in several countries (Marquez et al. 2008; Souza et al. 2008; Soutello et al. 2007; Suarez and Cristel 2007; Coles et al. 2006; Anziani et al. 2001; Dean et al. 1994). Sutherland and Leathwick (2011) mention that the presence of parasite resistance on cattle ranches represents a huge threat to the common strategy of GIN control given the greater environmental impact compared with small ruminant livestock. This greater impact is most likely brought about by the higher abundance of cattle and the greater quantity of parasiticides used per animal in relation to their greater weight.

In tropical and subtropical regions, and perhaps due to the greater prevalence and incidence of parasitosis, the development of AH resistance is critical. For example, studies conducted in Veracruz, Mexico, reported that 71.4 % of the cattle ranches had GIN populations resistant to benzimidazoles (Arnaud and Alonso-Díaz 2012), 80 % were resistant to ivermectin (Arnaud and Alonso-Díaz, unpublished data), and 82 % to imidazothiazoles (Becerra-Nava and Alonso-Díaz, unpublished data). Similarly, a high prevalence of herds with ivermectin resistance was reported in the states of Campeche (Encalada-Mena et al. 2008) and Yucatán (Canul-Ku et al.

Table 3 Anthelmintic and acaricidal resistance in ruminant livestock

				Domestic animals				
	Family	Resistance report	Place of detection	Bovine	Ovine	Equine	Goat	References
Gastrointestinal nematodes	Imidazothiazoles	Yes	Cuba		X			Arece et al. (2004)
			England		X		Taylor et al. (2009)	
			Slovakia		X		Čerňanská et al. (2006)	
			Australia		X		Sangster and Bjorn (1995)	
			Nicaragua		X		Rimbaud et al. (2005)	
			Mexico			X	Torres-Acosta et al. (2003b)	
			Malaysia			X	Dorny et al. (1994)	
			United States			X	Howell et al. (2008)	
			Brazil	X			Soutello et al. (2007)	
	Macrocyclic lactones	Yes	Mexico	X				Canul-Ku et al. (2012)
			Mexico	X		Encalada-Mena et al. (2008)		
			Mexico		X	Torres-Acosta et al. (2012b)		
			New Zealand	X		Vermunt et al. (1995)		
			Argentina	X		Fiel et al. (2001)		
			Argentina	X		Anziani et al. (2001)		

(continued)

Table 3 (continued)

Family	Resistance report	Place of detection	Domestic animals				References
			Bovine	Ovine	Equine	Goat	
		Colombia	X		Marquez et al. (2008)		
		Nicaragua	X		Soto et al. (2007)		
		Argentina	X		Suarez and Cristel (2007)		
		Brazil	X		Soutello et al. (2007)		
		Slovakia		X			Čerňanská et al. (2006)
		New Zealand		X			Hughes et al. (2007)
		Brazil			X		Molento et al. (2008)
		Canada			X		Slocombe et al. (2007)
		Australia				X	Veale (2002)
		United States				X	Howell et al. (2008)
Benzimidazoles	Yes	Norway			X		Fredrik and Bjørn (1996)
		Germany			X		Wirtherle et al. (2004)
		United States			X		Kaplan et al. (2004)
		France		X			Palcy et al. (2010)
		France				X	Silvestre and Humbert (2002)
		Mexico		X			Torres-Acosta et al. (2003a)
		Mexico	X				Arnaud and Alonso-Díaz (2012)

			Colombia	X				Marquez et al. (2008)
			Nicaragua	X				Soto et al. (2007)
			Mexico				X	Torres-Acosta et al. (2003b)
			Malaysia		X	Dorny et al. (1994)		
			United States		X	Howell et al. (2008)		
			Argentina	X		Suarez and Cristel (2007)		
			Brazil	X		Soutello et al. (2007)		
Ticks	Organophosphorus	Yes	Venezuela	X				Bravo et al. (2008)
			Mexico	X				Rodríguez-Vivas et al. (2006a)
	Pyrethroids	Yes	Mexico	X				Miller et al. (2007)
			Mexico	X				Rodríguez-Vivas et al. (2006a)
			Mexico	X				Fernández-Salas et al. (2012a)
			Brazil	X				Mendes et al. (2011)
	Amidines	Yes	Mexico	X				Soberanes et al. (2002)
			Mexico	X				Rodríguez-Vivas et al. (2006b)
			Mexico	X				Fernández-Salas et al. (2012a)
			Mexico	X				Li et al. (2004)
			Colombia	X				Benavides et al. (2000)

(continued)

