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Cellulosic Energy Cropping Systems

Douglas L. Karlen
Editor



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This book was conceived and initiated by Dr. David I. Bransby, and it is to him that the final product is dedicated. David is a professor in the Agronomy and Soils Department in the College of Agriculture at Auburn University in Auburn, Alabama, U.S.A. A native of South Africa, David arrived at Auburn in 1987 to teach and conduct research in forage and livestock management. Shortly thereafter, he was asked to provide oversight and leadership for a federal, multistate grant focused on high-yielding, low-input herbaceous plants that could be converted to bioenergy. David insisted he was not qualified because he knew nothing about converting biomass to energy and even thought "it was a crazy idea." He was quickly reassured that "nobody else knew anything about it, either; renewable energy was a totally new area."

David immediately began learning all he could about the production of energy from biomass while simultaneously educating himself, as an immigrant, about U.S. agriculture. Suddenly he realized that the two topics could provide a nearly perfect union. He surmised that the major commodities were often being overproduced and that the government response through decades of farm programs had created "stagnation in U.S. agriculture by discouraging new ideas and change."

Nearly three decades later, David has built two research and outreach programs, one in forage and livestock management and one in energy crops and bioenergy, that have both received national and international recognition. A cornerstone of these programs has been David's emphasis on outreach, built on a philosophy that "the ultimate goal of applied research should be to benefit society, and this goal cannot be achieved without getting involved in outreach." Through his personal involvement with many different stakeholder groups, David concludes that he has "gathered valuable information that has helped me design more relevant research and improve the content of the courses I teach."

David is convinced that biofuels made from switchgrass and other agricultural crops and by-products can reduce America's dependence on foreign oil, strengthen farm economies and revitalize rural communities. "Energy crops, while not a total solution, would help by giving farmers new markets and reducing their dependence on farm subsidies." He has continued his endeavors because "I believe this is really important stuff. It's going to play a major role in our country's future."

Contents

Foreword

This volume on cellulosic energy cropping systems is a valuable addition to the Wiley Series on Renewable Resources. The editor, Doug Karlen, has provided guidance for fifty expert co-authors from around the world to make meaningful contributions that detail an extremely diverse and complex topic. The result is an easy-to-use source of cutting edge information with an international perspective on all aspects of cellulosic energy cropping systems that will be extremely beneficial to students, the private sector, legislators and lay people alike. Chapters are well organized; the information provided is based largely on scientific research but also includes valuable observations, ideas and advice that are not available in refereed scientific journals. For those who wish to review any particular topic in more detail, a comprehensive list of references is provided at the end of each chapter.

As efforts to commercialize numerous biofuel, biopower, and bioproduct conversion processes around the world steadily increase, it has become evident that optimization of the connection between the feedstock and conversion phases in the supply chain is often a very major challenge, and potentially poses the greatest risk of project failure. In particular, understanding by managers in the feedstock phase of needs in the conversion phase are often tenuous, and vice versa. In this regard, chapter sequence is helpful: following an excellent broad introduction to cellulosic energy crops in the first chapter, overviews of conversion technologies for production of biofuels, and of biomass heat and power are provided in Chapters 2 and 3, respectively. This ensures that the reader has a basic understanding of these processes prior to reviewing information on cellulosic energy crops; for those who wish to explore these topics further, considerably more information is provided in other volumes of the Wiley Series on Renewable Resources.

The heart of this volume comprises comprehensive accounts of current best management practices for production of both herbaceous (Miscanthus, switchgrass, sugarcane, energy cane, napier grass, sorghum and crop residues) and woody (eucalyptus, pine, poplar and willow) cellulosic energy feedstocks that offer most potential globally. While the importance of a systems approach is emphasized or implied throughout, separate chapters on logistics of herbaceous and woody energy crops address this issue in detail. The all-important topic of sustainability is covered in the next three chapters, one each on economic, environmental and social sustainability. Never before have new crops been scrutinized and regulated, as much as is expected for cellulosic energy crops, due largely to a substantial increase in international awareness of global climate change and its impact on society. The final two chapters provide accounts of challenges and solutions related to commercialization of cellulosic cropping systems in the fledgling industry, and selected global examples of these systems.

In summary, this volume provides a unique and comprehensive source of up-to-date information on cellulosic energy cropping systems that is valuable to anyone interested in this topic: it will be prescribed reading for both undergraduate and graduate students who register for my course on Bioenergy and the Environment.

David Bransby
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Series Preface

Renewable resources, their use and modification are involved in a multitude of important processes with a major influence on our everyday lives. Applications can be found in the energy sector, chemistry, pharmacy, the textile industry, paints and coatings, to name but a few.

The area interconnects several scientific disciplines (agriculture, biochemistry, chemistry, technology, environmental sciences, forestry . . .), which makes it very difficult to have an expert view on the complicated interaction. Therefore, the idea to create a series of scientific books, focusing on specific topics concerning renewable resources, has been very opportune and can help to clarify some of the underlying connections in this area.

In a very fast changing world, trends are not only characteristic for fashion and political standpoints; also, science is not free from hypes and buzzwords. The use of renewable resources is again more important nowadays; however, it is not part of a hype or a fashion. As the lively discussions among scientists continue about how many years we will still be able to use fossil fuels – opinions ranging from 50 years to 500 years – they do agree that the reserve is limited and that it is essential not only to search for new energy carriers but also for new material sources.

In this respect, renewable resources are a crucial area in the search for alternatives for fossil-based raw materials and energy. In the field of energy supply, biomass and renewable-based resources will be part of the solution alongside other alternatives such as solar energy, wind energy, hydraulic power, hydrogen technology and nuclear energy.

In the field of material sciences, the impact of renewable resources will probably be even bigger. Integral utilization of crops and the use of waste streams in certain industries will grow in importance, leading to a more sustainable way of producing materials.

Although our society was much more (almost exclusively) based on renewable resources centuries ago, this disappeared in the Western world in the nineteenth century. Now it is time to focus again on this field of research. However, it should not mean a 'retour à la nature', but it should be a multidisciplinary effort on a highly technological level to perform research towards new opportunities, to develop new crops and products from renewable resources. This will be essential to guarantee a level of comfort for a growing number of people living on our planet. It is 'the' challenge for the coming generations of scientists to develop more sustainable ways to create prosperity and to fight poverty and hunger in the world. A global approach is certainly favoured.

This challenge can only be dealt with if scientists are attracted to this area and are recognized for their efforts in this interdisciplinary field. It is, therefore, also essential that consumers recognize the fate of renewable resources in a number of products.

Furthermore, scientists do need to communicate and discuss the relevance of their work. The use and modification of renewable resources may not follow the path of the genetic engineering concept in view of consumer acceptance in Europe. Related to this aspect, the series will certainly help to increase the visibility of the importance of renewable resources.

Being convinced of the value of the renewables approach for the industrial world, as well as for developing countries, I was myself delighted to collaborate on this series of books focusing on different aspects of renewable resources. I hope that readers become aware of the complexity, the interaction and interconnections, and the challenges of this field and that they will help to communicate on the importance of renewable resources.

I certainly want to thank the people of Wiley's Chichester office, especially David Hughes, Jenny Cossham and Lyn Roberts, in seeing the need for such a series of books on renewable resources, for initiating and supporting it and for helping to carry the project to the end.

Last, but not least, I want to thank my family, especially my wife Hilde and children Paulien and Pieter-Jan, for their patience and for giving me the time to work on the series when other activities seemed to be more inviting.

Christian V. Stevens, Faculty of Bioscience Engineering
Ghent University, Belgium
Series Editor 'Renewable Resources'
June 2005

Preface

As stated in the Dedication, this book was conceived and initiated by Dr. David I. Bransby, who strongly believes that "research should not be an end in itself, but the first step in a process for generating and transferring information or technologies that are of value to the communities we serve." David chose to focus the book on plant biomass because even though fats and oils can be used for bioenergy production, plant biomass is more abundant than animal biomass and thus offers much greater potential for energy production. Plant biomass can provide a variety of inputs including starch, oil, and sugar, but it is the lignocellulosic (cellulosic) biomass itself that is most abundant. Composed of cellulose, hemi-cellulose, and lignin these cell wall components are renewed on an annual basis around the globe.

There are also numerous technologies that are ready or under development for converting cellulosic biomass to heat, electricity and/or liquid fuels. With that in mind, David set out to produce a book that provided comprehensive documentation of how cellulosic energy crops such as switchgrass, Miscanthus, and sorghum and the cellulosic fraction of sugarcane, maize and wheat residues could be sustainably produced and converted to affordable energy through liquid fuels and electricity. Unfortunately, due to an on-going battle with diabetes, David was unable to complete the project. I am very humbled to have been able to pick up the gauntlet and with the outstanding help of many of my friends and colleagues complete this very important project. It is our hope as editor and authors of this work that readers around the globe will catch hold of David's inspiration and continue the ground-breaking work in the area, building new programs where none existed before, and continuing to build an awareness of the potential benefits of bioenergy to the public at large and to policy makers. The target audience for this book is society as a whole, but especially those elected officials who are often ultimately responsible for building new programs through their critical enabling legislation.

The book is divided into five sections. The first (I) provides general background related not only to the challenges and various potential cellulosic feedstocks (Chapter 1) but also to technologies for production of liquid fuels and biochemicals (Chapter 2) or production of heat and electricity (Chapter 3). Section II hones in on each of the herbaceous crops that have been identified as a potential cellulosic feedstock for not only bioenergy but also bioproduct development. Miscanthus (Chapter 4), switchgrass (Chapter 5), sugarcane and energy cane (Chapter 6), sorghums (Chapter 7) and crop residues (Chapter 8) are examined in detail by reviewing their phylogeny, cultural practices, and opportunities for genetic improvement. Section III follows a similar format although the focus is on woody crops, including eucalyptus (Chapter 9), pine (Chapter 10), poplar (Chapter 11), and willow (Chapter 12).

Section IV moves toward David's ultimate goal of commercialization by reviewing critical logistical issues associated with both herbaceous (Chapter 13) and woody (Chapter 14) feedstocks. Alternate strategies for harvesting, transporting, and storing various cellulosic materials are examined. Finally, Section V tackles the challenge where "the rubber meets the road", that is, moving the technology from the researchers to society as a whole.

To achieve long-term sustainability, emerging cellulosic bioenergy and/or bioproducts industries must meet three crucial and equally important challenges. One is that the new enterprise(s) must be economical (Chapter 15). The second is they must not have adverse environmental impacts (Chapter 16), and, finally, they must be socially acceptable (Chapter 17). The final two chapters are intended to provide readers with case study examples of an actual bioenergy commercialization project (Chapter 18) and a glimpse at activities in Brazil, China, and India (Chapter 19).

In summary, to meet ever increasing global needs for sustainable food, feed, fiber, and fuel supplies, greater attention must be given to soil, water, and air resources. Redirecting from an increased trajectory of expanded row crops to cellulosic energy crops and crop rotations is one component needed to achieve the intensified productivity required for high quality agricultural products that are economically viable, socially acceptable, and adaptable. This book is intended to help: (1) identify suitable cellulosic energy crops that are adapted to a wide range of climates and soils; (2) develop best management practices for sustainably growing, harvesting, storing, transporting and pre-processing these crops with minimal negative impacts on the environment and food production; (3) develop integrated cellulosic energy cropping systems for supplying commercial processing plants; and (4) educating landowners, technology owners, students, policy makers and the general public on how to use cellulosic energy crops to maximize the many benefits they offer. It is my hope that we have successfully provided the information in a format that will enable all of us to achieve this important twenty-first century goal.

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1

Introduction to Cellulosic Energy Crops

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1.1 Cellulosic Biomass: Definition, Photosynthesis, and Composition

Plants, through photosynthesis, convert solar energy, carbon dioxide, and water into sugars and other derived organic materials, referred to as biomass, and release oxygen as a by-product. Humans have long used plant biomass for a variety of applications, such as fuel for warmth and cooking, lumber and other building materials, textiles, and papermaking. More recently, plant biomass has been considered as a feedstock for biofuels production – the focus of this book – with first-generation fuels being made from edible portions of plants, including starch, sucrose, and seed oils. Next-generation biofuels will be produced from non-edible cell wall components (described below) that comprise the majority of plant biomass.

Photosynthesis consists of two stages: a series of light-dependent reactions that are independent of temperature (light reactions) and a series of temperature-dependent reactions that are independent of light (dark reactions). The light reactions convert light energy into chemical energy in the form of adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide phosphate (NADPH). The dark reactions, in turn, use the chemical energy stored in ATP and NADPH to convert carbon dioxide and water into carbohydrate.

About half of the light energy falls outside the photosynthetically active spectrum; some of the available energy is reflected away and not captured. Further energy is lost during the light absorption process, and during carbohydrate synthesis and respiration. As a result, photosynthesis typically converts less than 1% of the available solar energy into chemical energy stored in the chemical bonds of the structural components of biomass [1].

Cellulosic Energy Cropping Systems, First Edition. Edited by Douglas L. Karlen.

Plants have evolved three photosynthetic pathways, each in response to distinct environmental conditions. One is called the C_3 pathway because the initial product of carbon fixation is a three-carbon compound (phosphoglyceric acid, or PGA). When carbon dioxide levels inside a leaf become low, especially on hot dry days, a plant is forced to close its stomata (microscopic pores on the surface of land plants) to prevent excess water loss. If the plant continues to fix carbon when its stomata are closed, carbon dioxide is depleted and oxygen accumulates in the leaf. To alleviate this situation, the plant uses a process called photorespiration in which a molecule ordinarily used in carbon fixation (ribulose-1,5-bisphosphate, or RuBP) combines instead with oxygen, catalyzed by the enzyme RuBisCO, which also figures prominently in carbon fixation. This reduces photosynthetic efficiency in two ways: firstly, it creates competition between oxygen and carbon dioxide for the active sites of RuBisCO – sites that take up oxygen are not available for carbon dioxide; secondly, the process re-releases carbon dioxide that had been fixed. Photorespiration reduces photosynthetic efficiency by 35–50%, depending upon environmental conditions, with warm, arid habitats promoting greater photorespiration [1].

In response, many plant species in warm, dry climates have evolved two alternative photosynthetic pathways – the C_4 pathway and crassulacean acid metabolism (CAM) photosynthesis, both of which significantly reduce photorespiration and enhance efficiency. Both convert carbon dioxide into a four-carbon intermediate using the enzyme phosphoenolpyruvate (PEP) carboxylase – which does not react with oxygen – rather than RuBisCO. C_4 plants fix carbon dioxide during the day; CAM plants, to keep stomata closed during the day, fix carbon dioxide at night [2].

The highest reported solar energy conversion efficiency is about 2.4% for C_3 plants and 3.7% for C_4 species [3]. CAM plants are estimated to be 15% more efficient than C_3 plants, but 10% less efficient than C_4 plants [4]. Zhu *et al.* [3] estimate the theoretical maximum efficiency to be 4.6 and 6% for C_3 and C_4 crops, respectively. The C_3 pathway is the oldest – originating around 2800 million years ago – and most widespread, both taxonomically and environmentally, accounting for about 95% of total plant species [5]. C_4 photosynthesis is found in about 1% of plant species [5] and is most prevalent in grasses, with about 50% of the species using the pathway [6]. CAM occurs in about 4% of total plant species [5].

The energy crops considered in this volume all have either a C_3 or C_4 photosynthetic pathway. They include:

- C_3 pathway: wheat straw, eucalyptus, poplar, willow, pine
- C_4 pathway: miscanthus, switchgrass, sugarcane, energy cane, sorghum, corn stover.

Though not considered here, examples of potential energy crops having the CAM pathway include agave and opuntia. More detailed treatments of photosynthesis are available elsewhere [2, 7].

Each of the above plant species contains cellulosic biomass, that is, the fibrous, generally inedible portions of plants, rich in the polysaccharide cellulose, which make up the majority of all plant material. Cellulosic biomass can generally be grouped into four categories: herbaceous plants, woody plants, aquatic plants, and residual material such corn stover, sugarcane bagasse, paper sludge, and animal manure. Terrestrial cellulosic energy crops and agricultural crop residues are the primary focus of this book.

Cellulosic biomass contains varying amounts of cellulose, hemicellulose, lignin, protein, ash, and extractives. Cellulose, a structural component of the primary cell wall in plants, generally comprises the largest fraction, with 40–50% on a dry weight basis being typical. The material is a polymer of glucose, a six-carbon sugar, joined by 1–4 beta-linkages. Linear cellulose chains, which have an average molecular weight of about 100 000, are generally arrayed in parallel and held together with extensive hydrogen bonding forming macromolecular fibers 3–6 nm in diameter called microfibrils. The material is well ordered, largely crystalline, and highly recalcitrant to rapid reaction under many conditions.

Hemicellulose, another polysaccharide – one that binds tightly, but non-covalently, to the surface of each cellulose microfibril – usually comprises 20–35% of the dry mass of biomass. In contrast to cellulose, hemicellulose is composed of multiple sugars – the identity and proportion of which depend on the type of plant – and has a heterogeneous, non-crystalline branched structure. As a result, hemicellulose is generally more reactive than cellulose and is readily hydrolyzed by dilute acid or base as well as hemicellulase enzymes. Xylose, a five-carbon sugar, is the dominant constituent of hemicellulose in plants other than softwoods; for softwoods, mannose is often the most abundant sugar.

Lignin is an amorphous polymer of phenyl–propane subunits (six-carbon rings linked to three-carbon chains) joined together by ether and carbon–carbon linkages, and covalently bound to hemicellulose. The subunits may have zero, one, or two methoxyl groups attached to the rings, giving rise to three structures – denoted I, II, and III, respectively. The proportions of each structure depend on the plant type. Structure I is commonly found in grasses, structure II in softwoods, and structure III in hardwoods. Lignin both creates a net around carbohydrate-rich microfibrils in plant cell walls and penetrates the interstitial space in the cell wall, driving out water and strengthening the wall. The dry mass fraction of lignin in plants typically ranges from 7–30%. Leafy herbaceous plants are generally at the low end of this range, woody plants at the high end, with softwoods having more lignin than hardwoods.

Smaller amounts of protein and minerals are also present in plant tissues. As plants mature, wall composition shifts from moderate levels of protein and almost no lignin to very low concentrations of protein and substantial amounts of lignin. Protein content can be significant (e.g. 10% dry mass) in early-season herbaceous crops, but is relatively low in late-season harvests and minimal in most woody crops.

Plants require a variety of inorganic minerals for proper growth, including both macronutrients (N, P, K, Ca, S, Mg) and micronutrients, or trace elements (B, Cl, Mn, Fe, Zn, Cu, Mo, Ni, Se, Na, Si). Plant roots, mediated by transport proteins, absorb mineral nutrients as ions in soil water. Each mineral participates in distinct biological functions within the plant. Nitrogen, for example, is involved in all aspects of plant metabolism, with its foremost function being to provide amino groups in amino acids, the building blocks of every protein. Potassium, meanwhile, is essential for activating a multitude of enzymes, including pyruvate kinases involved in glycolysis, and is one of the most important contributors to cell turgidity in plants. Another vital macronutrient, calcium, is essential for providing structure and rigidity to cell walls, and is used as a signaling compound in response to mechanical stimuli, pathogen attack, temperature shock, drought, and changes in nutrient status. When plant biomass is converted to fuels, chemicals, electricity, and/or heat, inorganic minerals remain as ash, with the amount residual ash being dependent upon plant species. Herbaceous plant species typically have higher levels of ash (e.g. 5–10% dry mass) than do woody species ($<$2% dry mass).

The term "extractives" is also commonly used when characterizing the composition of plant biomass. Extractives are materials in the biomass that can be dissolved in a solvent (typically water and/or ethanol), including resins, fats and fatty acids, phenolics, phytosterols, salts, minerals, soluble sugars, and other compounds.

More detailed consideration of the composition of cellulosic biomass can be found elsewhere [8, 9]. Representative compositions for many of the biomass crops considered in subsequent chapters are listed in Table 1.1.

1.2 Cellulosic Biomass Properties and Their Relevance to Downstream Processing

The choice of biomass feedstock is a critical driver in determining key performance metrics of bioenergy – including economic viability, scale of production (both at individual facilities and in aggregate), and environmental impact. For commodities such as fuels or electricity, feedstock cost typically represents two-thirds of the product cost, or more [26]; therefore, selecting a cost-effective feedstock is essential. As is discussed in Part IV of this book, the logistics of growing, harvesting, storing, and transporting biomass – unique for a given feedstock type – affects the feasible size of the processing facility, which, in turn, impacts the overall sector scale. Each feedstock also has a particular set of environmental attributes – for example, water use, wildlife habitat, soil quality, and so on – that significantly affects the environmental performance of the bioenergy system.

In assessing the suitability of a biomass feedstock for a given conversion process, several material properties are important to consider, including: (1) moisture content; (2) energy density; (3) fixed carbon/volatile matter ratio; (4) ash content; (5) alkali metal content; and (6) carbohydrate/lignin ratio. The first five properties are especially important in thermochemical processing. For biological conversion, the first and last properties are of primary concern.

1.2.1 Moisture Content

Biomass moisture content is defined as the amount of water in the biomass expressed as a percentage of the material's weight; reporting on a wet basis is most common. Moisture content at harvest for woody feedstocks is usually 40–60% (wet basis); for herbaceous crops, it typically ranges from 10 to 70% (wet basis) depending upon the species, climate, geographic location, and stage of maturation. Biomass net energy density per unit mass decreases with increasing moisture content. Transport efficiency of biomass feedstock, therefore, decreases as moisture content increases. Storage of high-moisture biomass is also less efficient, both because of reduced energy density and increased probability of biological degradation, fire risk, and mold formation. Moisture content also affects downstream processing, especially for thermochemical conversion. High-moisture feedstocks must be dried to levels of less than 50% for conventional combustion and less than 20% for gasification and pyrolysis. In biological processing for which some form of thermal pretreatment is used, moisture content can also significantly affect the energy efficiency of the process.

Table 1.1 Representative compositions, proximate analysis, ultimate analysis, and energy density for several lignocellulosic feedstocks.

		Herbaceous Crops				Crop Residues		Woody Crops			
Composition/ Property	Units	Miscanthus	Switchgrass	Energy Cane	Sorghum	Corn Stover	Wheat Straw	Eucalyptus	Poplar	Willow	Pine
Productivity	Mg/ha/yr	1–44	7–10	26.7	7.8	1.2–3.6	0.1–1.75	33	7–48	14–16	11
Moisture	% WM	4–5	13–65	73	87	15–35	5–8	59–63	53–63	44–60	49–62
Components											
Cellulose	% DM	40–60	31–35	43	45	31–38	32.6	47–50	39–43	44.1	42
Hemicellulose	% DM	20–40	24–28	24	27	19–25	22.6	13–14	17–19	21.8	21
Lignin	% DM	10–30	17–22	22	21	17–21	16.9	27–28	24–28	20.4	26
Extractives	% DM	0.3–2.2	5–17	nr	nr	3–12	13.0	0.6–4.2	1.3–2.4	5.4	3
Ash	% DM	2.2–3.5	5–6	0.8	0.4	10–14	10.2	0.6–1.2	2–7	2.1	0.3
Juice	% WM	na	na	54	72	na	na	na	na	na	na
Juice Sugars	% juice	na	na	10	12	na	na	na	na	na	na
Proximate Analysis											
Volatile Matter	% DM	72.6–78.2	72.6–77.9	78.6–81.1	78.3	70.2–74.8	69.4	79.5–82.5	78.2–80.1	87.6	80.5
Fixed Carbon	% DM	15.1–20.4	17.0–22.1	17.0–18.8	18.0	20.0–22.6	21.5	17.2–19.0	18.3–19.9	10.7	19.4
Ultimate Analysis											
C	% DM	47.1–49.7	46.6–48.5	48.2–49.0	47.5	44.8–48.0	43.9	49.5–49.9	49.4–51.7	49.9	50.3
H	% DM	5.4–5.9	5.3–5.7	5.5–6.0	6.7	5.4–6.1	5.3	5.7–6.3	4.5–6.4	6.5	6.0
O	% DM	41.4–44.6	38.2–42.1	39.2–41.6	41.1	37.0–41.4	38.8	42.0–43.5	35.1–42.4	39.9	42.1
N	% DM	0.1–1.0	0.4–0.7	0.2	0.9	0.6–0.7	0.6	0.1–0.5	0.2–0.5	0.2	0.0
S	% DM	0.07–0.19	0.07–0.11	0.02–0.03	0.09	0.06–0.1	0.2	0.01–0.04	0.02–0.03	nr	0.0
Energy Density											
LHV	MJ/kg	17–20	18–19	19.0	19.1	18–19	17.4	20	20	19.3	20.0
Sources:		[10]	[11, 12]	[11, 13]	[13, 14]	[11, 15, 16]	[11, 17, 18]	[11, 19–21]	[11, 22]	[19, 23, 24]	[11, 19, 21, 25]

WM = wet mass; DM = dry mass; na = not applicable; nr = not reported.

1.2.2 Energy Density

Energy density, often termed "heating value", refers to the amount of energy released per unit fuel combusted, usually measured in terms of energy content per unit mass for solids (e.g. MJ/kg) and per unit volume for liquids (e.g. MJ/l). Energy density can be expressed in two forms, higher heating value (HHV) or lower heating value (LHV). HHV represents the total energy released when the fuel is combusted in air, including the latent heat contained in the resulting water vapor product – the maximum potentially recoverable energy from a given feedstock. The latent heat contained in the water vapor, however, typically cannot be used effectively. LHV, therefore, is the appropriate value to use when quantifying the energy available for subsequent use. As noted above, moisture content significantly affects biomass feedstock energy density. Freshly cut wood, for example, might have as much as 60% moisture and a relatively low energy content (e.g., 6 MJ/kg). In contrast, oven-dried wood with little moisture might have up to 18 MJ/kg. Representative LHV values for many of the biomass crops considered in subsequent chapters are listed in Table 1.1.

1.2.3 Fixed Carbon/Volatile Matter Ratio

Fuel analysis that quantifies the amount of chemical energy stored as volatile matter (VM) and fixed carbon (FC) has been developed for solid fuels such as coal. The VM of a solid fuel is the portion released as gas (including moisture) by heating to 950°C in the absence of air for seven minutes; the FC is the mass remaining after the volatiles have been driven off, excluding the ash and moisture contents. Fuel analysis based upon VM content, ash, and moisture, with the FC determined by difference, is termed the proximate analysis of a fuel. Elemental analysis of a fuel, presented as C, N, H, O and S, together with the ash content, is termed the ultimate analysis of a fuel. The ratio of FC to VM provides an indication of the ease with which the solid fuel can be ignited and subsequently gasified, or oxidized, depending on how the fuel is to be converted. Representative proximate and ultimate analyses for many of the biomass crops considered in subsequent chapters are listed in Table 1.1.

1.2.4 Ash Content

Conversion of biomass feedstock, either thermochemically or biochemically, results in a solid residue. In themochemical processing via combustion in air, the residue consists solely of ash. For biochemical processing, it contains both ash and other unconverted material, especially lignin. The bioprocess residue can be further processed thermochemically to yield ash as the final solid residue. The ash content negatively affects the energy density of the feedstock. Ash can also pose operational problems in thermochemical processing, such as slagging in which the ash melts and fuses together. Relatively low-cost control measures, such as leaching the raw feedstock with water and using different mineral additives (e.g. kaolinite, clinochlore, ankerite), can be used to reduce negative effects [27]. Potential end uses of ash include mineral agricultural fertilizer [28] and construction material additive [29]. Representative ash content values for many of the biomass crops considered in subsequent chapters are listed in Table 1.1. As can be seen from the table, herbaceous feedstocks tend to have higher ash contents (e.g. $\geq$5%) than woody feedstocks (e.g. $<$2%).

1.2.5 Alkali Metal Content

During thermochemical conversion, alkali metals (Na, K, Mg, P, Ca) present in the ash react with silica – originating both from the biomass itself and from soil introduced during harvesting – to produce a sticky, mobile liquid phase that can contribute to slagging, deposition, and corrosion of process equipment. As noted above, water leaching and fuel additives can be used to reduce the damaging effects of ash components, including alkali metals.

1.2.6 Carbohydrate/Lignin Ratio

In biological processing, carbohydrate present in cellulose (and potentially hemicellulose) is converted to fuels and/or chemicals, while the lignin fraction remains unaffected. Furthermore, the recalcitrance of cellulosic biomass to bioconversion typically increases with increasing lignin content, requiring more severe pretreatment, which decreases process efficiency. Bioconversion processes, therefore, favor feedstocks with high carbohydrate to lignin ratios. Representative cellulose, hemicellulose, and lignin values for many of the biomass crops considered in subsequent chapters are listed in Table 1.1.

1.3 Desirable Traits and Potential Supply of Cellulosic Energy Crops

Given the world's finite land resource, the most important trait for cellulosic energy crops is productivity – the annual dry matter produced per unit land area. As listed in Table 1.1, productivity of the crops considered in this book ranges from 0.1 to 1.75 Mg/ha/yr (dry basis) for wheat straw, to as high as 44 Mg/ha/yr (dry basis) for miscanthus. The best energy crops will also have few inputs and low production costs. Easily established, robust perennial crops having long life spans (e.g. $\geq$10 years) are favored over annual crops, as are those having low fertilizer, pesticide, and insecticide requirements. Native, non-invasive species that provide good habitats for wildlife are preferred.

Feedstocks used in thermochemical processing should be harvested when moisture content is relatively low to minimize preliminary energy intensive drying. Low moisture is not as critical in bioconversion feedstocks, for which wet storage can sometimes be a viable option. Ideally, ash content should be low (e.g. $<$1%), ash melting temperatures should be high (e.g. >1500°C), with low levels of particularly damaging elements, including alkali metals, alkaline earth metals, silicon, chlorine, and sulfur.

Conventional plant breeding – which involves manipulating the genes of a species via selection and hybridization so that desired genes are packaged together in the same plant and as many detrimental genes as possible are excluded – has traditionally been used to enhance desired agronomic traits such as productivity, water use efficiency, and crop lifespan. Breeding systems have been developed, and continue to be developed, that can be used to improve virtually all plant species. The productivity of corn, for example, has more than quadrupled since the 1930s largely through conventional breeding [30]. Biomass productivity can potentially be increased even further using more sophisticated biotechnology techniques. Recent molecular and genetic studies have identified a number of regulators of plant biomass production – for example, vegetative meristem activities, cell elongation, photosynthetic efficiency, and secondary wall biosynthesis – that might be manipulated to enhance energy crop yields [31].

The potential to produce viable energy feedstocks is vast. A detailed study led by the Oak Ridge National Laboratory estimates that the United States could produce 602–1009 million dry tons annually by 2022, and 767–1305 million annual dry tons by 2030, at a price of $60 per dry ton [32]. (The low value in the range assumes a 1% annual increase in yield; the high value, a 4% annual increase.) This excludes resources that are currently being used, such as corn grain and forest products industry residues. When currently used resources are included, the total biomass estimate jumps to over one billion dry tons per year for the lower productivity case – enough to displace about half of the country's current gasoline consumption (134 billion gallons/year) if converted to ethanol at a yield of 100 gallons/dry ton. Estimates for the global annual supply of biomass feedstocks range from 100 to 400 EJ/year – equivalent to 6 to 24 billion dry tons. If converted to ethanol, this represents 120–460% of current global gasoline consumption (338 billion gallons/year).

1.4 The Case for Cellulosic Energy Crops

With ever-increasing indications that resource use is exceeding the planet's biocapacity [33] – largely driven by non-renewable fossil fuel consumption – it is clear that humankind must shift to sustainable practices in order for a peaceful, equitable, and thriving future to be possible. Furthermore, given mounting evidence of climate change – to the point that some say we are now living in a new geologic epoch, the Anthropocene [34] – this transformation must begin now and be completed within decades, not centuries. Indeed, it is fair to characterize this transition, moving from finite resource capital to renewable resource income, as the defining challenge of our time.

Most sustainable paths from primary resources to human needs pass through either plant biomass or renewable electricity, with biomass being the only foreseeable source of organic fuels, chemicals, and materials, as well as food. In comparison, other large-scale sustainable energy sources are most readily converted to electricity and heat. Because liquid organic fuels have a greater energy density than batteries, both today and with anticipated improvements in battery technology, it is reasonable to expect that organic fuels will meet a significant fraction of transportation energy demand for the indefinite future. This is particularly true for long-distance travel via personal vehicles and for heavy-duty applications, such as aviation and long-haul trucking, which account for more than half of global transportation energy [35]. Biofuels would, therefore, appear to be an essential component of tomorrow's sustainable world rather than a discretionary option.

Cellulosic biomass energy potentially offers many environmental benefits that contribute to its sustainability, some of which are:

- Fossil fuel displacement.
- Lower emissions of greenhouse gases and other air pollutants.
- Enhanced soil quality.
- Reduced soil erosion.
- Reduced nutrient run-off.
- Enhanced biodiversity.

Demirbas [36], Rowe *et al.* [37], Arjum [38], and Skinner *et al.* [39] provide more detailed reviews and discussion of these and other potential benefits.

In addition to the environment, cellulosic biomass energy also has the potential to enhance energy security and rural economic development. Nations dependent upon petroleum face increasing security costs to ensure the steady supply of oil. The United States, for example, according to the RAND Corporation [40], spends about $75.5–93 billion per year – representing between 12 and 15% of its current defense budget – to secure the supply and transit of oil. Furthermore, major oil supplying countries hold leverage over nations relying upon imports, as the oil producers control price stability. This directly affects foreign policy, forcing import nations to prioritize stability over values such as democracy, transparency, and human rights. Even if a country could produce 100% of the oil it uses, its consumers would still be vulnerable to global price fluctuations based on supply disruptions in unstable regions. Beyond consumerism, modern militaries invest for the long term – new airplanes, ships, and vehicles are expected to last decades. This requires alternative energy sources to be able to accommodate infrastructure that is likely to be in place for years.

In recognition of this, the United States Department of Defense has developed an alternative fuels policy to "ensure operational military readiness, improve battle space effectiveness," and increase "the ability to use multiple, reliable fuel sources [41]." Consistent with this, the US Navy has plans to deploy a "Great Green Fleet" strike group of ships and aircraft running entirely on alternative fuel blends – including cellulosic fuels – by 2016 [42]. It also has a goal of meeting 50% of its total energy consumption from alternative sources by 2020. To help enable these goals, the Navy – together with the Departments of Energy and Agriculture – signed a Memorandum of Understanding (MOU) to "assist the development and support of a sustainable commercial biofuels industry [43]." The MOU calls for $510 million in funding over three years to develop advanced biofuels that meet military specifications, are price competitively with petroleum, are at geographically diverse locations with ready market access, and have no significant impact on the food supply.

A cellulosic biofuels industry, by generating demand for agricultural products, has the potential to significantly increase employment in rural areas in sectors ranging from farming to feedstock transportation to plant construction and operation. Workers would be required in a variety of occupations, including: scientists and engineers conducting research and development; construction workers building plants and maintaining infrastructure; agricultural workers growing and harvesting energy crops; plant workers processing feedstocks into fuel; and sales workers selling the biofuels. Brazil's sugar/ethanol industry directly employs about 489 000 workers, with an additional 511 000 workers engaged in supporting agricultural activities [44]; the United States corn ethanol industry directly employs about 400 000 [45]. A study forecasting the impact of advanced biofuels on the US economy estimates that the industry could create over 800 000 jobs by 2022 [46].

Cellulosic biofuels also have the potential to promote rural economic activity within developing nations and improve the lives of the world's poor. Farmers would have increased demand for their products, including crop residues from existing crops, and employ additional workers to produce the energy feedstocks. They would also be able to make use of degraded or marginal land not suitable for food production. Care must be taken, however, to include small landholders in the sector's development and to adequately invest in local workforce training for feedstock production, production facilities construction, and process operation. In addition, to the extent possible, the sector should be developed around existing industries, such as sugarcane processing, to lower investment barriers [47]. Also, selection of feedstock supply chains that do not compromise food security is critical. Significant potential exists to actually enhance food security through bioenergy production – by using inedible crops grown on marginal land, for example, or integrating production of food, animal feed, and bioenergy. One can envision many benefits that might be realized: employment and development of marketable skills; introduction of agricultural infrastructure and knowledge; energy democratization, self-sufficiency, and availability for agricultural processing; and an economically rewarding way to restore degraded land. Bioenergy could potentially improve both food security and economic security for the rural poor [48].

Such benefits, however, are by no means guaranteed. The environmental impact of biomass energy very much depends upon how the given system is designed and implemented. Detractors of bioenergy have called into question its sustainability, citing a number of concerns, including:

- Food versus fuel.
- Land use change (direct and indirect).
- Water use.
- Invasive species.
- Biodiversity.

This productive debate has prompted an expanding literature analyzing and discussing the keys to "getting biofuels right," so that the promise of sustainable bioenergy can be realized [49–51]. To minimize both competition with food production and land use change effects, multiple classes of feedstocks are available, including energy crops grown on abandoned agricultural lands; food crop residues such as corn stover and wheat straw; sustainably harvested forest residues; double crops grown between the summer growing seasons of conventional row crops; mixed cropping systems in which food and energy crops are grown simultaneously; municipal and industrial wastes; and harvesting invasive species for bioenergy [49, 50, 52–54]. Water use can be minimized by selecting crops having low irrigation requirements, by using non-potable sources such as wastewater or high-saline water for any necessary irrigation [55, 56], and using subsurface drip irrigation to minimize evaporative losses [57]. The potential for non-native energy crops becoming invasive can be limited by proper preliminary risk assessment, including test plots [58], regular monitoring and stewardship programs [59], and by using sterile plant varieties [60]. The impact of a given energy crop upon biodiversity depends strongly on specific regional circumstances, the type of land and land use shifts involved, and the associated management practices [61]. Herbaceous perennial crops, in particular, appear to be capable of providing suitable habitats for a variety of species, especially with careful attention to crop placement and when mixed cultures are used [62–65]. By incorporating many of the above strategies, Dale *et al.* [51] calculated that, using the 114 million hectares of cropland currently allocated in the United States for animal feed, corn ethanol, and exports, 400 billion liters of cellulosic ethanol (80% of current gasoline demand) could be made – all while producing the same amount of food. In summarizing their findings, the authors write:

> Our analysis shows that the U.S. can produce very large amounts of biofuels, maintain domestic food supplies, continue our contribution to international food supplies, increase soil fertility, and significantly reduce GHGs. If so, then integrating biofuel production with animal feed

> production may also be a pathway available to many other countries. Resolving the apparent "food versus fuel" conflict seems to be more a matter of making the right choices rather than hard resource and technical constraints. If we so choose, we can quite readily adapt our agricultural system to produce food, animal feed, and sustainable biofuels.

Any human activity involving new technology can potentially be harmful if not thoughtfully planned and appropriately conducted. The early-generation Altamont Pass wind farm in California, for example, unwittingly located on a major bird migratory route, results in thousands of bird deaths every year [66]. To remedy the problem, the farm's owners are installing new, less destructive turbines and shutting down a significant fraction of the turbines during the migration season [67]. In the case of cellulosic biomass, if care is taken to address the key concerns noted above, the resource could very likely contribute substantially – indeed, uniquely and essentially, by accommodating energy services not easily met by other means – towards achieving a sustainable global energy future. Kline *et al.* [50] succinctly capture the promise of this vision:

> When biofuel crops are grown in appropriate places and under sustainable conditions, they offer a host of benefits: reduced fossil fuel use; diversified fuel supplies; increased employment; decreased greenhouse gas emissions; enhanced habitat for wildlife; improved soil and water quality; and more stable global land use, thereby reducing pressure to clear new land.

This book – through detailed consideration of cellulosic energy crop production; the logistics of feedstock harvest, storage, and transport; and commercial deployment that is mindful of economic, environmental, and social concerns – seeks to disseminate knowledge that can help make large-scale, sustainable bioenergy a reality.

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2

Conversion Technologies for the Production of Liquid Fuels and Biochemicals

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2.1 Introduction

Until the last century, plant-based resources were largely focused towards food, feed, and fiber production. In addition, biomass has been a major source of energy for mankind worldwide. However, plant/crop-based renewable resources are also a viable alternative to the current dependence on non-renewable, diminishing fossil fuels, to alleviate greenhouse gas (GHG) emissions, and a strategic option to meet the growing need for industrial building blocks and bioenergy. Indeed, biomass seems a very promising resource for substituting fossil hydrocarbons as a renewable source of energy and as a sustainable raw material for various industrial sectors. Over the past decades, the use of biomass has increased rapidly in many parts of the world, mainly to meet the often ambitious targets for energy supply.

Developing biomass into a sustainable, domestic source of affordable biochemicals and biofuels requires the flexibility to use a wide variety of, preferably, non-food biomass resources. Lignocellulosic biomass such as agricultural and forestry residues and herbaceous energy crops can serve as low-cost renewable feedstock for many, next-generation, bio-derived products. However, the use of biomass as feedstock for the production of materials, products or energy requires new technologies well adapted to the physical characteristics of the biomass. The use of plant/crop resources for energy, or as basic building

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blocks for industrial production, has been limited because of a poor fit with the hydrocarbon processing system that has been successfully developed to utilize fossil fuels [1]. Although biomass is a nearly universal feedstock, characterized by a high versatility, domestic availability, and renewability, at the same time it has also its limitations. Over the years, numerous research and development efforts have been undertaken to develop and apply new cost-efficient conversion processes for lignocellulosic biomass. This chapter gives an overview of the conversion technologies for liquid fuels and biochemicals.

2.2 Biomass Conversion Technologies

Generally, two main routes for the conversion of lignocellulosic biomass can be distinguished, which can lead to the production of biofuels and other value-added commodity chemicals (Figure 2.1):

The (Bio)Chemical Route: Biochemical conversion makes use of the enzymes of bacteria or other microorganisms to break down and convert the biomass. In most cases the microorganisms themselves are used to perform the conversion processes, such as fermentation, anaerobic digestion or composting. Sometimes, only the isolated enzymes are used, also known as biocatalysis. Plant monomers can also be further converted chemically.

The Thermochemical Route: Thermochemical conversion includes processes in which heat and pressure are the dominant mechanisms to convert the biomass into another chemical form.