Table 3 (continued)

				Domestic animals				
	Family	Resistance report	Place of detection	Bovine	Ovine	Equine	Goat	References
	Phenylpyrazolic	Yes	Uruguay	X				Cuore et al. (2007)
			Uruguay	X				Castro-Janer et al. (2011)
	Macrocyclic lactones	Yes	Brazil	X				Martins and Furlong (2001)
			Mexico	X				Pérez-Cogollo et al. (2010a)
			Mexico	X				Fernández-Salas et al. (2012b)
	Fluazuron	No						
Flies	Organophosphorus	Yes	Mexico	X				Almazán-García et al. (2004)
	Pyrethroids	Yes	Mexico/United States	X				Li et al. (2003)
			Chile	X				Oyarzún et al. (2011)
			United States	X				Guerrero et al. (1997)

2012). In other latitudes, the number of reports of ranches with GINs resistant to AHs has been increasing over the last 5 years (Table 3). The high presence of AH resistance on cattle ranches is a factor which will continue to limit the productivity and health of livestock. As a response to the lack of drug efficacy, ranchers are using higher doses of AHs without considering aspects such as ecological impact or presence of chemical residues in milk and meat for human consumption.

6.2 Acaricide Resistance on Cattle Ranches

Over the last two decades, a large number of reports have been published on ectoparasiticide resistance (Table 3), especially regarding *Rhipicephalus microplus* (Canestrini). In tropical and subtropical regions, the issue of tick populations being resistant or multiresistant is a large public and animal health concern. There are reports of *R. microplus* populations resistant to amidines, organophosphates, pyrethroids, and recently to ivermectin and fipronil (see Table 3). Even more, strains of *R. microplus* multiresistant to four families of acaricides and endectocides have also been identified (Fernández-Salas et al. 2012a, b). Reports of *R. microplus* resistant to ivermectin have recently been documented in Latin America. The first cases of *R. microplus* populations resistant to ivermectin were reported in Brazil (Klafke et al. 2006; Martins and Furlong 2001) and Uruguay (Castro-Janer et al. 2011). In Mexico, the first tick population resistant to ivermectin was reported by Pérez-Cogollo et al. (2010a). Later, the same authors reported 100 % of *R. microplus* tick populations resistant to ivermectin (30/30), but in that study only those populations with a history of macrocyclic lactone use were included (Pérez-Cogollo et al. 2010b). Recent epidemiological studies have evaluated the spatial distribution of resistance to ivermectin, the classification of phenotypic resistance of *R. microplus* to ivermectin, and factors involved in the development of resistance. More than two-thirds of the 53 farms sampled in Veracruz, Mexico, showed some level of ivermectin-resistant *R. microplus* populations, and those farms using macrocyclic lactones ≥ 4 times per year had a higher probability of developing *R. microplus* resistant to ivermectin (Fernández-Salas et al. 2012b).

When the main families of parasiticides are no longer effective against GINs and ectoparasites, urgent reevaluations of existing strategies are needed, suggesting that it is time to shift toward integrated parasite control strategies. The latter includes novel approaches such as biological control and selective use of AH drugs that are still useful (according to the resistance diagnostic tests at the ranch level). A more strict prevention program should then be implemented to avoid mobilization of livestock with resistant or multiresistant parasites strains.

7 Improving the Use of Existing Parasiticide Drugs

Studies conducted at the ranch level indicate that one of the primary factors leading to the development of resistance is the misuse (in quantity and frequency of application) of existing parasiticides and the lack of understanding of novel approaches. For example, 100 % of cattle ranchers routinely and exclusively use chemical products to control parasites in the Mexican tropics (Arnaud and Alonso-Díaz 2012). Yet, this does not mean that these products are used adequately. There are some practices, such as correct dose administration, which could be improved to obtain better efficacy of existing medications and to prolong the half-lives of useful parasiticides. Also, most ranchers do not weigh their animals before AH administrations. When animals are not weighed, AHs are managed according to one of two criteria:

1. Animal weight is calculated individually.
2. Animal weight is calculated based on the herd average.

Although it is possible to deworm low-weight animals, a number of those with weights greater than the mean would be underdosed, rendering the therapeutic levels of AH drugs insufficient to eliminate 100 % of the GINs. This means that a proportion of parasites might be in contact with low AH doses and, therefore, could develop AH resistance in a few generations. It is necessary to promote the correct use of parasiticides among ruminant owners and professionals and better methods of determining animal weight (e.g., thoracic perimeter) with higher precision (Arnaud and Alonso-Díaz 2012).

Another frequent form of inappropriate parasiticide use is their indiscriminate application without considering economical thresholds or the population dynamics of specific parasites. Hence, parasite control is commonly interpreted as an eradication strategy. Adverse consequences of intensive treatment include the accumulation of drugs in animal products, the development of resistance, and the negative effects on nontarget organisms. Regional epidemiological studies of parasites might help to build more sustainable parasite control schemes that would help to prolong the life of existing parasiticides. These types of studies should be conducted to understand the population dynamics of parasites, the diversity of parasites throughout the year, and the susceptibility and resistance of hosts. Nearly 30 years ago, Barger (1985) mentioned that important nematodes of sheep are over-dispersed with more than half of the worms contained in less than half of the hosts. Today, as predicted, epidemiological studies in tropical and subtropical regions monitoring the elimination of eggs per gram of feces or the level of tick infestations indicate that nearly 30 % of the animals within a population are affected by parasites at levels higher than the economic threshold (Alonso-Díaz, unpublished data), and this proportion of animals needs to be treated as a means of protecting the rest of the herd. This idea has been the basis of implementing targeted selective treatments in small ruminants (Kenyon et al. 2009).

Such selective use of parasiticides might have several advantages (Hoste and Torres-Acosta 2011; Waller 1993):

(i) Treating a small proportion of animals, only those more affected by parasites, might improve their productivity and save money without imposing a strong selection for AH resistance.
(ii) The remaining untreated animals might contribute a proportion of parasites having low tolerance, thus delaying the development of resistance.
(iii) A reduced use of medicinal drugs reduces environmental impact.
(iv) The presence of low to moderate levels of parasites might help to maintain the immunity responses (premunity) against parasites and the diseases transmitted by them (e.g., babesiosis and anaplasmosis). The latter may help by maintaining enzootic instability.

Perhaps, a major disadvantage of selectively treating animals is identifying only those animals which are strongly affected by parasitism. At the ranch level, there are several factors that might confound the diagnosis of parasitism. Many diseases can cause reduced body condition or may cause anemia or diarrhea such as unbalanced diets, undernourishment, paratuberculosis, pseudotuberculosis, lack of teeth, and food-borne toxicosis (Torres-Acosta et al. 2009).

Due to their broad-spectrum effect against endoparasites and ectoparasites, their negative environmental impact, and their wide use as parasiticides, macrocyclic lactones should be carefully handled. These endectocides are derived from the actinomycetes *Streptomyces avermitilis* and are used for the control of GINs and ectoparasites (Sumano and Ocampo 2006; Lifschitz et al. 2002). Ivermectin is the most promoted and widely utilized macrocyclic lactone for the control of several parasites in many animal species around the world (Rodríguez-Vivas et al. 2010). In Mexico, the pharmaceutical industry reported that ivermectin is the preferred AH to control GINs in ruminants and it is also used to control cattle ticks (Rodríguez-Vivas et al. 2010; Soberanes 2010). In a recent study on the use of macrocyclic lactones on ranches, it was observed that 84.9 % (45/53) used them as antiparasitic agents. The most commonly used macrocyclic lactone was ivermectin (84.4 %) (38/45), followed by moxidectin (8.9 %) (4/45) and doramectin (6.7 %) (3/45). Nearly 87 % (39/45) of producers do not weigh their cattle before applying macrocyclic lactones. Most producers applied macrocyclic lactones on their ranches routinely (77.8 %) (35/45), while the remainder (22.2 %) (10/45) applied them only when parasitism by GINs, based on the body condition of cattle, was suspected. In 51.1 % (23/45) of the ranches, macrocyclic lactones were used ≥4 times per year, while the remainder applied them 2–3 times per year. Slightly more than 62 % (28/45) of producers had utilized macrocyclic lactones for more than 5 years, while 37.8 % (17/45) had used them for less than 5 years (Fernández-Salas et al. 2012a, b).

Excessive use of macrocyclic lactones can negatively impact the environment because the use of broad-spectrum parasiticides can affect nontarget organisms as well as the targeted parasites. Thus, ranchers and veterinarians frequently use broad-spectrum parasiticides (macrocyclic lactones) to control GINs, but also try to impact secondary pests such as ticks and flies (Canul-Ku et al. 2012). Further, using endectocides more than four times per year has been reported to increase the risk of developing resistant *R. microplus* populations (Fernández-Salas et al. 2012a, b).