The bioconversion of lignocellulosic residues to biofuels and biochemicals is more complicated than the bioconversion of sugar or starch-based feedstock. Plant cell walls are naturally resistant to microbial and enzymatic (fungal and bacterial) deconstruction. This recalcitrant nature of the lignocellulosic feedstock (resistance of plant cell walls to deconstruction) therefore poses a significant hurdle in the biochemical route and necessitates

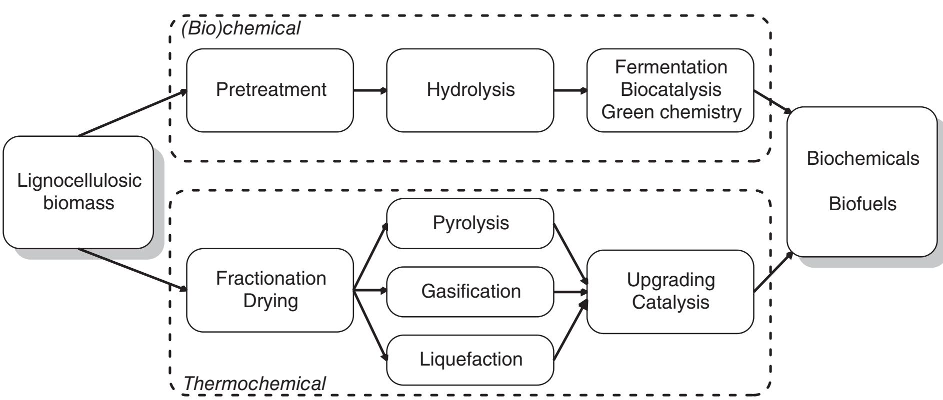

Figure 2.1 *Schematic representation of the two routes for the conversion of lignocellulosic biomass.*

extra pretreatment steps before this lignocellulosic biomass can serve as low-cost feedstock for the production of fuel ethanol and other value-added commodity chemicals. Plant cell walls are comprised of long chains (polymers) of sugars (carbohydrates such as cellulose and hemicellulose), which can be converted into common monomer sugars such as glucose, xylose, and so on, the ideal substrates for chemical, physical, and fermentation processes [2]. However, these polymers are bound together by lignin, which has to be degraded first before the sugar polymers become accessible to hydrolysis by chemical or biological means. Lignin is a complex structure containing aromatic groups linked in a three-dimensional structure that is particularly difficult to biodegrade [3]. Lignins perform an important role in strengthening cell walls by cross-linking polysaccharides, thus providing support to structural elements in the overall plant body. This also helps the plant to resist moisture and biological attack [4]. These same properties, however, constitute one of the drawbacks of using lignocellulosic material in fermentation, as they make lignocellulose resistant to physical, chemical, and biological degradation. The higher the proportion of lignin, the higher the resistance to chemical and enzymatic degradation [5]. Overcoming the recalcitrance of lignocellulosic biomass is a key step in the biochemical production of fuels and chemicals; it is the main goal of the pretreatment.

In the thermochemical conversion route, the recalcitrant nature of the lignocellulosic biomass poses no problems to the technology. However, other limitations of the biomass need to be taken into account in this case: the energy density of biomass is low compared to that of coal, liquid petroleum or petroleum-derived fuels. And most biomass, as received, has a high burden of physically adsorbed moisture, up to 50% by weight [6].

2.3 (Bio)Chemical Conversion Route

Biochemical conversion comprises breaking down or "cracking" biomass by using physical, chemical, enzymatic and/or microbial action, to make the polymeric carbohydrates of the biomass (hemicellulose and cellulose) available as (fermentable) sugars, which can then be converted into biofuels and bioproducts using microorganisms (bacteria, yeast, fungi, etc.) and their enzymes or chemically converted using specific catalysts. A general overview of the different process steps of the biochemical conversion of lignocellulosic biomass is given in Figure 2.2.

Firstly, a reduction in particle size is often needed to make material handling easier and to increase surface/volume ratio, so as to enable better accessibility of the processed material in the next pretreatment step. Size reduction is most often done by a mechanical process such as crushing, milling, chipping, grinding or pulverizing to the required particle size.

2.3.1 Pretreatment

The following step is the pretreatment of the fractionated material. The main goal of pretreatment is to overcome this lignocellulosic recalcitrance, to separate the cellulose from the matrix polymers, and to make it more accessible for enzymatic hydrolysis. Reports have shown that pretreatment can improve sugar yields to greater than 90% theoretical yield for biomass such as wood, grasses, and corn [8, 9]. Pretreatment technologies for lignocellulosic biomass include thermal, (thermo)chemical, physical and biological methods or various combinations thereof [5, 9].

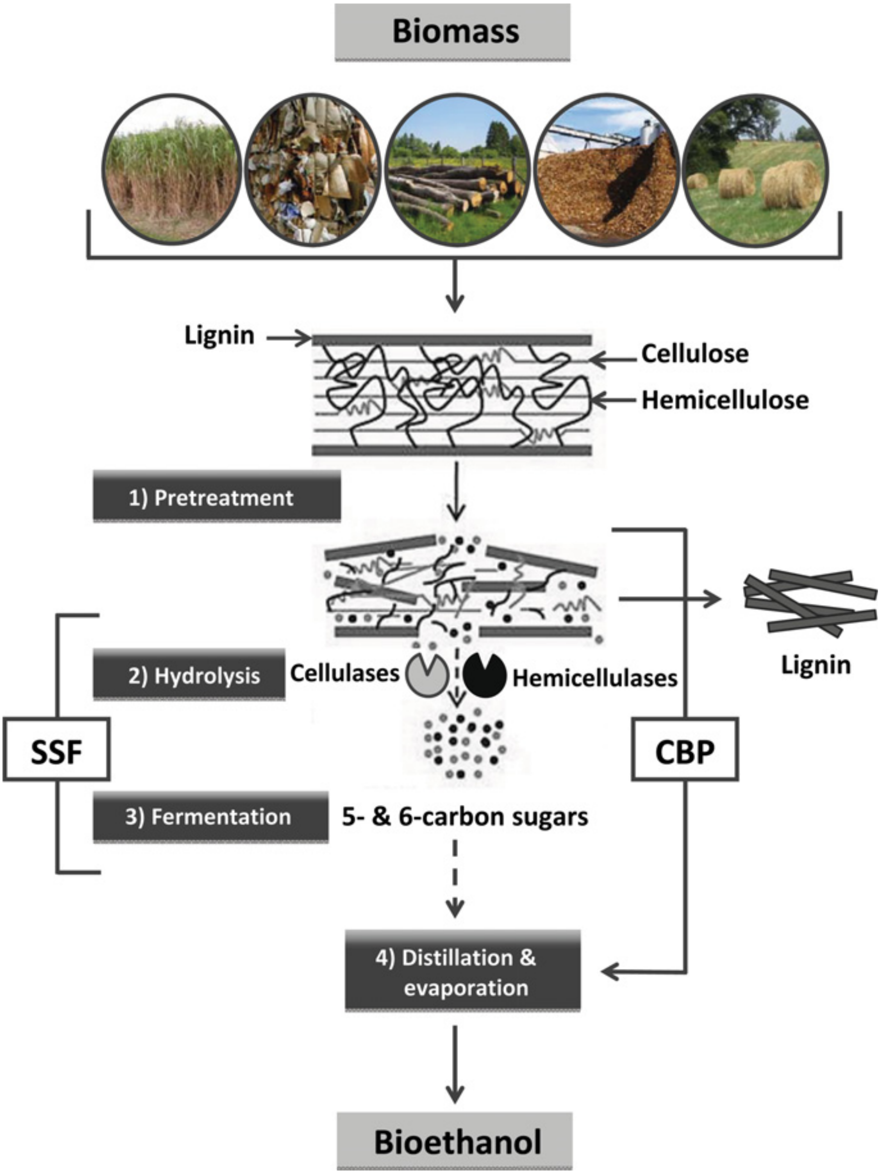

Figure 2.2 *Schematic picture for the conversion of lignocellulosic biomass into bioethanol highlighting the major steps. Hydrolysis and fermentation can be performed separately (SHF, indicated by broken arrows) or as simultaneous saccharification and fermentation (SSF). In consolidated bioprocessing (CBP), however, all bioconversion steps are minimized to one step in a single reactor using one or more microorganisms. (Reproduced from Dashtban, M., Schraft, H. and Qin, W. Fungal Bioconversion of Lignocellulosic Residues; Opportunities & Perspectives.* Int J Biol Sci *2009;* ***5****(6):578–595. doi:10.7150/ijbs.5.578 © 2009, Ivyspring International Publisher [7]).*

In general, pretreatment processes produce a solid pretreated biomass residue that is more amenable to enzymatic hydrolysis by cellulases and related enzymes than native biomass. Many pretreatment approaches, such as dilute acid and steam/pressurized hot water based methods, seek to achieve this by hydrolyzing a significant amount of the hemicellulose fraction of biomass and recovering the resulting soluble monomeric and/or oligomeric sugars. Other pretreatment processes, such as alkaline-based methods, are generally more effective at solubilizing a greater fraction of lignin while leaving behind much of the hemicellulose in an insoluble, polymeric form [10]. Most pretreatment approaches do not hydrolyze significant amounts of the cellulose fraction of biomass but enable more efficient enzymatic hydrolysis of the cellulose by removal of the surrounding hemicellulose and/or lignin along with modification of the cellulose microfibril structure [11]. Biological pretreatment uses microorganisms and their enzymes selectively for delignification of lignocellulosic residues and has the advantages of a low energy demand, minimal waste production and a lack of environmental effects [7, 12, 13]. It has been suggested that there will probably not be a general pretreatment procedure and that different raw materials will require different pretreatments [10]. Table 2.1 gives an overview of the different pretreatment technologies.

The choice of the optimum pretreatment process depends very much on the objective of the biomass pretreatment, its economic assessment and environmental impact. Technological factors, such as energy balance, solvent recycling and corrosion, as well as environmental factors, such as wastewater treatment, should all be considered carefully when selecting a method [5]. Diverse advantages have been reported for most of the pretreatment methods, which make them interesting for industrial applications. Only a small number of pretreatment methods has been reported as being potentially cost effective thus far. These include steam explosion, liquid hot water, dilute acid pretreatments, lime, and ammonia pretreatments [11, 16, 18, 19]. The complete depolymerization of these renewable feedstock in a cost-effective manner with minimal formation of degradation products represents a significant challenge for microbiologists and chemical engineers. Obstacles in the existing pretreatment processes include insufficient separation of cellulose and lignin (which reduces the effectiveness of subsequent enzymatic cellulose hydrolysis), formation of by-products that inhibit microbial growth and fermentation (e.g. acetic acid from hemicellulose, furans from sugars and phenolic compounds from the lignin fraction [20]), high use of chemicals and/or energy, and considerable waste production. Research is focused on converting biomass into its constituents in a market competitive and environmentally sustainable way [21].

2.3.2 Hydrolysis

Hydrolysis is the process by which water splits a larger molecule into two smaller molecules. In the case of the hydrolysis of polysaccharides to soluble sugars this is called “saccharification”. The goal of this process is the de-polymerization of cellulose and hemicelluloses into soluble monomer sugars (hexoses and pentoses). This can be accomplished by two different processes: (1) acid hydrolysis with a variety of low acid–high temperature or high acid–low temperature conditions being suitable to both the breakdown of the structure of the biomass and the release of free sugars, and (2) enzymatic hydrolysis after some sort of pretreatment which allows enzymatic attack of the polymers [22, 23]. The C_6 dominated cellulose

Table 2.1 *Overview pretreatment methods [9, 14–17].*

Method	Technologies	Advantages	Disadvantages
Biological	Microbial Fungal	• Good cellulose and lignin degradation • Low energy requirements • No chemicals required	• Not very efficient • Requires long treatment times
Physical	Freeze/thaw Cycles Radiation Mechanical Sheering	• No chemical or water inputs • No toxic residuals	• High energy input • Limited effectiveness • Expensive
Thermal	Steam Explosion Liquid Hot Water Wet Oxidation	• Hydrolyzes significant fraction of hemicellulose • Prevents lignin re-precipitation • Relatively well understood	• High energy input • Often requires additional processing or the addition of a catalyst for maximum yield
(Thermo-) Chemical	***Acid Catalyzed*** Nitric acid Sulfur Dioxide Sulfuric acid Hydrochloric acid Phosphoric acid	• Hydrolyzes significant fraction of hemicellulose • Can reduce cost	• Corrosion problems • Some undesirable glucose degradation • By-products can inhibit fermentation • (disadvantage less for diluted acids)
	Base Catalyzed Ammonia (AFEX, ARP, SAA[a]) Lime ($Ca(OH)_2$) Lye (NaOH, KOH)	• More effective at solubilizing a greater fraction of lignin • Can reduce cellulase requirement • Minimal formation of fermentation inhibitors	• Not efficient when high lignin content • Environmental/safety issues (except for lime) • Leaves much of the hemicellulose in an insoluble polymeric form
	Solvent-Based Organosolv *(Numerous organic or aqueous solvent mixtures incl. methanol, ethanol, acetone, ethylene glycol and tetrahydrofurfuryl alcohol)* Ionic Liquids	• Very selective pretreatment method yielding the 3 separate fractions • Very effective for high-lignin lignocellulose materials • Recovery of relatively pure lignin as a by-product • Environmental friendly • Minimal formation of degradation products	• Significantly more expensive • High energy input • Solvents need to be drained and recycled • Expensive • Significant negative effects on cellulase activity possible • Further research needed
	Other CO_2 Explosion	• Low environmental impact • Increases accessible surface area • Cost effective • No generation of toxic compounds	• High cost of equipment • Lignin and hemicelluloses not affected • Very high pressure requirements • Hydrolytic yield increases proportionately with the moisture content of the unprocessed feedstock

[a]AFEX: Ammonia Fiber Expansion; ARP: Ammonia Recycled Percolation; SAA: Soaking Aqueous Ammonia.

can be enzymatically hydrolyzed by cellulases; for the C_5 dominated hemicellulose the hemicellulases (such as xylanase) can be used.

Acid (sulfuric or hydrochloric) can serve both for disruption and hydrolysis of the cellulosic polymers and is currently seen as the most technologically mature method of sugar release from biomass. A major disadvantage of acid hydrolysis is the potential degradation of the released monosaccharides that leads to reduced sugar yields [13, 23]. Other drawbacks are the cost of acid, the requirement to neutralize the acid after treatment and the production of inhibitory by-products such as furfural and hydroxymetyl furfural [22, 24, 25].

Enzymatic degradation of lignocellulosic biomass on the other hand is very specific and side reactions, such as degeneration of sugars, do not occur. High yields are therefore possible. In addition, the mild conversion conditions lower the maintenance costs of the production plant [23]. High temperature and low pH tolerant enzymes are preferred for the hydrolysis due to the fact that most current pretreatment strategies rely on acid and heat [26]. In addition, thermostable enzymes have several advantages, including higher specific activity and higher stability, which improve the overall hydrolytic performance [27]. Ultimately, improvement in catalytic efficiencies of enzymes will reduce the cost of hydrolysis by enabling lower enzyme dosages [7].

Although acid hydrolysis methods have long industrial histories and are, therefore, more mature, enzymatic hydrolysis is seen as the most economically promising method for reducing costs while improving yields and a key to cost-effective production of monosaccharides [28]. Research is focusing on advanced screening processes of natural enzymes and developed man-made enzymes to increase the efficiency and improve enzymatic hydrolysis [29].

2.3.3 Fermentation

The released sugars can now be converted into a broad spectrum of biochemicals and biofuels through fermentation. An enormous variety of microorganisms, such as yeasts, bacteria, or fungi, exist that can be added to the mixture of free sugars to be fermented into advanced biochemicals, including biofuels. Although organisms exist to break down virtually any organic material, six-carbon sugars, and especially glucose, are widely available in the plant and animal world. Hence, there is more experience fermenting six-carbon sugars (as present in cellulose) than the five-carbon sugars (as present in hemicellulose), but both are valuable fermentation feedstock, especially with recent advances in fermenting five-carbon sugars. Cost-effective processes will require the rapid, complete and simultaneous fermentation of all sugars. Therefore, new developments are focusing on optimizing the biochemical conversion pathway by integrating several processing steps. In the Simultaneous Saccharification and Fermentation process (SSF), cellulose hydrolysis and C_6 fermentation are performed in one step. In the Simultaneous Saccharification and Cocurrent Fermentation process (SSCF), cellulose hydrolysis and the fermentation of both C_5 and C_6 sugars is performed. The ultimate step is the Consolidated BioProcessing (CBP), combining C_5 and C_6 hydrolysis and fermentation in one single process step (Figure 2.2).

Challenges faced are the inhibition of the yeast by the end-product, so lowering the yield, high distillation cost, formation of un-productive by-products such as acetates or furfural that cause inhibition of the fermentation process. In addition, hydrolysates of lignocellulose contain compounds that are inhibitory to most microorganisms. Tolerance to harsh environments, including elevated temperatures, high salt, and low pH, will be essential. Currently available strains are severely limited in pentose utilization and exhibit poor hydrolysate tolerance. New genetically modified microorganisms are being developed, designed in such a way that they are able to ferment different sugars, get round inhibition or tolerate harsh environments, as such leading to a higher overall yield [30].

2.3.4 Biocatalysis

Alternatively, the transformation of organic compounds into all kind of industrial products can also be performed by biocatalysis. Biocatalysis can be defined as the use of biological systems (including whole cells or isolated components thereof, natural and modified enzymes and catalytic antibodies) to perform chemical transformations on organic compounds [31–33]. Millions of years of evolution have created thousands of microorganisms containing enzymes known to catalyze almost every chemical reaction. Biocatalysis is increasingly used in the chemical industry and has developed into a main contributor for sustainable chemistry. Biocatalytic reactions are typically performed at normal temperatures and pressures, whereby no dangerous intermediate products are needed, nor are dangerous waste products generated. Biocatalysts, substrates, intermediates, by-products and the product itself are biodegradable. Water is usually used as a solvent. The use of enzymes as biocatalysts can have significant performance benefits compared to conventional chemical technology; for example, a high reaction selectivity, higher reaction rate, increased conversion efficiency, improved product purity, lowered energy consumption and a significant decrease in chemical waste generation. There are also frequent disadvantages, however, including difficult enzyme recovery, low product concentration, low productivity due to substrate and/or product inhibition and, hence, high recovery costs [34]. An important route to improving the performance of enzymes in non-natural environments and their ability to work in continuous processes is to immobilize them by either adsorption, covalent attachment or by incorporation in hydrophobic organic–inorganic hybrid materials [35–38].

As they are typically very selective (contrary to most conventional chemical catalysts), enzymes are particularly useful to produce, for example, chiral molecules or enantiomerically pure compounds [39]. Biocatalysts can be used to initiate major chemical reactions, such as the direct polymerization of phenols, the direct oxidation of propylene, or highly selective transformations with polyfunctional substrates, such as sugars [34]. A wide variety of chemical substances are already industrially produced through the use of enzymes [40]. Numerous syntheses are conducted exclusively using enzymes (lipases, amylases, proteases, and, also, increasingly, cellulases [34]). As now all the molecular and biological tools to make enzymes more stable and even to discover more stable enzymes are available, more bulk chemical products from enzymatic processes can be expected in the coming years [41].

2.3.5 Catalysis

The transformation of organic compounds into all kind of industrial products can also be done using chemical catalysts. Chemical catalysis uses an added – but not consumed – substance to augment a chemical reaction. Catalytic conversion will be a primary tool for industry to produce valuable fuels, chemicals, and materials from biomass platform chemicals.

Catalytic conversion of biomass is best developed for producing synthesis gas, or syngas. In addition, research is being performed on the use of chemocatalysis for the production of biofuels out of lignocellulosic biomass. Heterogeneous catalysis offers potential to selectively convert lignocellulosic biomass into various useful chemicals; this methodology has progressed rapidly in the last several years [42]. Promising technologies are 'Aqueous Phase Reforming' for the production of liquid alkanes or hydrogen from biomass-derived sugars, as developed by Virent Energy Systems (www.virent.com). Different approaches and strategies are also available for catalytic lignin valorization. Generally, lignin reduction catalytic systems produce bulk chemicals with reduced functionality, whereas lignin oxidation catalytic systems produce fine chemicals with increased functionality [43]. Chemical catalysis further offers a large variety of possibilities to upgrade sugars: sugars can be hydrogenated to C_5–C_6 polyols (or sugar alcohols) such as xylitol, mannitol and sorbitol, hydrogenolysed to C_2–C_3 glycols, or further upgraded via oxidation or halogenation reactions [44–46]. Catalysts are also involved in liquefaction, fast pyrolysis and gasification to convert lignocellulosic biomass into value-added fine chemicals and biohydrocarbon fuels [47].

2.4 Thermochemical Conversion Route

Alternatively, biomass can be converted into fuels and chemicals indirectly (by gasification to syngas followed by catalytic conversion to liquid fuels or basic chemicals) or directly to a liquid product by thermochemical means such as pyrolysis or liquefaction. Thermochemical conversion processes use heat and pressure to convert biomass into liquid, bio-oil or gaseous intermediates. These intermediates, such as syngas and bio-oil, subsequently go through customized processing to produce biopower, biofuels or building blocks for biochemicals.

Thermochemical processes allow productive use of a wide spectrum of biomass resources. The relative high temperatures of thermochemical processes (300–1000°C) overcome the natural resistance of biomass to chemical or enzymatic conversion, thus expanding the range of feedstock that can be potentially used. Common thermochemical conversion pathways include gasification, pyrolysis and, to a lesser extent, liquefaction. The difference between the three processes is determined by three main parameters: the oxygen level (λ), pressure and temperature ([16, 48]; Figure 2.3).

2.4.1 Pyrolysis

The study of pyrolysis is gaining increasing importance, as it is not only an independent process but is also a first step in the gasification or combustion process. Pyrolysis refers to the thermal decomposition of biomass and organic compounds in the absence of oxygen to produce biochar, oil and/or gas, depending on the temperature and reaction time. In *slow* pyrolysis charcoal or biochar is produced (temperature ~300°C, reaction time of hours). In *fast* pyrolysis (t° 400–500°C, reaction time of minutes or seconds) and *flash* pyrolysis (t° >700°C, reaction time of fractions of a second) mainly a liquid bio-oil is formed [49]. All pyrolysis products (char, oil, gas) can be used for the generation of heat and power. The dark-brown mobile liquid produced by fast pyrolysis can serve as an intermediate for a wide variety of applications. Clean-up, conditioning, and stabilization of the bio-oil are necessary to convert it into a product suitable for delivery to a petroleum refinery or future biorefinery, where it can be further upgraded to renewable biofuels (diesel, ethanol, bio

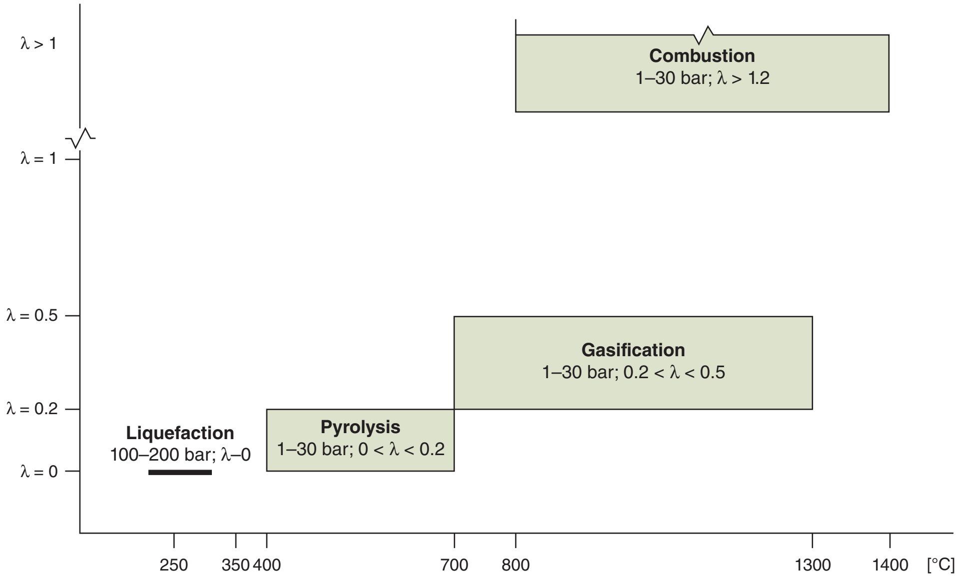

Figure 2.3 *Characteristic conditions of the thermochemical conversion processes. (Reproduced with permission from the International Energy Agency [16]).*

jet fuel) and chemicals [49, 50]. Pyrolysis offers the possibility of decoupling liquid fuel production from energy production by converting the biomass into a liquid with increased energy content that can be easily stored and transported and that has a more consistent (and specified) quality compared to the solid biomass.

Despite rapid development over the last few decades, bio-oil production through pyrolysis is still an immature technology and is not commercially feasible yet. Pyrolysis bio-oil needs to overcome many technical, economic and social barriers to compete with traditional fossil fuels [51]. In particular, the complexity of the bio-oil constitutes a big challenge.

2.4.2 Gasification

Gasification is a process that converts organic or fossil based carbonaceous materials into carbon monoxide, hydrogen, carbon dioxide and methane. This is achieved by reacting the material at high temperatures (>700°C), without combustion, with a controlled amount of oxygen and/or steam. The gasification processes may be distinguished according to the gasification agent used. When biomass is heated with no oxygen or only about one-third of the oxygen needed for efficient combustion, it gasifies to a mixture of primarily carbon monoxide and hydrogen – called *synthesis gas or syngas* (typically 40% CO, 40% H_2, 3% CH_4 and 17% CO_2, dry basis), which can be used to make methanol, ammonia and diesel fuel with known commercial catalytic processes. When air is the oxidant, nitrogen accounts for about half of the product gas. This dilutes the concentration of hydrogen and carbon monoxide gases, resulting in a low-energy fuel gas or *producer gas* (typically 22% CO, 18% H_2, 3% CH_4, 6% CO_2 and 51% N_2) [16].

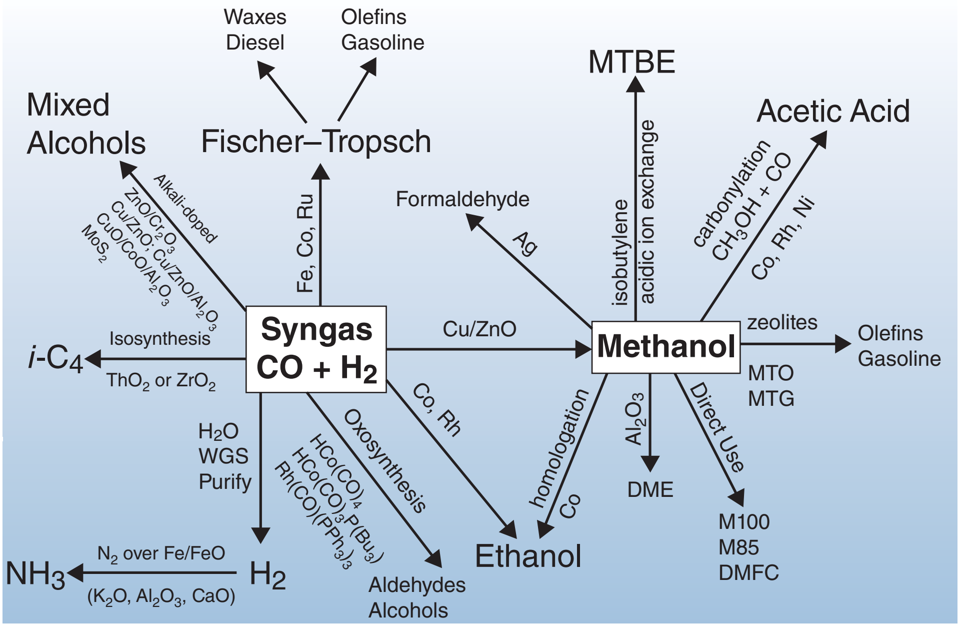

Figure 2.4 *Overview of different catalytic conversion processes for syngas. (Reprinted with permission from National Renewable Energy Laboratory Technical Report (NREL/TP-510-34929) titled "Preliminary Screening – Technical and Economic Assessment of Synthesis Gas to Fuels and Chemicals with Emphasis on the Potential for Biomass-Derived Syngas" (December, 2003) by P.L. Spath and D.C. Dayton, http://www.nrel.gov/docs/fy04osti/34929.pdf [53]).*

After leaving the gasifier, the product gas has to be cleaned and, depending on further processing steps, upgraded. The reasons for gas cleaning are to prevent corrosion, erosion and deposits in the process lines as well as to prevent poisoning of catalysts. Contaminants such as tars and inorganic components (halides, alkalis, ash) present in the syngas can deactivate the catalysts and must be removed prior to catalytic conversion [52]. Upgrading encompasses modification of the CO/H_2 ratio or removal of inert gas fractions, mainly CO_2 [16].

Starting from the cleaned and upgraded synthesis gas, several fuel processing pathways are possible: the application of (thermo)chemical processes such as Fischer–Tropsch (providing diesel/gas like biofuel) or methanol synthesis as well as biotechnological processing towards alcohols is possible [16].

The syngas produced by gasification of biomass can be converted into a large number of organic compounds that are useful as chemical feedstocks, fuels and solvents (Figure 2.4). Collectively, the process of converting CO and H_2 mixtures to liquid hydrocarbons over a transition metal catalyst has become known as the Fischer–Tropsch (FT) synthesis, invented in the 1920s by the German engineers Franz Fischer and Hans Tropsch. At the center of this transformation is a selective catalyst that works under heat and pressure to convert the carbon monoxide and hydrogen into larger, more useful compounds. Currently the FT reaction is successfully used for fuel production from coal (CtL = Coal-to-Liquid) or natural gas (GtL = Gas-to-Liquid). Variations on this synthesis pathway soon followed for the selective production of methanol, mixed alcohols, and isosynthesis products. Another outcome of Fischer–Tropsch Synthesis was the hydroformylation of olefins, discovered in 1938 [53]. Catalysts play a pivotal role in syngas conversion reactions. In fact, fuels and chemicals synthesis from syngas does not occur in the absence of appropriate catalysts [53].

The formation of tars, and measures to deal with their removal, are significant challenges in biomass gasification. Advances in catalyst preparations are also needed in order to make large-scale biomass to liquid facilities practical [52].

Alternatively, syngas can be converted into alcohols, such as ethanol and butanol, or other chemicals, such as organic acids and methane, through syngas fermentation. The main advantages of this microbiological process are the mild process conditions (ambient temperature and pressure), lower sensitivity of the used microorganisms towards sulfur (resulting in reduced gas cleaning costs), independence of the H_2:CO ratio for bioconversion, aseptic operation of syngas fermentation due to generation of syngas at higher temperatures, no issue of noble metal poisoning and a higher reaction specificity. Biological catalysts (such as *Clostridium ljungdahlii*, *Clostridium autoethanogenum*, *Acetobacterium woodii*, *Clostridium carboxidivorans* and *Peptostreptococcus productus*) are able to ferment syngas into liquid fuel more effectively than the chemical catalysts (e.g. iron, copper or cobalt) [54, 55]. Low volumetric productivity, poor solubility of gaseous substrates in the liquid phase, inhibition of microorganisms, syngas quality and product recovery are the major issues to be addressed in order to make syngas fermentation more economically feasible [16, 56, 57].

2.4.3 Liquefaction

The thermochemical direct liquefaction process involves converting biomass to an oily liquid by contacting the biomass with water at elevated temperatures (250–350°C) with sufficient pressure to maintain the water primarily in the liquid phase (12–20 MPa) for residence times up to 30 minutes (Figure 2.3). It mimics the natural geological processes thought to be involved in the production of fossil fuels. Alkali may be added to promote organic conversion. In the liquefaction process, the carbonaceous materials are converted to liquefied products through a complex sequence of changes in physical structure and chemical bonds [58]. The primary product is an organic liquid with reduced oxygen content (about 10%) and the primary by-product is water containing soluble organic compounds. The resulting intermediates can be converted to hydrocarbon fuels and commodity chemicals for products similar to those produced from petroleum [16]. Work done on the determination of the reaction mechanisms of liquefaction, mainly with pure cellulose, suggests that the technique offers a potential alternative synthetic route to phenolics, furans and other chemicals [59]. Liquefaction is suitable for high moisture content biomass, such as aquatic biomass, garbage, organic sludge and so on.

2.4.4 Hydrothermal Upgrading (HTU) Process

During the period 1982–1993, the Royal Dutch Shell Laboratory developed the HTU (Hydro-Thermal Upgrading) process to convert wet biomass such as wood, plants or organic waste into a liquid fuel, so-called biocrude. Biomass is firstly treated in an aqueous slurry at 200°C and 30 bar, followed by a treatment at 330°C and 200 bar. This process results in a biocrude, an oil with low oxygen content, which can be further upgraded by a catalytic hydrodeoxygenation step to a high-quality naphtha or diesel oil with very low oxygen, nitrogen and sulfur contents that can be blended in any ratio to fossil diesel [60, 61].

2.5 Summary and Conclusions

Lignocellulosic biomass is seen as an attractive feedstock for future supplies of renewable fuels and biochemicals. Their abundant supply makes them attractive candidates to replace oil-based liquid fuels and chemicals. Substantial investment is occurring in conversion technologies and in determining the most economic, practical and cleanest technology for the production of these lignocellulosic-based chemicals.

Two main routes can be distinguished for the conversion of lignocellulosic biomass: the biochemical route and the thermochemical route. The key bottleneck in the biochemical conversion of lignocellulosic biomass is the initial conversion of the biomass into sugars. Further improvement of the physicochemical pretreatment processes and new biotechnological solutions are needed to improve the efficiency of this conversion. This "biomass recalcitrance" remains one of the most significant hurdles to producing economically feasible chemicals from lignocellulosic biomass via the biochemical route [7]. Continued research and development is needed to develop and scale-up new biochemical routes.

Thermochemical processes can easily overcome this natural resistance of biomass due to the relative high temperatures that are used. Therefore, a broader range of feedstock can potentially be used. However, also for the thermochemical route technical and commercial barriers still exist [62]. Innovative R&D is needed to improve the energy efficiency and cost effectiveness of thermochemical conversion technologies. Gasification technology is considered to be ready for deployment between now and 2020. Other thermochemical routes like pyrolysis or liquefaction are not as well developed [63].

It is likely there will be no single preferred conversion technology for the production of cellulosic fuels or chemicals, but rather technologies appropriate for specific feedstock [52]. Feedstock restrictions for thermochemical conversion mostly pertain to particle size, moisture and ash content.

Overall it can be concluded that significant investment into research, pilot and demonstration plants is ongoing and will be further needed to develop commercially viable processes utilizing biochemical and thermochemical conversion technologies for the production of biofuels and biochemicals from lignocellulosic biomass.

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3

Technologies for Production of Heat and Electricity

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3.1 Introduction

In 1978, the United States enacted the Public Utilities Regulatory Policy Act (PURPA) giving small electricity producers (less than 80 MW) a natural monopoly by requiring electric utilities to purchase the small companies' surplus electricity at a price equal to the cost the utility would have incurred by producing the electricity themselves. As a result, biopower experienced a threefold increase in grid-connected capacity, created 66 000 jobs, and had an industrial investment of $15 billion dollars during the next decade. Despite these historic advancements, biopower has not experienced further substantial growth. Currently, avoidance costs from electric utilities remain low due to the vast supply of natural gas and innovations in natural gas turbines. As a result, it is difficult for renewable fuels to compete and developments in renewable energy technology have slowed (Figure 3.1). However, interest in environmental sustainability has caused some state governments to implement renewable portfolio standards (RPSs) requiring that a minimum amount of renewable energy (wind, solar, biomass, or geothermal) be included in the electricity generation portfolio of each state. As of February 2012, 30 states and the District of Columbia have enforceable RPS programs [2]. Despite these regulations, biomass makes up a small portion of the current power industry because of high biomass feedstock costs and low overall efficiencies.

Biopower produces less than 2% of the total electricity in the United States [1], while coal and natural gas supply over 65%; hydropower and nuclear make up the remainder. The primary reasons biopower contributes such a small percentage of the overall electricity production are the size and efficiency of its plants. The average size of biopower plants is

Cellulosic Energy Cropping Systems, First Edition. Edited by Douglas L. Karlen.

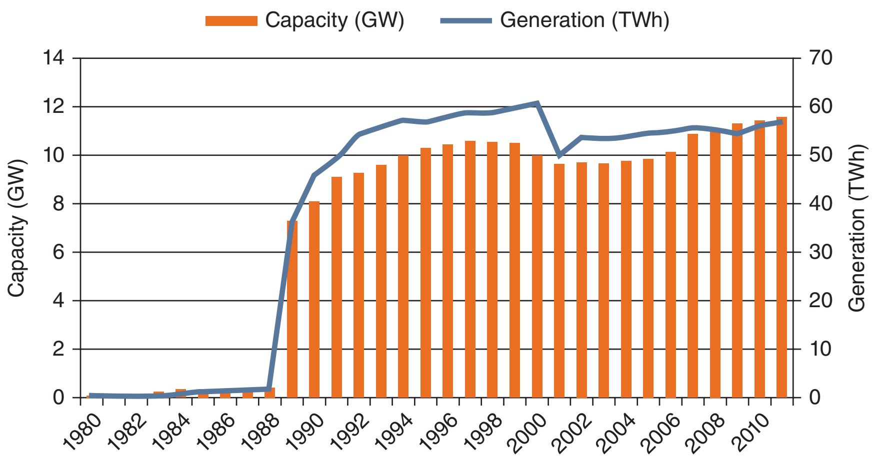

Figure 3.1 *Biopower capacity in the United States [1].*

20 MW (maximum 75 MW); while a typical coal plant ranges from 100 to 250 MW. The small plant sizes (which lead to higher capital cost per kilowatt-hour of power produced) and low efficiencies (which increase sensitivity to fluctuation in feedstock price) have led to electricity costs of 8–12 ¢/kWh [3]. Therefore, for biopower to increase its contribution to the U.S. energy supply, plant size and efficiency must increase to be competitive with current fossil fuel technologies. Additionally, as biopower increases the demand for biomass supply will tend to increase the price of biomass. For the biopower industry to continue to expand the biomass must remain cost competitive.

Biomass is a desirable source of energy because it is renewable, sustainable, widely available throughout the world, and amenable to conversion. Biomass is composed of cellulose, hemicellulose, and lignin components. Cellulose is generally the dominant fraction, representing about 40–50% of the material by weight, with hemicellulose representing 20–50% of the material, and lignin making up the remaining portion [4–6]. Although the outward appearance of the various forms of cellulosic biomass, such as wood, grass, municipal solid waste (MSW), or agricultural residues, is different, all of these materials have a similar cellulosic composition. Elementally, however, biomass varies considerably, thereby presenting technical challenges at virtually every phase of its conversion to useful energy forms and products.

Despite the variances among cellulosic sources, there are a variety of technologies for converting biomass into energy. These technologies are generally divided into two groups: biochemical (biological-based) and thermochemical (heat-based) conversion processes. Although there are specific technologies within each of these general categories, biochemical conversion technologies (i.e., enzymatic hydrolysis), generally operate on wet feedstocks with a high carbohydrate content at the time of conversion [7]. In contrast, thermochemical conversion processes (e.g., combustion, gasification, and pyrolysis), generally require a dry feedstock, low in ash content, and having a small, consistent particle size [8, 9]. As a result of these generalizations, herbaceous feedstocks that are naturally higher in ash and carbohydrates are generally allotted to biochemical conversion, while woody

Table 3.1 Comparison of the main thermochemical conversion processes [10].

Biomass conversion process	Air (or steam) supply	Temperature range (°C)	Products
Combustion	In excess	800–1200	Heat
Gasification	Less than stoichiometric oxygen required	800–1200	Heat, syngas fuel, char
Pyrolysis	Total absence	300–600	Heat, bio-oil, combustible gas, char
Hydrothermal liquefaction	Excess steam	300–350	Bio-oil

feedstocks with their lower ash content are directed to thermochemical conversion. Thermochemical conversion is more aptly used to create heat and electricity due to destruction of chemical bonds while biochemical processes are more suited to develop liquid fuels. With the exception of anaerobic digestion, biochemical conversion is not discussed in this chapter. The main thermochemical processes under which biomass can be converted into energy include:

- Combustion
- Gasification
- Pyrolysis
- Hydrothermal Liquefaction.

In general, the specific thermochemical process being used is determined by the operating air supply and temperature conditions. Combustion occurs in the presence of excess oxygen, gasification takes place when the quantity of oxygen is insufficient for stoichiometric requirements, and pyrolysis happens in the complete absence of air. As a result, gasification can actually be characterized as an intermediate between combustion and pyrolysis; an alternative between having an over-sufficient oxygen supply to biomass and its absolute absence from the process. The operating conditions required for the main thermochemical conversion processes are summarized in Table 3.1.

3.2 Combustion

Combustion or burning is the most common means of converting biomass to usable energy and heat. Historically, woody biomass, from timber harvesting, sawmills, and pulp and paper production, has been used to generate electricity and heat at co-located, direct-fired boilers. Agricultural residue, primarily from wheat and corn harvests, has also contributed to biopower production. These practices have grown the biopower industry into the third largest generator of renewable electricity in the nation, providing 12% of the United States' renewable generation capacity in 2010 [11]. There are two mainstream methods of combustion, direct combustion and co-fired combustion.