8 Parasiticides in Domesticated Livestock: Ecotoxicity and Environmental Cost

Even though medicinal drugs are formulated to deliver minimum levels of active ingredients with maximum efficacy, their excreted levels in the environment (after treatment) might have a detrimental effect on nontarget animals and microorganisms in the soil, water, and aquatic sediments that have pivotal roles in ecosystem functioning.

The impact of parasiticides with regard to ecotoxicity and environmental contamination is one of the most studied topics (Horvat et al. 2012; Floate et al. 2005; Boxall et al. 2004; Steel 1993) (Table 3). Among the veterinary medicines, parasiticides (i.e., ivermectin, levamisole, fenbendazole, triclabendazole, nitroxinil, amitraz, cypermethrin, deltamethrin, diazinon) have been identified as having the highest potential of entering the environment in large quantities (Boxall et al. 2003). In tropical and subtropical ruminant livestock, all the parasiticides discussed previously are widely used but with different methods of administration (topical, oral, injection, dips, or poured on the external surface of an animal) to control endoparasites and/or ectoparasites. After treatment, parasiticides are eliminated from the body either unchanged, as closely related compounds, or as metabolites. These medicines can also enter the environment indirectly as slurries applied over the land, atmospheric emissions, and through the disposal of unused medicines and their containers (Boxall 2004). Some chemical medicines such as endectocides enter the environment mainly through the feces of treated animals (Beynon 2012a), while benzimidazoles and imidazothiazoles are mainly excreted in urine (McKellar 1997).

Parasiticides used to treat grazing and browsing animals are excreted into soils and surface waters *via* feces and urine (Boxall 2004, 2008). In intensive livestock production systems, the main route is through the application of slurries and manure to land. Other possible sources of excretion include milk, bile, and hair. The exact excretion and degradation pathways are related to factors such as administration route, chemical structure, differences in the pharmacokinetics of AHs among domesticated livestock species (Boxall et al. 2003), as well as the concentration and quality of the medical compound used. For example, when an acaricide is applied as a dip (aspersion and immersion) for ruminant livestock to control ectoparasites, it is highly probable that some amount of unchanged compound enters into the environment *via* soil or surface water. In tropical and subtropical regions, to control ticks and flies, animals are immersed in 10,000 L of water containing sufficient concentrations of pyrethroids, organophosphates, or amidines. Frequently, these chemicals are discharged directly to surface waters such as rivers and lakes, negatively impacting nontarget aquatic organisms (see Table 2). Fortunately, the use of immersion dips to control ectoparasites is currently not used due to their high cost and management difficulty that can put workers at risk. Aspersion dips is the most frequently used method to control ectoparasites (Alonso-Díaz et al. 2007a).

The macrocyclic lactones are the veterinary drugs most frequently studied in ecotoxicology and are often selected for use because of their persistence, toxicity, and wide distribution (Römbke et al. 2010; Floate et al. 2005; Steel 1993). Due to their broad-spectrum effect against endoparasites and ectoparasites, these chemical compounds negatively impact dung and soil fauna and affect invertebrate larvae in dung at fairly low concentrations (Römbke et al. 2010; Boxall 2004). Due to their highly lipophyllic nature, endectocides such as ivermectin are also excreted substantially in milk. For reasons of consumer safety, the use of endectocides in animals, from which milk is produced for human consumption, should not be authorized. This information should be distributed to all personally involved in the control of parasites in domesticated livestock. Indeed, government programs should be implemented in developing and underdeveloped countries to regulate the use of these chemical products and the efficacy of their use in order to reduce their negative impacts. Although these products are not authorized for use on dual-purpose and dairy farms, in some regions of tropical Mexico, ranchers are using ivermectin at high concentrations (3.15 %) to control parasites in dual-purpose farms (milk and meat production), which could detrimentally impact human and animal health because of their slow release.

Other AH compounds such as benzimidazoles, imidazothiazoles, and tetrahydropyrimidines are primarily excreted in the urine. The benzimidazoles and imidazothiazoles, in particular, affect the fauna in dung from cattle and small ruminants (see Table 2).

9 How Do Agroecologically Oriented Operations Affect the Introduction and Spread of Endoparasites and Ectoparasites to Other Animals and Humans?

Among the primary cultural changes required for livestock production is the new paradigm for controlling parasitic infections. Since the 1990s, groups of researchers from Australia, Denmark, France, Mexico, New Zealand, South Africa, the United Kingdom, and the United States have been developing novel approaches for parasite control in livestock (Knox et al. 2012). The basic premise behind the methods is to reduce the dependence on AH and acaricide medications for the control of parasites. Over time, these ideas spread to additional countries in the developing world where scientists, following this philosophy, worked to develop control schemes that would be feasible even in the event of a total AH failure. Several countries in Latin America, the Caribbean, Africa, and Asia initiated their own quests toward developing alternative approaches to parasite control (Torres-Acosta and Hoste 2008). A list of methods is provided in Table 4, and we describe the principal characteristics for the two most commonly used parasiticides within

Table 4 The most commonly explored novel approaches for parasite control in ruminant livestock

Gastrointestinal nematodes	Ectoparasites (*Rhipicephalus microplus*)
Improvement of resistance	
Resistant breeds	Resistant breeds
Vaccines	Vaccines
Nutritional improvement	Nutritional improvement of the host
Reduction of infectivity	
Rotational grazing scheme	Rotational grazing scheme
Nematophagous fungi	Burning the paddock
Burning the paddock	
Combined grazing	
Non-conventional antiparasitics	
Bioactive plants	Bioactive plants
Copper oxide wire particles	Entomopathogenic fungi

ruminant livestock. At present there is a great deal of information on the impact of single options against parasites. However, it is well known that a single technique, irrespective of its capacity, is not sufficient to control parasites sustainably. Thus, researchers are looking at combining strategies as the most effective means of achieving the sustainable control of parasites (Hoste and Torres-Acosta 2011; Hoste et al. 2011).

9.1 Can Agroecologically Oriented Approaches Provide Better Outcomes?

The best form of controlling GINs or ectoparasites in livestock is to simultaneously attack the parasites in different ways (Krecek and Waller 2006). By doing so, the parasites are less capable of defending themselves or developing resistance than if only one method is applied. Novel approaches have three different objectives (Hoste and Torres-Acosta 2011):

(a) Improve livestock defense mechanisms against internal and external parasites
(b) Destroy or avoid the infective stages of the parasites in the field
(c) Destroy the parasitic stages within and/or outside of the animal

The best combination should aim to include two or more different but novel mechanisms of action. Some examples recently used to control helminthes are (letters at the end refer to the novel objectives each approach attempts to address):

Scheme 1 (Martinez-Ortiz de Montellano et al. 2007):

- Nutritional improvement of resilience and resistance (a).
- Use genetically resistant breeds of sheep or goats (livestock) (a).

- Livestock are fed forage rich in tannins (b, c).
- Livestock are dosed with copper oxide wire particles which are effective (AH effect) only against parasites such as *H. contortus* (c).

Scheme 2 (C. Flota-Bañuelos, unpublished data):

- Nutritional improvement of resilience and resistance (a).
- Use genetically resistant breeds of sheep (livestock) (a).
- Use a rotational grazing scheme (b).

Scheme 3 (Mendoza-de-Gives and Torres-Acosta (2012)):

- Nutritional improvement of resilience and resistance (a).
- Use genetically resistant breeds of sheep or goats (livestock) (a).
- Use nematode-trapping fungi which can consume free living larvae (L1, L2, and L3) of GINs found in feces, thus reducing the risk of future infections by those larvae (b).

Important here is that including combinations of novel approaches to control GINs on cattle ranches has been less explored than on ranches with small ruminants. By using combinations of control methodologies, it is less likely that parasite resistance to conventional drugs will develop. Although the combination of methodologies will not achieve total control over the parasites and the livestock will experience low levels of parasite infections, they will have the advantage of maintaining active immune systems that will better recognize and respond to future challenges from parasite infection.

10 Advances in Biological Control for Domesticated Livestock with Emphasis on Tick and Gastrointestinal Nematode (GIN) Control

There is increasing interest in exploring biological control methods, especially using fungi, to control invertebrate pests, parasites (Leger 2007), and GINs (Ojeda-Robertos et al. 2008). The premise of this parasite control strategy is that all pests and parasites have natural enemies. Those enemies may help to maintain parasite populations at levels below economic thresholds.

There are four basic steps required for the proper implementation of biological control:

1. *Know the biology, ecology, and population dynamics of both predators and pests.* Epidemiological studies are needed to develop integrated pest (parasite) management programs capable of reducing parasite burdens below economic thresholds for dairy and meat production. A basic step in controlling parasites is the collection of information on their population dynamics in each particular geographical setting (Maldonado-Simán et al. 2009; Alonso-Díaz et al. 2007b).

The selection of biological isolates for parasite control should be performed in accordance with previous studies of virulence and environmental persistence in specific ecological niches that are compatible with the overall habitat of the target insect (Leger 2007).