3.2.1 Direct-Fired Combustion

Direct-fired combustion is the most common technology currently used to generate electricity. Direct combustion typically burns biomass in a boiler to produce steam that is

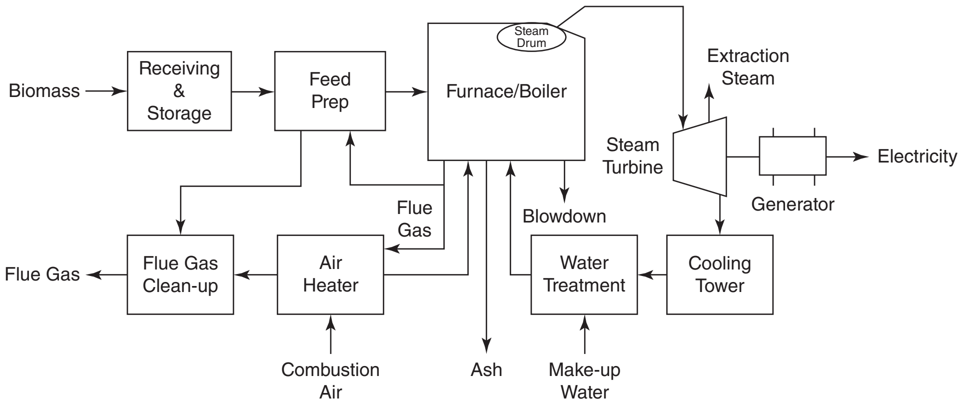

Figure 3.2 *Direct-fired biomass electricity generating system schematic [12].*

then used to power turbines to produce electricity (Figure 3.2). Direct-fired systems are typically smaller in size, 10–50 MW, due to the feedstock requirements and draw radius limitations [11]. In some cases, steam is released from the turbine at medium pressures and temperatures and is used for process heating and cooling to help improve the economics.

3.2.2 Co-Fired Combustion

Co-fired combustion involves using biomass to supplement the primary feed, typically coal or natural gas. Two methods of co-firing biomass exist. The first method, direct co-firing, involves biomass being co-fed directly into the boilers with the coal or natural gas. Direct co-fire technology allows up to 20% of the feed to be supplied by biomass without significant changes to the facility [13]. The second, indirect co-firing, involves first gasifying biomass then co-firing the resulting gases in a combustion system. Co-firing is an immediate, low-cost option for efficiently and cleanly converting biomass to electricity by adding biomass as a partial substitute fuel in high-efficiency coal boilers. There is little or no loss in total boiler efficiency after adjusting combustion output for the new mixture. Co-firing with biomass will also help reduce greenhouse gas emissions, primarily SO_2, NO_X and CO_2.

Opportunities for biomass co-firing are great because large-scale coal-powered boilers represent 310 GW of generating capacity [1]. While direct co-firing usually requires less modification to a generation system, it restricts the amount and type of biomass that can be used. Indirect co-firing through gasification allows for removing alkali metals and chlorine, which can cause fouling, slagging and corrosion in a coal or natural gas boiler system, from the feedstock. Indirect co-firing also reduces the effects of feedstock variability. Biomass feedstocks, by their nature, have a high degree of variability in terms of moisture content, heating value and ash profile. By using gasification to convert these fuels to a gaseous form, much of this variability can be reduced or eliminated. This has the effect of making operation of the boiler more stable [14]. There are a lot of issues yet to be completely solved with co-firing biomass with coal; however, biomass co-firing has been a proven opportunity for coal facilities for more than a decade [13].

3.3 Repowering

Repowering is the option of replacing existing equipment with new technology. The United States has roughly 1400 operating coal-fired generating units producing almost 2 billion MWh of electricity per year [1]. By 2015, more than 90% of those units will be over 30 years old. Furthermore, in addition to producing almost 50% of the United States' electric power, these older units produce almost 35% of the total CO_2 emissions in the United States and up to 40% of the ground level air pollutants such as SO_2 and NO_X [15, 16]. As these systems age, steam production efficiency declines and the units struggle to meet emission compliance. An alternative to shutting down many of these facilities could be to "repower".

Repowering can involve partial or total replacement of existing infrastructure. The extent of repowering depends on many factors including: (1) environmental discharge limits, (2) permitting requirements, (3) increased demand or generating load, (4) fuel cost, and (5) transmission requirements. For example, converting a coal burning facility to a biomass burning facility requires boiler modifications, addition of a gasifier, and addition of biomass handling facilities. These changes are essential because biomass has a lower heating value and more material will be required to produce the same amount of energy. Repowering, however, increases environmental performance, as the conversion from coal to biomass can reduce NO_X emissions by 60%, SO_2 by 80% and particulate matter by 80%. The down side is that biomass prices tend to fluctuate and competition for biomass is steadily increasing. High biomass feedstock prices will seriously impact the economics of repowered systems [3].

3.4 Gasification

Gasification is a high-temperature process used to produce a fuel gas that can be burned directly to make electricity or used to produce methanol, hydrogen or other synthetic fuels. Gasification converts organic materials into CO, H, H_2O, CH_4 and CO_2 by heating material in a vessel (>700°C) and controlling the amount of oxygen and steam to avoid combustion. The gasification process breaks the feed material down to a molecular level, so impurities like nitrogen, sulfur, and mercury can easily be removed and sold as valuable industrial commodities. Synthetic gas or syngas is produced from the biomass gasification process [17]. Gasification is currently widely used on an industrial scale to generate electricity with fossil fuels but is limited with biomass.

Biomass gasification is a more complicated process and with less commercial references than other conventional biomass to energy practices (e.g., combustion) but the benefits are higher energy efficiency and cleaner fuel. The two main advantages that gasification has over biochemical conversion are the speed with which the end product is produced (minutes for gasification compared to days for biochemical conversion) and gasification's ability to extract the energy held in lignin, the complex structural part of biomass. Fermentation methods currently are unable to extract the energy stored in lignin, but this does present the possibility of using gasification as a waste treatment method for materials that cannot be fermented at biochemical conversion facilities [18].

3.5 Pyrolysis

Pyrolysis is a high-temperature process that converts organic material into solid, liquid and gaseous materials in the absence of oxygen. It uses a similar thermochemical process as

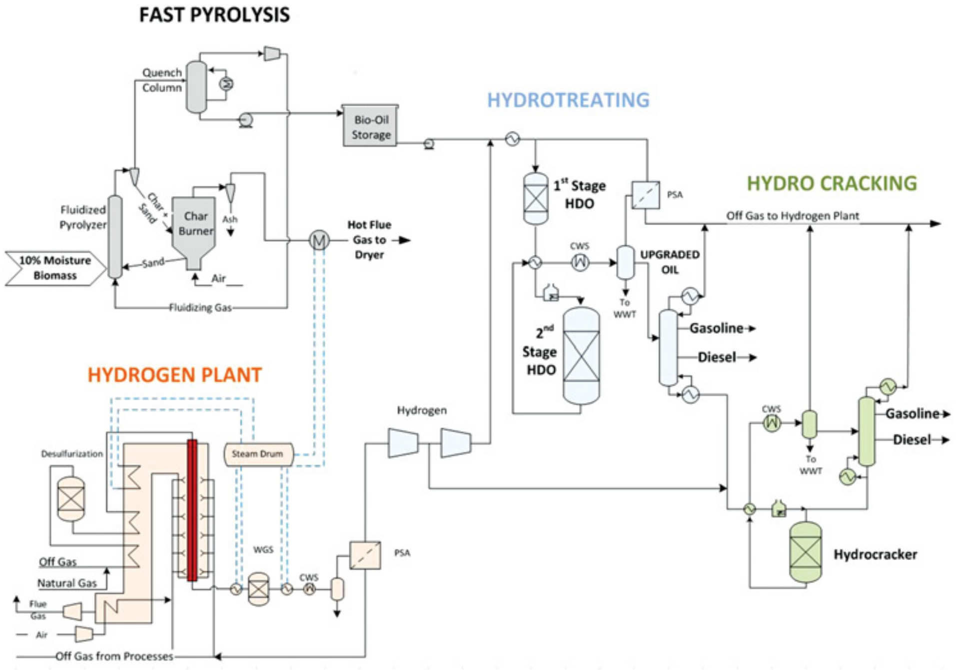

Figure 3.3 *Fast pyrolysis unit co-located with upgrading facility. (Source: Pacific Northwest National Laboratory).*

gasification but under different operating conditions, therefore transforming biomass into a liquid rather than a gas. Like the products of gasification, pyrolysis oil can be burned to generate electricity or used as a chemical source for making fuels, plastics, adhesives, or other bioproducts (Figure 3.3).

Recent improvements in pyrolysis methodology have increased production and overall efficiency, especially fast pyrolysis, which involves heating biomass at a rapid rate then condensing vapors rapidly. Fast pyrolysis converts 40–75% of the (dry) biomass into the liquid bio-oil, about 10–20% of the biomass into char (solid porous carbon particles) and 10–30% into an uncondensable gas. The char and gas can be used as fuel to provide process heat or sold for higher-value uses (e.g., for the production of activated carbon, various chemicals, or charcoal). Present fast pyrolysis reactors use a fluidized bed, entrained flow, ablative vortex, and rotating cone technology. After conversion from biomass to raw pyrolysis oil, the pyrolysis oil is stabilized and converted to a conventional hydrocarbon fuel by removing the oxygen through hydrotreating [19]. The upgrading step involves mixing pyrolysis oil with hydrogen under pressure and at moderate temperatures (<400°C or 750°F) over fixed-bed reactors.

Dual-stage processing, where mild hydrotreating is followed by more severe hydrotreating, has been found to overcome the reactivity of the bio-oil [19]. Overall, the pyrolysis oil is almost completely deoxygenated by a combination of hydrodeoxygenation and decarboxylation. The off-gas is treated and the hydrogen gas that is recovered is recycled back to the reactors. The liquid phase from the hydrotreater includes waste water and product oil, the latter of which is heated and then sent to a distillation tower. The bottom product from the distillation tower is stable oil with less than 2% oxygen. Other energy streams are recovered and recycled in the process [19].

This product can be transported and easily stored, thus creating the possibility to decouple the primary biomass conversion process and prime mover, regarding time, location, and scale of the process. Fast pyrolysis technology can have relatively low investment costs and high energy efficiencies compared to other processes, especially on a small scale.

The major problems of current flash pyrolysis reactors are the quality and stability of the bio-oil, as both are strongly affected by the char/ash content. Besides the known problems concerning solid particles in the bio-oil, the char fines will catalyze repolymerization reactions, resulting in a higher viscosity. The char can be removed by filtering the condensed oil products, although one disadvantage of this is that the alkali, concentrated in the char, will dissolve in the bio-oil because of the high acidity the oil (pH = 2–3). Another option to remove char is hot gas cleaning of the oil vapor. However, for either option, additional capital investments will be required [20].

3.6 Direct Hydrothermal Liquefaction

Direct hydrothermal liquefaction involves converting high-moisture biomass to an oily liquid. Depending on the biomass used, the resulting bio-oil can have a heating value comparable to bunker crude oil (30–40 MJ/kg). The resulting oil can be burned in boilers or upgraded and refined into higher value fuel or chemical compounds. Direct hydrothermal liquefaction works by contacting biomass with water at elevated temperatures (300–350°C) and sufficient pressure to maintain the water in the liquid phase (12–20 MPa) [21]. Additionally, alkali catalysts may be added to promote organic conversion. In the process, water acts as a necessary reaction medium, therefore eliminating the need to dry down biomass and, thus, reducing the total energy footprint. Hydrothermal liquefaction processes have the potential to become an important group of technologies for converting wet biomass or organic waste into bio-oil for fuel or other applications. The hydrothermal liquefaction process holds significant potential, particularly for producing specific fuels targeted for the heavy transport sector, combustion purposes, and as a raw material for further chemical processing [22].

The robust reaction conditions and aqueous environment make hydrothermal liquefaction well suited for the conversion of low-lipid, fast-growing algae that proliferate in wastewater treatment facilities [23]. Integrating algae cultivation into a wastewater treatment plant offers the synergetic benefit of providing nutrient remediation because algae capture and use dissolved nitrogen and phosphorous present in wastewater to support growth [23]. These plentiful nutrients would otherwise be released into the environment, creating harmful eutrophication of natural systems. By converting nutrient waste into a resource, environmental pollution will be reduced, as energy is created and water resources are preserved [24].

3.7 Anaerobic Digestion

Anaerobic digestion is a biological process in which bacteria break down organic matter in the absence of oxygen. A biodigester or digester is an airtight chamber in which anaerobic digestion of manure, sewage, food waste, or other organic waste streams occurs [25].

Anaerobic digestion occurs in an aqueous environment, allowing high-moisture feedstock (less than 40% dry matter) to be used without any pretreatment [26].

Digesters have been used commercially for over 30 years and are currently found in the agricultural, wastewater treatment, and food waste management sectors. Anaerobic digestion produces commodities such as biogas (a blend of methane and carbon dioxide), biosolids (used as a soil amendment), animal bedding, and fertilizer. Biogas can be used as a fuel to generate electricity, as a boiler fuel for steam production, space or water heating, or upgraded to natural gas for pipeline injection or for vehicle fuel (compressed natural gas (CNG) and liquefied natural gas (LNG)) [27]. Regardless of the type of device, control of biogas emissions leads to significant reductions in greenhouse gas emissions. Additional benefits of anaerobic digestion include potential water pollution control opportunities, and additional revenue streams or financial savings. Finally, digester projects may be eligible to sell renewable energy credits (RECs) and/or carbon offsets, which can improve project economics. Despite their potential to address pressing environmental concerns and generate revenue, digester use is not widespread in the United States.

3.8 Integrated Biorefineries

Integrated biorefineries combine an assortment of existing technologies including those discussed earlier and other novel ones to convert biomass into biofuels, high-value bio-products, as well as heat and power. The idea behind an integrated biorefinery is to be able to produce a variety of high-value products as efficiently as the current petrochemical industry. Within the integrated biorefinery, heat and electricity are produced through conversion technologies, then used to produce high-value products, recycled to aid conversion, or sold on the commercial market (Figure 3.4). To be feasible, an integrated biorefinery must overcome a variety of challenges, including diversity of feedstocks, sustainability, and economic viability. Currently, pilot-, demonstration- and commercial-scale integrated biorefineries are operating in the United States [29].

The concept of integrated refineries has been implemented within the petroleum industry for many years. A typical oil refinery is capable of producing a variety of products, ranging from liquid petroleum gas, gasoline, jet and diesel fuels, wax, lubricants, bitumen, and petrochemicals, from which it manages production to maximize profit. This same concept also applies to integrated biorefineries. By producing a variety of products, the integrated

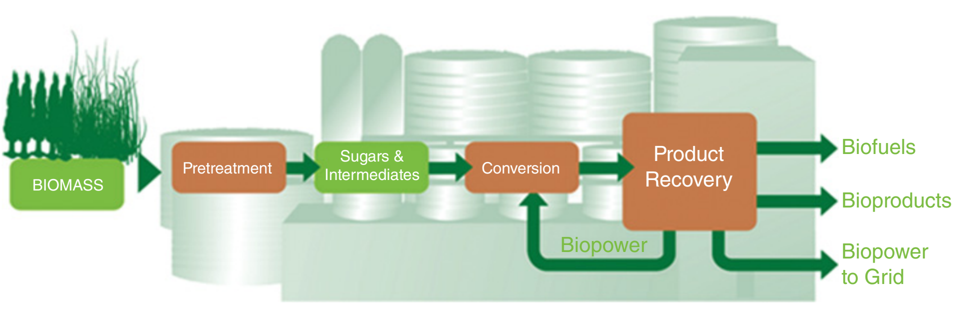

Figure 3.4 *An example of an integrated biorefinery [28].*

biorefinery could help support a marginally viable biofuel market until it matures. The difficulties with an integrated biorefinery include guaranteeing a sustainable biomass supply that matches the desired product stream at a reasonable price. As the demand for biomass increases, the cost of acquiring material will likely increase, thus increasing pressure on the entire bioenergy industry.

3.9 Summary

There are a variety of technologies for the production of heat and electricity from biomass, including combustion, gasification, pyrolysis, hydrothermal liquefaction, and anaerobic digestion. Additionally, these technologies can be combined in the idea of the integrated biorefinery to produce electricity, heat, biofuels, and bioproducts. The main benefit to using these technologies is the reduction of greenhouse gas emissions, but there are still a number of challenges these technologies must overcome. For example, biomass continues to be high in moisture, low in density, unstable, and produces less energy than coal and natural gas, therefore increasing the cost per unit energy produced. Developing technology improvements and innovative uses will help overcome some of these challenges. For example, gasification and anaerobic digestion could be used in small modular systems with internal combustion or generators to provide electricity to remote areas. Small modular system could also be used to fill in gaps with distributed energy generation systems; however, large systems will continue to face issues with insufficient infrastructure, storage of large quantities of biomass requiring large areas, and current supply systems designed for local systems, and environmental regulations being driven by individual states.

There are a number of drivers that are pushing industry to adopt biopower technologies, including the Renewable Fuel Standard and the Renewable Portfolio Standards [30, 31]. These policies give a financial incentive to produce bioenergy. In spite of these policies, the increase in bioenergy production has not accelerated as expected. There are a variety of barriers that need to be addressed for the bioenergy industry to succeed. These include:

- Access to low cost sustainable biomass.
- Additional research into technologies that increase efficiencies and decrease operational costs.
- Additional policies and incentives, such as a CO_2 tax.

The bioenergy industry has already proven to have a place in the overall energy portfolio and will continue to grow. The only questions are how fast and in what direction.

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4

Miscanthus Genetics and Agronomy for Bioenergy Feedstock

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4.1 Introduction

Miscanthus, a tall, perennial, rhizomatous C_4 grass of the Poaceae family [1, 2] is a good candidate for a cellulosic energy crop. The name Miscanthus originates from the Greek mischos (pedicel) and anthos (flower) and refers to the stalked or pedicellate spikelets of the Miscanthus inflorescence. Several species belong to the genus with ploidy ranging from diploid to hexaploid [3]. The basic chromosome number corresponds to $x = 19$ [4]. Miscanthus is capable of high biomass production with minimal inputs [5]. Tropical and subtropical genotypes of Miscanthus grow to 3–4 m when cultivated in Europe and even higher in the warm and wet climates of south-east Asia. Miscanthus rhizomes, or microplants, are planted in spring with canes developing during the summer and harvested annually during the late autumn or winter, following the second or third growing season. The lifetime of the crop varies from 20 to 25 years [6]; long-term Miscanthus plantations can contribute to soil carbon storage [7]. Miscanthus spreads naturally via its underground

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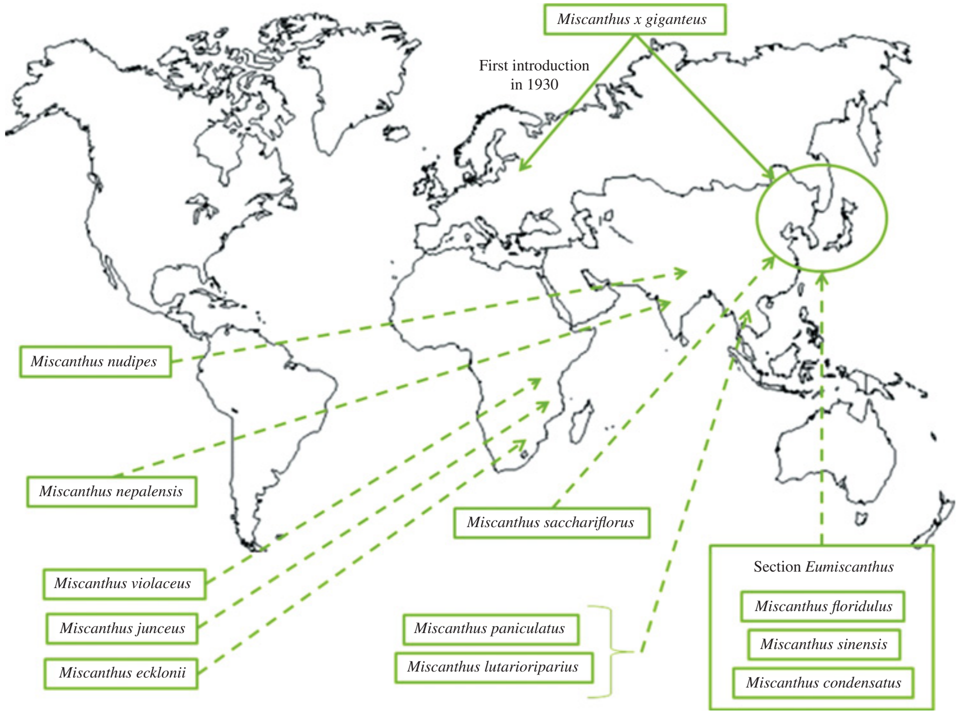

Figure 4.1 *Geographical distribution of* Miscanthus s.l. *in the world. (Adapted from Deuter [19], Hodkinson* et al. *[11] and Clifton-Brown* et al. *[3]).*

storage organs or rhizomes but some species can also be seed-propagated. As Miscanthus is propagated vegetatively, the clone is the most common variety type. This chapter provides details about Miscanthus as a cellulosic energy crop.

4.2 Phylogeny, Growth, Yield and Chemical Composition

4.2.1 Phylogeny

Miscanthus is a C_4 perennial grass of tropical and subtropical origins with a wide area of distribution (Figure 4.1). It belongs to the Poaceae family, a subfamily of Panicoidae, the tribe of Andropogoneae and the subtribe of Saccharineae. Among others, the genera *Miscanthus, Saccharum* and *Erianthus* belong to this subtribe [8]. The phylogeny of *Miscanthus* was first described by Andersson in 1856 [9]. *Miscanthus* was introduced into Europe by Aksel Olsen, who brought it from Japan to Denmark in 1935 (reported by Atienza *et al*. [10]). *Miscanthus sensu lato* (*s.l*) comprises more than 20 species [11] while *Miscanthus sensu stricto* (*s.s.*) contains about 12 species [3]. There is no consensus yet on the definition of *Miscanthus* (*s.l.* or *s.s.*), the taxonomic system to be used or the number of species, subspecies, varieties and forms to be recognized. This can be attributed to the existence of natural interspecific hybrids, the famous one being *M.* × *giganteus*, issued

Table 4.1 *Ranges of the main components of biomass for combustion. (Data collected from [39, 51–54] for* M. × giganteus).

% of dry weight	mean	min	max
C	48.6	48.5	48.7
H	5.7	5.5	5.9
S	0.1	0.0	0.1
N	0.4	0.3	0.5
Cl	0.2	0.1	0.2
Ash	2.7	1.7	3.1
% of ash dry weight	**mean**	**min**	**max**
SiO_2	53.3	47.0	63.7
K_2O	18.8	14.8	23.7
CaO	6.3	4.6	7.7
P_2O_5	4.1	2.3	7.1
Fe_2O_3	0.5	0.2	1.0
Al_2O_3	0.7	0.2	1.7
MgO	3.2	1.9	4.6
Na_2O	0.6	0.2	0.8

from a cross between *M. sacchariflorus* and *M. sinensis*. Furthermore, the distribution of each Miscanthus species has not been fully investigated [9].

Miscanthus is closely related to other genera of the "*Saccharum* complex" (the *Saccharum* genera belonging to this complex) and *Saccharum–Miscanthus* hybrids, that is, miscanes, are used to create varieties of miscane [12]. Alix *et al*. [13] (Table 4.1) concluded that *Miscanthus* was more similar to *Saccharum* than *Erianthus* while Cai *et al*. [14] (Table 4.1) placed *Miscanthus* between *Erianthus* and *Saccharum*. However, a phylogenetic analysis of more than 57 species belonging to the tribe Andropogoneae showed that *Saccharum* was in fact more closely related to *Miscanthus* than to other species in the *Saccharum* complex [11].

The original taxonomy of *Miscanthus* first described by Andersson (1856) has been subsequently modified many times using morphological measurements as reported by Sun *et al*. [9]. Recently, Sun *et al*. [9] revised the taxonomy of 500 *Miscanthus* accessions according to 41 morphological characters, of which 24 were qualitative traits and 17 quantitative traits (Figure 4.2).

Molecular methods have enabled the phylogeny of *Miscanthus* to be even more clearly defined such as in situations where morphological characters were not efficient. Molecular data, especially DNA data, provide a direct assessment of genetic diversity and unlike morphological characters are not influenced by environmental factors [15]. Using nuclear DNA, Greef *et al*. [16] assessed the genetic diversity of European Miscanthus species with Amplified Fragment Polymorphism (ALFP) and found it was a powerful tool in evaluating genetic diversity and hybrid success and in identifying incorrect classifications. Kim *et al*. [17] developed a sequence-characterized amplified region (SCAR) marker that clearly distinguishes *M. sacchariflorus*, *M. sinensis* and *M.* × *giganteus*. Using chloroplast DNA, De Cesare *et al*. [18] identified six chloroplast Single Sequence Repeat (cpSSRs) markers capable of differentiating most Miscanthus species.

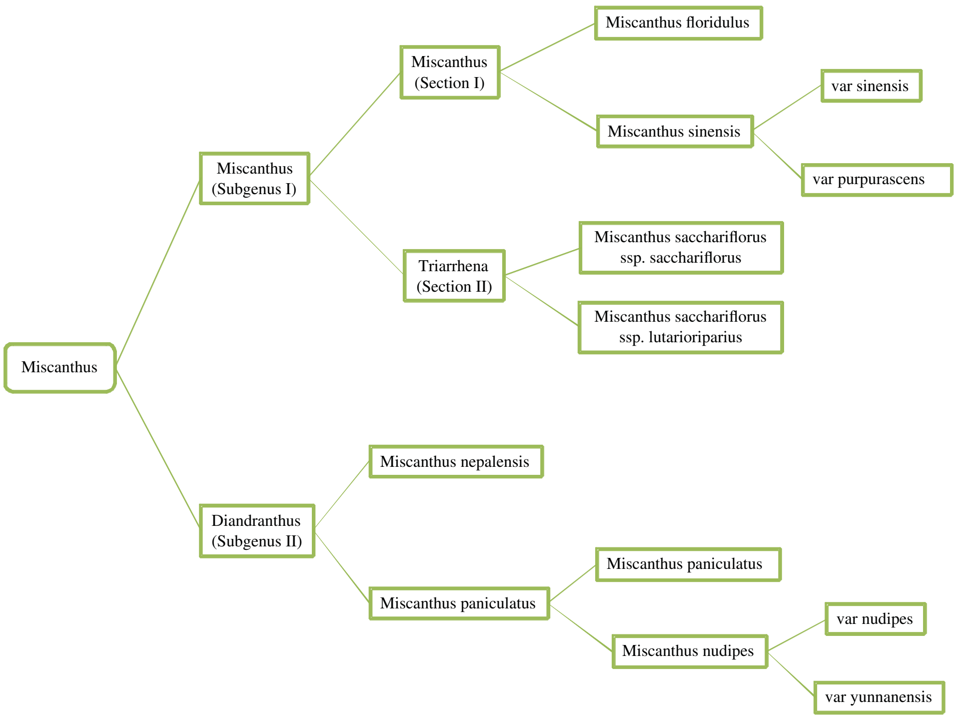

Figure 4.2 *Taxonomy of Miscanthus Andersson from China. (Adapted from Sun* et al. *[9]. The corresponding key to taxa is reported by Sun* et al. *[9]).*

4.2.2 Growth

4.2.2.1 Main Features

To date, most of the information gained on the growth and physiology of Miscanthus has come from studies of *Miscanthus* × *giganteus*, which has been shown to reach a maximum aboveground yield of 46 t ha^{-1} under non-irrigated conditions [20] and 49 t ha^{-1} under irrigated conditions [21]. However, as detailed in Section 4.2.3 (Genetic Diversity for Biomass Production), the aboveground yield of Miscanthus can vary greatly depending on climatic and seasonal conditions, soil type, crop management and crop age.

The root system of *Miscanthus* × *giganteus* is composed of a coarse cluster of rhizomes from which a mass of fine roots grow [22, 23]. These fine roots represent just under a third of the total belowground biomass and can reach a depth of 250 cm in sandy loams [22, 23]. The rhizome biomass of *M.* × *giganteus* has been shown to reach a maximum of 23.8 tDM ha^{-1}, by the end of summer, with this amount maintained until early winter [20].

Aboveground growth is triggered once temperatures reach 6 or 10°C with the emergence of stems from buds located just below the soil surface [24]. After stem emergence, tillering increases rapidly throughout May–July with up to 40 stems per plant recorded for *M.* × *giganteus* in the United Kingdom [25]. The number of productive shoots decreases over the course of the growing period, with the youngest tillers dying off. The oldest tillers continue to grow through to August–September and even October, depending on the climate and the time between emergence and flowering. The harvestable number of stems per plant varies between species, with *M. sinensis* silberspinne producing about 200 stems per plant or about five times as many stems as *M.* × *giganteus* (40 stems per plant) at three years of age [26].

Leaf area increases throughout the growing season to reach a peak at flowering, after which the canopy starts to senesce [27]. In *Miscanthus* × *giganteus*, the maximum leaf area index (LAI) obtained each season increases with crop age reaching about 7–8 m^2 m^{-2} in summer for a three-year-old stand [28]. At the onset of plant senescence, all stems left standing gradually dry out during winter until February–March, when the crop is ready for harvest. The light extinction coefficient (k) through the leaf cover of the crop provides a measurement of the capacity of leaves to intercept light. The k-value for *M.* × *giganteus* has been recorded at 0.56 [27] and 0.68 [29] and for *M. sinensis* Goliath at 0.66 [30]. However, most of these values need to be validated, especially at the interspecific level.

4.2.2.2 Use Efficiencies for Radiation, Water and Nitrogen

Potential biomass production depends on the accumulated amount of photosynthetically active radiation (ΣPAR) intercepted by the crop over the course of its growth and the efficiency with which the crop is able to convert this radiation into carbohydrates, which is known as the radiation use efficiency or RUE [31]. The contribution of each of these processes to biomass production is crop specific [32]. As a C_4 plant, *M.* × *giganteus* has a naturally high RUE, which has been assessed at 4.09 [21], just short of its theoretical maximum of 4.6 gDM MJ^{-1} [33]. Water deficit has been shown to reduce the RUE of *M.* × *giganteus* by 30–80% [27] with *M.* × *giganteus* being more sensitive to drought than *Micanthus sinensis* [34].

Water use efficiency (WUE) of *M.* × *giganteus* has been shown to be higher in the United Kingdom and France than in the Mediterranean environment [27], with adult stands reaching between 9.1 and 9.5 gDM l^{-1} in the United Kingdom [35] and between 6 and 10 gDM l^{-1} in France [36].

M. × *giganteus* exhibits high nitrogen use efficiency (NUE) with 200 g g^{-1} determined in February for aboveground biomass and 180 g g^{-1} for the total crop including the annual increase in rhizome mass [37]. Minimum nitrogen content in the belowground biomass of a mature *Miscanthus* × *giganteus* crop ranged from 70 to 370 kgN ha^{-1} depending on harvest date and nitrogen treatments [28]. The transfer of nitrogen from the belowground biomass to the aboveground biomass at the beginning of growth can account for as much as 79% of the total nitrogen content of the belowground biomass [28] (Figure 4.3). Nutrient accumulation in the aboveground biomass peaks during late summer.

During crop senescence in autumn, nutrients are again remobilized but this time from the aboveground biomass to the belowground biomass (i.e. autumn remobilization). Strullu *et al.* [28] found that 42% of the maximum nitrogen content of the aerial organs of *Miscanthus* × *giganteus* was relocated to the belowground biomass by an October harvest compared to 71% by a February harvest. It would appear, therefore, that only a small

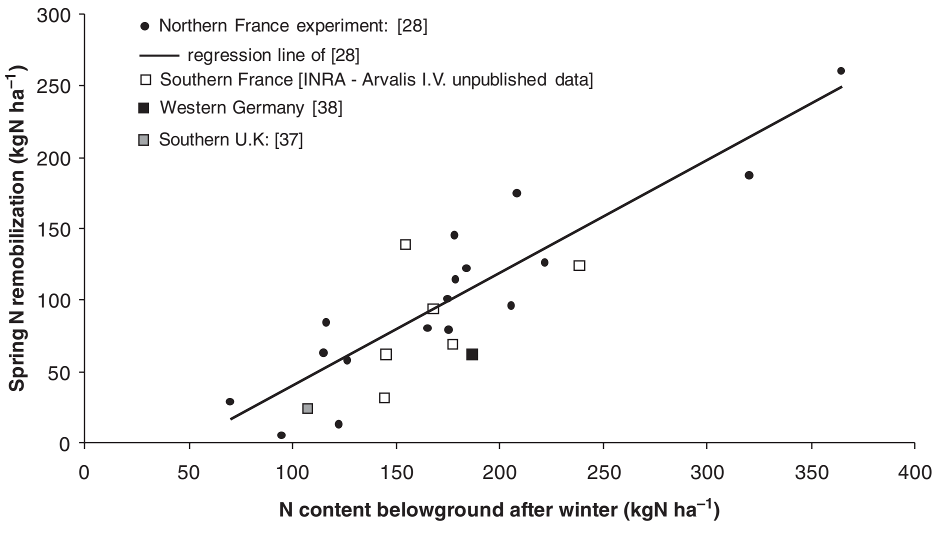

Figure 4.3 The spring remobilization of nitrogen from the belowground biomass to the aboveground biomass accounts for different percentages of the nitrogen content of the belowground biomass at the beginning of growth [28, 37, 38].

proportion of plant nutrients are harvested during the winter harvest with the majority of nutrients being translocated to the rhizome and recycled to the soil.

4.2.3 Genetic Diversity for Biomass Production

Only a few *Miscanthus* species – *M.* × *giganteus*, *M. sinensis* and *M. sacchariflorus* – have been investigated regarding biomass productivity and composition for breeding potential.

Miscanthus × *giganteus*, in particular, has demonstrated high productivity [39] in low input systems and a higher energy output:input ratio than maize [3]. However, *Miscanthus* × *giganteus* has a narrow genetic diversity [16] and is not adapted to all climatic zones [40, 41]. It is crucial that the genetic diversity of the *Miscanthus* genus is investigated to determine if varieties suited to a broader range of environments can be developed.

Biomass yields increase each year in young Miscanthus plants, reaching a plateau after 2–5 years in *M.* × *giganteus*, depending on environmental conditions [3]. *M.* × *giganteus* and *M. sacchariflorus* took less time to reach a yield plateau than *M. sinensis* hybrids and *M. sinensis* genotypes [42]. During each growing season, yields peak during flowering [27] and then decline through the winter partly due to leaf loss [24] (Figure 4.4). In addition to time of harvest, biomass yield is influenced by environmental conditions [43] and genotype [24]. *M.* × *giganteus* and *M. floridulus* achieved higher aboveground biomass yields than *M. sinensis* and *M. sacchariflorus* in field trials in northern France [26]. In this study ploidy levels appeared to influence biomass production, with triploid and tetraploid forms of *M. sinensis* and *M. sacchariflorus* more productive than diploid forms. Zub *et al.* [26] also showed that plant height and shoot diameter were traits that contributed the most to biomass yield, regardless of harvest date or crop age.

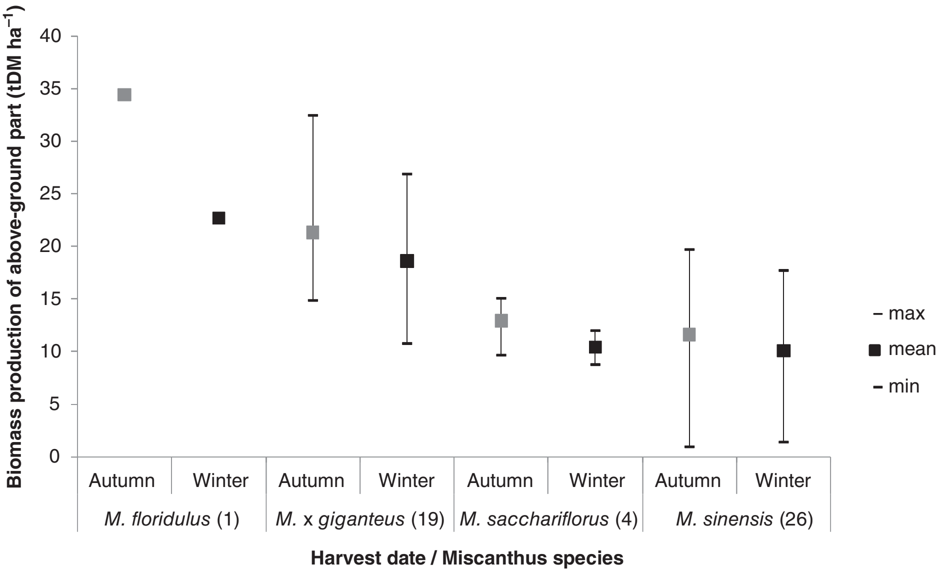

Figure 4.4 *Variability for biomass production during the third year among four Miscanthus species based on the scientific literature [1, 26, 40, 42, 44–50] for autumn and late winter harvests. Clone numbers are mentioned in brackets. The* M. floridulus *clone might be a* M. × giganteus *var Floridulus clone.*

4.2.4 Genetic Diversity for Biomass Composition

To date, Miscanthus biomass has been mainly used to generate renewable heat, electricity and combined heat and power. Its use in biofuel production is under investigation in several countries, as is its potential as a component in bio-based concrete materials and bio-based plastic composites (Section 4.4.1, Past and Current Projects). The composition of Miscanthus biomass must be optimized to suit to each end use (Table 4.1). However, the biomass composition of Miscanthus species varies widely and it is critical that new Miscanthus varieties are developed to provide consistent biomass compositions suited to specific industrial processes.

For biomass combustion, it is essential that the moisture, ash and mineral content of the biomass are minimized, as these reduce process efficiency [1, 43]. *M. sinensis* genotypes have a higher combustion quality because they contain lower contents of chlorine and potassium than *M.* × *giganteus* [55]. Delaying harvest from autumn until late winter can also improve the combustion quality of Miscanthus biomass because moisture, ash, potassium, chlorine and nitrogen contents are lowest at this time [43, 56]. Ranges of the main biomass components are illustrated for *M.* × *giganteus* (Table 4.1). The differing mineral and ash content of Miscanthus leaves and stems between clones or harvest dates provides an opportunity to manipulate biomass composition better suited to combustion [1, 57, 58].

Efficient biofuel production requires high levels of cellulose and hemicellulose and low lignin content. From biomass components, the cellulose shows the highest content at 41–52% of biomass dry matter (Figure 4.5), the hemicellulose displays 24–34% and the lignin varies from 8.8 to 12.6% [40, 47, 53, 56, 59, 60]. Cellulose, hemicellulose and lignin

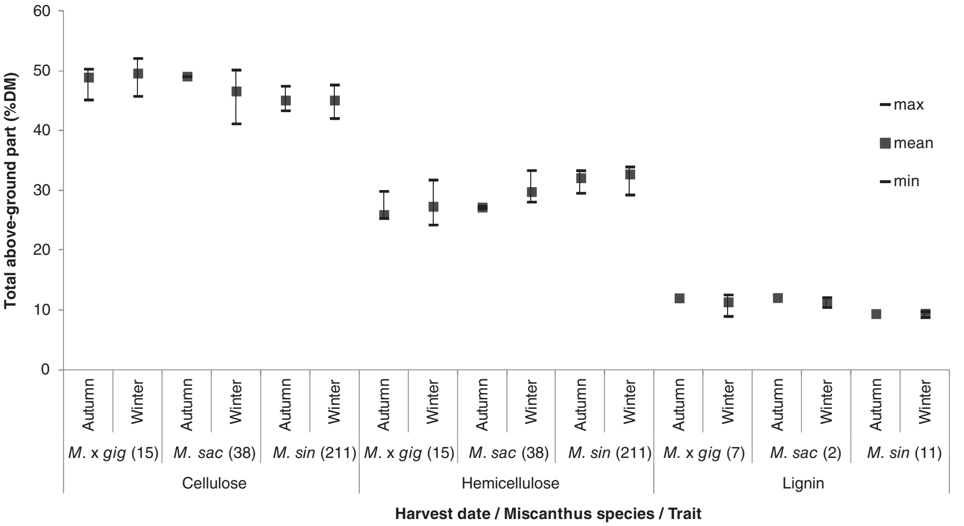

***Figure 4.5** Variability for cell wall composition in cellulose, hemicellulose and lignin (determined by the Van Soest method [62]) among three Miscanthus species based on the scientific literature [40, 47, 53, 56, 59, 60] for autumn and late winter harvests. Data based on several years and different clones and expressed in percentage of the aboveground dry matter (DM). Clone numbers are indicated in brackets.* M. × gig, M. sac, *and* M. sin *corresponded to* M. × giganteus, M. sacchariflorus *and* M. sinensis *species, respectively.*

contents tend to increase between autumn and late winter in Miscanthus species. Between species, *M.* × *giganteus* and *M. sacchariflorus* species globally have higher cellulose and lignin contents and lower hemicellulose content than *M. sinensis* species (Figure 4.5). One exception to this is the work by Lygin *et al*. [61], who found that the *M. sinensis* "Grosse Fontaine" clone had higher cellulose content than *M.* × *giganteus*.

In summary, it would appear there is sufficient genetic variation in biomass productivity and biomass composition to breed Miscanthus varieties well suited to bioenergy use.

4.3 Cultural Practices

4.3.1 Establishment

Successful establishment is critical for Miscanthus because it ensures biomass production in the year of planting [63–65], which in turn improves its frost tolerance in areas such as northern Europe [24]. In addition, a well established crop ensures rapid growth in the second year, with more nutrients translocated to the rhizome upon which winter survival and re-growth depend [24, 66, 67].

The sterile hybrid *Miscanthus* × *giganteus*, which must be vegetatively propagated, makes up the majority of Miscanthus currently cultivated in Europe [65]. *Miscanthus* × *giganteus* is propagated using either macro or micropropagation methods. In macropropagation, small rhizome sections are obtained through mechanical division and planted out. In micropropagation, plantlets are generated via tissue culture and then established in the field. Other genotypes, such as *M. sinensis*, can be propagated either vegetatively or by seed [68, 69].