2. *Avoid disrupting the efficacy of the biological control strategy by using chemical products and/or detrimental cultural practices.* In some locations, ranchers burn grass or other vegetation during some seasons to control weeds and to increase the area available for grass production. High temperatures negatively affect beneficial organisms, such as entomopathogenic fungi, which are sensitive to temperatures higher than 50 °C (Fernandes et al. 2012). Also, the use of some chemical medications to control GINs in ruminants might detrimentally affect the development of some fungi, which have beneficial environmental effects. In particular, benzimidazoles, which are excreted relatively unchanged in feces, are likely to have residual effects on saprophytic fungi which invade feces (Waller 1993). Thus, when an integrated pest (parasite) management plan for GINs is adopted by using combined biological control schemes [e.g., *Duddingtonia flagrans* (Dudd.) R.C. Cook, and chemical AHs], the use of benzimidazoles might affect the efficacy of the fungus, and caution is advised.
3. *Understand the economic effect of parasitism based on the economic threshold of the pest.* In tropical regions, particularly with regard to ectoparasites (ticks and flies), owners or professionals involved in the management of domesticated livestock do not tolerate the presence of a single parasite. This form of parasite control is an eradication strategy based on the indiscriminate use of chemical products. Schemes based on the intensive use of parasiticides to eliminate or eradicate infections and infestations are often justified on economic grounds. When stronger therapeutic interventions are applied, a greater development of resistance occurs (Fernández-Salas et al. 2012a, b). Secondary pests may even appear as an ecological niche substitution. When *R. microplus* (a single-host tick) is subjected to strong chemical control, *Amblyomma cajennense* (Fabricius) (a three-host tick) may replace them in their ecological niche. Due to the different biology of *A. cajennense*, their control is more complicated. In some countries like Australia, economic thresholds have been determined for *R. microplus* which causes significant economic losses to cattle ranches when the number of adult engorged ticks is higher than 20 per animal and for *Haematobia irritans* (L.) when the fly burden is 225 horn flies per cow.
4. *Teach ranchers and professionals about the use and expected responses when using biological control.* Perhaps, when compared with chemical applications, the slow mortality rate and inconsistent results of biological control experiments in general have deterred its development (Leger 2007). Some chemical acaricides like amidines have a rapid “knockdown effect” during their application, whereas in biological control (e.g., using the entomopathogenic fungus *M. anisopliae*), it

usually takes 5–15 days to kill the parasites. Yet, the use of biological control over time has consistently provided more than 80 % control, resulting in a low expected parasite level (based on an economical threshold) (Alonso-Díaz et al. 2007b).

10.1 Effect of the Entomopathogenic Fungus Metarhizium anisopliae Against Rhipicephalus microplus: Experiences at the Ranch Level

Biological control using entomopathogenic fungi is one of the most promising options for tick control (Polar et al. 2005). The fungus *Metarhizium anisopliae* (Metchnikoff) Sorokin has been extensively studied as a key regulatory organism for biocontrol (Dutra et al. 2004; Frazzon et al. 2000). *Metarhizium anisopliae* invades *R. microplus* using a process involving the adhesion of conidia to the cuticle, conidia germination, and subsequent formation of appressoria and penetration through the cuticle, resulting in massive penetration 72 h post-inoculation (Arruda et al. 2005).

The *M. anisopliae Ma34* strain is 100 % effective on eggs, nymphs, and adults of *R. microplus* when used at 10^8 conidia ml^{-1} (Ojeda-Chi et al. 2010). In Veracruz, Mexico, an evaluation of the efficacy of *M. anisopliae* for controlling *R. microplus* on naturally infested cattle was performed (Alonso-Díaz et al. 2007b). In this study, the fungus was applied directly on livestock and considered the following basic information:

1. The population dynamics of the parasite in order to apply the fungus before the period of maximum infestation.
2. The fungus was applied at 19:00 h to avoid high temperatures and direct impact of ultraviolet rays which might affect the efficacy of the fungus on *R. microplus*.

There was no evidence of any local or systemic adverse reaction in treated livestock, and all cattle remained healthy throughout the experiment. The effect of the entomopathogenic fungus *M. anisopliae* as a natural control of *R. microplus* infections on cattle is shown in Table 5. Seven days after the second treatment application (2 dips) and during the third application, a significant difference ($P < 0.01$) was observed between treatment and control groups. In the third treatment, cattle in the control group had a maximum level of infestation with *R. microplus* (an average of 243 engorged females) in contrast to 30 engorged females per animal in the treated group. From the second treatment to the end of the experiment, cattle in the treated group had lower tick infestations ($P < 0.05$). More than 80 % efficacy was observed from the third treatment to the end of the experiment (except at the end of the third treatment). Thus, the use of *M. anisopliae* (strain *Ma34*) appears to be a viable method for controlling *R. microplus* in the field.