Table 4.2 *Summary of optimal conditions to ensure good establishment of Miscanthus by rhizome (based on* Miscanthus × giganteus*) or by seeds (based on* Miscanthus sinensis*).*

	Seed of *M. sinensis*[a]	Rhizome of *Miscanthus × giganteus*
Soil temperature	Base temperature: 8.3–11.6°C [65, 68] Recommended temperature >16°C [65, 68] but optimum temperature 25°C [68, 70] Light and fluctuating diurnal temperatures enhance germination [71, 72]	Base temperature: 8.5°C [73] Optimum temperature: 25°C [74] Recommended date in Northern Europe from March until May [24, 75, 76]
Soil moisture	Base water potential: –1.46 Mpa [68] Cultural practices to keep soil moisture: Irrigation [65, 77], fine seedbed [77], rolling seedbed [77], mulch [77]	Soil moisture recommended >40% [78, 79] Cultural practices to keep soil moisture: Irrigation [39, 66, 74], fine seedbed [78], rolling seedbed [78], mulch [74]
Planting depth and density	Sowing depth proposed [77]: 10 mm Sowing density proposed [77]: 500 seeds m^{-2} *There is no study on the optimal depth and density; the values proposed are order of magnitude from Christian et al.* [58]	Planting depth: at 100 mm [67, 80] Planting depth if high risk of frost: 200 mm [75, 81] Planting density 1–4 plants m^{-2} [6, 24, 39, 68, 69]
pH	4 < pH < 8.5 [70]	5.5 < pH < 7.5 [76]
Plant material quality	Seed characteristics: Seeds are very small (250–1000 mg for 1000 seeds) [39] and have low nutrient reserves Large seeds have faster germination [70] Heavy seeds produce larger seedlings [19] Breaking dormancy: 1–10 ppm giberrellic acid [70] Chilling seed [19, 68]	Rhizome characteristics: At least 100 mm and optimum 200 mm [75] At least 20–40 g [67, 79] optimum 60–75 g [67] Minimum 2–3 buds [76] 5-yr old [69]
Storage	Cold storage 4°C [19, 68]	≤4°C until 4 mo [74, 79]
Weed control	Chemically [39, 82, 83] or manually [74, 75]	Chemically [39, 82, 83] or manually [74, 75]
Machine	Seed drill [77, 84]	(modified) potato planter, bespoke planter [76, 78, 79]

[a]Combination of several studies on different genotypes of M. sinensis.

Successful establishment depends on many factors acting individually or in combination [63, 64] (Table 4.2).

Rhizome or macropropagation appears to be the best propagation method because:

- Seed production is limited in northerly latitudes where the growing period is too short to ensure sufficient flowering and fertile seed production. Soil temperatures in spring in some areas such as northern Europe (Denmark, UK, etc.) are not high enough for seed germination [64, 65, 75].
- Micropropagation results in a lower survival rate during winter of the first year [66, 75, 84–86] and is more expensive [64, 69, 75] than macropropagation. It is more suited to areas such as southern Europe with mild winters and low frost risk.

- Stem segment propagation requires high temperatures (about 25–30°C) to be successful [64, 87]. Such conditions are not achieved in temperate climates. This method also results in lower emergence rates than rhizome propagation [87] and is impractical as the best time to cut stems is in late summer while planting occurs in spring, making it necessary to store the stem-propagated plants over winter [75].

Much of the research on establishment of has been done in Europe, where Miscanthus is being investigated as a bioenergy feedstock [88, 89]. However, the findings can be transferred to other environments, such as North America [39].

4.3.2 Fertilization

The fertilizer requirements, and in particular nitrogen requirements, of biomass crops have significant implications for the carbon footprint and environmental impact of biomass production systems.

Cadoux *et al*. [90] reviewed 27 studies dealing with the nitrogen, phosphorus and potassium (NPK) requirements of *Miscanthus* × *giganteus*. While significant amounts of nitrogen, phosphorus and potassium are taken up by the crop, only a fraction of this peak nutrient content is removed during the winter harvest due to translocation of nutrients from shoots to rhizomes during winter (Table 4.3). In addition, leaf fall and nutrient leaching from the stems returns some of the absorbed nitrogen, phosphorus and potassium to the soil [37, 38], a proportion of which is used by the crop in subsequent years, along with remobilized nutrients from the rhizomes [28, 37, 38, 91].

The yield response of *M.* × *giganteus* to nitrogen fertilization is limited and varies between sites [90, 92, 93]. Just over half of eleven studies reviewed by Cadoux *et al.* [90] concluded a positive response of *M.* × *giganteus* to nitrogen, while five showed an absence of a response. In the studies showing a positive response to nitrogen, the response was generally moderate except under irrigation, where the response was higher. The absence of response in the remaining studies can be explained by the plants having sourced their nitrogen via rhizome remobilization and from available soil mineral nitrogen. Crop age also impacts on the nitrogen response with young plants requiring little to no nitrogen in the first few years. For example, using a meta-analysis, Miguez *et al*. [63] found Miscanthus did

Table 4.3 *Median nutrient content and concentration at three growth stages of* Miscanthus × giganteus *from a review of 27 studies. (Adapted with permission from [90]. Copyright © 2012, Elsevier).*

		N	P	K
Maximum nutrient content	Nutrient content (kg ha^{-1})	241	27.5	279
	Nutrient content (g kg^{-1})	7.8	1.17	15.2
	Date	August	August	August
Maximum DM production	Nutrient content (kg ha^{-1})	167	22.5	252
	Nutrient content (g kg^{-1})	5.0	0.8	8.8
	Date	October	September	November
Winter harvest	Nutrient content (kg ha^{-1})	76	6.8	95
	Nutrient content (g kg^{-1})	4.9	0.45	7.0
	Date	February	February	February

not respond to nitrogen fertilizer during the first two growing seasons and then responded only slightly to a nitrogen rate of 100 kg ha^{-1}.

The environmental impacts of over fertilization must be taken into account when considering the nitrogen requirements of Miscanthus. Christian *et al.* [46] compared the nitrogen balance of Miscanthus crops over 10 years. For crops not fertilized, the nitrogen balance after a decade was negative (–254 kg ha^{-1}), implying an overall decline in soil nitrogen reserves. In crops treated with nitrogen at a rate of 120 kg ha^{-1} yr^{-1}, biomass yield was not significantly different from unfertilized crops while the nitrogen balance was positive (790 kg ha^{-1} after 10 years) with 280% more nitrogen having leached from the system than the unfertilized treatment.

As stated by Cadoux *et al.* [90], fertilizer recommendations for Miscanthus will be a compromise between the needs of the crop and the need to maintain soil nutrient reserves while limiting nutrient losses. As the exact nutrient needs of Miscanthus are not yet known, Cadoux *et al.* [90] proposed that nutrient recommendations should be based on the amount of nutrients removed or likely to be removed at harvest (using expected yield and median concentrations given in Table 4.3). For nitrogen, they recommended no fertilization during the first two years of cultivation because nitrogen requirements are low at this stage while the risk of nitrate leaching is high [94].

While *M.* $\times$ *giganteus* shows only a small yield response to nitrogen input, some variability in nitrogen response is likely among Miscanthus species, especially in relation to rhizome development and internal nutrient cycling. It would be valuable for breeding purposes to determine which progenitor species has contributed *M.* $\times$ *giganteus's* efficient yield response to nitrogen.

4.3.3 Disease, Pest Control

The exotic status of Miscanthus and its current small area of cultivation is an advantage in terms of the number of pests and diseases found in native areas that might threaten its production [95, 96]. However, as the area in Miscanthus cultivation increases new pest and disease threats are likely to emerge.

Fusarium has been implicated in Miscanthus crop failure but its significance has not yet been quantified [97].

The common rustic moth (*Mesapamea secalis*) and the ghost moth larvae (*Hepialus humuli*) have also caused production problems for Miscanthus crops [76]. In addition, the larvae of armyworms (*Spodoptera frugiperda*) have been shown to infest plots of *Miscanthus* $\times$ *giganteus* [98] along with the aphid *Rhopalosiphum maidis* [99]. In the United States, plant-parasitic nematodes (*Helicotylenchus, Xiphinema, Paratylenchus, Hoplolaimus, Tylenchorhynchus, Criconemella, Longidorus, Heterodera, Paratrichodorus, Hemicriconemoides, Pratylenchus*) have been identified as potential pathogens in Miscanthus biofuel crops [100].

Many other insects such as *Thysanoptera, Hexapoda, arthropods, Tetranychus, Tetranychidae, Prostigmata, mites, Acari, Arachnida* have been identified in Miscanthus [101] but their prevalence is far less than insect pests of sugarcane [102]. In the United Kingdom, Clifton-Brown *et al.* [3] reported the presence of cereal leaf aphid *Rhopalosiphum maidis*, although this pest appears to be more of problem in greenhouses than the field. Bradshaw *et al.* [99] suggested aphids (*Rhopalosiphum maidis, Sipha flava, Spodoptera frugiperda*)

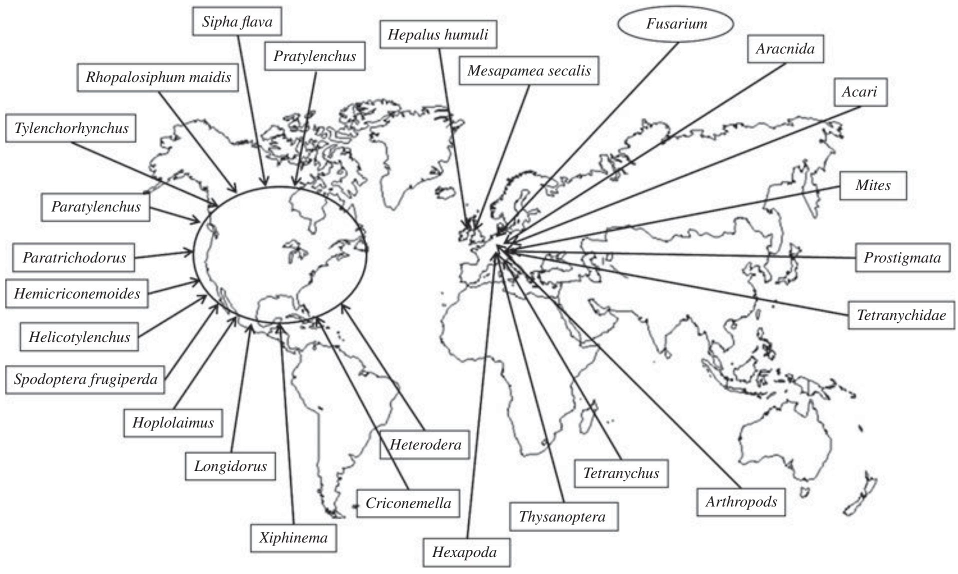

Figure 4.6 *Cartography of world diseases (orange) and pests (purple) of Miscanthus. Information collected from Thinggard [97], Gottwald and Adam [101], DEFRA [76], Clifton-Brown* et al. *[76], Prasifka* et al. *[98], Bradshaw* et al. *[99], Mekete* et al. *[100].*

have the potential to damage young Miscanthus. Other cereal aphids and aphid-transmitted viruses could also be potential problems in Miscanthus. Finally, in comparison to sugarcane, where more than 1500 insect species have been identified, it appears that few insects have been reported to feed on *Miscanthus* × *giganteus* [98].

In summary, although few pests and diseases of *Miscanthus* have been identified in the cultivation area (Figure 4.6), the species appears robust with a high tolerance to pests and diseases. This will hopefully reduce the requirement for chemical pest control [103] although the genetic basis for this apparent high pest tolerance still needs to be verified with the likely increase of the cultivation area.

4.3.4 Invasiveness

Candidate crops for biofuel production are generally chosen for their rapid growth rate, high resource-use efficiency (regarding water, radiation and nutrients) and broad tolerance of pests, diseases and stressful environments [104–107]. However, the traits that characterize an ideal biofuel crop are also the same traits that characterize many invasive species [93, 104–106].

The potential invasiveness of Miscanthus species has been assessed in various locations using either a weed risk assessment (WRA) or field observations (Table 4.1). WRA is a model adapted from the Australian weed risk assessment system or AWRA developed by Pheloung [108] to a local environment. The WRA uses an additive approach, with set scores ranging from –3 to 5 for each of 49 questions dealing with the species' growth habit and persistence, distribution, reproductive system and whether it has become a weed elsewhere.

Using the WRA, *M.* × *giganteus* identifies as noninvasive (Table 4.4) due largely to its sterility and, thus, dramatically reduced risk of escaping into natural environments [92, 105, 106, 109]. This contrasts with *M. sinensis*, which identifies as invasive at most locations. However, not all genotypes of *M. sinensis* would be expected to present the same invasiveness risk, since sterile triploid clones exist within this species [110], but unfortunately the genotypes used in the *M. sinensis* study were not specified. Nevertheless, many invasive species do not produce fertile seeds but are serious invaders as *Arundo donax*, *Polygonum cuspidatum* and so on [104–106, 109].

In addition, *M.* × *giganteus* rhizomes have a slow rate of lateral growth (only spread at a space around 10 cm per year) compared to *M. sacchariflorus*, which has extensive creeping rhizomes (can spread several meters in a few years), which increased the risk of spreading due to erosion and water transport [93, 110]. Therefore, *M. sacchariflorus* is defined as invasive.

It is important to note that invasiveness evaluations using risk assessment systems are not absolute, as they must incorporate subjectivity and uncertainty [116]. For example, the WRA can produce incorrect answers and provides non definitive answers in almost one-third of all cases [106, 116]. Therefore, it is recommended that a combined assessment approach be used that incorporates pre-entry and post-entry evaluation tools [105, 106, 116].

1. Pre-entry evaluation
   - WRA to identify invaders and benign species and reject or accept them for introduction. The protocol used would be based on the biology of the target species and its ecology, climatic requirements, history and biogeography relative to the target regions. [106, 109]
   - Climate matching analysis (e.g. CLIMEX model [119]) to determine the climatic and agronomic regions at risk of a potential invasion.
   - Evaluate the potential for the proposed bioenergy crop to hybridize with related species or taxa.
2. Post entry evaluations

   Any species conditionally accepted would then require i*n situ* ecological analyses:
   - Agronomic trials in quarantined field trials in the new environments.
   - Long-term experiments to determine the competitiveness of the proposed bioenergy crop within native or managed ecosystems in the new environment.
   - An efficient management plan covering the eradication of each feedstock in case of invasiveness after commercialization [106, 109].

Breeding and management programs will also help to minimize the invasive risk of Miscanthus [109] by minimizing seed production and rhizome spread.

4.3.5 Harvest Management

The canes of Miscanthus are harvested once each year, from the second year after establishment using a self-propelled forage harvester, like that used for harvesting silage maize or by hay harvesting equipment, including cutters, conditioners and balers [92, 120]. Hay harvesting equipment is used more frequently as it generates a denser feedstock, thus decreasing transport volume [120].

Table 4.4 *Potential invasiveness of* Miscanthus.

Country	Miscanthus species	Assessment method	Invasiveness	Reference
U.S.A.	*M.* × *giganteus* *M. sinensis*	WRA Literature	Noninvasive Invasive	[106]
North Carolina Pennsylvania Washington, DC Iowa Minnesota	*M. sinensis* *M. sinensis* *M. sinensis* *M. sacchariflorus* *M. sacchariflorus*	Literature	Invasive Invasive Invasive Occasionally invasive Occasionally invasive	[111, 112]
Ohio New Jersey North Carolina Kentucky Pennsylvania	*M. sinensis* *M. sinensis* *M. sinensis* *M. sinensis* *M. sinensis*	Field observation (distance from location of original plantings, area, density)	Invasive	[109]
Hawaii Massachusetts Connecticut	*M. floridulus* *M. sacchariflorus* *M. sinensis*	Unspecified	Noxious weed Prohibited Potentially invasive, not banned	[104, 113]
Florida U.S.A.	*M.* × *giganteus* M. × giganteus	WRA WRA	Noninvasive Noninvasive	[114]
Australia	*M.* × *giganteus* *M. sinensis*	Unspecified	Prohibited Weed	[115]
Japan (Kyoto)	*M. sinensis*		Weed	[116]
Italy	*M. sinensis*	WRA	Invasive	[117]
Overall analysis	*M.* × *giganteus* *M. sinensis* *M. sacchariflorus*	Overall analysis	Non invasive Invasive Invasive	[93]
Overall analysis	*M.* × *giganteus*	Literature	Non invasive	[118]
World	*M.* × *giganteus* *M. sinensis* *M. sacchariflorus*	CLIMEX	– Global niche distributions for the invasive species of agronomical origins are similar to the bioenergy crops. – Large climate niche (broad climatic tolerance) of bioenergy crops positively correlated with invasiveness. This does not indicate invasiveness but broad climatic tolerance have to be considered in evaluation of invasiveness of bioenergy crops	[107]

Miscanthus is generally harvested in late winter when biomass quality is at its peak for combustion processes and before crop growth increases again from early spring. By late winter, the composition of biomass is more suited for bioenergy such as combustion (see section genetic diversity for biomass composition). Moisture content is also lower in late winter, enabling a higher production of net energy. In one study, moisture content was shown to decrease by more than half between early and late winter, from 47 to 52% in December to 16–20% in March [43].

A disadvantage of a late winter harvest is that there is less harvestable biomass at this time due to the loss of senescent leaves and the remobilization of nutrients from aboveground to belowground biomass [28]. More than a third of the aboveground biomass can be lost in *M.* × *giganteus* between the early harvest period of September or October and the late winter harvest time of February to March [28, 37, 38]. Similar yield losses have been observed for *M. sinensis* and *M. sacchariflorus* [24]. An early harvest might better suit cellulosic ethanol production because there should be more lignocellulose sugar available at this time [121]. However, it is likely that early harvested crops will subsequently require more nitrogen and other fertilizer, as considerably more nutrients are exported from the system with an early rather than a late harvest. For example, Strullu *et al*. [28] showed that *M.* × *giganteus* crops harvested in late winter mobilized 71% of their peak nitrogen content to belowground biomass compared with just 42% of the peak nitrogen content of early harvested plants. In the same trial, the nitrogen content of senescent leaves collected over winter from the soil of 2–3 year-old crops amounted to 15.5 ± 3.5 kgN ha^{-1} yr^{-1} in late harvested treatments but was negligible in early harvested treatments [50]. An early harvest is, therefore, likely to increase the crop's requirement for added nitrogen and other fertilizer.

In addition, leaf fall during winter provides carbon to the soil and the litter layer by senescent leaves can also help control weeds. In the same field trial, senescent leaves correspond to about 3 tDM ha^{-1} yr^{-1}, which correspond to about 1.3 tC ha^{-1} yr^{-1} [50]. This was smaller than the amount measured by Kahle *et al*. [122] for older plants (4.5 tDM ha^{-1} yr^{-1}, corresponding to about 2 tC ha^{-1} yr^{-1}). The weight of the litter formed by senescent leaves of *Miscanthus* × *giganteus* accumulated at the soil surface was measured every year during nine years of cultivation by Christian *et al*. [46]. It increased during the four first years and was then fairly constant in time (with about 6 tDM ha^{-1} on average), probably because the fall of new senescent leaves each year was compensated by leaves decomposition.

In summary, a winter harvest has advantages over an earlier harvest. It allows a remobilization of nutrient from aboveground to belowground biomass and it can contribute to enhance carbon sequestration in soil. Nevertheless, the quality of the canes at that date might reduce accessibility of the cellulose and hemicellulose, which would require appropriate processes for some end-uses such as biofuel.

4.4 Genetic Improvement

4.4.1 Past and Current Projects

In Europe, the production potential of *M.* × *giganteus* has been investigated extensively in trials across northern Europe since 1983 [39]. Between 1993 and 1995, the Miscanthus productivity network, as part of the European agro-industry research program, carried out growth and yield trials on *M.* × *giganteus* in 16 locations throughout northern and southern Europe [15, 123]. Later, attention was given to breeding and genetics of Miscanthus. In 1997, the European Miscanthus Improvement (EMI) project was established to investigate the genetic diversity of Miscanthus. Through this project, the biomass productivity and chemical composition of 15 Miscanthus genotypes was assessed in different environments across Europe [3, 53]. The genotypic variation identified by the EMI project stimulated private and public breeding programs involving Miscanthus in the United States and Europe [3]. In 1998, the European BIOMIS project was focused on *Miscanthus sinensis*. Through a genetic approach, its final objective was to achieve a significant reduction of costs for expensive heat exchangers used in thermal conversion [124].

In 2011 a European project, OPTIMISC (Optimizing Miscanthus Biomass Production), was established between12 partners from Europe, China and Russia. OPTIMISC will run until 2016 and has been established to improve the bioenergy potential of Miscanthus via the trialing of novel elite genotypes across Europe, the Ukraine and Russia. The Miscanthus genotypes will be particularly investigated for their tolerance to water, salinity and cold stress and for their ability to be converted into biofuels and high-value bioproducts.

In France, a novel project called Biomass for the Future (BFF) started in 2012 with the aim of developing industrial clusters of biomass production from dedicated crops of Miscanthus (northern France) and sorghum (southern France). These crops will be improved for their performance in lignocellulosic biomass, with an environmental impact and a composition suitable for industrial applications (combustion, anaerobic digestion, building materials and plastics) and second-generation biofuels production. In the context of sustainable agriculture, BFF will contribute to the enhancement of marginal agricultural land and the development of a new green economy by involving all local stakeholders in a dedicated area. BFF is developed in synergy with biorefinery projects in France and other European countries.

In the United States, Miscanthus research started in 2001 at the University of Illinois at Urbana-Champaign has since expanded to other US universities (http://www.extension.org). Several public–private partnerships investigating aspects of Miscanthus have recently been created, including the Energy Biosciences Institute, the Mendel Biotech Company and the CERES Company. The Energy Biosciences Institute incorporates a range of partner institutions, including the University of California at Berkeley, the University of Illinois at Urbana-Champaign, the Department of Energy Lawrence Berkeley National Laboratory and the International Energy Company BP. In addition, Mendel Biotech in collaboration with the private German nursery company TINPLANT was involved in breeding services for Miscanthus from 2007 to 2011 (http://www.mendelbio.com/). Finally, the private company California CERES is working with experts from IBERS (The Institute of Biological, Environmental and Rural Sciences at Aberystwyth University in the UK) to develop Miscanthus varieties that can be sown more economically from seed (http://www.ceres.net/).

Other projects are focused on biofuels where Miscanthus constitutes one of the feedstocks. Among others, the French research and development project Futurol aims to develop and market processes and technologies for second-generation bioethanol production from nonfood lignocellulosic feedstock such as Miscanthus. It runs from 2008 until 2016. Supported by this project, the first pilot plant for second-generation agrofuels production was established in October 2011. In October 2010, the SUNLIBB (Sustainable Liquid

Biofuels from Biomass Biorefining) project was established combining European and Brazilian research to improve the cell wall characteristics of Miscanthus for biofuel and production. The aim is to identify key genes involved in the biomass saccharification process and to develop genotypes with improved biofuel conversion efficiencies and clones with improved cell wall characteristics for biofuels, biochemicals and biomaterials.

4.4.2 Genetic Resources

In contrast to sorghum, there is practically no public germplasm collection for Miscanthus, apart from a few collection activities by botanical gardens, research institutes and private companies. These collections comprise ornamental accessions and a small number of landraces [125].

In Europe, the private German nursery company TINPLANT has developed a large Miscanthus collection of about 1050 accessions that includes several species: *M.* × *giganteus, M. sinensis, M. sacchariflorus, M. tinctorius, M. condensatus, M. floridulus* and some hybrids [126]. More recently, the French company Aelred has been developing a breeding program since 2010.

The Royal Botanic Gardens, Kew, in the United Kingdom has a collection of 125 plants of the genus *Miscanthus* and various associated species. Trinity College Dublin Botanic Gardens has a collection of Miscanthus accessions assembled from various national and international projects. Most of the material obtained by Trinity College Dublin was donated by various botanic gardens and research institutes throughout the world. The Agriculture Development and Advisory Service (ADAS) in the United Kingdom also holds a collection of Miscanthus.

Among research institutes, the Department of Agroecology and Environment at Denmark's Aarhus University holds a large collection of Miscanthus genotypes collected in part from Japan and established as part of the EU-projects EMI and BIOMIS. At the Institute of Biological, Environmental and Rural Sciences (IBERS) in Aberystwyth, UK, a Miscanthus breeding program that began in 2004, with germplasm assembled from European collections based at academic institutions, horticultural companies and from Asia [127]. The collection includes accessions of *M. sinensis, M. sacchariflorus* and naturally occurring inter-specific hybrids and constitutes the largest Miscanthus collection outside Asia [128].

Miscanthus breeding and research activities at Wageningen UR Plant Breeding in The Netherlands and at INRA in Estrées-Mons, France, are focused on the development of new varieties suitable to bioenergy production and specific environments.

In Asia, the Institute of Botany from the Chinese Academy of Sciences in Beijing holds a large Miscanthus collection [9]. In 2010, the Institute developed a key for Miscanthus taxa, collecting 500 representative samples from each of the various species. The possibility of domesticating Miscanthus crops within China is also being investigated [129, 130]. In Japan, the Field Science Center for the Northern Biosphere has collected *Miscanthus sinensis* genetic resources from various parts of Japan (www.hokudai.ac.jp). In Korea 200 accessions of Miscanthus have so far been collected by the University of Seoul [17].

Finally, most of these germplasm collections are connected with Miscanthus breeding programs. Nevertheless, the development of miscanes, interspecific hybrids between species from the *Saccharum* and *Miscanthus* genus, is under investigation [13] and will also require the use of collections of *Saccharum*.

4.4.3 Traits and Varieties of Interest

Miscanthus genetic improvement programs are focused largely on biomass productivity and composition, along with traits that limit invasiveness, such as rhizome growth habit and reproductive sterility, and those enhancing tolerance to abiotic and biotic stress [3, 24].

Plant height, stem diameter, lateness at panicle emergence, and growth rate are the main traits positively correlated to Miscanthus yield [26]. However, the heritability of these traits needs to be determined before their success in developing new varieties can be established.

For varieties propagated by rhizome or microplants, the clone will be the common varietal type. Seed propagated varieties could be developed in some species, but must be sterile to limit their invasiveness risk. Seed weight and seed pelleting methods will be important considerations of any seed-based varieties. The variety type is the clone when the propagation is vegetative. As for grasses, the synthetic variety type would be expected within seed-propagated Miscanthus species.

The low invasiveness potential of *M.* × *giganteus* and *M. sinensis* (Section 4.3.4, Invasiveness) and the high biomass yields of *M.* × *giganteus* make these species good candidates for Miscanthus breeding programs. Nevertheless, it is critical to ensure a low invasiveness by minimizing seed production and rhizome spread. The most effective method would be to induce sterility (male and female) via triploidy (as in the current *M.* × *giganteus*). For seed-propagated varieties, sterility can also be obtained either by manipulating expression of plant hormones or cytotoxin genes in reproductive tissues. Breeding or selecting for late flowering and slow rhizome growth would also help to reduce invasiveness by minimizing seed production and rhizome spread. There is likely to be a large variation in flowering time within genotypes of *M. sinensis* due to its native distribution across wide range environments [110, 127].

Finally, developing triploid versions of *M.* × *giganteus* or *M. sinensis* will be important in reducing the invasiveness of new Miscanthus varieties [26]. The development of seed-based varieties is also under investigation by several institutes and companies. In addition, the breeding and productive potentials of *M. floridulus* and other Miscanthus species still need to be determined.

4.4.4 Tools for Genetic Studies Breeding and Phenotyping

Among the fertile germplasm, accessions should be selected as parents to be used in crosses for breeding purposes or to create mapping populations for genetic studies. As a Miscanthus crop takes several years to mature, genetic markers and phenotypic methods need to be developed to speed up the breeding process.

4.4.4.1 Tools for Genetic Studies and Breeding

The polyploid nature and the relative large size of the Miscanthus genome complicate genetic analyses. Using flow cytometry and stomatal cell analyses, Rayburn *et al.* [131] found *M.* × *giganteus* had a genome size of 7.0 pg (6.8 Gb, the number of DNA base pairs per nucleus being assumed 0.965×10^9 bp per pg by the author) while *Miscanthus sinensis* and *Miscanthus sacchariflorus* had genome sizes of 5.5 pg (5.3 Gb) and 4.5 pg (4.3 Gb) respectively (Table 4.5). It is clear that there are many gaps that require further

Table 4.5 *Comparaison of bioenergy grasses. (Adapted from Vermerris [135], Butterfield* et al. *[132], Rayburn [131]).*

Common name	Species name	Subfamily	Genome size (Mb)	Basic chromosome number (Monoploid)	Level of ploidy	Photosynthesis	Propagation	Genome sequence
Maize	*Zea mays* L.	Panicoideae	2500	x = 10	2n = 2x = 20	C_4	Outcrossing, inbreeding	Schnable *et al*. (2009)
Sorghum	*Sorghum bibolor* (L.) Moench	Panicoideae	750	x = 10	2n = 2x = 20	C_4	Outcrossing, inbreeding	Paterson *et al*. (2009a)
Sugarcane	*Saccharum officinarum*	Panicoideae	1852	x = 10	2n = 80	C_4	Vegetative, outcrossing	In progress
Sugarcane	*Saccharum spontaneum*	Panicoideae	1520	x = 8	2n = 40–128	C_4	Vegetative, outcrossing	In progress
Miscanthus	*Miscanthus* × *giganteus*	Panicoideae	6848	x = 19	3x = 57	C_4	Vegetative, inbreeding	In progress
Miscanthus	*Miscanthus sacchariflorus*	Panicoideae	5379–16 137[a]	x = 19	2x to 6x	C_4	Vegetative, inbreeding	In progress
Miscanthus	*Miscanthus sinensis*	Panicoideae	4401–13 203[a]	x = 19	2x to 6x	C_4	Vegetative, inbreeding	In progress

[a]Determinated by flow cytometry [131].

investigation. However, further studies will be facilitated by the use of plants such as sugarcane, sorghum and maize, which are likely to be good models for genomics and breeding issues in Miscanthus.

Detailed DNA mapping and sequencing studies in plants related to Miscanthus will provide relevant genetic tools and information. For example, *Sorghum Bicolor* is diploid and, with a relatively small genome of about 730 Mb, has been completely sequenced [132]. Although sugarcane is related to Miscanthus [11], its genome is much more complicated due to its very high degree of polyploidy (about 12x for modern cultivars, Le Cunff *et al.* [133]). The monoploid genome size for *S. officinarum* (x = 10) is about 926 Mb while that of *S. spontaneum* (x = 8) is about 760 Mb (Butterfield *et al.* [132]). Maize is less related to Miscanthus than sugarcane and sorghum but its genome has been fully sequenced [134]. Syntenic regions or candidate gene sequences can be expected and exploited for comparative genetic studies. From the conserved syntenic regions, markers can be developed in Miscanthus and related to traits of interest for marker-assisted selection.

A wide diversity of molecular markers are available from plants related to Miscanthus but their transferability for use in Miscanthus needs to be determined. First comparisons are promising, however, with Hernandez *et al.* [136] showing that 75% of the maize microsatellites tested gave highly reproducible amplification with Miscanthus DNA. More recently, Swaminathan *et al.* [137] showed that sorghum could be used as a reference genome sequence for Andropogoneae grasses. In a survey of the complex *Miscanthus × giganteus* genome using 454 pyrosequencing of genomic DNA and Illumina sequencing-by-synthesis of small RNA, Swaminathan *et al.* [137] found that the coding fraction of the *Miscanthus × giganteus* genome had a high level of sequence identity to that of other grasses (sorghum, maize and rice). In addition, Kim *et al.* [138] designed SSRs from sugarcane expressed sequence tags (ESTs) and in applying these to a Miscanthus mapping population succeeded in generating EST–SSR-based genetic maps of Miscanthus.

Genetic linkage maps offer an efficient tool in the study of the inheritance of quantitative traits. Most Miscanthus species are self-incompatible, resulting in a high level of heterozygosity from outcrossing. Grattapaglia and Sederoff [139] proposed a two-way pseudo-testcross model for the genetic mapping of highly heterozygous organisms.

Several maps are available for marker-assisted studies in Miscanthus. The first genetic map of Miscanthus was constructed with this pseudo-testcross strategy using intraspecific hybrids from a cross between two *Miscanthus sinensis* clones [10]. 383 RAPD markers were developed for this map but a higher density of molecular markers was needed due to the high number of linkage groups (28) relative to the basic chromosome number (x = 19). This map had a total length of 1074.5 cM. A decade later, Kim *et al.* [138] developed a genetic map with highly heterozygous individuals being interspecific hybrids from a controlled cross between heterozygous single plants of *M. sacchariflorus* Robustus (2n = 2x = 38) and *M. sinensis* (2n = 2x = 38). Their map used cDNA-derived SSR loci and comprised 23 linkage groups with 303 markers and was 2238.3 cM in total length. Ma *et al.* [140] created a high-resolution genetic map of *Miscanthus sinensis* using genome sequencing and comprising 3745 SNP markers spanning cM on 19 linkage groups with a 0.64 cM average resolution.

Miscanthus linkage groups of the map developed by Kim *et al.* [138] were aligned successfully to the Sorghum chromosomes. A duplication of the whole genome was produced and corresponds to the Miscanthus lineage after the divergence of subtribes Sorghinae and Saccharinae [138]. Comparative genomics analyses of their map to the genomes of sorghum, maize, rice and *Brachypodium distachyon* [140] indicated that sorghum had the closest syntenic relationship to Miscanthus. This validates the use of sorghum as a model for the genomics of Miscanthus.

Breeding programs will be directly guided in the future by the genome sequencing of *Miscanthus* × *giganteus* and its close relatives, to capture, for example, the genes of interest present in these species. It is noticeable that sequencing efforts of four Miscanthus species (*M.* × *giganteus*, *M. sinensis*, *M. sacchariflorus*, and *M. floridulus*) are ongoing along with the creation of genomic resources by the Energy Biosciences Institute (http://www.energybiosciencesinstitute.org/) and by the Joint Genome Institute (http://www.jgi.doe.gov/).

4.4.4.2 Tools for Propagation

Miscanthus can be vegetatively propagated by rhizome division but this process is time consuming. Developing an efficient tissue culture system would provide an alternative to rhizome division and be useful for breeding purposes. Tissue culture enables a large number of plants to be generated and stored regardless of the season. In addition, the risk of transferring diseases between fields is lower than propagation by manual rhizome separation [141].

Somatic embryogenesis and clonal propagation are two methods used for *in vitro* propagation of Miscanthus. With somatic embryogenesis, considerable differences exist in the capacity of explants types of the same genotype to produce an embryogenic callus and regenerate plants [142, 143]. The growth stage of inflorescences used for the somatic embryogenesis is very important, with younger inflorescences showing a significantly higher callus induction rate than more developed inflorescences [144,145]. Immature inflorescences are abundant and can easily be obtained from field-grown *M.* × *giganteus* during the summer or from greenhouse grown plants throughout the year. *In vitro* propagated plants are more cold tolerant in their first season than plants obtained *in vivo* [146]. Plants propagated from rhizome division are larger and have a higher yield than plants propagated via somatic embryogenesis [66]. In clonal propagation involving organogenesis, new plants are produced from shoots obtained from a culture of axillary buds [64, 147]. Plantlets from vegetative regeneration are genetically identical (Rambaud, personal communication). In addition, clonal propagation can also be applied to seedlings. Figure 4.7 presents the different stages of the clonal propagation of Miscanthus from seeds.

This last efficient plant regeneration system would be helpful for genetic improvement through future biotechnology research. It is interesting, for example, to handle tissue culture in order to produce transgenes. Recently, particle bombardment-mediated transformation [148] and *Agrobacterium* transformations [149] were used to insert genes of interest in Miscanthus genome for agronomical genetic traits and introduce genetic variations.

4.4.4.3 Tools for Phenotyping

Tools are under development to assess biomass yield and composition and their related traits in Miscanthus.

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Figure 4.7 *Seeds and different stages of* Miscanthus *vegetative propagation. A: seeds, B: young plantlet (15–18 days), C: plantlet (30–35 days), D: vegetative multiplication plantlet.*

For biomass production, Zub *et al*. [26] showed that biomass yield during the second year could be used to predict the biomass yield of the third year, whatever the harvest date. This correlation requires further investigation over a longer period and on a wider sample of genotypes to determine whether the yield difference between harvest dates is the same for juvenile and mature phases of the crop.

In addition, Zub *et al*. [150] found that the aboveground volume including the stem number, the stem diameter and the plant height was a good predictor of plant biomass yield. Within genotypes, strong positive relationships were observed between biomass yield and the aboveground volume regardless of crop year (equal to 0.70 and 0.82 for autumn and winter harvests during the second year, respectively).

For biomass production, Hodgson *et al*. [59] developed Near-Infrared Reflectance Spectroscopy (NIRS) calibration models for biomass quality to determine acid detergent lignin (ADL), acid detergent fiber (ADF), and neutral detergent fiber (NDF) from sample spectra of *M.* × *giganteus*, *M. sacchariflorus* and *M. sinensis*. The corresponding concentrations were predicted with a good degree of accuracy based on the coefficient of determination (values of R^2 being higher than 0.80), standard error of calibration, and standard error of cross-validation values.

Regarding the statistical analysis, the residual model error in the analysis of variance model needs to be small to enable the comparisons between genotypes for quantitative traits. In Miscanthus, the residual term was high during the second and third years of the crop (Zub *et al*. [150]) and could hamper inter-genotypic comparisons for traits such as aboveground biomass yield or related traits. Without more plots or samples (it is indeed important for the breeder and the producer to save place and cost), one way for reducing the residual term is to take into account intra-genotypic competition effect in the statistical model [150]. As it implies observations at the plant level, intragenotypic effect assessment requires easy-to-measure variables, such as the stand volume as a predictor of the aboveground biomass [150, 151].

Modeling of emergence and plant growth using three and four-parameter logistic functions and the Gompertz function were tested to best describe the dynamics of crop emergence and of plant growth. The Gompertz function was found to be the best to estimate emergence dynamics while four-parameter logistic to estimate growth dynamics [151].

In contrast to the genetic tools, where intensive research has been conducted during the last decade, the phenotypic evaluation represents a bottleneck for Miscanthus, since high throughput tools are still required today.

4.5 Conclusion

The development of renewable energy sources is being investigated across the world and there is a growing demand for bioenergy feedstock that does not compete with food production and which has a low environmental impact. Miscanthus is developing as a serious player in the renewable energy sector. To realize its potential, new varieties are needed with the productivity and processing traits required for bioenergy production. This will require a full exploration of the genetic resource base of Miscanthus and its related species and the development of appropriate genetic tools. Many such projects are in progress throughout the world and the next decade is likely to deliver exciting new developments for Miscanthus as a renewable energy source.

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5

Switchgrass

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5.1 Overview

Switchgrass (*Panicum virgatum* L.) is a perennial warm-season grass native to the grasslands of North America, is a model perennial grass for bioenergy, and is the most advanced herbaceous perennial bioenergy feedstock. Best management practices have been developed for switchgrass bioenergy production for the agroecoregions to which it is adapted. Field production of switchgrass likely will occur on cropland that is marginally productive for row crops, similar to land that was enrolled in the Conservation Reserve Program. Long-term, field-scale research demonstrates that switchgrass for bioenergy is productive, profitable for the farmer, and protective of the environment.

Switchgrass was selected by the Bioenergy Feedstock Development Program (BFDP) at the U.S. Department of Energy (DoE) as a model herbaceous species because of its potential to simultaneously meet energy demands and address global climate change [1]. It is a perennial, warm-season (C_4) grass native to North America that is broadly adapted throughout the United States and is found in every state east of the Rocky Mountains [2]. Like many perennial C_4 grasses, switchgrass is highly tolerant to abiotic stresses such as drought, temperature extremes, and salinity. For that reason, it is being recommended for biomass production on marginally productive cropland where it would have minimal land use competition with commercial food crops [3].

5.2 Phylogeny, Growth, Yield and Chemical Composition

Switchgrass is a highly polymorphic species with considerable morphological and physiological variation. Much of this variation can be explained by ecotype, the main taxonomic

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subdivision named largely for phenotypic differentiation based on habitat [4]. The two ecotypes (upland and lowland) were initially distinguished by phenotypes but now can be separated by cytotypes and gene cluster, using numerous genetic markers [5]. Common upland cultivars are "Shawnee" and "Summer", whereas common lowland cultivars are "Alamo" and "Kanlow".

Lowland ecotypes are mostly tetraploids ($2n = 4x = 36$), whereas upland ecotypes are commonly tetraploid ($2n = 4x = 36$) or octoploid ($2n = 8x = 72$) with hexaploid ($2n = 6x = 54$) reported rarely [6, 7]. Aneuploids appear to be common in switchgrass, particularly at higher ploidy levels [8]. Many molecular methods have been developed and used for studying the genetic relationship between upland and lowland cytotypes. The genetic relationship among 14 populations of upland and lowland switchgrass ecotypes has been characterized by using 92 polymorphic RAPD markers [9]. Hultquist *et al.* [10] used chloroplast DNA restriction fragment length polymorphisms to show that these upland and lowland ecotypes are genetically different in chloroplast DNA. A deletion of 49 nucleotides in trnL-UAA introns was identified in lowland cp genome [11]. Several recent studies have investigated nuclear polymorphisms using simple sequence repeats derived from expressed sequences tags (EST-SSRs) and identified several lowland and upland subpopulations [7, 12–15].

Lowland ecotypes generally are taller, coarser, and more caespitose in growth form than upland ecotypes. Generally, they are better adapted to wetter and warmer environments, whereas upland ecotypes are best adapted to drier and colder environments [4, 16]. In general, lowland ecotypes have greater biomass and better disease resistance than upland ecotypes [4, 16]. Both ecotypes are largely self-incompatible and plants are cross-pollinated by wind [16].

Switchgrass has the typical anatomical and physiological characteristics of a C_4 grass [16]. Seedling development has three phases: germination, emergence, and adventitious root development [17]. Optimum temperature for switchgrass seed germination and seedling growth is between 20 and 30°C, while germination and seedling growth are significantly reduced at soil temperature <20°C [18, 19]. Seed germination is initiated with the radicle protrusion and the coleoptile emergence from the seed coat. Once the coleoptile emerges, it is pushed to the soil surface by elongation of the subcoleoptile internode, typical of the panicoid seedling development [17]. When the coleoptile reaches the soil surface, the subcoleoptile internode elongation stops, adventitious roots form, and water uptake and photosynthesis begin for plant growth. This is why proper seeding depth is critical for successful switchgrass establishment. Seeds planted deeper than 1 cm can result in poor establishment because seedling energy reserves are used for subcoleoptile elongation and adventitious root development is delayed [17]. Several tillers may be produced within six weeks of emergence.

Switchgrass growth during the establishment year varies depending on region, weather, soil fertility, and competition with weeds [20], but in general it is feasible to produce and harvest 50% of the cultivar's yield potential after a killing frost. Furthermore, in the first full growing season after seeding, it is very feasible to produce and harvest 75–100% of the cultivar's yield potential [20–22] with many fields in the central Great Plains approaching full production of 8–13 Mg ha^{-1} [23].

New growth in post-establishment years starts in early spring, with new tillers being initiated from axillary buds on the crown and/or rhizomes [24–26]. Moore *et al.* [27] presented the phenologic development of switchgrass by maturity stages: emergence, vegetative/leaf development, stem elongation, reproductive/floral development, and seed development and ripening. Although the durations of each stage are dependent on genetics, both photoperiod and temperature play a critical role on vegetative growth and reproductive development [28–30]. Mitchell *et al.* [29] and Castro *et al.* [31] indicated that photoperiod is the primary determinant of switchgrass development, but temperature or heat units can significantly modify reproductive development.

Switchgrass biomass yield is influenced by agroecoregion and management practices, such as ecotype, cultivar, fertilization, and harvest timing. Maughan [32] reported a meta-analysis of 106 sites from 45 studies covering the eastern two thirds of the United States and southeastern Canada. Switchgrass biomass yield across all regions of the study, including both lowland and upland ecotypes, averaged 6.6 $\pm$ 3.0 Mg ha^{-1} during the establishment year, increased to 9.1 $\pm$ 5.5 Mg ha^{-1} in the second year, and reached a maximum of 10.9 $\pm$ 5.2 Mg ha^{-1} in the third year. During the post-establishment years, biomass yield for lowland and upland ecotypes was 11.1 $\pm$ 6.1 and 6.7 $\pm$ 3.2 Mg ha^{-1}, respectively. Among regions, the lower central region, equivalent to U.S. Plant Hardness Zones 6 and 7, had the highest biomass of 6.7 $\pm$ 3.2 Mg ha^{-1} and the north region, equivalent to U.S. Plant Hardness Zones 3 and 4, had the lowest biomass yield of 7.3 $\pm$ 3.1 Mg ha^{-1}. High-yielding cultivars developed for biomass yield in the Great Plains and Midwest are in the release process for commercial availability.

Lignocellulosic biomass is composed primarily of structural carbohydrates, cellulose and hemicellulose, and lignin, polyphenols, with a lower concentration of other proteins, nutrients, acids, salts, and minerals. Structural carbohydrates, which generally comprise two-thirds of the dry biomass, can be hydrolyzed to sugars and those sugars can be fermented to ethanol or other forms of liquid fuel. Even though lignin is not converted to fuel by the fermentation process, other conversion technologies, such as gasification and fast pyrolysis, could use lignin as an energy source. Biomass yield is the most important characteristic for sustainable bioenergy production. However, feedstock chemical composition and its consistency, which directly influence conversion process yield, are also very important.

Switchgrass has a similar feedstock composition to other lignocellulosic feedstocks. Lee *et al.* [33] reported that switchgrass biomass has 37% cellulose, 29% hemicellulose, 19% lignin, 3% crude protein, and 6% ash when harvested in late autumn or after a killing frost. They also indicated that the chemical composition of switchgrass is relatively similar to other crop residues, such as corn (*Zea mays*) stover and wheat (*Triticum aestivum*) straw. However, growth environment and genetics cause significant variation in feedstock composition [34]. Feedstock composition also has a significant impact on conversion efficiency, with one study demonstrating a range in potential ethanol production from 61 to 127 mg g^{-1} [34]. The range of composition data collected from multiples studies explained this variation, with cellulose, hemicellulose, and lignin varying from 31 to 45%, 22 to 25%, and 18 to 22%t, respectively.

Harvest timing is a major cultural practice affecting feedstock composition [33, 35–39]. Delaying harvest to after a killing frost provided biomass with higher structural carbohydrates and lignin as well as lower protein and ash compared to biomass harvested at anthesis. Further delaying harvest to the following spring reduced ash and protein concentrations even more [33, 35, 36]. Dien *et al.* [40] reported switchgrass mineral components were related to plant maturity (Table 5.1). Other studies indicate that either late season or

Table 5.1 *Stage of maturity is the primary factor controlling switchgrass biomass composition within a cultivar.*

	Composition (g kg^{-1})								
Stage of Maturity	Ca	K	P	Si	Cl	Mg	S	Ash	CP
Pre-boot	3.64	21.64	2.17	52.10	0.68	2.22	1.32	89	65
Anthesis	2.80	10.20	3.43	34.57	0.21	1.62	0.63	57	32
Post-frost	3.90	8.44	4.23	40.45	0.14	2.37	0.63	57	30

Adapted from Dien *et al.* [40] for Cave-in-Rock harvested near Mead, NE. All values are reported on a dry matter basis.

post-frost harvest are likely to provide biomass with lower nitrogen, phosphorus, potassium, and chlorine [36, 38, 41]. Consequently, cultural practices can be used to provide a feedstock with the most desirable composition profile [21].

5.3 Cultural Practices

Specific cultural practices for establishing and managing switchgrass have been developed for most agroecoregions. Establishing switchgrass has inherent risks, but they can be moderated with good management [22]. In the switchgrass establishment phase, excellent progress has been made by improving grass drills for minimum till establishment. Critical issues included developing optimal seedbed preparation procedures that provided proper seeding depth settings on grass drills (Figure 5.1), registering herbicides for weed control, and improving planting times to provide suitable soil temperatures and the greatest opportunity for precipitation [22]. Due to these advancements, realistic goals include achieving

Figure 5.1 *Depth bands on grassland drills regulate the depth with which small-seeded perennial grass seeds are placed below the soil surface. Switchgrass should be seeded no deeper than 1.25 cm below the soil surface to promote rapid establishment.*

establishment year yields equal to 50% of the cultivar's yield potential and essentially achieving full yield potential in the second year [22]. This is important for switchgrass production because as Perrin *et al.* [42] reported failing to establish successful stands in the seeding year can cost farmers more than \$300 ha^{-1}.

5.3.1 Establishment and Weed Management

Managing weeds is one of the most important factors for sustainable switchgrass biomass production. Since switchgrass seedlings develop more slowly than annual weeds, controlling weeds immediately after planting is critical for successful establishment. Additionally, the economic feasibility of switchgrass for bioenergy is dependent on establishing stands with a harvestable yield in the planting year [42]. Poor establishment caused by weed pressure can delay full production of biomass for two or more years [43]. Well-established switchgrass is less likely to have weed issues.

Weed pressure can be minimized in the establishment year by no-till seeding into glyphosate-tolerant soybean stubble, which provides an excellent seedbed. Switchgrass seed germination is slow and seedling vigor is low compared to annual grassy weeds. Consequently, it is important to plant high quality seed in properly prepared seedbeds [22]. If heavy weed pressure is expected, delay seeding until the first flush of weeds, then apply a broad-spectrum herbicide like glyphosate [N-(phosphonomethyl) glycine) before planting.

Applying pre-emergent and post-emergent herbicides shows a significant effectiveness in controlling and reducing weed populations during the establishment year. Normally, switchgrass establishment is not interrupted by broadleaf weeds. Herbicides, such as 2,4-D (2,4-dichlorophenoxyacteic acid) can control the broadleaf weed effectively, but should not be applied until after the switchgrass seedlings have reached the four- or five-leaf stage [21]. Early grassy weed growth is reduced with herbicides. The herbicides utilized in the forage industry will control weeds but label directions are critical for safe and proper application. The forage industry has used atrazine [2chloro-N-ethy-N′-(1-methylethyl)-1, 3, 5-triazine-2, 4-diamine] as a pre-emergent to control cool-season annual grasses and broad leaf weeds [44]. Quinclorac (3,7-dichloro-8-quinlinecarboxylic acid) is another common herbicide that can be used as a pre-emergent or post-emergent herbicide to control most of annual warm-season grass weeds [23, 45]. Mitchell *et al.* [23] reported that a combination of atrazine and quinclorac applied immediately after planting provided the best weed control and most rapid establishment for upland and lowland switchgrass ecotypes in Nebraska, South Dakota, and North Dakota, U.S.A. Although some herbicides work well for establishing switchgrass, not all herbicides are labeled for application on the crop in all states. Always read and follow label directions.

Weed competition in post-establishment years is not a major issue for well-established stands, but if stands are poor during the establishment year, they typically have increased weed pressure in subsequent years. Switchgrass stands with seedling densities below 10 plants per square meter are considered to be poor and should be over-seeded or reseeded [21]. As long as adequate switchgrass frequency of occurrence (i.e., $>$40%) has been achieved in the seeding year, weed control is relatively easy during the post-establishment years. One of the most effective methods to control cool-season annual or perennial weeds is with the application of a broad-spectrum herbicide, such as glyphosate. Switchgrass must be dormant when glyphosate is applied, either prior to spring green-up or after senescence in late summer or early autumn. Once switchgrass starts to grow, canopy development is much faster than annual warm-season weeds and summer annual weeds are usually not an issue.

5.3.2 Fertilization

Switchgrass fertilizer recommendations are a function of site productivity, cultivar yield potential, and management practices such as time of harvest [46]. Although switchgrass in extensively managed native grasslands tolerates low fertility soils, optimizing biomass and maintaining stand persistence in intensively managed bioenergy production fields requires fertilization. The primary limiting nutrient for switchgrass biomass is nitrogen and biomass increases as nitrogen rate increase. However, excessive fertilizer application can result in nitrogen leaching out of the root zone or nitrogen runoff and cause groundwater contamination [46].

Nitrogen application is not recommended during the planting year because nitrogen encourages weed growth, increases establishment costs, and increases economic risk if the stand fails [47]. In established stands, nitrogen fertilizer recommendations should be based on available soil nitrogen, anticipated biomass yield and when the switchgrass will be harvested. Soil sampling to a depth of 1.5–2 m is needed, since fertilizer application rates should be based on the difference between crop need and available soil nitrogen. Harvesting biomass removes nitrogen from the system and this must be replaced to meet future plant growth demands, but harvesting at different stages impacts the quantity of nitrogen removal by the crop. For example, a switchgrass field harvested after a killing frost that produces 11 Mg ha^{-1} of dry matter (DM) with a crude protein concentration of 4% (0.64% N) will remove about 70 kgN ha^{-1}. Therefore, 6–7 kgN ha^{-1} yr^{-1} should be applied for each 1 Mg ha^{-1} of anticipated biomass yield [22]. However, if harvesting at anthesis, 10 kgN ha^{-1} yr^{-1} should be applied for each 1 Mg ha^{-1} of anticipated yield, since the biomass will have a nitrogen concentration of 1.1–1.3% [46]. To prevent leaching and/or runoff, these recommendations may need to be adjusted for local soil mineralization and atmospheric nitrogen deposition.

Nitrogen fertilization rates are generally higher in the southern United States than in the northern Great Plains. For example, in Alabama, Ma *et al.* [48] reported switchgrass yields increased as nitrogen rate increased up to 224 kgN ha^{-1}. In Texas, the optimum nitrogen rate for Alamo switchgrass was 168 kgN ha^{-1}, and biomass yield averaged 14.5 and 10.7 Mg ha^{-1} yr^{-1} at Stephenville and Beeville, respectively [49]. Biomass declined over time on plots that received no nitrogen and was sustainable only with the application of at least 168 kgN ha^{-1} yr^{-1}. In Nebraska and Iowa, biomass yields of 'Cave-In-Rock' switchgrass, an upland cultivar, increased as nitrogen rate increased from 0 to 300 kgN ha^{-1}, but residual soil nitrogen increased when more than 120 kgN ha^{-1} was applied [44]. Biomass production was optimized with the application of 120 kgN ha^{-1}, with about the same amount of nitrogen being applied as was removed by the crop.

Phosphorus and potassium are generally adequate for switchgrass growth on most cropland soils [50]. Although switchgrass response to phosphorus has been variable, it may respond to fertilizer phosphorus if soil-test phosphorus is low or the site is very acidic (i.e., pH 4.3–4.9) soil [21, 51, 52]. Switchgrass did not respond to applied phosphorus in Texas [49] or in low-phosphorus soils in Iowa [53]. Quantifying the response of bioenergy-specific switchgrass cultivars to nitrogen, phosphorus, potassium and other nutrients is a major research need in all agroecoregions.

5.3.3 Disease and Pest Management

A number of diseases and insects have been reported for switchgrass and some concerns have been raised regarding large scale planting for feedstock production in the future [54]. However, no diseases or insects have demonstrated economic concerns to date. The list of diseases reported in the literature includes: rust associated with *Puccinia spp.*, anthracnose caused by *Collectotrichum spp.*, smut caused by *Tilletia maclaganii*, sharp eye spot caused by *Phyzotonia cerealis*, helminthosporium spot blotch caused by *Bipolaris sorokiniana*, and viral disease caused by Panicum mosaic virus (PMV), Phoma leaf spot (*Phoma spp.*), and Fursarium root rot, *Fusarium spp.* [55–64]. Most of these diseases are reported from a few field observations, with some cultivars being more susceptible to specific diseases. Individual genotypes can have susceptibility to diseases, but released cultivars and germplasms have been selected for a range of resistance to many diseases [16]. Sanderson [56] indicated that higher anthracnose infection was observed in Trailblazer than in Cave-in-Rock. Cave-In-Rock is the cultivar most susceptible to smut [16]. Smut infection can significantly reduce switchgrass biomass and seed production. In Iowa, a smut-infected seed field did not produce seed for several years [60, 65]. Thomsen *et al.* [66] reported that smut infection reduced Cave-in-Rock switchgrass biomass yield by as much as 40%. Consequently, smut seems to be the most serious disease at the present.

Few insects have been reported in switchgrass and, at present, generally appear to pose a limited threat. Grasshoppers (*Orthoptera*) are common herbage feeding insects that could affect switchgrass biomass productivity [16]. Recently, two other insects have been identified in switchgrass fields and natural populations in the US Midwest. Prasifka *et al.* [67] identified a stem-boring caterpillar (*Blastobasis repartella* Dietz) and its distribution and symptoms. Infestation of *B. repartella* can cause death of young tillers of switchgrass but its damage on biomass yield was not quantified. Reducing seed production is the primary concern with insects in switchgrass. Boe and Gagne [68] discovered a new species of gall midge [*Chilophaga virgate* Gagne (Diptera: *Cecidomyiidae*)]) in South Dakota. Infestation of the gall midge was observed in the peduncle inside the sheath of the flag leaf and the inflorescence never emerged. Depending on infestation rate, switchgrass seed production could be reduced by the gall midge. For example, the bluestem seed midge (*Contarinia wattsi* Gagne) was reported to reduce big bluestem (*Andropogon gerardii* Vitman) seed production by about 40% [69] and has been observed by the authors in heavy infestations in switchgrass.

5.3.4 Harvest Management

The primary objectives with switchgrass harvest management are to maximize biomass recovery, match feedstock quality to the conversion platform, and maintain productive stands [22]. Productive stands can be maintained indefinitely with proper harvest timing, cutting height and maintaining adequate nitrogen fertility [22, 70].

Switchgrass best management practices and extension guidelines have been developed for most regions [22, 71, 72]. Mitchell *et al.* [22] reported that high-yielding switchgrass fields (>12 Mg ha^{-1}) can be harvested and baled with commercially available equipment, but self-propelled swathers with rotary heads are needed to optimize efficiency and handle the volume of material harvested from switchgrass bioenergy production fields that may approach 20 Mg ha^{-1}. A cutting height of 10–15 cm maintains stands and keeps the windrows elevated to facilitate air movement and more rapid drying to less than 20% moisture content prior to baling [21]. Switchgrass biomass is packaged for storage and transportation in large round or large rectangular bales, with large round bales generally having less storage losses, whereas rectangular bales tend to be easier to handle and load on trucks for transport without road width restrictions [22].

Switchgrass research supports a single annual harvest for optimizing biomass and energy inputs, as well as maintaining stands. In Texas, Sanderson *et al.* [73] harvested several switchgrass strains once or twice per growing season from multiple environments and concluded that a single harvest in autumn maximized biomass and maintained stands. In Nebraska and Iowa, switchgrass harvested once at anthesis optimized biomass recovery [46]. Harvesting after frost minimizes nitrogen removal [69], reduces nitrogen fertilizer requirements for the following year by about 30%, and ensures stand persistence and productivity, especially during drought [21, 22]. In the first nine years of a long-term study, Follett *et al.* [70] reported switchgrass biomass was greatest in plots fertilized with 120 kgN ha^{-1} and harvested at a stubble height of 10 cm after a killing frost. These management practices ensure carbohydrate translocation to the plant crowns for setting new tiller buds and maintaining stand productivity [22]. For thermochemical conversion platforms and biopower, it is recommend harvesting after a killing frost because nitrogen, calcium, and other plant nutrients that function as contaminants are minimized in plant tissue [20]. More detail on harvest and storage management is given by Mitchell and Schmer [20].

5.4 Genetic Improvement

Switchgrass is a cross-pollinated species with a gametophytic self-incompatability system [74]. The species has two main ploidy levels (tetraploid and octoploid) that are largely cross incompatible, but controlled mating of breeding populations with the same ploidy level can be made using the procedure described by Martinez-Reyna and Vogel [74]. However, all released switchgrass cultivars to date are improved populations or synthetic cultivars [21]. Since the release of ‘Nebraska 28’, the first switchgrass cultivar for which certified seed was produced, numerous strains have been evaluated, selected, and improved by identifying and capitalizing on the genetic variability of desirable traits [21]. These traits have included forage or biomass yield, *in vitro* dry matter digestibility (IVDMD), cell wall composition, protein concentration, plant height, seed yield, seedling tiller number, rust resistance, maturity, and biotic and abiotic stress tolerance [21].

Approximately 35 switchgrass cultivars have been documented and released. Most of these cultivars were derived from direct seed increases of wild populations without selection, and were meant to represent a particular geographic region, habitat, or hardiness zone [4]. Their intended use was for prairie or savanna restoration projects and they were often given “place” names to reflect their origin, for example, ‘Alamo’, ‘Kanlow’, ‘Grenville’, and ‘Carthage’. However, as the demand for switchgrass increased in the livestock industry in the mid and late twentieth century, and later due to demand for research information on bioenergy feedstocks, many of these cultivars were used for multiple purposes. As of this writing, 14 switchgrass cultivars represent genetic improvements as a result of selection and breeding (Table 5.2). Historically, switchgrass breeding programs have focused on improving establishment characteristics, biomass yield and quality, and insect and disease resistance [21].

Table 5.2 *Improved switchgrass cultivars and germplasm releases representing significant breeding and selection activities.*

Cultivar	PI Number[a]	Ecotype	Ploidy	Year of release	Principal traits selected during cultivar development[b]	USDA Hardiness Zones[c]
EG2101		Upland	8x	2009	Biomass yield, spring vigor, rust resistance	4, 5, 6
Pathfinder	642192	Upland	8x	1967	Biomass yield and vigor	4, 5
Shawnee	591824	Upland	8x	1996	IVDMD, biomass yield	5, 6, 7
Sunburst	598136	Upland	8x	1998	Large seed size and mass	3, 4, 5
Trailblazer	549094	Upland	8x	1984	IVDMD, biomass yield	4, 5
Summer	642191	Upland	4x	1963	Earliness, rust resistance	4, 5
BoMaster	645256	Lowland	4x	2006	IVDMD, biomass yield	6, 7, 8
Cimarron		Lowland	4x	2008	Biomass yield	6, 7, 8
Colony	658520	Lowland	4x	2009	IVDMD, biomass yield	6, 7, 8
EG1101		Lowland	4x	2009	Biomass yield, spring vigor, rust resistance	8, 9, 10
EG1102		Lowland	4x	2009	Biomass yield, spring vigor, rust resistance	6, 7, 8
Expresso		Lowland	4x	2013	Rapid germination	6, 7, 8
Liberty		Lowland	4x	2013	Biomass yield, low lignin	4, 5, 6
Performer	644818	Lowland	4x	2006	IVDMD, biomass yield	6, 7, 8
TEM-LoDorm	636468	Lowland	4x	2007	Reduced post-harvest seed dormancy	6, 7, 8

[a] GRIN accession number (http://www.ars-grin.gov/). Empty cells indicate that a cultivar is not available through GRIN.
[b] IVDMD = in vitro dry matter digestibility.
[c] USDA Hardiness Zones are defined in approximately 5°C increments of mean annual minimum temperature (http://www.usna.usda.gov/Hardzone/ushzmap.html).

Seed dormancy, a frequent trait of wild switchgrass populations, has been gradually decreased by multiple cycles of recurrent selection in many breeding populations and cultivars [4]. Selection for increased IVDMD for ruminant livestock production systems resulted in reduced lignin concentration and altered lignin composition [75,76]. These modifications to lignin are also expected to have a significant positive impact on conversion of cellulosic biomass to energy in fermentation systems [77, 78]. Most breeding efforts have focused on increasing biomass yield, the most significant factor limiting economic sustainability of switchgrass as a cellulosic energy crop [42]. Proper cultivar selection, matching cultivars to geographic regions according to their origin and environmental adaptations [79], combined with sustained breeding efforts, have increased biomass yield by 20–30% between 1992 and 2002 [80]. Additional improvements, not yet documented through cultivar commercialization, suggest that breeders have increased switchgrass biomass yield by up to 50% in some geographic regions [4].

Both intra and interpopulation improvement methods are employed for switchgrass improvement. Intrapopulation improvement involves the use of recurrent selection for one or more traits, increasing the frequency of favorable alleles for those traits [4, 81, 82]. Recurrent selection can be conducted under different conditions, including spaced plantings, row plots, and sward plots. Spaced plantings generally are considered to be useful for the early generations of a breeding program, in which there may be many plants without sufficient vigor or adaptation to be considered for selection. As populations are improved, more effort may be required to measure complex traits, such as biomass yield, under more realistic (competitive) conditions, requiring the use of closely spaced plants or drill plots [4]. Cycle time for most intrapopulation switchgrass improvement programs ranges from two to seven years, with each cycle having the potential to generate a new candidate cultivar. Switchgrass breeders generally have worked together to generate uniform field evaluations of candidate cultivars across a broader geographic region than would be possible for a single breeding program.

Interpopulation improvement represents a new venture in switchgrass breeding. Recent studies indicate that the evolutionary divergence between upland and lowland ecotypes can be exploited to create F1 hybrids with superior performance to either of their parents [83,84] Two significant challenges in such a system will be (i) synchronization of flowering between the two parent genotypes, which can differ by up to six weeks in flowering time and (ii) vegetative propagation of the parent genotypes for hybrid seed production [4]. Growth regulators may assist in synchronizing flowering time, while micropropagation is the most likely mechanism for vegetative propagation of the parent genotypes. We are many years from a maize-like hybrid production system based on inbred lines, but the recent discovery of some switchgrass genotypes that tolerate high rates of self-pollination suggests that development of inbred lines may be a viable long-term goal.

Molecular biology tools and methods have been rapidly incorporated into a framework for switchgrass improvement, especially with recent advances in both cost and efficiency of molecular methods. Genetic transformation of specifically targeted lignin genes is highly effective in reducing recalcitrance of switchgrass biomass in a fermentation system, increasing rates of sugar release and reducing pre-treatment requirements [85–87]. Risk assessment studies are currently underway, designed to evaluate the potential impacts of both pollen and seed migration into existing natural prairie sites. Numerous DNA-marker studies have been conducted on a wide array of switchgrass germplasm, helping to develop and characterize regional gene pools, clarify the geographic origin of germplasm, and to gain a clearer understanding of the origins and evolution of switchgrass [13–15] With recent advancements in DNA-marker technologies, genomic selection has become a viable strategy for use in switchgrass improvement programs. Genomic selection allows simultaneous selection pressure on a large number of genes affecting the traits of interest, including genes with large or small effects and those located in nearly every portion of the genome. Switchgrass is still an undomesticated plant, with nearly all cultivars no more than four or five generations removed from the wild, and the future of switchgrass breeding and genetics holds great promise for significant improvements and advancements.

5.5 Summary

Long-term, field-scale research demonstrates clearly that switchgrass for biofuel production is feasible for the agroecoregions to which it is adapted and can help meet transportation fuel demands in the United States. Currently-available best management practices typically result in establishment year yields equal to 50% of the yield potential of the cultivar and near full yield potential in year 2. Although some insects and diseases do occur on switchgrass, it appears unlikely that insects and diseases will have a significant impact on the long-term productivity of switchgrass. Field production of switchgrass is best-adapted to cropland that is marginally productive for row crops, similar to land that was enrolled in the Conservation Reserve Program. Ongoing breeding efforts are improving switchgrass yield and, based on previous advancements in yield, likely will increase biomass yield by another 20–30% with the release of bioenergy-specific cultivars during the next decade.

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6

Sugarcane, Energy Cane and Napier Grass

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6.1 Sugar and Energy Cane

The 2007 Energy Independence and Security Act mandates that 16 billion of the targeted 36 billion gallons of biofuels must be derived from cellulosic sources. Sugarcane as a biofuel feedstock has tremendous potential as a source of this biofuel [1, 2]. Sugarcane is a major agronomic crop grown in approximately 80 countries within the latitudes of 30°N and 35°S [3, 4]. Utilization of the entire aboveground sugarcane plant and the development of high-fiber/low-Brix types of sugarcane as a potential bioenergy feedstock for cellulosic conversion technologies has been reviewed [5–10]. Sugarcane grown solely for the production of energy is commonly referred to as energy cane [11]. For energy cane to be sustainable, it must economically produce high and consistent yields [7]. This chapter discusses the production of sugar/energy cane as a dedicated bioenergy feedstock with an emphasis to areas where sugarcane may not be traditionally grown. Information on the production of energy cane is limited; however, its production should be somewhat similar to the production of sugarcane for sugar and much of the information presented will be based on research conducted on the production of sugarcane for sugar.

6.1.1 Phylogeny, Growth, Yield, and Chemical Composition

Sugarcane is a tall growing, jointed bunch grass that is cultivated as a perennial crop primarily for its ability to produce and store sucrose in its stem. It is a highly efficient "solar

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cell" with an estimated energy in:energy out (I/O) ratio of 1:8 when it is allowed to grow for 12 months under tropical conditions and its harvested dry matter (sugar and fiber) is processed for ethanol instead of sugar [12–15]. Under more temperate environments, where sunlight duration and intensity fluctuates (seasonally and daily) and cooler temperatures and occasional frosts shorten the growing season, I/O ratios of 1:3 are easily obtainable with current sugarcane varieties if ethanol production from both sugar and fiber is the goal [9]. Solar energy recoveries for energy cane, sorghum, and tropical maize have independently been reported as 2.24, 2.23, and 2.85%, respectively [16, 17]. Thus, energy cane is no more efficient in converting solar energy into chemical energy, but the extended growth phase allows it to capture more solar energy over an entire growth season relative to the other C_4 grasses. This extended growth phase is attributed to tillers remaining functional and the continuous activity of apical meristems throughout most of the year. Moreover, continued stem elongation, increased internode density, and continued canopy development of tillers allows for storage of solar energy as dry biomass in an extended spatial area [17–19]. The theoretical maximum for aboveground sugarcane dry matter (DM) yield is estimated to be 140 Mg ha^{-1} annually [20]. This is dependent on temperature and sunlight, and would probably occur only under tropical conditions.

The theoretical maximum fresh weight yield of sugarcane biomass is 358 Mg ha^{-1} yr^{-1} [5]. Early generation hybrids between sugarcane and *S. spontaneum* have been shown to produce sustained biomass yields approaching the theoretical maximum in Louisiana over a five-year period [21]. Unfortunately, the high biomass yields in these early generation hybrids are the result of high fiber yields, and not high sucrose yields, and as such they are generally crossed back to elite clones of sugar cane two or three times before a sugarcane clone worthy of commercial sugarcane production can be released [7].

With the quest to produce second generation fuels from cellulosic biomass these early generation F_1 hybrids are ideal biofeedstock candidates, that is, energy canes. Most of these hybrids can produce DM yields of 30 Mg ha^{-1} annually over four fall harvests, with about 20 Mg ha^{-1} being fiber and 10 Mg ha^{-1} being Brix [22]. One of the first sugarcane varieties developed for biomass production and utilization for the cogeneration of electricity was "L79-1002" [23]. The authors reported DM yields of 66.6 Mg ha^{-1} at a latitude of 30.4°N on 1.8-m wide rows. These yields from this variety were from fiber (27.9% on a fresh weight basis) and Brix (10.4% on a fresh weight basis).

Sugar and fiber levels in the harvested cane stalks are generally dependent on the variety, the length of the growing season, the amount of extraneous matter present, and the harvesting conditions. Sugarcane, once delivered to the raw sugar factory for milling, is separated into its water, Brix (soluble solids, of which approximately 80% is sucrose), fiber (bagasse) and sediment (ash, soil, etc.) fractions. The bagasse fraction in commercial sugar varieties consists of 38% cellulose, 19% hemicellulose, 22% lignin, 4% protein, and 3% ash, with the remaining 14% consisting of sugar, soil from harvesting, and other types of solids [21, 24]. The average fiber yield does not take into consideration leafy material removed in the field during the harvesting process, or the conditions under which the crop was harvested. When sugarcane is mechanically harvested for sugar without a pre-harvest burning of the standing cane, 4–6 Mg ha^{-1} of leaf litter is deposited back on the soil surface [25–27]. Moreover, in Louisiana, where sugarcane is grown on mineral soils, if the crop is harvested under wet and muddy conditions it is not uncommon to see 5–10% contamination with soil.

6.1.2 Cultural Practices

The production and processing of sugarcane is a centuries-old industry. The development of an efficient biofuels industry revolving around the production of energy cane as its principle feedstock will begin by initially adopting and then modifying production practices being used by the sugarcane industry. To this end, the discussions that follow for energy cane will be based to a large extent on the research generated to improve the production efficiency of sugarcane.

6.1.2.1 Establishment

Sugarcane is vegetatively propagated by planting either the whole stalk or stalk pieces (billets) containing two to three nodes per piece in the soil and covering with 5–8 cm of soil. Inter-row spacing ranges from 1 to 1.8 m, with the wider row spacings being the norm when sugarcane culture and harvesting are highly mechanized. Primary shoots and roots develop from the nodal buds with shoot emergence generally occurring 14–21 days after planting. Planting generally occurs a few weeks prior to the start of the harvest season. Growers typically produce their own stalks for planting (seed cane); hence, they delay planting until stalk numbers and heights are at their highest to maximize planting ratios and the amount of sugarcane available for processing to raw sugar. Sladden *et al.* [28] found that, in North Alabama, energy cane could produce dry weight yields over a four-year period of 15.9–32.4 Mg ha^{-1}, with the greatest yield occurring when sugarcane was planted in late summer at a depth of 10 cm. Burner *et al.* [3] also suggested that late summer, early planting could be used to extend energy cane planting beyond 32°N. Much of the aboveground growth that occurs will be winter-killed, but it can offer some protection against freezing to the belowground stubble buds of the newly planted crop prior to the beginning of the initial growing season (plant-cane crop) of the crop cycle the following spring. In subsequent years the residue generated during harvest could be used to offer some protection against freezing as well in more temperate climates.

Winter survival of belowground stubble buds will be problematic if energy cane is grown in more temperate areas due to saturated soils in the winter that encourage stalk rotting organisms and due to recurring freezes [29]. Thus cultural practices aimed at improving winter survival of the underground stubble buds will be critical to the sustained production of energy cane over multiple ratoon crops. As suggested by Sladden *et al.* [28] and Taggart [30] covering vegetative pieces of sugarcane with a thick layer of soil can provide some protection against freezing temperatures. Another form of winter protection, especially for the ratoon crops, is the blanket of leaf litter, that for sugar production from sugarcane is generally removed at harvest and deposited on the field's surface as a uniform blanket [31].

Yields tend to decrease with each yearly harvest of a crop cycle, especially where harvesting is done mechanically in the more temperate climates [19]. To sustain continuous farm yields, sugarcane growers strive to keep equal percentages of cane as: plant cane (first growing season – never been harvested), first ratoon (second growing season – harvested once), second ratoon (third growing season – harvested twice) and third ratoon (fourth growing season – harvested three times), and so on. Under this scenario where the harvest of the third-ratoon crop would end the crop cycle, a grower would have 20% of the crop as plant cane, 20% as first ratoon, 20% as second ratoon, and 20% as third ratoon. The remaining 20% would either be fallow and being readied to plant or has just been planted. Energy cane is anticipated to produce more ratoon crops and more stalks per hectare. With more ratoon crops and more stalks available to use as seed cane, the percentage of fields planted each year would decrease and the hectares planted per hectare of seed cane used would be greater and, as a result, planting costs should be significantly lower than the costs associated with sugarcane production. As discussed below, harvest dates and harvesting conditions can affect ratoon yields and the decision to plow out fields prematurely and prepare them for re-planting.

Once the crop emerges, it goes through a period of tillering, producing secondary and tertiary tillers from compressed belowground nodal buds on the primary shoots. Stand establishment through tillering occurs over several weeks. Dry conditions and sunlight promote tillering at the beginning of each growing season, whereas frequent rainfall and cloudy conditions discourage excessive tillering. Many of these tillers will die off after canopy closure due to intraspecific competition.

The tillering phase is followed by a period of aboveground nodal formation and rapid internodal elongation. This period, referred to as the "grand growth period", can last several months. During this period it is not uncommon to get growth of 2–4 cm per day. The grand growth period may last 140–196 days and is responsible for sugarcane's biomass accumulation [17]. It is during this grand growth period that rainfall or irrigation is critical to sustain this rate of growth. The grand growth period is followed by a ripening or sugar accumulation stage [32]. Sugarcane is fairly deep rooted and like sweet sorghum can tolerate droughty conditions for a brief period [1]. Dry conditions and the shortening of day length generally trigger the ripening of the crop whereby photosynthates form stored sucrose. This is generally in the fall of the year, 10–12 months after the emergence of the crop in tropical environments and 8–10 months after emergence in subtropical environments. In either case the growing season ends with the harvest of the crop.

6.1.2.2 Fertilization

Like all grass crops, sugarcane and energy cane will respond with greater yields to the application of nitrogen, phosphorus and potassium, as well as additions of sulfur and some minor elements. The carryover of applied nutrients also contributes to the early vigor of the subsequent ratoon crop. Optimum soil pH for sustained crop yields is generally in the range of 5.5 to 7.5, with the target being 6.5 [33]. For sugarcane, optimum nitrogen, phosphorus, and potassium rates are dependent on soil type and production year of the crops cycle, with the lower rates applied to the plant cane crop on light textured soil and the higher rate to the ratoon crops growing on heavy textured soil. Fertilization generally occurs during the mid to late phases of the tillering stage. The early generation hybrids being developed as energy cane appear to be more efficient in the utilization of applied nutrients. Research to date has not identified the ideal rates of fertilizer application for energy cane. Where sugar is a desired product, the use of higher rates of nitrogen, for instance, results in higher yields of cane but sucrose levels are lower; hence, sugar per hectare yields may be unchanged [34]. In terms of sucrose production efficiency, with excessive nitrogen more biomass has to be harvested, transported, and processed for the same amount of sugar produced. These expenses are further compounded by the added cost of the fertilizer. For cellulosic biofuel production, the addition of extra fertilizer may be of a benefit to get more biomass. However, the effect of the added fertilizer on the composition of the stalk is not known. Mislevy *et al.* [35] found only a slight benefit in biomass yield when nitrogen rate was increased from 168 to 336 kg ha^{-1}. The nitrogen content in the aboveground biomass was 5 and 4 g kg^{-1} at the 336 and 168 kg ha^{-1} rates, respectively. Some varieties of sugarcane have been shown to have the capability of maintaining a beneficial association with nitrogen fixing endophytic bacteria, which could be exploited as a means of reducing nitrogen requirements [36, 37].

6.1.2.3 Disease, Insect, and Weed Control

A continuing supply of early emerging, high stalk population, disease and insect resistant varieties from breeding stations has been the major contributor to the management of yield-robbing pests. Major diseases of sugarcane include: (1) viruses: potyviruses that cause mosaic (*Sugarcane mosaic virus* and *Sorghum mosaic virus*) and sugarcane yellow leaf (*Sugarcane yellow leaf virus*); (2) bacteria: ratoon stunting disease (*Leifsonia xyli* subsp. *xyli*), leaf scald (*Xanthomonas albilineans*), and sugarcane brown rust (*Puccinia melanocephala*); and (3) fungi: sugarcane smut (*Ustilago scitaminea*). This complex of bacterial, fungal, and viral diseases are threats to energy cane as race changes are common. In most cane growing regions, sugarcane is grown as a monoculture. deVries *et al.* [1] concluded that of the various energy feedstocks being considered, the risk of yield loss associated with the buildup of soil-borne diseases in a continuous cropping system was the least with sugarcane, especially if a short fallow period or a legume is included between cane cycles.

The stem borers (Lepidoptera: Crambidae), including the sugarcane borer [(*Diatraea saccharalis* (Fabricius)] and the Mexican rice borer [*Eoreuma loftini* (Dyar)], represent the major insect threats to both sugarcane and energy cane. Economical control of both of these stalk borers in sugarcane is currently obtained by an integrated pest management program (IPM) that utilizes varietal resistance, manipulation of cultural practices, biological control through natural predators, and the judicious use of insecticides including Lepidoptera-specific insecticides. Insecticides are applied only when pressures exceed established economic thresholds, and these are determined by using frequent scouting during the grand growth period [38]. The impact of these borers is primarily on sugar production; hence, their impact on energy cane has not been thoroughly researched. However, it is likely that pest management in energy cane will mirror IPM as practiced in sugarcane. Borer preference appears to be more towards the low-fiber, high-sugar varieties and less towards the high-fiber, low-sugar varieties of sugarcane, which may be an advantage for energy cane [39]. Energy cane is expected to be grown to a large extent on low-rent, marginal, or underutilized land and in many cases adjacent to traditional food, feed, and fiber crops, where other types of disease and insect pressures may be encountered. Energy cane may harbor diseases and insect pests that may be injurious to the food crops as well; however, these canes may also serve as important overwintering sites for beneficial insects, thereby enhancing the role of biological control.

Broad spectrum pre-emergence and post-emergence herbicides are labeled for use in sugarcane, and presumably this labeling will allow their use in the non-food use energy cane as well [40]. The non-food use designation may also allow the use of herbicides not currently labeled for use in sugarcane. Perennial weeds, such as johnsongrass (*Sorghum halepense*), Bermuda grass (*Cynodon dactylon*), and nutsedge (*Cyperus* spp.) and a multitude of annual species, but most importantly itchgrass [*Rottboellia cochinchinensis*) and morning glory (*Ipomoea* spp.), are particularly problematic, as cultivation is limited to only in the early spring and to the inter-row space for a period of five or more years [41]. The most critical applications of herbicide are at planting and at the start of each growing season of the crop cycle when the crop is in its infancy period [42]. Energy cane appears to be more competitive with weeds than sugarcane because it emerges faster and produces more shoots. Because of the wide row spacing to accommodate mechanical culture and harvesting, an application of herbicide at the start of each growing season is recommended for sugarcane. As energy cane may be more aggressive, applications of herbicide may not be needed after the first ratoon production year.

6.1.2.4 Harvest Management

The length of the growing season dictates biomass yields. In the tropics the growing season begins immediately after the planting of the crop (plant cane crop) or the harvest of the crop (ratoon crops). In the tropics the peak of the harvest season is dictated by the maturation (optimum sucrose accumulation) of sugarcane or biomass accumulation of energy cane. Both would be expected to occur 10–12 months after emergence. As temperature fluctuation is minimal in the tropics, the harvest season can extend over a nearly 12-month period. In the more temperate environments the growing season begins regardless of production year in the spring after a period of winter dormancy following the last killing freeze/frost and when soil temperatures warm to 18–20°C [18]. Likewise, the growing season ends at harvest or when apical meristems are killed by a freeze/frost. Hence, in more temperate climates the growing season may only be 7–10 months in length [29].

In the more temperate climates the first crops of the multiyear production cycle (plant cane and first ratoon) tend to grow more aggressively than the older ratoon crops and benefit more from a longer growing season. As a result, the older ratoon crops should be harvested first. Early harvest, though necessary in temperate environments where sucrose crystallization is a target, has consequences such as lower biomass yields, higher stalk moisture contents, and reduced stubble longevity [19]. Most tall grasses, including energy cane, will not tolerate continuous harvesting at an immature stage without sacrificing yield in the subsequent ratoon crop [17, 19, 35, 43–45]. Harvest date will affect both the quantity and the chemical composition of the harvested product [35, 45]. Mislevy *et al.* [45] found that following four yearly harvests in October, yields were nearly tenfold lower than when energy cane was harvested yearly in December. By year four there was essentially no survival in the early harvested plots while the late harvested plots saw only a 1% reduction between the plant cane and third ratoon crops. Of the chemical components measured, only protein and *in vitro* organic matter digestion decreased quadratically with plant maturity. Burner *et al.* [3] suggested that delaying harvest beyond a freeze in more temperate climates could improve feedstock quality for cellulosic conversion by reducing water concentrations, but this could also reduce the yield of leaves, lignin, ash, and cellulose.

Forage harvesters, sugarcane harvesters, and cutting/baling type harvesters are being evaluated for their efficiencies in harvesting energy cane and delivering a quality biomass product to the biorefinery. Mislevy and Fluck [43] used a cutting fluffing, raking and baling method to harvest energy cane. They estimated that it cost \$11.80 Mg^{-1} DM to harvest using this system but for every unit of fossil fuel energy invested in harvesting operations, 49–58 units of biomass energy was harvested. When they added all costs from production to harvesting they predicted that 24 000 MJ ha^{-1} of fossil fuel energy would be required but the yield would be 13 to 15-fold higher in fuel equivalents.

As the crop does not dry easily, the excess water will have to be removed. If water removal is done at the biorefinery, which appears to be the most efficient based on economies of scale and methodology available, size of the harvested material and density of the load as well as the storability of the delivered material will be issues that must be considered [46]. Other issues when it comes to mechanical harvesters will include: the value of the leafy material (CO_2 sequestration and nutrient cycling if left on the field versus fiber for fuel) and the need to harvest in wet weather. With the sugarcane chopper harvester, extractor fan speeds can be adjusted to remove various quantities of leaf material from the stalks during harvest [31]. During wet-weather harvesting, the blanket of leaf material generated during the harvest with a sugarcane harvester offers some traction to the harvesting and transporting equipment.