Table 5 Number of ticks and efficacy of the entomopathogenic fungus *Metarhizium anisopliae*, strain *Ma34*, against natural infestation by engorging female *Rhipicephalus microplus* (4.5–8.0 mm) on cattle in the Mexican tropics

		Average number of engorging female ticks[a]		
No. dips	Days	Control group	Treated group	Efficacy %
1	0	10.6^b	7.2^b	32.1
	1	7.8^b	8.2^b	1
	3	6.2^b	3.4^b	45.2
	5	4.2^b	2^b	52.4
	7	4.2^b	3.8^b	9.5
	14	3^b	4.6^b	0.0
2	1	2.4^b	2.6^b	0.0
	3	2.8^b	1.6^b	42.9
	5	6.8^b	6.4^b	5.9
	7	19^b	8^c	57.9
	14	95.6^b	23.2^c	75.7
3	1	135.4^b	16.2^c	88.0
	3	243^b	30.6^c	87.4
	5	174.6^b	29.4^c	83.2
	7	135^b	26.2^c	80.6
	14	15^b	9^b	40.0
4	1	18.4^b	10^c	45.7
	3	14.6^b	5.2^c	64.4
	5	25^b	2.2^c	91.2
	7	20.2^b	2.4^c	88.1
	14	6.6^b	1.6^c	75.8

[a] Values with different letters in the same rows are significantly different ($P < 0.05$) (From: Alonso-Díaz et al. 2007b)

11 Supplementary Feeding to Improve Resilience and Resistance Against GINs

Feeding (dietary) management can help to control GIN infections in small ruminants, thus reducing rancher dependence on conventional and more costly AH treatments. Many reviews summarize the research published over the last two decades. The interaction between nutrition and parasitism is a multidisciplinary field involving veterinarians, animal scientists, and agronomists, all of whom are searching for practical means of manipulating nutritional resources while simultaneously controlling for GINs in ruminants (Torres-Acosta et al. 2012a; Petkevicius 2007; Knox et al. 2006; Hoste et al. 2005; Houdijk and Athanasiadou 2003; Coop and Kyriazakis 1999; Coop and Holmes 1996).

In general, nutritional manipulation can be used in diverse production systems. Under temperate climatic conditions, dietary protein supply, especially bypass proteins (protein which is not digested in the rumen and is available for digestion in the abomasum and later absorption in the intestine), has been the most important source of nutrients for the improvement of resilience and resistance (Blackburn et al. 1991, 1992). In the tropics, an increased protein supply for Criollo kids infected with *Haemonchus contortus* (Rudolphi) Cobb, without the simultaneous availability of more energy (Hoste et al. 2005), resulted in reduced nutrient-use efficiency because a large proportion of the protein supplemented to kids was excreted as N in their urine and feces compared to non-supplemented kids. Also, livestock provided with normal protein diets grew at the same rate as those supplemented with protein, and there was no effect on fecal egg counts (FEC) (see also Haile et al. 2002; Singh et al. 1995). Thus, protein supplementation alone, without a simultaneous provision of energy, might not provide the expected effect on livestock, perhaps because of the adverse effects of excess ammonia (Provenza 2006) and the need for energy to eliminate excess N (Van Soest 1994).

As previously described, under hot, humid, and subhumid tropical conditions, most ranchers maintain their livestock under constant nutritional stress (e.g., reduced availability of animal feed, lack of access to grasslands, high feed prices). Thus, it is difficult for livestock to achieve high levels of production, leading to increased stress for survival, especially during the dry season when forage production and water availability are low (Anderson 1982). Under such circumstances, improvement in resilience and resistance is feasible by providing supplementary feed as an economically viable method for GIN control (Torres-Acosta et al. 2006, 2012a; Louvandini et al. 2006; Gutiérrez-Segura et al. 2003). In addition to the nutrients they contain, which have an indirect effect related to improvement of the immune response and improved resilience, some tropical forage can also provide a direct AH effect against GINs due to the bioactive compounds they contain such as tannins (Sandoval-Castro et al. 2012; Martínez-Ortiz de Montellano et al. 2010; Kahiya et al. 2003). Thus, nutritional manipulation improves resilience and resistance in livestock and reduces the abundance of different GIN species and their subsequent effects on livestock health irrespective of the stage in a parasites' life cycle. The advantages of supplementary feeding include:

(a) Reduced physiopathological impact of GINs (Martínez-Ortiz de Montellano et al. 2007; Torres-Acosta et al. 2006; Gutiérrez-Segura et al. 2003).
(b) Improved productivity (Coop and Holmes 1996). The supplement is essentially improving the nutritional status of the livestock (Louvandini et al. 2006; Torres-Acosta et al. 2006) leading to reductions of natural infections (Retama-Flores et al. 2011) or the dilution of nematode egg counts in the feces (Tarazona 1986).
(c) There are also possible direct AH effects from the supplements because some ingredients can have "pharmacological-like" effects (e.g., condensed tannins) (Martínez-Ortiz de Montellano et al. 2010; Brunet et al. 2008).

Supplementary feeding can reduce dependency on AH treatments. However, at least with the available information from field trials on small ruminant production, the level of production for infected kids and lambs with supplementation is still below the maximum production that can be achieved with supplemented animals under suppressive AH schemes (Louvandini et al. 2006; Torres-Acosta et al. 2006).

Thus, the combined use of other control strategies (e.g., nematode-trapping fungi, copper oxide wire particles) can further improve the outcome of supplementary feeding in terms of production (Martínez-Ortiz de Montellano et al. 2007). Yet, conclusive information is still lacking, so the sustainability of the application of nutritional strategies against GINs under hot, humid, and subhumid tropical conditions will require more investigation.

The control or management of GIN infections in the tropics requires much knowledge of the nutritional issues at the location where the methods will be applied, although some level of ignorance on nutritional requirements is expected. Sufficient knowledge can be obtained relatively quickly and affordably from local extension specialists, animal nutritionists, and ranchers. Such efforts should include appropriate characterization of the production systems (e.g., breeding strategies, herd sizes, available facilities, and animal breeds), seasonality of forage production, availability and affordability of different forage plants, crops, and crop by-products, all of which are crucial in the design of nutritional strategies (Torres-Acosta et al. 2012a).

12 Concluding Remarks

The future of controlling endoparasitic and ectoparasitic problems is strongly agroecological in nature. It is essentially a balance between maintaining low levels of infection in livestock (below the economic threshold) while providing for well-nourished animals, even with the presence of parasites. The ranchers and their advisors must change their current view of parasite control strategies (i.e., that of zero parasites). They must stop using antiparasitic drugs as the sole tool for parasite control and start using them in combination with other control methods. They must implement selective antiparasitic treatment schemes (using effective conventional drugs only with those animals more affected by parasites) together with other alternative control measures. The new perspective for ranchers will be to use two or more of the tools that are naturally available with those developed for parasite control: genetically resistant animals, improvement of animal nutrition, production systems with fewer animals per hectare, combined grazing with two or more herbivore species, or using plants with bioactive ingredients to treat their livestock naturally. Researchers should also try to provide ranchers with more useful tools for the control of parasites at lower cost. While vaccines for controlling ticks and GINs are already available in some parts of the world, ranchers are not using them because they are expensive. The same is true for natural enemies of parasites such as fungi.

The introduction of novel approaches for parasite control represents a global cultural challenge. We expect to see future ranchers managing subclinically and/or clinically parasitized animals so they can achieve an optimum level of production and maintain livestock welfare without negatively affecting other organisms around them. However, this implies a revolution in societal perspective to accept research oriented toward achieving such a goal. People in need of accepting new concepts of parasite control include governments, academic institutions, ranches, and marketing and extension services. If all parts of the information chain are not in agreement regarding goal achievement, then efforts will be inefficient and likely will not produce the desired results for parasite control. At present, the challenge seems impossible, and with global warming and the shift toward using less fossil fuels, society will need to think more locally or regionally about the production of animal protein and the search for solutions to local to regional problems. Presently, researchers of parasite control are strongly searching for new methods of controlling endoparasites and ectoparasites. However, the end users are still motivated by the economic inertia of the antiparasitic medicines from pharmaceutical companies. Eventually, the increase in the frequency of resistance will compel them to shift their traditional forms of parasite control toward the acceptance of novel strategies. The only issue that remains to be addressed then is that if the present route (too little improvement, too late for improvement to be effective) continues to be followed for parasite control, a great deal of irreparable damage may be levied against future efforts to provide for effective, agroecologically sound, and sustainable combined strategies. Such a situation will be highly damaging in developing and underdeveloped regions of the world which experience greater economic and production stresses connected to continued increases in population growth and thus are more susceptible to economic influences promising “quick fixes.”

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