Storage of a wet product is of concern to a biorefinery. Woodard *et al.* [47] and Woodard and Prine [17] found that energy cane was a good candidate for ensilage fermentation because it contained adequate levels of water-soluble carbohydrates that provided energy for fermentation bacteria to proliferate, particularly those genera that ferment available substrates to lactic acid. In addition, the fresh biomass possessed low buffering capabilities.

Soil collected during mechanical harvesting, especially of lodged sugarcane, interferes with raw sugar recovery in a raw sugar factory and will also pose problems for a biorefinery; hence, the cutting height of the stalk above the soil line will be a quantity versus quality issue. The goal will be to deliver as much of the aboveground stalk as possible to insure high biomass yields while also maintaining quality at an acceptable level. For sugar production, sugarcane stalks are generally cut 3–5 cm above the soil surface. Cutting lower increases tonnage but can increase the amount of soil in the delivery, which affects sugar recovery and, ultimately, results in a penalty to the grower. The young, soft internodes at the top $20+\%$ of the stalk contain more water than fiber and are not nearly as dense as the lower portions of the stalk. For sugar recovery this section is removed during harvesting and this may have to be done with energy cane as well to improve transport efficiency, as the cost to harvest and transport this section of the stalk may outweigh any gains in fuel yield.

There would be some value in collecting the leaf litter with the stalks in a cellulosic conversion process [48]. Leaves represented as much as one third of the biomass and had large cellulose ($\leq$482 g kg^{-1}) and lignin (167 g kg^{-1}) concentrations [3]. During the harvest of green sugarcane, the extraneous leaf material is removed to increase efficiency by reducing transportation costs and the recovery of raw sugar. In Mauritius, it was estimated that energy production could be increased by up to 50% by adding the extraneous leaf matter into the energy production system [49]. Mislevy *et al.* [35] found that the percentage of green leaves decreased from 70% when harvested in October to 17% when harvested in December, with green leaves only being at the top of the stalk for the December harvest. At the later harvest, an additional 17–20% was dry leaves.

Since the leafy material adds to harvesting and shipping costs and affects sugar recovery in sugar production, the majority of the leaves are removed in the field, either mechanically during harvest, or by burning prior to harvest. Burning restrictions are dictating that much of the sugarcane be mechanically harvested green. Where sugarcane is grown for sugar and sufficient moisture is available during the growing season, the 8–10 cm blanket of residue that is generated (6–24 Mg ha^{-1}) must be removed prior to the start of the next production year of the crop cycle, as the blanket of residue suppresses the emergence of the ratoon crop [25–27, 50]. However, the residue can have some positive benefits, such as weed suppression, moisture conservation, nutrient re-cycling, carbon sequestration, reduced soil loss, additional traction during wet-weather harvesting, and, where grown in extreme subtropical conditions, belowgrown stubble bud protection from freezes [51]. deVries *et al.* [1] estimated that in tropical areas 2.1 t ha^{-1} of effective organic matter has to be returned to the soil to maintain soil organic matter levels for a sustained 100 Mg ha^{-1} fresh cane yield. Research is needed to take advantage of the positive attributes of the post-harvest residue without discouraging crop growth.

Currently, the bagasse has value to the raw sugar factory, as it is burned in the boilers to generate the steam and electricity needed to process the cane into its saleable sugar and molasses components with excess electricity also to be sold. The amount of bagasse needed to power a biorefinery would be considerably lower if the need for sugar crystallization is eliminated [2]. The blanket of leaf litter generated during green-cane harvesting is burned in many of the sugarcane growing areas because it inhibits the growth of the subsequent ratoon crop, but this material could be collected to increase bagasse supply.

6.1.3 Genetic Improvement

The greatest needs to make energy cane a suitable feedstock for the biofuels industry are: (1) cold tolerance for expansion outside current tropical and subtropical cropping regions; (2) drought and flood (saturated soil) tolerance to allow growth on marginal soils prone to flooding or where irrigation is not viable; (3) insect and disease resistance; and (4) further exploitation of some varieties of sugar cane that encourages symbiotic relationships with endophytic nitrogen fixing bacteria [37].

Sugarcane is a complex *Saccharum* spp. hybrid ($2n = 100$–130). Hence, the possible genetic combinations are extremely large [9]. Much of the genetic improvement in sugarcane has come from the introgression of genes from sugar cane's wild species, *Saccharum spontaneum* [9, 52]. The early generation (F_1) hybrids resulting from crosses involving *S. spontaneum* as the male parent and elite sugarcane clones as the female parent, produce high biomass yields and tolerance to a number of biotic and abiotic stresses to include tolerance to: diseases, insect pests, and temperature and soil moisture extremes. These hybrids are also good stubblers, which contributes to their longevity as perennial crops following annual harvests, tend to resist lodging, and are more efficient in utilizing available nutrients than their female parent [21, 53]. Sugarcane's wild species, *S. spontaneum*, has been used in breeding programs around the world as a valuable source of abiotic and biotic stress tolerant and stubble longevity genes [53–57]. *S. spontaneum*, considered a noxious weed in the United States, can be found growing naturally in the continents of Africa, Asia, and Australia in environments ranging from tropical to temperate. For breeding programs in the more temperate climates, the source of *S. spontaneum* has come from the foothills of the Himalayas [55, 56, 58, 59]. Sugarcane has been successfully crossed with its wild relatives *Erianthus* [60] and *Miscanthus* [61] to obtain additional cold and disease and insect tolerance. Therefore, with a focused breeding program for bioenergy feedstocks, a rich source of genetic diversity, and the plasticity of autopolyploid genomes, it should be possible to develop a pipeline of energy cane varieties that can be grown sustainably in areas outside the traditional cane growing areas and, especially, on marginal land, where the sustainable production of conventional agronomic crops is difficult [62].

In Louisiana, fertilizer nitrogen represents a significant input for plant cane (\$101 ha^{-1}) and ratoon (\$126 ha^{-1}) sugarcane crops [63] and is based on 90 kgN ha^{-1} for plant cane and 112 kgN ha^{-1} for ratoon crops. Lima *et al.* [37] observed in Brazil that lower rates of nitrogen did not affect yields of sugarcane due to benefits from associative nitrogen fixing endophytic bacteria. Breeding programs could improve nitrogen use efficiency by incorporating genes from these types of sugarcane into their breeding program.

Sugarcane breeding programs have reported sugar yield gains in the order of 1–2% per year [64]. The economic sustainability of growing energy cane in non-traditional cane growing regions will require further biomass yield gains of this magnitude, or greater, with a goal of ensuring that the I/O ratio of 1:8 projected for tropical countries can be met and ultimately exceeded under non-traditional cane growing conditions. Sugarcane varietal development using conventional breeding and selection techniques takes 12–13 years from the time a cross is made until a variety is released for planting. Since the crop is vegetatively propagated, it takes another three or four additional years to have a sufficient supply of material from a newly released variety to supply a biorefinery for processing. Therefore, geneticists will need a clear signal from bioprocessors as to the value of the sugar, leaf litter, bagasse, and the water that this crop produces.

6.2 Napier grass

Napier grass, [*Pennisetum purpureum* (L.) Schum.], also known as elephant grass is native to equatorial Africa and is a major forage crop in the wet tropics of the world. It resembles sugar or energy cane in stature and in methods of propagation. It is considered a viable feedstock for bioenergy due to the perennial nature and yields similar to energy cane in Florida and Georgia [65].

6.2.1 Phylogeny, Growth, Yield and Chemical Composition

Napier grass is in the Panicoideae subfamily of the Paniceae tribe [66, 67]. *P. purpureum* is an allo-tetraploid with a base chromosome number 28 ($2n = 4x = 28$) with A and B genomes [68] and is phylogenetically similar to *P. glaucum* [69]. The A genome is homologous to pearl millet (*P. glaucum* L.) and is larger than the B genome, which controls the perennial growth habit of napier grass [70].

Napier grass is a tall bunch-type grass that produces a deep root system and rhizomes and can reach 6–7 m in height. The species is tropical in nature and performs well in climate zones 8 and 9 with temperatures of 30–35C [71]. Though frost will kill all aboveground plant material, well established plants will re-emerge in the spring if the soil does not freeze [70]. Napier grass responds well to irrigation and fertilizer but has drought tolerance due to a deep root system [72]. Napier grass has day length sensitivity and generally flowering will be initiated when day length is reduced to 11 hours or less. However, there appears to be an interaction on flowering initiation between day length and temperature [70].

Dry matter (DM) yield of napier grass varies due to cultivar and environment. The cultivar 'Merkeron' [73] was compared to the switchgrass cultivar 'Alamo' at three locations in

Georgia. Merkeron yielded 27 Mg ha^{-1} versus 15 Mg ha^{-1} for Alamo when averaged over six years [74]. Yields of between 30 and 60 Mg ha^{-1} yr^{-1} of DM have been reported for lines tested in southern and central Florida [75] and from 20–30 Mg ha^{-1} yr^{-1} in northern areas of the South [76]. Yields decreased significantly from the 31 Mg ha^{-1} yr^{-1} averaged for the first two years of a four-year study with no fertilizer inputs at Tifton, GA [65].

Napier grass leaves have high value as forage due to high crude protein and good digestibility [70]. The composition of napier grass leaves and stem vary widely. As a measure of forage quality, the percent *in vitro* dry matter digestibility (IVDMD) ranged from 35 to 60% for leaves and from 21 to 51% for stems among mature plants from a diverse germplasm nursery at Tifton, GA [77]. From the same nursery the percentage of neutral detergent fiber (NDF) ranged from 62 to 85%, and the percentage acid detergent fiber (ADF) from 34 to 60% for both leaves and stems. Lignin content is much greater in stems. The percentage acid detergent lignin (ADL) from leaves can range from 2 to 5% while stems have between 5 and 13% [77]. Hemicellulose tends to be higher in leaves than in stems [78]. Tall, high biomass genotypes generally average 20% leaf DM after a full season of growth. Leaf dry matter generally is negatively correlated with plant height; however, some tall accessions have relatively high leaf dry matter [79]. The protein content of napier grass leaves are the highest among perennial grasses [80], which may allow for production of plant protein-derived bioplastic polymers [81].

Compared with switchgrass, harvested napier grass after frost had a higher ash, nitrogen, potassium and phosphorus content in a four-year study at Tifton, GA [65]. It was found that with no addition of nutrients to plants, the uptake of potassium was dramatically reduced the second year while maintaining high yields, indicating that napier grass is a luxury consumer of potassium.

Biochemical conversion to ethanol has been shown to have potential for young napier grass plants. When four- to eight-week-old napier grass material is pretreated with esterase and subsequently cellulase, free sugar release is comparable to corn leaves [77] or bermuda grass [82]. Conversion of mature Merkeron by simultaneous saccharification and fermentation (SSF) resulted in 107 mg g^{-1} of ethanol compared to 122 mg g^{-1} for Coastal bermuda grass [83].

6.2.2 Cultural Practices

6.2.2.1 Establishment

Napier grass is generally vegetatively propagated via stem cuttings of mature plants but can also be established from rhizomes. Genotypes do not produce large numbers of seed and released cultivars such as "Merkeron" are heterozygous such that progeny from them will be heterogeneous. Acreage can be multiplied by up to 20$\times$ from mature stem material when planted in late summer to early fall though, it is more labor intensive and costly [70]. Methods for establishing napier grass through planting techniques have been established [84], but further improvements in mechanization for harvesting planting material are needed. Woodard *et al.* [85] reported that the tall napier grass is easily established from stem cuttings, especially from the lower stalk (more mature). Greenhouse studies in at Tifton, GA confirm this result (data unpublished). Maximum planting depths should not exceed 10 cm. In one study the number of shoots that emerged from stem cuttings increased as the stems were cut into shorter pieces due to apical dominance, that is, the buds at nodes at either end of the cutting tended to begin growth while buds at nodes between the outer nodes remained dormant [70]. In a study at Tifton, GA stem length did not affect the germination of Merkeron, though time of planting in the fall did have a large effect on spring emergence. Over two years in Tifton, there was a fivefold improvement in spring emergence when planting material in September versus October or later [86].

6.2.2.2 Fertilization

High napier grass yields require soils with adequate nutrients and water. Merkeron DM yields decreased from year two after establishment (30.5 Mg ha^{-1} yr^{-1}) to year three (11.4 Mg ha^{-1} yr^{-1}) by 63% without the addition of nitrogen fertilizer in Coastal Plain sandy-loam soils [65]. Under no fertilizer application in East Africa, DM yields dropped dramatically after the first year after establishment [87]. Annual NPK fertilizer rates of 225–25–90 kg ha^{-1} were recommended for Merkeron after it was released [88]. In Florida, the accession PI 300086 yielded 40 Mg ha^{-1} yr^{-1} when fertilized with 330 kgN ha^{-1} yr^{-1} and harvested at 3-cm cutting height above the soil after 24 weeks of growth [89]. Averaged across two years, DM yield increased from approximately 20 (6-wk treatment) to 40 (24-wk treatment) Mg ha^{-1} yr^{-1}. Though the majority of studies have been conducted with inorganic fertilizer, studies have investigated the use of organic fertilizers such as municipal biosolids. Replacing up to one third of surface applied inorganic nitrogen with municipal biosolids (MBS) resulted in equal dry matter yields in a study in Florida [90] but it also depends on the timing of application due to temperature and rainfall [91]. However, DM yields were equal to inorganic nitrogen when incorporating MBS [92].

6.2.2.3 Disease and Pest Control

Diseases and insect pests have generally been minimal on napier grass grown in the United States. In Africa, a leafhopper (*Recilia banda* Kramer) has recently been identified as a vector to Napier stunt disease [93]. This disease is caused by a phytoplasma and has caused significant yield losses in East Africa [94, 95]. Other diseases observed in Africa are sooty mold (*Khuskia oryzae*), generally associated with aphids and white mold (*Beniowskia sphaeroidea*) [87]. The most significant disease observed in the United States is eye spot (*Helminthosporium ocellum* Faris) [96], but resistance to this disease has been bred into the released cultivar Merkeron and resistance is found in many of the plant introductions. Insect damage is rare, partly due to thick pubescence on leaves and stems of most genotypes. However, two-lined spittlebug (*Prosapia bicincta* Say) has been shown to reduce stand loss of napier grass $\times$ pearl millet hybrids [97]. Weed control is essential at planting and spring re-emergence for good napier grass establishment and early growth. No herbicides are currently labeled for napier grass. Cutts *et al.* [98] studied 13 herbicides singly or in combination. Atrazine performed the best for most broad leaf weeds, pendimethalin for Texas millet (*Urochloa texanum*), and sulfentrazone for yellow nutsedge (*Cyperus esculentus*).

6.2.2.4 Harvest Management

Maximum yields are obtained under long growing seasons and warm temperatures. Calhoun and Prine [89] determined that napier grass yields increased from approximately 20 to 40 Mg ha^{-1} yr^{-1} when harvested at 3-cm stubble every 6 or 24 weeks, respectively, which is consistent with other studies [70]. However, Woodard and Prine [97] found that harvesting interval varies by genotype. Shorter cutting height above the soil and harvest intervals can substantially reduce persistence of stands [70]. Napier grass can be persistent and productive when cut at a 10-cm stubble height if the harvest interval was nine weeks or longer [99].

There are large differences between stem and leaf cell wall composition, thus leaf/stem ratios can be important, depending on the end use. The leaf/stem ratio declines with increased age or height of plants [70, 100, 101]. Also, harvesting napier grass as chopped or baled hay requires a fast reduction in moisture content. Early season moisture content can be as high as 90%, however, at maturity it is normally reduced to 70–75%. To reduce moisture content mechanical treatments will be required. Roller crushing of the harvested material reduced drying times fourfold for stalks separated from leaves [102].

6.2.3 Genetic Improvement

Germplasm of napier grass made its way throughout the tropics over the past century and has been adapted for use as forage throughout the tropics. Tremendous phenotypic variability exists for plant height, leaf size, hairiness, inflorescence size and color, and stem thickness [70]. A collection of over 100 accessions and breeding lines has been maintained at Tifton, GA for the past 35 years [70]. This collection has been assessed for traits such as leaf/stem ratios, leaf retention and cell wall components [70]. Harris *et al.* [79] used amplified fragment length polymorphisms (AFLP) to determine genetic relatedness of the collection. They differentiated five heterotic groups from 89 accessions characterized through principal component analysis of 218 polymorphic AFLP markers. Three of the clusters originated from Kenya, a separate group from Puerto Rico and another cluster from breeding lines related to Merkeron [79]. Formal breeding efforts have been limited primarily to the Western hemisphere. A number of cultivars have been released in South America [70, 103]. Merkeron was the first napier grass release in the United States [73]. A breeding program began in Florida in the 1980s and, in collaboration with the Tifton program, released "Mott" a dwarf derivative from Merkeron which was developed as forage [104].

A method of crossing napier grass is facilitated by the fact that flower heads are protogynous, so crossing is done by pollinating prior to anther emergence [70]. Since clonally propagated parents are heterozygous, the F_1 hybrids are generally heterogeneous, and single plant selections are increased by stem cuttings, in a similar manner as for sugarcane, for further testing. Napier grass has been crossed with pearl millet to produce sterile triploids that can be productive [105]. Fertile hexaploids have been recovered through chromosome doubling with colchicine [68, 77]. Apomictic napier grass may also be possible through numerous back-crosses with an apomictic relative *P. squamulatum* [70, 77]. An apospory-specific genomic region (ASGR) has been identified [106], such that selection for the trait could be facilitated through markers.

To date, marker-assisted breeding has not been employed for napier grass. Some recent work has documented its genetic diversity. Isozymes and molecular size variations in specific proteins have been performed on napier grass accessions [107, 108]. Moderate polymorphism has been shown among accessions via RAPD (Random amplified polymorphic DNA) markers [109, 110] and they were able to differentiate the geographic origins of the accessions. AFLP markers were used to measure diversity among napier grass accessions [79] and SSR markers developed for pearl millet (*P. glaucum* (L) R. Br.); a related species [111] could be used for marker-assisted breeding.

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7

Sorghum

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7.1 Introduction

Sorghum (*Sorghum bicolor* L. Moench) is an important crop species in the United States and around the world. Because of its substantial heat and drought tolerance, sorghum production is traditional in semi-arid, subtropical and tropical regions. In addition to abiotic stress tolerance, sorghum is very responsive (in terms of productivity) to more favorable conditions. While primarily known as a cereal grain, sorghum is grown throughout the world as a forage, syrup and more recently, energy crop. In 2008, U.S. farmers harvested about 2.9 million hectares of grain sorghum (USDA NASS, http://www.nass.usda.gov/). Worldwide, the top 20 grain sorghum producing countries harvested 49 472 518 metric tonnes of grain in 2007 (FAOSTAT, http://faostat.fao.org/). Unfortunately, production statistics for the other types of sorghum (i.e., forage and sweet) are not reported.

With renewed national and international emphasis on sustainable bioenergy, interest in sorghum as a bioenergy crop has increased for several reasons [1]. Firstly, sorghum has an established production history as a crop in the United States and around the world. This history eliminates the time required for crop domestication, production and market development and reduces concerns regarding producer acceptance and adoption. Secondly, there is a well established seed industry that is knowledgeable regarding genetic improvement and proficient in seed production. Thirdly, the annual nature of the crop, while a detraction to some, increases the speed and efficiency at which sorghum can be genetically improved and deployed in a production environment. Finally, sorghum has evolved as a standard genetic model for improvement of bioenergy crops. Combined, these factors confirm that sorghum will play an important role in the development and evolution of dedicated energy crops.

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Within this chapter, a brief summary of sorghum growth and development, composition, relevant production issues and genetic improvement approaches are discussed.

7.2 Sorghum Phenology, Genetic Structure and Types

The cultivated sorghums are all varieties or hybrids from *S. bicolor* L. Moench. The sorghum species is quite diverse but very consistent both genetically and botanically. All *S. bicolor* is a genetic diploid with base chromosome number of n = 10 and 2n = 2x = 20. While there is evidence that the crop is an ancient tetraploid, it is a functional diploid [2]. The genome size is larger than rice but substantially smaller than corn (*Zea mays*) or other grasses species and the complete genome has been sequenced [3]. In addition to *S. bicolor*, there are several additional Sorghum species, but none are systematically cultivated and many are perennial. Those species have variable growth habits and chromosome numbers but they do represent an additional source of genetic variability if needed. Of these, *Sorghum halepense* is likely the most infamous because it is the persistent and aggressive weed known as johnsongrass.

Botanically, sorghum is a member of the Panicodeae family. It is a typical grass with a deep and fibrous root system, primary culm and the capacity for both basal and axillary tillering. Reproductively, sorghum has a complete flower that is exerted through the top leaf sheath prior to anthesis. Sorghum species are predominantly self-pollinated but outcrossing does occur at rates between 2 and 30%; the precise amount of cross-pollination is a function of both genotype and environment [4]. While it is self-pollinated, sorghum is highly amenable to commercial hybrid seed production through the use of cytoplasmic male sterility systems. The crop is typically grown and managed as an annual but it is technically a perennial; once harvested, it will regrow unless environmental conditions (e.g., freezing temperatures) preclude further growth. Among commonly grown cereal crops, sorghum has a high water use efficiency and very good heat and drought tolerance. Plant maturity and height are highly variable and influenced by both the genetics of the species and the environment.

As an energy crop, sorghum is unique in that there are several types of sorghum that are and can be used for biofuel or bioproduct production, with the defining factor in these crops being the primary source of fermentable carbohydrates. Grain sorghum, long used as feed grain, is now a significant contributor to biofuel production in the United States [5]. Sweet sorghum, long used as a sweetener, is now being deployed in conjunction with sugarcane in sugar to ethanol conversion facilities and biomass sorghums produce significant quantities of structural carbohydrates. Different types of forage sorghums, commonly grown for animal grazing, hay or silage, are integrated into the biomass sorghums and occasionally, and sometimes incorrectly, into the sweet sorghum group.

7.2.1 Types of Sorghum for Energy Production

Grain sorghum is grown primarily for starch, a primary component of the grain and like corn, a substantial portion of the U.S. grain sorghum crop (approximately 33%) is used for ethanol production [5]. The primary goal of most grain sorghum breeding programs is to enhance and protect productivity of the grain crop. While variation for seed composition (i.e., starch) exists in sorghum [6,7], simply increasing grain yield increases ethanol yield, because total starch per unit area is increased. In addition to maximizing productivity, protection of yield potential is equally important, especially drought tolerance, since production of grain sorghum occurs mostly drier areas of the world.

Sweet sorghum genotypes produce high quantities of simple sugars by having a very juicy stalk and high concentrations of soluble sugars. Traditionally, sweet sorghums have been used as a sweetener; extracted juice is cooked and sugars are concentrated in syrup. Sweet sorghums are known in various parts of Africa and they became popular in Asia and North America in the seventeenth and eighteenth centuries [8]. In the early twentieth century, the United States was producing 20 million gallons of sorghum syrup annually. Production dropped after World War II as crystal sugar became more available; today, sorghum syrup production is essentially artisanal and it is concentrated within the southeastern United States. Sweet sorghums are usually tall, with thick stalks and low grain yields compared to grain sorghum varieties. For energy production, sweet sorghum is processed in a similar manner to sugarcane; in fact, sugarcane processes and equipment provide a logical starting point for utilizing sweet sorghum [9]. Sweet sorghums have relatively high biomass yield potential; Hunter and Anderson [10] estimated that sorghum has the potential to produce up to 8000 liters of ethanol per hectare, or about twice as much as that of maize and 30% more than sugarcane ethanol in Brazil. Much of the carbohydrate content of the stalk juice of sweet sorghum is sucrose and/or glucose and it is fermentable without starch hydrolysis. This has advantages and disadvantages because the fermentation process can proceed without pretreatment (advantage) but fermentation must be initiated quickly because of the instability of the sugars in the stalks and/or juice (disadvantage). Preliminary results indicate that there can be a reduction of 16.8% sugar yield if juice extraction is delayed by 48 hours [11]. The residue (bagasse) is also a rich source of structural carbohydrates that can be used for energy production or as an animal feed [12].

For these reasons, the duration of the harvest season is important for sweet sorghum production and crop complementation production systems or storage processes must be developed [13]. Subtropical and tropical regions, which have longer harvest seasons, have an inherent production advantage for sweet sorghum. In addition, there is a logical and economically beneficial complementation between sweet sorghum and sugarcane and this can extend the harvest and milling season [14]. Sweet sorghum complements sugarcane in this scheme because it can be harvested twice in one year in tropical environments and because of its enhanced drought tolerance and water use efficiency.

Energy sorghum is a specific type of photoperiod sensitive sorghum that, when grown in long day environments, accumulates large quantities of biomass [1, 15]. Because they are photoperiod sensitive, they will not flower until day length drops below a specific length of time under temperate climates and the plants will never reach anthesis due to cold temperatures [16]. This characteristic causes an extended vegetative growing season, allowing the plant to capture and convert solar energy into biomass, provided adequate moisture is available for growth. In addition, a plant that is in a vegetative growth stage is inherently more drought tolerant than when in reproductive growth stages. Biomass sorghum cultivars will reduce growth during periods of drought but then resume growth when moisture is available. Therefore, this reduces the crop's sensitivity to drought stress and its timing. Biomass sorghum is produced primarily for structural carbohydrates but it does produce some non-structural carbohydrates, albeit at lower levels than either sweet sorghum or grain sorghum.

7.2.2 Basic Phenological Traits of Importance in Sorghum

Regardless of the type of sorghum being grown, the basic growth and development of the crop is similar. Differences between grain sorghum, forage sorghum and energy sorghum are due to specific changes in a few very important traits within the species. Those traits include tillering and regrowth, plant height, stem type, maturity and grain yield potential.

All commercial sorghums have a fibrous non-rhizomatous root system. For a mature sorghum plant, roots can extend at least 1.5 m in all directions from the base of the plant. In addition, tillering is especially important in sorghum, but tiller characteristics and their desirability depend on which type of sorghum is being produced. Sorghum has the potential for both basal and nodal tillering. In general, profuse tillering is desirable in forage sorghum while reduced tillering is more desirable for both grain and energy sorghum. If ratoon crops are desired, then basal tillering is essential to facilitate regrowth after cutting or grazing. Increased tillering is also associated with reduced stem size [17]. Temperature and plant density also influence tillering potential [18].

Stem thickness and composition are additional defining characteristics of different sorghum types. In general, thicker stems are desirable in energy and grain sorghum while thinner stems are appropriate for forage sorghum. Stem thickness in sweet sorghum is highly variable, depending on regional preferences and the primary use of the cultivar (i.e., syrup, feed or ethanol production). While there is significant genetic variation for this trait, stem diameter is strongly influenced by management and environmental conditions. For example, planting density is the largest factor affecting stem diameter. Numerous studies show that plant density and stem thickness are negatively correlated: the greater plant density, the finer the stem [19].

In addition to stem diameter, stem morphology and sugar concentration in the stems also define sorghum type. Sweet sorghum cultivars have a very juicy stem while biomass sorghum typically has a pithier stalk. Juicy and pithy stemmed characteristics are both found in grain and forage sorghum lines. A single gene locus *D* was reported to control juiciness of the stem [20] but more recent analysis indicates that, while this gene is important, it is not the sole genetic factor influencing juiciness of the stalk [21]. Sugar concentration is critical for sweet sorghum but less so for other sorghum types. Sugar concentrations are also strongly influenced by both genotype and environment. For example, sugar concentrations typically peak in sweet sorghum approximately 20–30 days post anthesis and different genotypes with unique profiles of fermentable sugars have been identified [22].

Plant height is a primary factor in overall biomass yield potential; higher yields are correlated with taller plants [23, 24]. However, there are limits to height as taller plants are more prone to both stalk and root lodging, so the benefits of height must be effectively balanced with the risks [25]. Sorghum height is easily manipulated; four major height genes were identified [26] and many modifiers of these genes have been subsequently described [27, 28].

Of all sorghum traits, maturity is likely the most important because it influences so many agronomically important characteristics. Sorghum maturity is controlled by genes that are influenced by both day length (photoperiod sensitivity) and temperature [16].

Photoperiod sensitive sorghum cultivars require a defined length of darkness to induce panicle differentiation and development [15]. As sorghum was moved to more temperate climates and away from lower latitudes, photoperiod insensitive sorghums were necessary for the crop to produce grain before the growing season ended. Much of the early work to develop photoperiod insensitive sorghum in the United States was completed by producers who would identify and save seed of individual, early maturing mutants or segregants [26]. In these photoperiod insensitive sorghums, maturity is primarily influenced by temperature.

Six maturity genes have been described in photoperiod sensitive and insensitive sorghum and there are likely many more [29, 30]. These loci interact to produce an array of maturities in all types of sorghum cultivars. Maturity is important in forage sorghum because forage quality tends to decrease once the crop flowers and starts to produce grain. This is particularly critical in sorghum–Sudan grass hybrids that are grown for hay production. Because of the relationship between maturity and quality, sorghum breeders have developed photoperiod sensitive sorghum–Sudan grass hybrids and forage sorghum hybrids that maintain forage quality with yields similar to photoperiod insensitive hybrids [30].

7.2.3 Sorghum Composition

As with any bioenergy crop, biomass composition is important to breeders, producers and end users. However, the definition of quality varies greatly depending on who is defining it and the specific method being used for processing. In addition, the specific type of sorghum, the stage of growth, and the production environment strongly affect composition [31, 32]. For example, in forage sorghum, high protein content is important for forage quality, but lower protein content is more desirable for biomass sorghum, as nitrogen is of little value in the biomass; it is more valuable when it is returned and retained in the field [33]. Since bioenergy sorghum is grown to produce carbohydrates, the composition of both non-structural (sugar and starch) and structural carbohydrates (cellulose, hemicelluloses and lignin) is important. In biomass sorghum, structural composition of the biomass is the critical factor while in sweet sorghum, non-structural carbohydrates are of primary importance. In either case, sorghum has a significant range of variation in composition for both non-structural and structural composition [34, 35].

For structural carbohydrates, Stefaniak *et al.* [36] reported a twofold range in variation among sorghum types for lignin, hemicelluloses and cellulose. Dahlberg *et al.* [37] evaluated commercially available forage sorghum hybrids for composition and reported that existing hybrids could be used as a biomass source for ethanol production. While some of this variation is dependent on the environment and maturity [35, 38], there is a genetic component as well [35]. In addition to selection for optimum composition, all approaches will select against ash content, as excessive ash is an undesirable trait for biofuel processing. It must be noted that harvest approaches will also influence this trait, and therefore any process that reduces ash uptake is good.

Research examining variation in forage composition and its effects on digestion in animal systems is of relevance to the bioenergy breeder because several fermentation approaches mimic a ruminant digestive system. There is considerable debate as to the net gain of energy using current and proposed lignocellulosic ethanol conversions techniques [39]. However, the consensus is that this strategy of ethanol production from starch has a positive net energy gain utilizing current technologies [40]. There is also evidence that the overall energy balance for lignocellulosic ethanol will be more favorable than starch-based ethanol, if logistical and technical processing hurdles can be solved [41]. Additional improvements are needed to make lignocellulosic energy production more cost effective as compared to fossil fuels or other renewable energy sources [42, 43].

The biomass composition of energy sorghum varies depending upon genotype and environment in which it is grown, but the relative importance of these sources of variation is not well known. In a study containing six sorghum genotypes, ranging from grain to forage and sweet types, biomass yield varied by 82%, indicating the existence of genetic variability for biomass production among sorghum types [44]. In sweet sorghum, variations in composition of traits such as glucans (cellulose) ranging from 24.7 to 38.5%, xylans (hemicellulose) from 8.5 to 13.9% and lignin from 9.3 to 13.0% were reported [45]. Hoffmann [35] reported variation in biomass composition across 15 genotypes of photoperiod sorghum in five environments, cellulose ranged from 26.9 to 31.8%, xylan from 14.9 to 18.4% and lignin from 8.3 to 18.9%. The environment had a greater effect on composition than genotype *per se* in the six bioenergy sorghum cultivars [35].

7.3 Cultural Practices

7.3.1 Propagation Methods

Sorghum is a seed propagated annual crop that can be grown as either a self-pollinated variety or a hybrid. In regions of the world with a commercialized agricultural infrastructure, hybrids predominate while self-pollinated varieties are common in less developed regions of the world. For bioenergy production, there are inherent advantages to the use of hybrids. Firstly, hybrids allow producers to increase yield by maximizing heterosis. Heterosis for grain yield is usually between 150 and 200%; heterosis for biomass yield is typically 20–50% [45, 46]. Secondly, seed production for many of the biomass sorghum cultivars is only feasible using hybrid systems. For example, sweet sorghum varieties have inherently low grain yields, are usually at least three meters in height, and are grown in humid environments. These traits typically result in poor seed yield and low quality due to harvesting problems and weather-induced seed quality losses. For photoperiod sensitive biomass sorghum cultivars, seed production in a temperate environment is usually impossible. Consequently, hybrid seed production allows the manipulation of both height and maturity genes to produce high-quality seed on short parents that are day length insensitive, tall, and of variable maturity [1, 47].

7.3.2 Establishment

Unlike other bioenergy crops, stand establishment is typically not a problem and costs associated with planting sorghum are significantly lower than for other crops. Sorghum stand establishment requires a well-prepared seedbed and adequate moisture to initiate the germination process. Therefore, the planting and stand establishment process in energy sorghums is similar if not identical to that for grain sorghum [48].

Assuming moisture availability, the primary factor in sorghum stand establishment is temperature. Sorghum is a warm season crop that requires soil temperatures of at least 60°F (16°C) to initiate the germination process; temperatures below 60°F (16°C) will slow or even stop the process. In most regions where bioenergy sorghum will be grown, cool soil temperatures will not be a problem but in more temperate climates it must be monitored. There are efforts to improve the tolerance and growth of sorghum under cool temperatures [49, 50].

From a productivity standpoint, plant population and row spacing are probably the most critical management factors, with optimum density and spacing depending on the type of production system. For example, sweet sorghum processors prefer thick stalks that mimic sugarcane; however, higher yield is typically associated with higher plant densities [51]. Furthermore, row spacing modifications are limited to those that fit within existing harvesting equipment. Optimizing plant population and distribution to fit production programs is of significant importance [52].

7.3.3 Fertilization

Sorghum is an efficient user of soil nutrients because its fibrous root system efficiently captures nutrients within soil profile. Specific nutrient requirements of sorghum are very similar to that of other grass crops in that nitrogen, phosphorous, and potassium are the major compounds required for growth. In addition, micronutrients are needed in some situations depending on soil availability. For optimum productivity, a soil pH between 6.5 and 7.5 is best.

Relative nutrient requirements depend on the type of sorghum and yield potential of the crop. Nitrogen requirements in sorghum depend on the type of sorghum being produced. For example, biomass and sweet sorghums require less nitrogen per unit of biomass produced compared to either grain sorghum or corn [53]. However, total production by those crops was higher and, therefore, optimum fertilization rates for grain and biomass sorghums were similar when evaluated for the growing season [53]. As with any crop, collection of all aboveground biomass from the production environment is not sustainable long term due to the removal of soil nutrients and carbon [54]. Furthermore, the long duration of growth for biomass sorghum is mitigated by recycling of nitrogen throughout the growing season and relatively low stalk nitrogen content [33]. Additional research in this area will be of primary importance for optimizing productivity and nutrient utilization by sorghum cultivars.

7.3.4 Water Use

Throughout the world, sorghum is known and grown for its ability to use water efficiently and to maintain productivity during drought [55]. This is important because biomass production from energy crops is expected to be rainfed. The water use efficiency and/or drought tolerance of sorghum is due to a number of morphological and physiological traits [56]. As would be expected, there is significant variation in the Sorghum genus for drought tolerance among the types of sorghum (i.e., energy, grain, or sweet) and the genotypes within each group [57]. This variation has been used by breeders to enhance drought tolerance of grain sorghums [58] and has created interest in deploying it in energy sorghum cultivars as well.

There are differences in drought tolerance between sweet sorghum and energy sorghum that are related to maturity of the two groups [1]. In essentially all crops, reproductive growth, from the initiation to completion, is more sensitive to water stress than vegetative crop growth [59]. Since energy sorghum does not initiate reproductive growth until very late in the season (and in some cases, not at all), it has an inherently greater level of tolerance to water stress during the growing season than either grain or sweet sorghum cultivars. When drought occurs, energy sorghum can essentially become dormant and resume growth when moisture is available. Because sweet and grain sorghum genotypes flower, post-anthesis drought tolerance (i.e., "stay-green") is critical in these types [60]. Over the past 30 years, the stay-green trait has been integrated into many grain sorghum hybrids and cultivars. It is much less common in sweet sorghum because there has been a limited breeding effort in sweet sorghum until very recently. Given that stay-green is associated with increased non-structural carbohydrate accumulation in the stalk [61] and greater tolerance to charcoal rot lodging [62], it is likely that there will be little or no detrimental effect to introgression of this trait into sweet sorghum.

7.3.5 Disease and Pest Control

As a crop species domesticated thousands of years ago and distributed throughout the world, sorghum is a host plant for an array of plant pests and pathogens but only a few have significant economic importance [63, 64]. In addition, many of these pest or pathogen problems are localized to specific production regions or at certain times during the production cycle. For the most part, disease and insect pressures in sorghum are based on our knowledge of biotic stresses in either grain or forage sorghum. However, the relative importance of these pests is subject to change in energy sorghum due to differences in the type and timing of production. Given that the production area of energy sorghum will be different than traditional grain sorghum regions, the disease and insect pests will be different as well.

For bioenergy sorghum, several diseases and insects will be or already are of substantial economic importance. Of the diseases, anthracnose is probably the most significant but root and stalk rots, ergot, head smut, and downy mildew may also be problematic. For most of these diseases, breeding for host-plant resistance remains the most cost-effective method of control. Sorghum breeders and pathologists continue to screen germplasm to identify new sources of genetic resistance; breeders utilize these materials to produce improved varieties and hybrids, and thus reduce losses due to disease susceptibility [65]. In some situations, chemical control via seed treatment or application may be appropriate [52].

Insect pests that inhibit seedling growth or stalk integrity will likely be of significant importance in bioenergy sorghum, since these pests will stunt or reduce early season growth or reduce stalk integrity (later season) and cause stalk lodging. Alternatively, pests that attack the panicle and developing grain will be less important because energy hybrids are vegetative and typically do not flower. Furthermore, for sweet sorghum cultivars, the grain is significantly less valuable than the stalk. Therefore, stalk borers of all types (mostly *Lepidoptora* sp.) will be of significant importance. Unfortunately, there is minimal genetic resistance to stalk borers in sorghum; thus, control will have to be through the use of insecticides and effective management practices [66]. In addition, there is the potential to introduce transgenic BT genes into sorghum, provided that the potential market sales justify the costs of development and regulatory approval process.

7.3.6 Harvest Management

Within energy sorghum, delayed maturity is consistently associated with increased yield so long as moisture and nutrients are not limited. Thus, the initiation of harvest must coincide with optimum or near maximum yield. Another consideration is that there will be some form of continuous harvest, because storage of large stockpiles of biomass is not economically or logistically feasible. Given that there is wide diversity among sorghum types, ranging from single cut to multiple cut hybrids, it is crucial to identify optimum harvest windows, hybrid deployments and harvest schedules.

Multiple cut sorghum hybrids are usually forage type sorghum varieties that are specifically selected for both productivity and forage quality. Depending on the length of season and available resources (i.e., water, nutrients, pest control), these can be harvested up to four times in a single year [67]. These hybrids produce higher yields under multiple cut systems than if harvested only once and, thus, extend the harvest season over a period of months. However, this production system has higher nitrogen requirements and the forage composition is typically leafier with higher forage nutritive value [68]. This is advantageous for animal utilization, but may not be desirable for bioenergy conversion. Single cut hybrids accumulate higher biomass yields on a per cut basis, but they are not selected for regrowth and typically do not produce ratoon crops because the remaining season is short and the regrowth potential of these hybrids is low [1]. In these cases, regrowth might be best returned to the soil for building organic matter [54].

For single cut biomass hybrids, the optimum harvest time is based on balancing both the need for long harvest windows and the importance of achieving maximum yield. The growth rate for energy sorghum follows that of a typical grass crop with a lag phase followed by log phase and then a gradual reduction in growth rate of the crop [33]. Hoffman [35], in evaluating bioenergy sorghum cultivars reported that the log phase of yield accumulation was generally completed at approximately 120–130 days. Yields continued to increase but at a diminished rate from this point forward. Thus, this was the point at which harvest could commence.

For sweet sorghum, ratoon cropping has been minimally successful for several reasons. Firstly, productivity of the second harvest is highly variable, generally averaging only 75% of the first harvest [34]. Secondly, the quality of the ratoon crop is consistently poor, especially for juice production and stalk type. Thirdly, if regrowth occurs during short days under tropical climates, any photoperiod sensitive control of maturity is lost, causing the hybrid or variety to flower early and thus reduce yields [1, 69]. With a few exceptions, stalks and internodes of the ratoon crop are thinner and shorter [34]. Furthermore, tillers are more numerous presumably due to elimination of apical dominance and competition between basal tillers. This results in a crop that has limited potential to maximize juice volume. Fourthly, sweet sorghum will likely be used in combination with another sugar crop, probably sugarcane, to extend the mill season and productivity of the facility. Thus, a ratoon crop of sorghum is not needed because the mill will have transitioned to sugarcane or another sugar crop [14]. Finally, high-yielding sweet sorghum requires long seasons, meaning that there is little time for a ratoon crop to produce an acceptable yield. For these reasons, ratoon cropping of sweet sorghum is of limited value for an energy production system.

To evaluate the logistics of supplying a sugar mill over a growing season, Burks *et al.* [14] evaluated deployment of different maturity sweet sorghum cultivars along the U.S. Gulf Coast and determined that strategic planting of different maturity classes resulted in a three month harvest window with maximum yields during the middle of this season. Yields at the beginning were low due the need for early maturity hybrids and yields dropped toward the end due to the onset of cool weather. A clear understanding of the germplasm was necessary to effectively maximize productivity and to identify the crucial time for harvest initiation and transition to sugarcane processing. It is these systems that now must be developed not only for sugar-type crops but for all biomass crops if year-round conversion systems are to be deployed.

7.4 Genetic Improvement

The concept of breeding sorghum as a bioenergy crop is not new. Breeding efforts to improve sorghum as a bioenergy crop occurred during the energy crisis of the late 1970s [70]. Much of that work served as the basis for studies initiated during the past ten years. Breeding energy sorghum is similar to grain and forage sorghum improvement [65]. The primary difference between breeding grain and forage sorghum versus energy sorghum lies in the traits of importance to both producers and end users. For example, palatability is important in a forage crop but is not a consideration for an energy crop. Initial development was cultivar based but further improvements in energy sorghum will be deployed in hybrids. Thus, existing breeding strategies are well adapted for use in energy sorghum breeding.

7.4.1 Development of Hybrid Sorghum and Heterosis

Although sorghum is primarily self-pollinated it does outcross and researchers knew that hybrid vigor occurred in sorghum [71]. The development of sorghum hybrids did not occur until Stephens and Holland [72] identified methods to sterilize seed parents to produce hybrids by using a cytoplasmic male sterility system. This approach was first used to produce hybrids in 1956 and within five years hybrid sorghum seed was planted on over 90% of the total U.S. grain sorghum area. Soon after development of grain sorghum hybrids, forage sorghum hybrids for both hay and silage were developed and adopted. While hybrid forage sorghum cultivars have increased yield, another important consideration has been in the enhanced logistics of seed production (i.e., higher seed yield, easier harvest and better quality).

Over the past fifty years sorghum breeding programs have continued to improve and advance sorghum genetics. Traits such as increased yield with high inputs (e.g., water and fertilizer) became important, as was protection of yield potential from both biotic and abiotic stresses. These efforts have led to substantial improvements in yield potential, grain and forage quality, and the protection of this potential through abiotic and biotic stress tolerances. Further improvement relies on a thorough understanding of the crop and genetic control of traits of importance.

7.4.2 Current Sorghum Breeding Approaches

Today's sorghum breeding programs integrate both traditional and molecular approaches. When breeding new hybrids, each program develops inbred lines for test-cross evaluation. To develop inbred lines, most but not all sorghum breeding programs use some form of pedigree selection [4]. Test-cross evaluation is used to assess combining ability. Good general combining ability (GCA) is needed in the first test-cross and subsequent testing identifies the exact combinations with commercial potential. Predicting hybrid performance by evaluating inbred lines themselves is not typically an efficient use of resources [65].

If the new lines are seed parents (i.e., they do not restore fertility to male sterile inducing cytoplasm), they must be sterilized for use as a seed parent. Sterilization involves back-crossing to introgress sterility-inducing cytoplasm, which results in a sterile version of the seed parent. The use of off-season nurseries speeds the pace but sterilization and creation of an A-line (male sterile) version of the B-line (fertile seed parent) requires additional time. Since the advent of hybrids, sorghum germplasm has been placed into heterotic groups based on fertility restoration. While this classification was of necessity, there is some basis as most seed parents were in the kafir group while pollinator parents were typically caudatum and durra types. Since then breeding has evolved these into legitimate heterotic groups [73].

Sorghum genetics and genomics are well advanced. The sorghum genome has been sequenced [74], two high-density genetic maps and one cytogenetic map have been constructed [75–77]. Additionally, many agronomically important genes have been cloned [78–80] and a transformation system has been developed [81]. Finally, there are many published quantitative trait locus (QTL) studies in sorghum, and much of this information is being used for genetic characterization of sorghum germplasm in breeding programs.

7.4.3 Germplasm Collections and the Sorghum Conversion Program

The genetic variability present within sorghum is compiled in germplasm collections at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and the U.S. Sorghum Germplasm collection based in Griffin, GA, and Fort Collins, CO [82]. These repositories represent a valuable source of variation for future sorghum improvement. Most of this variation has limited direct use in temperate breeding programs due to photoperiod sensitivity. However, to make this diversity accessible, the sorghum conversion program was initiated in 1963 in the United States with a goal to introgress day-length insensitivity and dwarfing into exotic sorghum lines, making this germplasm accessible to all sorghum breeding programs [83]. During the active conversion program (approximately 40 years), over 700 photoperiod sensitive sorghum accessions were fully converted and released [84, 85]. The lines have had a tremendous impact on sorghum improvements worldwide; it is difficult to find a sorghum grown anywhere (especially in temperate regions) that does not have sorghum conversion germplasm in its pedigree. In addition, conversion lines have been extremely important for genetic research and genomic analysis of sorghum for an array of traits ranging from adaptation, tolerance to biotic and abiotic stress, and improvement of quality and composition of grain, forage and eventually energy cultivars.

7.4.4 Sweet Sorghum

Until recently, systematic breeding of sweet sorghum was sporadic with the USDA-ARS Meridian, Mississippi sweet sorghum breeding program being the only project devoted exclusively to this crop. Though it closed in 1988, many of the existing sweet sorghum varieties in the United States were derived from that program [86–88]. These varieties represent an array of different maturities, heights and agronomic packages adapted to regions as best identified by producers. They have become standards throughout the world and form the basis for sweet sorghum breeding programs that are being established in many regions of the world. With increasing interest in bioenergy, newer sweet sorghum varieties have been released in India and China [11].

Prior breeding efforts in energy and sweet sorghum focused on pure-line cultivar development. Sweet sorghum cultivars were selected from intentional crosses and advanced through several generations via self-pollination and selection to uniformity. Traits of importance included maturity, height, sugar yield, sugar concentration, sugar quality and agronomic adaptation to stalk rot, drought, and stem borers. Initial breeding efforts did not emphasize bagasse quality because it was of little importance to small-scale sweet sorghum producers. In an industrial setting, however, bagasse is substantially more important, as it represents an energy source to produce electricity or to be converted to ethanol itself once lignocellulosic conversion processes become profitable [43].

For reasons previously mentioned, hybrid sweet sorghum cultivars are crucial for industrial production systems. Because sugar concentration is a primarily additive trait, a true sweet sorghum hybrid is often difficult to produce, since most parental seed lines have low sugar concentrations in the juice and the resulting hybrids have intermediate sugar concentrations [89]. Consequently, even though juice volumes were heterotic, overall sugar yields were reduced relative to sweet sorghum varieties because of lower sugar concentrations in the parental seed lines. Therefore, it was necessary to develop sweet sorghum seed parents to produce true sweet sorghum hybrids. Development of pollinator parents was also important, but most sweet sorghum varieties can serve as pollinator parents as they typically restore fertility to their hybrids made using either A1 or A2 cytoplasm.

Sweet sorghum parental seed lines are being developed in several programs around the world [11]. Studies of these hybrids are superior to seed parents and numerically equal if not superior to pollen parents (i.e., sweet sorghum varieties) [45, 46]. While first generation hybrids did not always outperform their respective pollinator parents, hybrid seed production capacity was four to six times greater than for a pure-line sweet variety and it was much easier to harvest. Furthermore, it is logical to expect that yield and quality of subsequent hybrids will be better than those currently available. In India, excellent progress has been made in developing hybrid sweet sorghum lines from sweet and grain parents. From the ICRISAT sorghum improvement program, Reddy *et al.* [90] described six hybrids significantly lower in brix than the control genotype that were nonetheless significantly higher in sugar yield than the control. Additionally, and not surprisingly, these six hybrids also produced significantly greater grain yields than the sweet sorghum control.

Hybrid sweet sorghum breeding methodologies follow traditional sorghum breeding approaches with modifications in traits and selection protocol. For example, because of the additive effect of sugar concentration, it is critical to select for sugar concentration in both seed and pollinator parents. However, juice volume is more of a dominant trait; consequently, it may be selected in either parent and will be expressed in the hybrid. Most breeding programs will use a pedigree approach followed by sterilization of the seed parent and test-crossing of both types on standard testers [65]. In addition, and just like grain crops, a range of hybrid maturities will be necessary to ensure an optimal distribution of hybrids for a continual harvest season [14].

For improvement purposes it is best to define total sugar yield using the individual components that contribute to it, which are juice yield and soluble sugar concentration. Juice yield is related to biomass yield, and thus total biomass yield is critical in sweet sorghum breeding [34]. Often, reports in the literature estimate sugar yield using total dry biomass yield and a coefficient for juice content and soluble sugar concentration reported in the brix units. However, juice extractability and the proportion of sugar to total soluble materials must be considered in selection, which if based on brix and/or moisture content alone could be misleading [45]. Lodging and stress tolerance are also traits of interest for sweet sorghum breeders insofar as they affect harvestability, stability and fermentable sugar yield. Finally, an important trait unique to sweet sorghum (as compared to grain sorghum) is the duration of optimal sugar yield in the hybrids. It is generally agreed that sugar yields peak in sorghum prior to physiological maturity and, therefore, if that yield can be maintained for a longer period it could extend the economic harvest season, which is crucial for development of a sustainable biofuel industry.

7.4.5 Biomass Sorghum

Since biomass sorghum hybrids are photoperiod sensitive, seed production relies on either genetic control of photoperiod sensitivity or strategic planting in seed production environments. In the latter, day length during winter months in tropical environments is sufficiently short to allow seed production of hybrids. In this situation, the greatest challenge is planting seed and pollinator seed stock in time to ensure both reach anthesis at the same time. In temperate environments, such production is not possible because of cool temperatures during the winter season. Therefore, seed production must rely on genetic systems that allow production of a photoperiod sensitive hybrid using two photoperiod sensitive parental lines. Such a system was identified and characterized in forage sorghums [47, 65] and can be readily deployed within a bioenergy breeding program.

Breeding for biomass production uses approaches similar to those currently used to produce hybrid forage sorghum. Vegetative biomass yield will be the most important trait, as is the case with current forage types. In most cases, biomass sorghum cultivars are being bred for a single harvest management scheme. Although multiple cut types could be used, they most likely will be forage types, as those perform very well in multiple-cut production systems [91]. Inbred line development will follow the same approaches used for grain and forage sorghum. For energy sorghums, most of the breeding effort will focus on the pollinator parent because existing seed parent lines are suitable for use to produce biomass sorghum hybrids. Potential pollinator parents range from existing elite sorghum germplasm with good general combining ability to unique genotypes that maximize photoperiod sensitivity and are derived from exotic sorghum accessions. Initial screening for maturity, yield, composition and agronomic desirability will be used to identify pollinator parents, which can be improved through further breeding to complement existing seed parents for both maturity and dwarfing loci. This will allow for the production of hybrids using lines that are moderately short and photoperiod insensitive but that produce a hybrid that is tall and photoperiod sensitive [26, 47].

7.4.6 Breeding for Stress Tolerance

Equally important to development of yield and quality potential of energy sorghum is the inherent protection of that yield potential. Thus, breeding for tolerance to both abiotic and biotic stress is critical for adaptation and productivity.

Abiotic stress is defined as a yield limiting factor caused by a non-biological source. Examples of abiotic stress include but are not limited to temperature, moisture and soil fertility. Of these factors, Boyer [92] estimated that drought was the largest single factor in reducing grain sorghum yield. The same situation will be true in bioenergy sorghum cultivars, especially since production will be reliant on rainfall and not irrigation. Drought stress is a complicated condition that initiates the expression numerous genes in a myriad of signal transduction pathways [93]. Drought tolerance has been studied for many years and several different mechanisms of tolerance have been described. Stay-green is a post-flowering drought tolerance trait that can be described as delayed senescence. Therefore, it can mitigate effects of terminal drought stress on the final yield processes including grain fill and stalk development. This trait is of special interest to breeders of dual purpose sorghum varieties [94]. The stay-green trait includes modifications in stalk properties that affect biotic stresses such as charcoal stalk rot [56], and lodging [62]. Stay-green plants tend to be superior in digestibility by ruminant animals due to higher basal stem sugars [95]. Stay-green may be of particular importance in sweet sorghum as sugar accumulation is optimized during grain fill. A second and less well understood drought tolerance mechanism is pre-flowering drought tolerance. This is tolerance prior to flowering and is physiologically different than stay-green. In fact, only a few sorghum genotypes possess both types of tolerance. Additional studies are necessary, but this tolerance may be of particular value in biomass sorghum hybrids since they do not enter the reproductive growth phase.

Aluminum toxicity can limit sorghum production in acidic soils, which are common in the humid tropics [96]. Genetic variability for aluminum tolerance has been observed [96,97] and is commonly used in sorghum breeding programs in Brazil. In fact, Magalhaes *et al.* [98] identified and cloned the aluminum tolerance gene $Alt_{SB}{}^5$. Nitrogen use efficiency (NUE) in cereal crop production has been estimated to be at about 33% worldwide [99]. However, for lignocellulosic bioenergy production new experimental directions that emphasize improving biomass yield rather than grain production will need to be taken. Currently, experiments are being conducted using sweet sorghum to indentify genotypes and QTL that can improve NUE.

Biotic stresses are defined as yield limiting factors of a biological source, typically either an insect pest or a disease pathogen. There are numerous pathogens and pests that can reduce yield and quality of all types of sorghum. However, the relative importance of each biotic stress differs based on the type of sorghum and location of production. For example, biomass sorghum will generally be managed to eliminate or minimize reproductive growth. Consequently, pests and pathogens of reproductive growth are much less important. If grain is important, then breeding for resistance to midge and shoot fly are important because these pests reduce grain yield [100–103].

For energy sorghum, insects of greatest interest to breeders are those that affect harvested plant organs. For biomass sorghum, two of the most important insect pests include greenbugs, which stunt growth in young plants, and the borers because they affect stalk integrity. Tunneling in the stalk can disrupt vascular tissues causing nutrient or water deficiencies in addition to general weakening of stalks and subsequent lodging [64]. Additionally, stalk borer damage causes wounds that provide entry points for stalk rot pathogens [104]. Grain sorghum crops in the United States are not generally seriously infested with stalk boring insects, but in energy cultivars these may become very serious crop pests. Genetic variation for resistance to selected stem borer has been reported but it is not complete and breeding may be difficult [101, 105, 106]. Effective insecticide and management practices, as well as transgenic sources of resistance, will likely be critical for controlling these pests.

Among the most important sorghum diseases are anthracnose *Colletotrichum sublineolum*, and downy mildew *Peronosclerospora sorghi* (Weston and Uppal) C.G. Shaw. Considerable effort has been put into developing cultivars that are resistant to these pathogens. Anthracnose is one of the most economically important sorghum diseases [107, 108] and it is likely that this disease will become more important as production of energy sorghum increases. Anthracnose can affect all above ground plant organs and is among the most serious pathogens of sorghum [109]. At any one time, pathogen populations can be made up of many pathotypes making breeding for resistance particularly challenging [63]. Estimated yield losses due to anthracnose alone have been reported in excess of 50% [110]. Gene-for-gene relationships have not been conclusively demonstrated and, therefore, assignment of races or pathotypes has been difficult [108]. However, genetic variation for resistance has been reported [109, 111].

Another pathogen that affects sorghum production worldwide is downy mildew. Genetic variation for resistance to this pathogen has also been reported [112–114]. Multiple races of downy mildew that infect sorghum have been identified and, consequently, resistance genes have come from multiple sources [113]. Resistance to single races of this pathogen is reported as simply inherited and, therefore, resistance to the pathogen in general is described as oligogenic in most cases [115]. For example, resistance to the ICRISAT Centre race has been described as fitting the expected ratio of a two locus model with complementary and inhibitory interactions [114]. Thus, it is feasible to pyramid resistance genes for multiple races as new ones are identified. Oh *et al*. [116], linked RFLP (restriction fragment length polymorphism) markers to resistance for pathotypes 1 and 3. However, the fragment patterns could not be reconciled with original mapping cross making it impossible to locate the QTL. Therefore, more research is required to develop useful marker assisted selection schemes for downy mildew.

7.5 Summary and Conclusions

Sorghum is among the most versatile of crop species with wide environmental adaptation and a diversity of end uses. The successful breeding history of grain and forage sorghum demonstrates that biomass and sweet sorghum hybrids can be developed using the same approaches. The genetic resources available to sorghum breeders, contained in both the currently utilized breeding germplasm, as well as the extensive public germplasm collections, represent a rich repository of genetic variation, which is necessary for breeding progress. There remain significant needs and opportunities to develop the production logistics and management schemes to fully integrate sorghum and other grass genera into biomass production schemes that fit the needs of processing facilities.

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8

Crop Residues

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8.1 Overview

Crop residues (e.g., corn stover and small grain straw) are sometimes excluded when discussing cellulosic energy crops *per se*, but because of the vast area upon which they are grown and their current role in the development of cellulosic energy systems, this chapter will review several important attributes of this "herbaceous" feedstock. Crop residues are potential feedstock sources for second-generation biofuel production. These materials, along with dedicated energy crops (e.g., switchgrass [*Panicum virgatum* L.], Miscanthus [*Miscanthus* × *giganteus*]), are considered to have greater potential for biofuel production than current first-generation feedstock (i.e., corn grain) [1–3]. Production of ethanol and other fuel sources from these lignocellulosic materials is receiving increased financial support for research and development [4–6]. Furthermore, biofuel production from crop residues provides a multipurpose land use opportunity where grain can be harvested to meet food and feed demands, while a sustainable portion of the residues provide a potentially available biofuel feedstock.

Corn stover, the aboveground plant material left in fields after grain harvest, was identified as an important biomass source in the Billion-Ton Study (2005 BTS) [7]. The vast area from which this feedstock could potentially be harvested was confirmed by USDA National Agricultural Statistics Service (NASS) data showing that between 2005 and 2011, corn was harvested in the U.S.A. from an average of 32 460 000 ha each year [8]. Wheat straw was the other dominant residue identified in the 2005 BTS, and from 2005 through 2011, wheat was harvested in the U.S.A. from an average of 20 037 000 ha each year. Based on these

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vast harvest areas, the 2005 BTS projected total annual corn and wheat residue production to be approximately 250 and 90 million Mg, respectively, with a sustainable removal of 82 and 12 million Mg after accounting for that needed to mitigate wind and water erosion.

The 2005 BTS projections of available crop residue immediately raised concern among many soil scientists because harvesting residues as a biofuel feedstock or for any other purpose (e.g. animal feed) will decrease annual carbon input and may gradually diminish soil organic carbon (SOC) to a level that threatens the soil's production capacity [9]. Concerns within the U.S. Corn/Soybean Belt were accentuated knowing that for many soils artificial drainage, intensive annual tillage, and less diverse plant communities have already reduced SOC by 30–50% when compared to pre-cultivation levels [10]. Returning a portion of crop residues to replenish SOC was deemed essential for sustainability [11–16] because crop residues influence many vital soil, water, and air functions. Many scientists stated that caution must be used to ensure that harvesting residue for any use does not compromise ecosystem services or decrease overall soil productivity. Furthermore, others argued that for several current cropping systems, soil erosion and organic matter depletion indicate that crop residue returns to the soil are already insufficient [17, 18].

As a result of soil resource sustainability concerns raised by the 2005 BTS, a follow-up report (2011 BT2) was developed by the U.S. Department of Energy (DOE) to include (1) a spatial, county-by-county inventory of potentially available primary feedstocks, (2) price and available quantities (i.e. supply curves) for individual feedstocks, and (3) a more rigorous treatment and modeling of resource sustainability [19]. The 2011 BT2 recognizes the importance of crop yield variation and the need to balance the economic drivers with ecologically limiting factors [20]. Table 8.1 presents some of the estimated feedstock supplies for various crop residues at selected price levels. These values are also consistent with several other estimates including those used for the U.S. National Academy of Science (NAS) study on Liquid Transportation Fuels from Coal and Biomass [21]. The 2011 BT2 also provides a more realistic overview of total crop residue availability and sets some achievable research and development goals for available feedstock supplies by creating various production scenarios that strive for higher crop yields and integrate multiple cellulosic energy crops into potential production systems.

Several assessments examining the multiple roles that crop residues have for maintaining multiple ecological functions have been published since the 2005 BTS [22–30]. Therefore, this chapter focuses on current corn stover and wheat straw research designed to address

Table 8.1 *Estimated 2012 crop residue supplies (Mg) at selected prices using the 2011 BT2 baseline management scenario data.*

	Price ($/Mg)		
Crop residue	40	50	60
Barley straw	356 088	1 289 300	1 536 821
Corn stover	17 064 661	66 172 906	77 444 014
Oat straw	17 052	17 505	17 505
Sorghum stover	565 515	880 516	996 884
Wheat straw	6 062 751	16 759 637	20 481 511
Total	**24 066 067**	**85 119 864**	**100 476 735**

concerns raised by those previous reviews and to help ensure that commercial bioenergy develops in an economically, environmentally, and socially acceptable manner.

8.2 Corn Stover

Following the release of the 2005 BTS, a collaborative research team[1] (Table 8.2) with members from the USDA-Agricultural Research Service (ARS) Renewable Energy Assessment Project (REAP) and several universities was established as part of the Sun Grant Regional Partnership (RP) to determine the amount of corn stover that could be harvested in a sustainable manner [31]. The core treatments included no tillage or the least amount possible for economic crop production [e.g. Coastal Plain soils near Florence, SC, have a naturally occurring hardpan (E horizon)], so in-row subsoiling is needed each year prior to planting], three residue removal rates (none, approximately half, and the maximum mechanically collectable amount), and four replications. Leveraging the Sun Grant Partnership funds with long-term ARS research expanded both the number of treatments being evaluated as well as the number of years of study. For example, at Mead, NE, the rainfed and irrigated studies were initiated in 1999 and 2001, respectively. At Morris, MN, the study was initiated in 2005, taking advantage of a tillage experiment established in 1995. At Ames, IA, two studies were initiated in 2005 and one in 2008. Additional management practices being evaluated at one or more of the locations include alternate tillage practices (e.g. chisel plow or strip-tillage), use of cover crops, rotation with soybean, harvesting of cover crops as well as the corn stover, and application of biochar.

For each experimental site, soil samples were collected to a depth of 1.0–1.5 m, divided into increments of 0–5, 5–15, 15–30, 30–60, 60–90 and 90–150 cm, and analyzed for several soil quality indicators [e.g. total organic carbon (TOC), total nitrogen, pH, bulk density, and soil-test phosphorus (P) and potassium (K)]. The Soil Management Assessment Framework (SMAF) was used to evaluate and combine the different indicators, and thus establish a baseline soil quality index that could be used to determine long-term effects of the various stover harvest rates [15]. To date, TOC and soil-test potassium have had the lowest indicator scores at several RP and other REAP sites [16]. Longer-term data leveraged from the REAP plots at Brookings showed that through the first eight years TOC decreased as residue removal rates increased (Figure 8.1). A more detailed examination of samples collected in 2008 showed higher organic carbon content in all aggregate size classes from the low removal treatment than in the high removal treatment (Figure 8.2). Higher total protein was also measured in soil samples from the low removal treatment than from the high removal treatment.

Whole plant samples were collected and fractionated into bottom, top, cob, and grain fractions. Plant parts lying on the ground within the sampling area (1.5 m^2) were also collected. Harvest index values and total nutrient uptake were collected using those samples. Stover was collected using a variety of mechanical harvesting techniques, all resulting in post-harvest soil surface cover differences, such as those shown for the Lamberton, MN,

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Table 8.2 *The Regional Partnership Stover team's principle investigators, institutions, location, and site coordinates established to determine sustainable corn stover harvest strategies.*

Principle Investigators	Institution	Location	Site Coordinates	Dominant Soil or Soil Association
Doug Karlen[a] Stuart Birrell	USDA-ARS Iowa State Univ.	Ames, IA	42 01′ 75.667 N 93 76′ 44.830″ W	Clarion-Nicolet-Webster
Shannon Osborne Tom Schumacher	USDA-ARS South Dakota State Univ.	Brookings, SD	44 20′ 20.30″ N 96 47′ 31.82″ W	Kranzburg-Brookings
Jeff Novak Jim Frederick	USDA-ARS Clemson Univ.	Florence, SC	34 17′ 00.32″ N 79 44′ 30.37″ W	Goldsboro-Lynchburg-Coxville
Jane Johnson Lowell Rasmussen	USDA-ARS Univ. of Minnesota – Morris	Morris, MN	45 68′ 26.44″ N 95 80′ 22.03″ W	Barnes-Aastad
John Baker John Lamb	USDA-ARS Univ. of Minnesota – St. Paul	St. Paul, MN	44 42′ 57″ N 93 05′ 59″ W 43 43′ 40″ N 95 24′ 21″ W 44 21′ 35″ N 93 12′ 10″ W	Waukegan Normania-Ves-Webster Garwin
Gary Varvel Richard Ferguson	USDA-ARS Univ. of Nebraska	Mead, NE	41 16′ N (irrigated) 96 41′ W 41 15′ N (rain fed) 96 40′ W	Tomek Aksarben
Paul Adler Greg Roth	USDA-ARS Pennsylvania State Univ.	Univ. Park, PA	40 86′ N 77 85′ W	Opequon-Hagerstown complex

[a]Team Leader

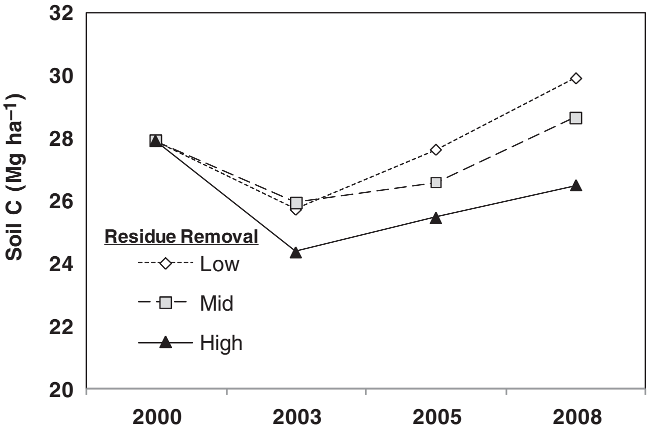

Figure 8.1 *Eight-year residue removal effect on SOC in the top 15 cm (6 inches) near Brookings, SD. (Figure provided by Shannon Osborne, USDA-ARS).*

site in the autumn (Figure 8.3) or the subsequent spring (Figure 8.4) following either conventional (chisel plow) or strip-tillage.

Additional data being collected at some but not all RP locations include greenhouse gas (GHG) emissions (CO_2 and nitrous oxide, N_2O), nitrate nitrogen (NO_3-N) and phosphorus concentrations in water leaching through the soil profile, microbial biomass carbon, particulate organic matter, glomalin-related soil proteins, the humic acid fraction of soil organic matter, aggregate stability, lignin, cellulose and other structural carbohydrates, and energy values for the various stover fractions. Collectively, these measurements are providing the data needed to develop the sustainable stover harvest strategies outlined through modeling in the 2011 BT2 report.

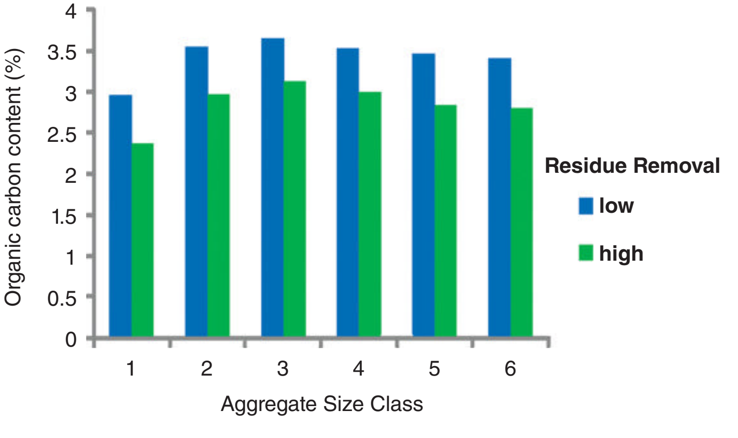

Figure 8.2 *Residue removal effects on organic carbon content in six soil aggregate size classes from the surface 5 cm near Brookings, SD. (Figure provided by Shannon Osborne, USDA-ARS).*

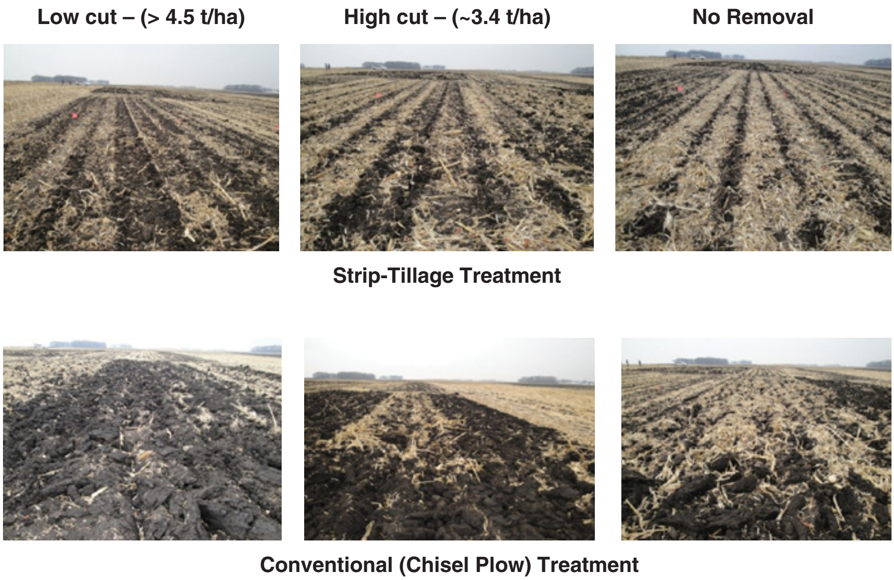

Figure 8.3 *Autumn (November 2010) soil cover following various corn stover harvest treatments and either conventional (chisel plow) or strip-tillage at the Lamberton, MN, research site. (Photos provided by John Baker, USDA-ARS).*

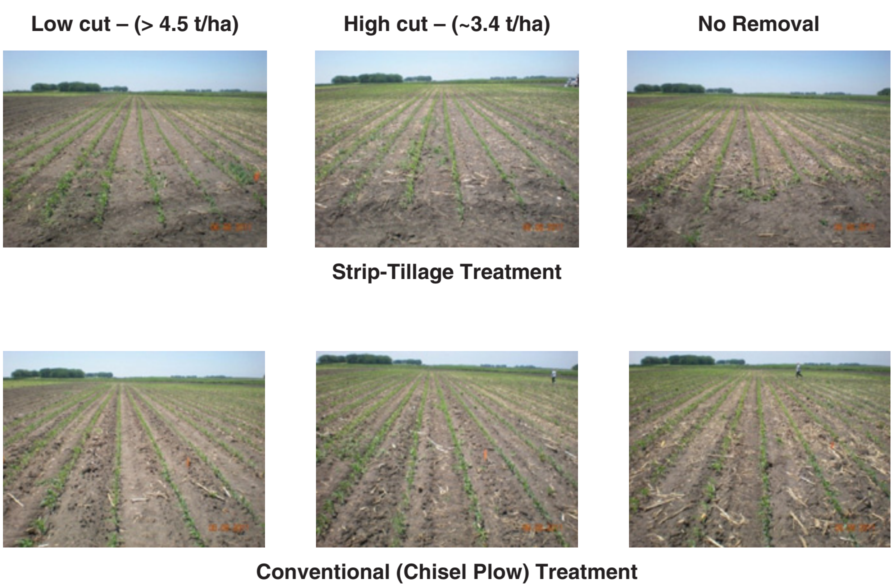

Figure 8.4 *Spring 2011 soil cover following various corn stover harvest treatments and either conventional (chisel plow) or strip-tillage in autumn 2010 at the Lamberton, MN, research site. (Photos provided by John Baker, USDA-ARS).*

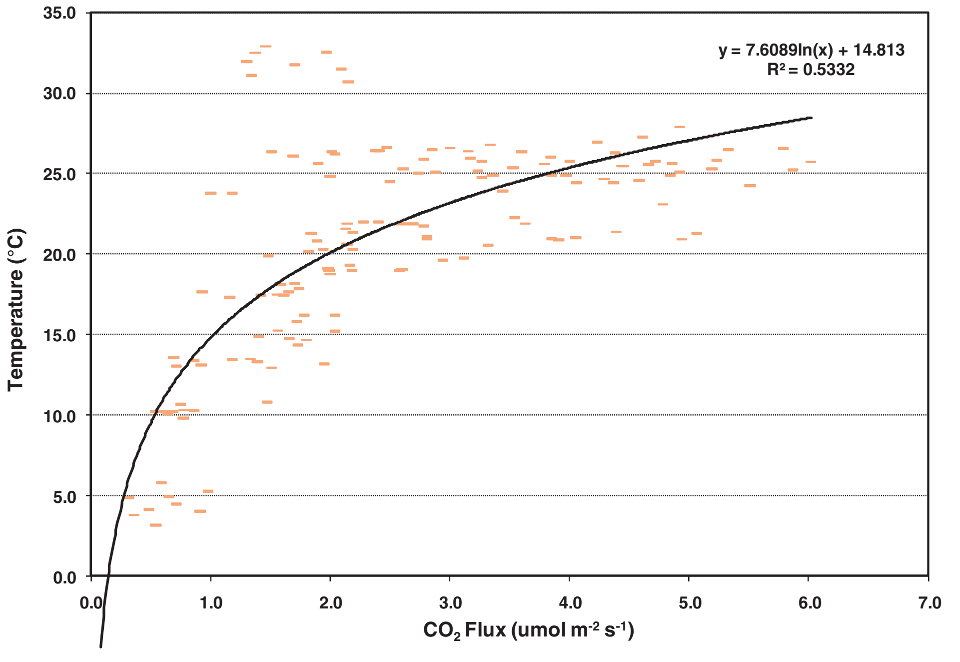

Figure 8.5 *Soil CO_2 flux versus soil temperature for all 2010 treatments at the Ames, IA, site. Each point represents the average of eight measurements (4 mid-row, 4 in-row). (Figure provided by Tom Sauer, USDA-ARS).*

One example (Figure 8.5) of the information being gathered shows the dependence of CO_2 flux on soil temperature. The relatively strong logarithmic relationship suggests that a temperature-based interpolation method (Q_{10}) will be most effective for estimating annual CO_2 fluxes. These results also suggest that management practices which result in warmer soil temperatures, for example, through residue removal, may lead to higher CO_2 fluxes. However, this effect will likely be offset by lower amount of available carbon substrate, that is, residue, so that the overall effect of stover harvest on annual CO_2 flux will likely be a reduction in treatment differences.

With regard to N_2O, Figure 8.6 shows that precipitation strongly influences the flux by reducing oxygen availability and stimulating denitrification. The lag between precipitation and maximum emission is evident, and is consistent with reports in the literature suggesting that the nitrous oxide flux is not maximized when the soil is saturated, but rather when water-filled pores space (WFPS) is about 65%. Annual sums of net N_2O emission at this site were highest for the non-removal treatment and lowest for the maximum collectable treatment. They were also positively correlated with cumulative soil respiration, indicating that carbon availability was a controlling factor with respect to denitrification.

As recognized in the 2011 BT2 report, crop yield is a major driver associated with the availability of stover as a potential cellulosic bioenergy feedstock. Corn produces the highest volume of residue of all the major crops grown in the U.S.A. and because of the approximate 1:1 relationship between grain yield and aboveground biomass, the volume of

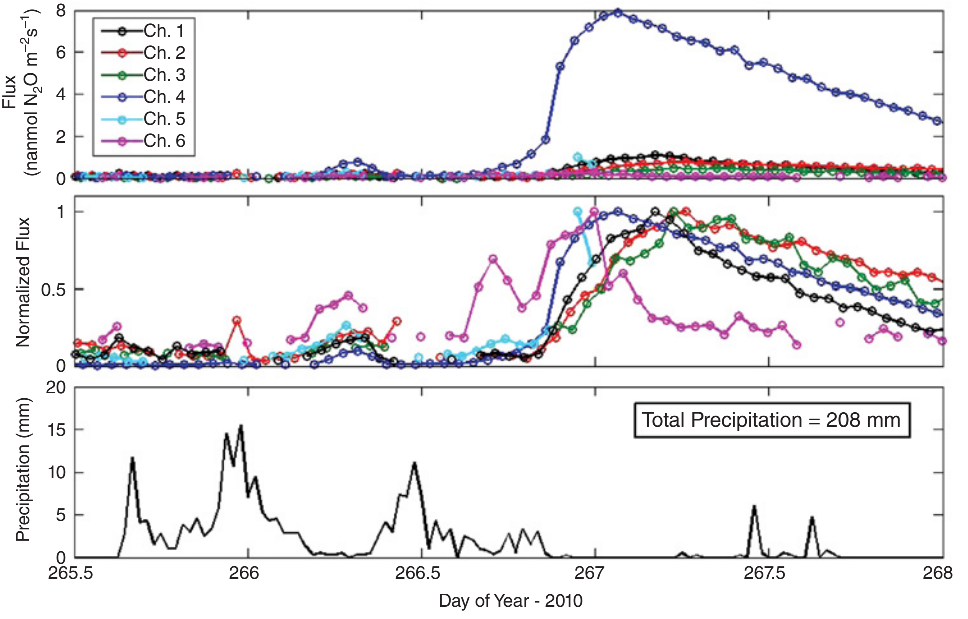

Figure 8.6 Nitrous oxide and rainfall relationships at the Rice County, MN, site in 2010. The "Ch. 1 to Ch. 6" designations simply refer to the six chambers used for the measurements. (Figure provided by John Baker, USDA-ARS).

available residue is directly proportional to grain yield (Table 8.3). To date, the RP studies have shown variable crop yield responses associated with stover harvest. This includes (1) no detectable short-term (3-year) effects at the Brookings, Florence, Morris, or University Park sites; (2) trends for increased yield when stover is harvested from no-till treatments at Ames and Mead; and (3) inconsistent site-differences at the Lamberton, Bauer Farm, and Rosemount sites in Minnesota. Another five-year assessment of stover removal effects near Ames, IA [16], showed that the most consistent grain yield response was a 21% lower average for continuous corn than for rotated corn. That study also showed that harvesting corn stover increased the average NPK removal by 29, 3 and 34 kg ha^{-1} for continuous corn and 42, 3, and 34 kg ha^{-1} for rotated corn, respectively, when compared to harvesting only the grain. Furthermore, it showed that the lower half of the corn plant contributed very little to the total available feedstock biomass because of its high water content and that it was not a desirable feedstock because of its high potassium, chloride, and ligin content, as well as an increased amount of soil contamination that interferes with both biochemical and thermochemical conversion processes.

So, what is the bottom line with regard to harvesting corn stover as a cellulosic feedstock? Firstly, producers must know their land. Prior to initiating any harvest strategy they should have good soil-test and nutrient management records for any areas from which crop residues may be harvested. Obviously, any land with erosion problems must be excluded and efforts should be made to use available stover in those areas to restore and rebuild the soil. Harvesting stubble will remove additional nutrients and could affect long-term soil organic matter levels, erosion rates, and water conservation. Producers should have and be using

Table 8.3 Projected available stover as a function of corn grain yield, after accounting for the amount of crop residue needed to protect soil resources against erosion and to sustain soil organic matter levels as suggested by Wilhelm et al. (2007) [13]. (Based on [13]. With permission Copyright © 2007, American Society of Agronomy).

Grain yield at 15.5% moisture		Dry stover	Total Stover[a]	Available[b] CC Stover	Available[c] CS Stover	Total Available
Bushels per acre	kg ha^{-1}	Mg ha^{-1}	Million Mg	Million Mg	Million Mg	Million Mg
150	9416	7.96	155	36.9	0.3	37
160	10 044	8.49	165	44.1	3.4	48
170	10 672	9.02	176	51.4	6.5	58
180	11 300	9.55	186	58.6	9.6	68
190	11 927	10.08	196	65.8	12.7	79
200	12 555	10.61	207	73.1	15.8	89
210	13 183	11.14	217	80.3	18.9	99
220	13 811	11.67	227	87.5	22.0	110
230	14 438	12.20	238	94.8	25.1	120
240	15 066	12.73	248	102.0	28.2	130
250	15 694	13.26	258	109.2	31.3	141
260	16 322	13.79	269	116.5	34.4	151
270	16 950	14.32	279	123.7	37.5	161
280	17 577	14.85	289	130.9	40.6	172
290	18 205	15.38	300	138.1	43.7	182
300	18 833	15.91	310	145.4	46.8	192

[a]Assuming stover collection from 60% of the 2005–2011 U.S.A. harvested corn area (32 460 000 ha) (i.e. 19 476 000 ha). This is approximately the area of corn production in Illinois, Iowa, Indiana, Nebraska, and Minnesota.
[b]Available after subtracting 5.25 Mg ha^{-1} for maintaining soil organic matter in continuous corn (CC) on 70% of the harvested area.
[c]Available after subtracting 7.90 Mg ha^{-1} for maintaining soil organic matter in a corn-soybean rotation on 30% of the harvested area.

long-term nutrient management and soil conservation plans. They should also be using the least amount of tillage possible. Again, avoid stover harvest from highly erosive areas and use routine soil-test and plant analyses to monitor the response on a routine basis. Finally, consider adopting other conservation practices, such as the inclusion of annual or perennial cover crops, buffer strips, and crop rotation, in order to enhance the sustainability of stover harvest.

8.3 Wheat Straw

Cereal grains (wheat, barley, oats, sorghum and rice) are widely grown in the United States and wheat straw constituted 20–25% of potential 2012 U.S. biofuel feedstocks (Table 8.1). Agronomic considerations for determining supplies of wheat straw that can be harvested sustainably include: (1) annual wheat straw yield and its stability; (2) straw harvesting efficiencies; (3) crop rotation and tillage practices for assessing soil conservation and sustainability factors; (4) nutrient removal and fertilizer replacement values; (5) site-specific field evaluations including economic factors that inform decision support systems; and (6) competing economic uses for harvested cereal straw. Addressing these issues has been the focus of several recent research efforts including the Sun Grant partnership

[32, 33], the U.S. Pacific Northwest, the Climate Friendly Farming™ project [34], and the USDA Solutions To Economic and Environmental Problems (STEEP) grant program [35].

In the United States, the amount of wheat straw potentially available for use as a biofuel feedstock was assessed through the Sun Grant partnership where the team used USDA-NASS county level grain yield data from 1999 through 2008 [32]. Grain yield data were combined with the harvest index (HI), the ratio of grain yield to total aboveground biomass (grain plus straw) at harvest, to estimate straw yields. The HI of wheat, however, is not a constant value [32], with reported values ranging from 0.20 to 0.70 with an average across locations and years of 0.44. This average is greater than the historic HI value of 0.375 commonly used for winter wheat [19], presumably because newer grain varieties are more efficient and produce less straw per unit of grain than older varieties. The HI data have important implications for estimating the amount of straw produced based on grain yield because an increase in HI from 0.375 to 0.44 results in a 24% reduction in estimated wheat straw yield. Consequently, generating straw yield maps for the United States based on grain yield can only be considered as a first step toward evaluating straw feedstocks for the purpose of siting biofuel plants. In addition to overall production, understanding the year-to-year stability of straw yield is also an important consideration for assessing feedstock supplies. Karow [32] noted that significant annual fluctuations in wheat straw stocks could occur where some areas with high average straw yields also had years with no or limited wheat straw yield.

Overall straw yield serves as a starting point for quantifying available biofuel feedstock that can be sustainably harvested. Factors such as straw harvesting efficiencies, residues (straw) required for controlling wind and water erosion, and for maintaining soil productivity then reduce the amount of straw that can be harvested without impairing the soil resource base. Current straw harvesting efficiencies (e.g. straw baling) are near 50% [7]; however, technological advances could increase residue harvesting efficiencies to around 75% [36]. It is more difficult to assess the multitude of crop rotation and soil tillage factors that influence how harvesting crop residues will affect soil conservation and other agroecosystem services. In many cases, conservation needs that depend on leaving adequate cereal residues in the field will be more limiting than current harvesting efficiencies.

In developing estimates for straw feedstocks that could be sustainably harvested, Kerstetter and Lyons [37] estimated that dry straw inputs of 3.4–5.6 Mg ha^{-1} yr^{-1} are required for conservation purposes in the western United States, whereas others [38] reported 4.5 Mg residue ha^{-1} yr^{-1} were needed. These numbers are similar to the 4–5 Mg residue ha^{-1} yr^{-1} reported [39] to be required for maintaining soil organic matter in dryland cropping systems near Pendleton, OR. Assuming a harvest index of 0.4, wheat grain yields of 2.0–3.3 Mg ha^{-1} yr^{-1} (3.0–5.0 Mg ha^{-1} yr^{-1} of wheat straw) would be needed to supply straw for conservation needs and harvestable straw estimates would need to be based on grain yields that exceed this threshold. An important point to realize in these calculations is that the quantities of residue required for conservation needs are on an annual basis. In many dryland scenarios, however, continuous wheat is seldom grown and crop rotations often include a fallow year when no crop or crop residues are produced [4]), or where other crops such as peas (*Pisum sativum*) or lentils (*Lens culinaris*) that produce far less residue than wheat are grown [14]. Thus, crop residue production must be quantified for an entire rotation in order to assess the average annual residue returns on a rotational basis. Therefore, in a two-year, wheat-fallow rotation, wheat will need to produce grain yields of 4.0–6.6

Mg ha^{-1}, twice that reported [37, 38] to meet conservation needs. Unfortunately, many estimates of wheat straw availability have assumed continuous wheat [37, 38]) production when assessing conservation needs. This has resulted in "sustainable harvest estimates" for wheat straw that are greatly inflated when compared to the actual amount available with other rotations. Accurate estimates of the wheat residue quantities returned to soil are in themselves insufficient to assess sustainable residue harvest, due to the important influence of other key factors such as crop rotation and tillage practice.

Evaluating the impact of straw harvest on important soil quality indicators such as SOC, aggregation, or erosion requires long-term research, since annual changes are generally very small and can be temporally dynamic. In recognition of this need, the Sun Grant partnership organized a symposium at the 2009 International American Society of Agronomy (ASA) meetings entitled "Residue Removal and Soil Quality – Findings from Long-Term Research Plots." Presentations at this symposium examined residue removal impacts in the context of various management practices including crop rotation, tillage, applied fertilizer and irrigation. The articles developed from this symposium were subsequently published in the *Agronomy Journal* (Huggins *et al.* [33]). The series includes results from long-term studies in Europe, Canada, Australia, and the United States. Key points included an assessment [40] that reviewed long-term studies from Europe, Australia, and Canada and cautioned against annual removal of straw because of the potential decrease in SOC. Due to the site-specific nature of residue harvest, they recommended that straw removal studies be coupled to areas where residue harvest is actually being considered and to not extrapolate using data from other areas.

Near Pendleton, OR [41], it was concluded from long-term dryland cropping system studies that residue removal in this predominantly wheat-fallow area will increase SOC depletion and that residue harvest will only be sustainable if wheat-fallow was replaced with continuous cropping and no-tillage. Nafziger and Dunker [42] reported on the long-term SOC trends under different crop rotation and fertilizer treatments at the University of Illinois Morrow Plots and emphasized the importance of adequate nutrient levels for maintaining SOC. Long-term plots at the University of Missouri Sanborn Field showed that the amount of field residues returned was positively related to SOC (Miles and Brown, 2011 [43]). Gollany *et al.* (2011) [44] evaluated five long-term field experiments in North America with the CQESTR model and concluded that increasing soil carbon inputs through manure additions and/or crop intensification as well as reducing tillage were important strategies for mitigating residue harvest impacts on SOC. Finally, in irrigated systems, Tarkalson *et al.* (2011) [30] reported that SOC either increased or remained constant when wheat residues were removed and hypothesized that belowground biomass production was important for maintaining or increasing SOC under irrigation. They also pointed out that irrigated cropping systems in the Pacific Northwest and elsewhere tend to be diversified with crops such as alfalfa (*Medicago sativa*), potato (*Solan* spp.), and sugarbeet (*Beta vulgaris*) in addition to wheat and corn, and that very little data on residue removal effects on SOC is available for those situations.

In combination, these papers conclude that under dryland or rainfed conditions, residue harvest will negatively impact soil organic matter and associated soil properties; however, harvest effects will be situation-dependent. Consequently, assessing residue harvest must be placed in a farming systems context that includes an evaluation of economic and environmental trade-offs specific for a given farm and location. Future challenges include the development of science-based, site-specific decision aids that enable growers to make economically sound and environmentally sustainable choices regarding residue harvest.

In 2009, USDA-ARS and land grant scientists in the Pacific Northwest established long-term field studies from a combination of current and new field locations to assess economic impacts of residue removal as well as effects on soil properties, soil-borne disease and crop performance [35]. Specific objectives of the project funded through the USDA Solutions To Economic and Environmental Problems (STEEP) grant program are to: (1) establish or use existing long-term field sites and assess impacts of wheat residue removal by mechanical harvest and burning on economic returns and subsequent crop performance; (2) assess environmental impacts (soil carbon sequestration, nutrient cycling, soil erosion) of residue removal by mechanical harvest and burning on established sites; and (3) develop field-scale and regional assessments of economic and environmental trade-offs associated with harvesting or burning crop residues.

Preliminary STEEP research from the Washington State University (WSU) Cook Agronomy Farm (CAF) estimated that the potential site-specific (37-ha field) lignocellulosic ethanol production from winter wheat residues would range from 813 to 1767 l ha^{-1} and average 1356 l ha^{-1}; thus, indicating that targeted harvesting of crop residues would be an important consideration. Harvesting only winter wheat residues, in a three-year rotation with spring wheat and spring peas (*Pisum sativum*), reduced residual carbon inputs to levels below that required to maintain SOC under conventional tillage practices. This occurred as a function of both residue removal and inclusion of the low residue producing spring pea crop in rotation with wheat. Harvesting winter wheat residues under conventional tillage resulted in negative Soil Conditioning Indices (SCI) throughout the field. In contrast, SCIs under no-till were positive despite residue harvesting. Increased nutrient removal is also a consideration associated with harvesting crop residues for any use. In the STEEP study, the estimated value of N, P, K, and sulfur (S) removed in harvested wheat residue was \$13.71 Mg^{-1}. In high residue producing areas of the field, the estimated value of harvested residue in fertilizer replacement dollars exceeded \$25 ha^{-1}. Based on the potential SOC impact and increased nutrient cost, we concluded that substantial trade-offs exist in harvesting wheat straw for biofuel and that trade-offs should be evaluated on a site-specific basis. Furthermore, support practices such as crop rotation, reduced tillage and site-specific nutrient management need to be considered if residue harvest is to be a sustainable option (Huggins and Kruger, 2010 [14]).

Potential impacts of crop residue removal on SOC were also simulated for different tillage and rotation scenarios in the Pacific Northwest using the CropSyst model [45]. Preliminary outcomes show that harvesting winter wheat residue at the lowest simulated removal rate (50%) resulted in SOC losses over a 30-year simulation (Figure 8.7). Harvesting less than 50% of the residue was not considered to be practical or a cost-effective use of producer time and equipment. Use of continuous no-till practices, however, partially compensated for the effects of winter wheat residue removal on SOC.

From an economic perspective dryland wheat growers typically receive from \$3 to \$5 Mg^{-1} in the Pacific Northwest, from custom operators who harvest the majority of the straw that is exported from this region. Traditionally, the primary motive for growers to sell residue is to reduce post-harvest tillage operations, thus reducing their total operating costs in high-yielding areas by \$35–60 ha^{-1} depending on tillage practices. However, growers have expressed concerns over long-term impacts of continual straw removal. Once the field

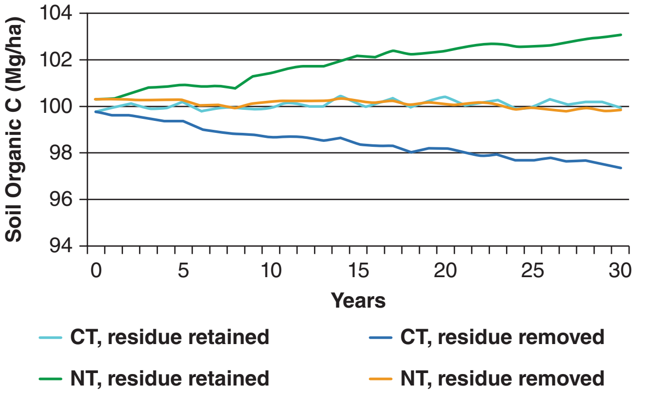

Figure 8.7 *Thirty-year simulated changes in soil organic carbon under a three-year crop rotation of winter wheat, spring wheat, spring pea using the CropSyst model. Simulations consist of conventional tillage (CT) and no-tillage (NT) and residue retained (no harvesting) and residue removed where 50% of the winter wheat residue is harvested (removed) and all other residue (spring wheat and pea) retained.*

studies and model simulations are more complete, we will estimate long-term economic impacts using partial enterprise budgets including nutrient replacement costs over time.

Sun Grant researchers are also evaluating existing straw markets to identify areas of potential residue harvest [32]. Existing markets for straw can be useful for identifying where straw is readily and reliably available. Identifying these potential markets is also important because they may significantly influence straw prices in a future biofuel market. With this background, the next steps in the DOE Sun Grant project are to identify those areas in the United States where sustained residue harvest seems feasible and to characterize those areas by determining: (1) What makes residue harvest possible in these areas? (2) Are these conditions likely to continue in the future? (3) If the area is irrigated, is the water source stable and will electricity costs affect production? (4) Are alternative markets already in place for harvested residues and, if so, at what cost would residues need to be purchased for biofuel use to be competitive? These and other questions need to be addressed as we think about residue harvest for biofuel use and the design of needed research and decision support systems for a residue-based biofuel system [33]).

8.4 Future Opportunities

Harvesting residues from corn and wheat will undoubtedly provide the most plentiful agricultural source of cellulosic biomass for the foreseeable future because of the extensive area upon which these crops are grown in the U.S.A. However, to achieve a sustainable harvest strategy only a portion of the total residue produced can be harvested and a sufficient amount must be left behind to meet all other critical ecosystem services and soil protection requirements. The ultimate challenge of balancing economic drivers favoring increased harvest to meet conversion demand with minimal transportation cost against the ecologically limiting factors (Figure 8.8) was well illustrated by Wilhelm *et al.* [20]. In fields where excess residue interferes with subsequent planting, stand establishment,

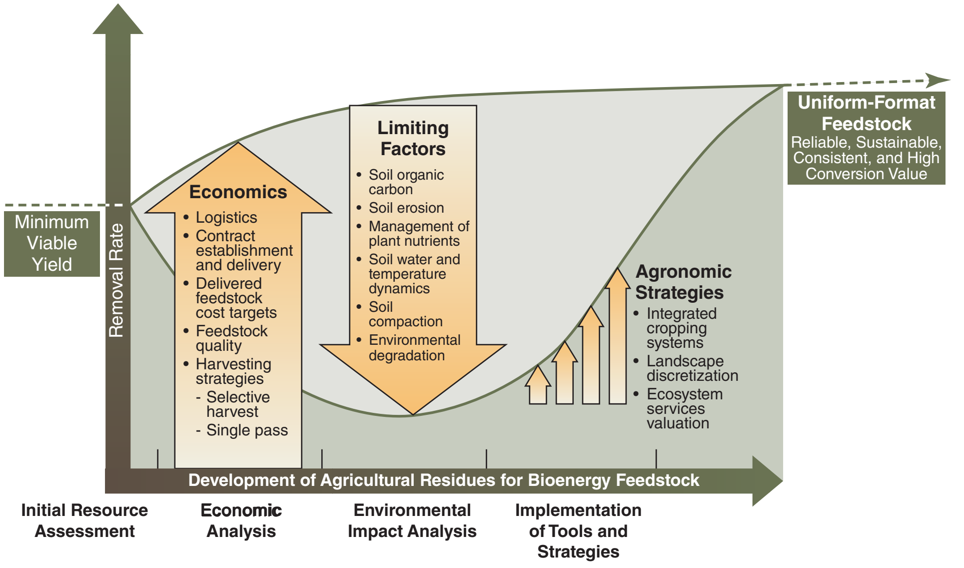

Figure 8.8 *A conceptual illustration of how economic drivers must be balanced against limiting factors based on soil protection and provision of ecosystem services. The bars to the right illustrate various soil and crop management practices that can be implemented to help ensure sustainable feedstock supplies are developed and available. (Reprinted with permission from [20], Copyright © 2010, Mary Ann Liebert Inc.).*

and nitrogen immobilization, partial residue harvest will likely increase subsequent yields. However, in more rolling and erosive landscapes most of the residue produced will likely be needed for soil protection. So, how can producers know whether or not they should consider harvesting their residues?

One strategy being developed with much of the REAP and RP data described above is the Residue Management Tool. This tool uses various databases and input information such as (1) the location and spatial extent of the potential harvest area, (2) crop rotations, (3) tillage management, (4) residue harvest methods, and (5) other land management practices to establish the potential for a safe and sustainable harvest. Every scenario involving these factors can be examined with the tool using an integrated systems model for which the input information can be defined. Using the location and spatial extent (which can be obtained directly from a combine using output files from the yield monitor), the site-specific crop yields, soils data, and climate data are assembled from the coupled databases. As the integrated residue removal tool executes its set of scenario runs, the data management modules are dynamically accessed to acquire and format the data needed for each of the models being coupled together. The integrated residue removal tool loops across the complete set of scenarios pushing each model output to the results database. The tool then aggregates the results calculated for each of the scenario runs.

Currently, the tool uses models such as RUSLE2 and WEPS to determine the amount of residue needed to mitigate water and wind erosion, and CQESTR or DAYCENT to monitor changes in the soil organic matter pool. Nutrient balance models (e.g. IFARM) and soil-test information help ensure those needs are being met and work is ongoing to develop least-limiting water relationships between soil aeration, compaction, and plant response. By connecting all of these models and supporting input information, various soil and crop management scenarios can be created and used to develop and guide sustainable crop residue harvest programs.

The initial version of the Residue Management Tool has been developed and is currently being evaluated for use with corn stover feedstock systems. However, since the tool is simply a computer framework that connects user supplied information about the location and spatial extent to be investigated, crop rotations, tillage management practices, residue removal methods, and land management practices, it can be easily adapted for other cellulosic energy crops by changing or adding additional simulation models to those it currently connects. Also, by expanding the spatial scale, the tool could be used to design landscape management scenarios [21] that could utilize multiple cellulosic energy crops to achieve economically viable feedstock production goals while simultaneously providing other ecosystem services, such as erosion control, nutrient cycling, buffering and filtering, wildlife habitat, carbon sequestration, and opportunities for rural development. The need for such an integrated framework was recently recognized by the Chicago Council on Global Affairs in a report that examined not only agronomic crops but also various waste streams as potential cellulosic feedstock for sustainable bioenergy production.

We conclude that although crop residues may often be excluded from cellulosic energy crop discussions, they will undoubtedly be part of cellulosic bioenergy systems for many years. The best option from our perspective is to integrate them into an overall feedstock production and delivery system that will be economically, environmentally, and socially acceptable for many years to come.

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9

Eucalyptus

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9.1 Phylogeny, Growth, Yield and Chemical Composition

9.1.1 Introduction and Phylogeny

Eucalyptus belongs to the *Myrtaceae* family and is comprised of more than 700 species. Most *Eucalyptus* species are native to Australia but a few are also native to New Guinea, Indonesia and Philippines. *Corymbia* and *Angophora* are two closely related genera with *Eucalyptus*. These three genera are collectively known as eucalypts, but *Corymbia* and *Angophora* have been classified as subgenera of the *Eucalyptus* genus in the recent taxonomic classification [1].

Eucalyptus is one of the most widely planted genera in the world but large scale plantations are mostly limited to tropical areas. *Eucalyptus* plantations worldwide cover a total of 17.9 million ha [2]. About 11 million ha are located in Asia while South America has about 5 million ha [2]. *Eucalyptus* has been an attractive species to farmers in developing countries because of its fast growth, straight form, coppicing ability and adaptation to various soil types.

Out of more than 700 species of *Eucalyptus*, only about 500 have the potential for commercial plantation [3]. *E. grandis* is one of the widely planted species because of its fast growth and higher productivity. Eighty percent of the *Eucalyptus* plantations worldwide are comprised of *E. grandis, E. urophylla, E. camaldulensis, E. globulus*, and their hybrids [4]. In the United States, there are approximately 50 000 ha of *Eucalyptus* planted in Florida, California and Hawaii [5]. Major species planted in the United States are *E. grandis, E. urograndis* (a hybrid between *E. urophylla* and *E. grandis*), *E. benthamii, E. globulus, E. robusta* and *E. camaldulensis*, but only the former three, as well as *E. amplifolia*, are commercially planted in the southeastern states.

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Table 9.1 Growth and yield potentials of commercial Eucalyptus species at high density bioenergy planting (2500–3000 trees/ha) in the Southeastern United States.

Species	Growth (m/yr)	Yield (GMtons/ha/yr)	Rotation (yr)
E. urograndis	4.5–7	45–67	2.5–3
E. grandis	4.5–6	40–56	2.5–3
E. amplifolia	3–5	18–25	4–5
E. benthamii	3–5	30–40	4–5

Eucalyptus species have various uses. It is a major source of wood for fuel and construction material in developing countries. Some species have been used in windbreaks in agricultural farms to modify microclimate and increase yields [6, 7]. In South America, Australia and South Florida, U.S.A., *Eucalyptus* is a major windbreak species to manage citrus canker. Lately, *Eucalyptus* has received wide attention because of its potential to supply the increasing wood demand from emerging biomass power plants. The pulp and paper industry has been using *Eucalyptus* for decades for fiber. Because of its fast growth and early canopy closure, some *Eucalyptus* species also have the potential to suppress light-dependent invasive species such as cogongrass (*Imperata cylindrica*) and restore degraded mined sites [8].

9.1.2 Growth and Yield

Commercialization of *Eucalyptus* species mainly depends on its growth rate and ease of propagation. Most species that are commercially available are fast growers that can be easily propagated, have good form and are adapted to various soil conditions. Growth and yield of *Eucalyptus* varies from species to species as well as with the geographical area (Tables 9.1 and 9.2). Generally, the faster growing species such as *E. grandis, E. urophylla* and *E. urograndis*, which are usually the ideal species for tropical areas, have higher yields (Table 9.2). On the other hand, these tropical varieties do not tolerate the cold winter temperatures of subtropical areas. Therefore, their planting range in the United States is limited to South Florida and Hawaii. When these tropical species are planted further north, trees are killed back to the ground during winter months and coppice every year. Even if they survive the cold winter, their growth is compromised due to cold stress.

Table 9.2 Mean annual increment (MAI) of some important Eucalyptus species.

Species	MAI (m^3/ha/yr)
E. deglupta	14–50
E. globulus	10–40
E. grandis	15–50
E. saligna	10–55
E. camaldulensis	15–30
E. urophylla	20–60
E. robusta	10–40

Source: [2].

Figure 9.1 *4.5-year-old* Eucalyptus urograndis *trees near Sebring, Florida. (Photo: © 2013 ArborGen Inc.; all rights reserved).*

ArborGen has genetically engineered *E. urograndis* by inserting a freeze tolerant gene (Figure 9.1). Results from field trials suggest that the superior line has growth rates and productivity similar to the conventional base clone, with better freeze tolerance up to about −8 to −9°C [9]. With this freeze tolerance achievement, the species can be planted as far north as N 30.5°. The U.S. Department of Agriculture's Biotechnology Regulatory Services is currently reviewing the species for deregulation.

9.1.3 Wood Composition

Biomass characteristics are important for both thermal and biochemical conversion and not all woods have the same properties. Therefore, ideal feedstock must be selected carefully based on the properties for efficient and higher output. Moisture content, caloric value, proportions of fixed carbon and ash content are important for thermal processes (such as combustion, pyrolysis, gasification and torrefaction) while moisture content and cellulose/lignin ratio are important for biochemical processes (such as fermentation and anerobic digestion) [10].

The moisture content of *Eucalyptus* is higher than 50% (wet basis), which usually causes concerns among processors because it is more than in softwoods and other hardwoods, which are usually between 45 and 50% (Table 9.3). High heating value is comparable to other hardwoods but lower than pine, which is currently the primary species for energy

Table 9.3 *Proximate Analysis of some* Eucalyptus *species.*

Species	Sample type	Moisture (% wet wt)	Ash (% dry wt)	Volatile matter (% dry wt)	Fixed carbon (% dry wt)	High heating value, HHV (MJ/kg)
E. saligna[a]	With bark	—	1.22	81.2	18.4	19.4
E. robusta[b]	With bark	56.2	1.26	79.9	18.9	19.7
E. urograndis[b]	With bark	54.4	0.84	82.7	16.5	19.4
E. globulus[b]	With bark	50.6	1.1	86.5	12.4	18.6
E. grandis[b]	With bark	51.9	0.72	84.8	14.5	19.3

[a]Biomass Feedstock Composition and Property Database (http://www.afdc.energy.gov/biomass/progs/search1.cgi).
[b][11].

wood exported from the southeastern United States in the form of pellets. Bark is the major source of ash in woody biomass. High ash content along with the presence of metals such as silicon can cause fouling and slagging at higher temperatures [10, 12]. This can significantly reduce the efficiency of power plants and increase operational costs. Ash content of woody biomass is less than 2%, whereas in grass species it can be as high as 5–7%. Ash content in *Eucalyptus* wood is approximately 1% (Table 9.3), but it can be further lowered by excluding bark.

Another chemical that is of major concern in woody biomass is chlorine. It is a corrosive element and in high concentrations in biomass can impact operations due to corrosion [12]. Corrosive action of chlorine can shorten the life of expensive equipment such as furnaces and boilers, requiring earlier replacement. Though short rotation woody crops are usually credited with higher chlorine content, study results show that chlorine content in *Eucalyptus* is usually less than 1% (Table 9.4).

Available data on chemical composition of *Eucalyptus* wood are mostly limited to pulping characteristics because of its wider use in the pulp and paper industry. With its potential to be used in the emerging bioenergy markets, other chemical properties are currently being studied (Table 9.5). *Eucalyptus* wood tends to have higher cellulose compared to other hardwoods. Compared to aspen, up to 9% more lignin has been recorded in *Eucalyptus* [14]. Access to sugar in lignocellulose biomass is still a challenge due to recalcitrance of cell wall [15] but, with appropriate pretreatment method under ideal conditions, *Eucalyptus* wood can be converted to biofuel [13, 16, 17]. Using biotechnology, lignin content can be manipulated in plants to increase sugar release. The U.S. Department of Energy's National Renewable

Table 9.4 *Ultimate Analysis (% dry wt) of some* Eucalyptus *species.*

Species	Sample type	C	H	N	S	O	Cl
E. saligna[a]	With bark	49.89	5.71	0.05	0.01	42.29	—
E. robusta[b]	With bark	52.57	5.81	0.35	0.03	39.89	0.09
E. urograndis[b]	With bark	51.96	5.86	0.31	0.02	40.92	0.09
E. globulus[b]	With bark	51.95	5.96	0.30	0.02	40.61	0.06
E. grandis[b]	With bark	51.26	5.76	0.30	0.02	41.90	0.04

[a]Biomass Feedstock Composition and Property Database (http://www.afdc.energy.gov/biomass/progs/search1.cgi).
[b][11].

Table 9.5 *Chemical composition of* Eucalyptus *wood.*

Species	Sample type	Total lignin (%)	Arabinan	Xylan	Manan	Galactan	Glucan
E. saligna[a]	With bark	26.9	0.3	10.4	1.2	0.7	48.1
E. urograndis	Without bark	28.0	0.3	10.3	0	0.8	38.8
E. grandis[b]	Without bark	32.4	0.3	11.4	0.3	0.9	39.7
E. amplifolia[b]	Without bark	34.5	0.4	11.1	0.5	1.3	37.4

[a]Biomass Feedstock Composition and Property Database (http://www.afdc.energy.gov/biomass/progs/search1.cgi).
[b][13].

Energy Laboratory study using ArborGen's lignin-modified *Eucalyptus* (with only half the lignin content compared to unmodified plants) shows that low-lignin *Eucalyptus* can release up to 99% of sugar whereas conventional unmodified plants release only up to 40–50%.

9.2 Cultural Practices

9.2.1 Establishment

One of the reasons why *Eucalyptus* has received so much attention lately is because of its potential to grow in marginal land. *Eucalyptus* grows best in well drained soils and high soil moisture can reduce tree growth [18]. In areas where soil is not well drained, trees can be planted on beds. Compared to conventional forestry plantations, *Eucalyptus* plantations require intensive site preparation. This can increase establishment cost but it is usually compensated by high crop yield and multiple coppice crops from the same planting.

Eucalyptus planting stock is almost exclusively produced as containerized seedlings. Containers are usually 100–150 cm^3 in volume and the trees are produced in 3–4 months. Tropical species such as *E. grandis, E. urograndis* and *E. saligna* can be propagated easily using rooted cuttings so that clonal varieties can be developed and planted. Cold tolerant species such as *E. amplifolia, E. benthamii* and *E. macarthurii* are much more difficult to propagate vegetatively and, to date, are almost always reproduced from seed.

Eucalyptus is extremely sensitive to weed competition. Studies show that *Eucalyptus* seedlings have less tolerance to interspecific competition [19,20]. In *E. globulus*, the effect of weed competition on tree growth was evident as early as two months after establishment [19]. Unlike pine plantations, weed control is, therefore, a must in the first year for successful establishment. Pre-emergent herbicide can be applied during site preparation to slow weed germination followed by directed sprays as needed after planting in the first year. Oust XP® is currently used as pre-emergent herbicide for weed control in *Eucalyptus* planting but care must be taken while using it in basic soils because of its potential to kill trees. SFM 75® is currently the only herbicide labeled for *Eucalyptus*, both for use during site preparation and over-the-top application. Because of its faster growth, crown closure occurs by the second year and competition control usually is not needed after that.

Preliminary results of collaborative studies between ArborGen and the University of Florida's North Florida Research and Education Center on the effectiveness of several herbicides and their rates on *Eucalyptus* show that among several herbicides tested, longer weed control is obtained with pre-emergent Oust XP® and Clearcast® (Pat Minogue, personal communication). Several herbicides can be used for competition control in *Eucalyptus* stands but the rate needs to be adjusted depending on the *Eucalyptus* genotype. Additional studies are currently underway to refine herbicide application rates.

9.2.2 Fertilization

In *Eucalyptus*, nutrient demand is higher in earlier years because of its vigorous growth. As for other plants, nitrogen and phosphorous are two important nutrients for *Eucalyptus*. A study in *E. globulus* suggests that nitrogen and phosphorous, which are responsible for tree growth, are important nutrients in the first year and their application in the first year can significantly impact growth in the later years, too [21]. In *E. grandis*, the application of phosphorous increased nitrogen and sulfur absorption, significantly improving growth [22]. Though boron is required in small amounts, it is important when trees are growing in marginal lands. Sandy soil usually lacks potassium and must be supplemented through fertilizer application. Earlier studies suggest that fertilizer application methods (broadcast application versus placing fertilizer in a hole next to the seedling) do not have a significant impact on *Eucalyptus* seedling growth [23, 24], but application timing can have significant effects on growth [25].

9.2.3 Disease and Pest Control

Because of large commercial plantations, *Eucalyptus* diseases in South America, Australia and Asian countries are widely studied and well understood, but information from North America is limited. In general, *Eucalyptus* diseases can broadly be classified into foliar diseases, stem cankers, bacterial wilt and nursery diseases [26]. Economically important *Eucalyptus* diseases and pests present worldwide and their impacts are discussed in detail in references [26–28].

Eucalyptus longhorned borers (*Phoracantha semipunctata* and *P. recurva*), snout beetle (*Gonipterus scutellatus*), tortoise beetle (*Trachymela sloanei*) and at least six psyllid species have been reported from California [29]. Galls of blue gum chalcid (*Leptocybe invasa* Fisher and LaSalle) were found for the first time in North America in the stem and leaves of *Eucalyptus* trees in Florida. The species is currently distributed in Broward, Palm Beach, Glades, Hendry, Lee and Dade Counties in Florida [30]. In 2001, the red gum lerp psyllid (*Glycaspis brimblecombei* Moore) and the *Eucalyptus* psyllid (*Blastopsylla occidentalis* Taylor), which are native to Australia, were also reported in the Orlando, Florida area for the first time. They have also been recorded in California [31]. *Eucalyptus* stem canker has also been observed in Florida.

9.2.4 Harvest Management (Cutting Height, Season, and Frequency)

Any forest tree harvester that leaves a clean cut stump can be used for harvesting *Eucalyptus* but care should be taken not to damage the stump if the plantation is to be managed for a coppice crop. A study in *E. globulus* shows that coppicing is influenced by lignotuber development, seedling stem diameter and vigorous growth before felling [32], but other factors such as condition of stump, cutting height and harvest season can also impact coppicing. During harvesting, bark can peel off easily from the stump, thereby reducing the chances of coppice. Therefore, harvesters with saw heads are recommended rather than those with shear heads for *Eucalyptus* harvest. Care should be taken not to run over the stumps during the harvesting operation.

Recommended cutting height is 15–20 cm above the ground. A tall stump increases the chances of coppice windthrow whereas a low stump reduces the chances of coppicing. Though it is difficult to achieve using commercial harvesters, the cut surface should be slightly angled (if possible) to allow water to drain from the surface easily. This minimizes the chances of fungal infection on the cut surface.

Depending on the species, rotation of *Eucalyptus* planted in high density bioenergy plantations can range between 2.5 and 5 years (Table 9.1). There is no specific season for *Eucalyptus* harvest but the spring season is ideal to encourage coppicing during summer. Harvesting during winter months (end of the year) can potentially lower coppice rate. Results from a study of oaks shows that stump mortality decreases when the trees are cut outside growing season [33].

9.3 Genetic Improvement

Intensive selection and improved silviculture have improved the growth rates. The U.S. Forest Service started genetic improvement of *Eucalyptus* in the southeastern United States in the 1960s. The Forest Service discontinued its program in the early 1980s when most tests were compromised due to cold weather. The University of Florida later started the genetic improvement of *E. grandis* and *E. amplifolia*. After extensive tests throughout the state of Florida, four commercial *E. grandis* cultivars *E. nergy*™ G1, G2, G3 and G4 with exceptional growth rate, freeze tolerance and stem form were released in 2009 [34]. Another new clone, G5 has been released recently. All five cultivars have differences in performance, genetics and wood properties. Four cultivars (G1–G4 cultivars) were planted at various sites across the state in 2009 and 2010 and produced exceptional growth rates and freeze tolerance. Work is underway to develop more *E. grandis* and *E. amplifolia* cultivars.

E. urograndis has been planted extensively in Brazil by pulp and paper and charcoal companies because of the hybrid's fast growth and excellent wood properties [35]. In the United States, *E. urograndis* is grown only in Hawaii and South Florida due to its tropical nature. ArborGen has genetically modified *E. urograndis* to increase its freeze tolerance. Conventional *E. urograndis* usually can tolerate temperatures as low as $-1°$C but the biotech varieties developed by ArborGen with freeze tolerant gene in them can tolerate approximately -8 to $-9°$C. Field trials were successfully conducted in the southeastern United States. The species can now be planted as far north as the Interstate-10 corridor up to East Texas.

North Carolina State University, in collaboration with several pulp and paper companies, began a testing program to identify cold hardy *Eucalyptus* that could survive winter temperatures in the southeastern United States in the 1970s [36]. The research project identified four species (*E. viminalis, E. macarthurii, E. nova-anglica* and *E. camphora*) with some freeze tolerance that could survive the fluctuating warm and freezing temperatures in the region. A series of severe freezes in the mid-1980s destroyed all but a few trees for which efforts were undertaken to continue a genetics program through vegetative propagation and transfer of selected trees to a milder climate for seed production [37]. Ultimately that project was terminated. Recently, North Carolina State University has renewed its research efforts at developing cold hardy eucalyptus adapted to the United States and a series of species screening trials were planted from Texas to North Carolina. There have been some encouraging early results with the species *E. benthamii*. The University and its collaborators are now looking at combining the cold tolerance of some species with the rapid growth, ease of propagation and wood properties of tropical species in a hybridization project (Steve McKeand, personal communication).

Westvaco Corp. began the testing of *E. benthamii* in the United States in the early 1990s. Several of the earlier trials are still present in the states of South Carolina, Gerogia, Florida and Texas. Seed collected from a mother tree in a South Carolina test has shown an exceptional potential of *E. benthamii* for genetic improvement (Figure 9.2). Trees planted near Chatom, Alabama had exceptional growth and tree form. Average tree height was about 12 m in three years. ArborGen has acquired seeds of 100 *E. benthamii* families from Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO); these are currently being tested in Florida, Alabama and Texas. Though there are significant differences between families, early growth results are exceptional (Figure 9.3). Tree size and form within a family are uniform. Some families were 2.5 m tall in seven months. The goal is to convert the tests to commercial seed orchards in the near future.

Figure 9.2 *3.5-year-old* E. benthamii *trees near Chatom, Alabama. Average tree height was 12 m. (Photo: © 2013 ArborGen Inc.; all rights reserved).*

Figure 9.3 *7-month-old* E. benthamii *progeny test at Bellamy, Florida. (Photo: © 2013 ArborGen Inc.; all rights reserved).*

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10
Pine

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10.1 Introduction

Pine branches, pine logs, and residues from sawmills have been burned for energy for over a thousand years. In some places, demand for fuel and building materials was so great that expansive pine forests (*Pinus* spp.) were "utterly destroyed." One example is in Scotland where 70% of the region was once covered by the "Great Wood of Caledon." However, by 1500 the *Pinus sylvestris* forests were all but gone. As a result, in 1503 the Scottish Parliament passed an act to encourage tree planting. Today, pines are the most commonly planted tree genus in the world and, in some regions, pine acreage is increasing due to planting seedlings on former agricultural lands.

Pines make up about 28% of tree plantations for the ten countries with the largest areas of planted forests [1]. Pines are the most commonly planted genus in Asia, Australia, Europe and North America [2]. According to some, conifers outnumber non-conifers three to one in regards to fast-growing tree plantations [3]. Some reasons to explain the preference for pines are the ease of seed collection, the ability to store seed for long periods, the low cost of producing high quality planting stock, a consistently high level of plantation success, rapid early growth, and relatively high demand for pine sawlogs.

Although pine biomass is used to produce energy, pines are generally not planted for the sole purpose of bioenergy. There are four basic reasons for this: establishing a pine plantation requires an investment of money; several species of hardwoods from natural stands are a preferred source of firewood; returns are often higher when pine logs are merchandized and sold to pulp, sawmills, or pole mills; and coal and oil are more convenient sources of energy than wood. Historically, the economic returns for pure bioenergy plantations are lower than for plantations harvested and sold to pulp mills, sawmills or pole mills.

Cellulosic Energy Cropping Systems, First Edition. Edited by Douglas L. Karlen.

10.1.1 Phylogeny, Chemical Composition

Pines evolved in the Northern Hemisphere, with most species naturally occurring between 20 and 70° latitude. The largest genus of conifers contains over 100 species, which may be divided into two or three subgenera. Some say the "hard pines" (subgenus *Pinus*) contain 64 species while "soft pines" (subgenus *Strobus*) contain 37 species. Members of the subgenus *Pinus* have two fibrovascular bundles per needle while the subgenus *Strobus* only has one.

Pine wood is composed of cellulose, hemicellulose, lignin, oleoresin, uronic anhydride, acetyl and ash. Cellulose, lignin and hemicellulose typically comprise more than 90% of the wood while resins may make up 9% of the oven-dry weight. On an equal mass basis, the economic value of the resins is generally higher than that for wood. The chemical structures and amounts can vary by species because of genetics involved in producing the cell wall and its components.

10.1.2 Heat of Combustion

The heat of combustion for wood is expressed as the high heating value (HHV) or low heating value (LHV). The HHV can be thought of as the gross amount of energy trapped in an odMg of wood while the LHV is the net energy after accounting for the moisture content of the wood. The HHV can be considered a theoretical value while the LHV is closer to the utilizable energy.

The quantity of usable heat produced by the complete combustion of pine logs (LHV) will vary depending upon the moisture content [4]. Although a cubic meter of wood contains the same mass of cellulose either green, air dried or oven dried, the amount of usable heat produced is greater for oven-dried wood (Table 10.1). This is because energy is required to turn water into steam. The more water the wood contains, the more energy will be used to produce steam.

Two methods are used when calculating the moisture content. In some reports, the denominator includes both wood and water and in other reports it does not include water (i.e. oven-dry basis). When the method is not specified, this difference can cause confusion. For example, if someone says wood has a moisture content of 50%, it would not be clear if this means half of the mass is water (i.e. green basis) or if 33% of the mass is water (i.e. 1/3 water and 2/3 wood). Therefore, in this chapter, we will include the designation "od" to indicate the denominator does not include water.

The energy contained in pine logs will also vary depending upon the resin content. The heat of combustion for pine increases by about 16.8 kWh/dry tonne for each percentage point increase in extractive content. Pine logs with high resin might have 20% more energy than logs with no resin [5]. In fact, the heat of combustion of pine resin can be higher than coal (Table 10.1). Certain "hard pines" produce more resin than other species. Pines known for their ability to produce lots of resin include *Pinus elliottii* and *Pinus palustris*. Wood from pines from the southern United States may contain about 5% extractives, but heartwood segments from old growth may contain 30–35% extractive content. This will cause the wood to be dense enough to sink when placed in water. This type of wood is commonly referred to as "fatwood" or "lighter wood" and is sold as kindling on the Internet for about $2.50 per kg (or $2500 per tonne). Unfortunately, the demand is generally low and, therefore, it may take some time to sell one Mg of "fatwood."

Table 10.1 Estimates of the amount of energy contained in a cubic meter for various energy sources. High heating values (HHV) are theoretical while actual heating value will depend on the efficiency of conversion.

Material	Volume	Mass (Mg)	Water mass (Mg)	MWh/m^3	GJ/m^3	GJ/Mg
Broken bituminous coal	$1\ m^3$	0.833	—	6.26	22.5	27
Crude oil	$1\ m^3$	0.898	—	10.75	38.7	43
Gasoline	$1\ m^3$	0.737	—	8.89	32	43.5
Natural gas	$1\ m^3$	*(717 g)*	—	0.0103	0.037	55.5
Pinus taeda		dry mass				
Stem wood	$1\ m^3$	0.47	—	2.61	9.4	20.0
Stem wood	$1\ m^3$	0.47	0.117	2.36[a]	8.48[a]	14.45[a]
Stem wood	$1\ m^3$	0.47	0.53	2.08[a]	7.48[a]	7.48[a]
Bark chips	$1\ m^3$	0.19	—	1.08	3.89	20.5
Wood chips	$1\ m^3$	0.18	—	1.0	3.6	20.0
Pine resin	$1\ m^3$	1.05	—	10.16	36.6	34.8
Charcoal	$1\ m^3$	0.2	—	1.59	5.73	28.7
Pinus elliottii						
Stem wood	$1\ m^3$	0.472	—	2.61	9.4	19.8
Stem wood + paraquat	$1\ m^3$	0.528	—	3.08	11.1	21.0
Lighte rwood	$1\ m^3$	1.03	—	7	25.3	24.6
Pinus radiata						
Stem wood	$1\ m^3$	0.45	—	2.33	8.4	20
Stem wood	$1\ m^3$	0.45	0.19	2.22[a]	7.99[a]	12.48[a]
Stem wood	$1\ m^3$	0.45	0.55	1.96[a]	7.06[a]	7.06[a]

[a] Low heating value.

10.1.3 Growth

The growth of pine varies depending upon species, soil properties, nematodes, weeds, climate, genetics, cultural practices, disease, and so on. Due in part to the climate, the growth of existing *Pinus longaeva* stands in Nevada is extremely slow and approaches 0 m^3/ha/yr. Natural stands of *Pinus banksiana* in Ontario may produce 3 m^3/ha/yr. In contrast, in more favorable climates, growth of planted pine may range from 8 m^3/ha/yr (*Pinus resinosa* in Prince Edward Island) to over 30 m^3/ha/yr (*Pinus radiata* in New Zealand and *Pinus taeda* in Brazil). These rates of growth only include stem volume and do not include branches, needles and roots. When including branches, some claim growth rates of *Pinus elliottii* in Florida are greater than 50 m^3/ha/yr [6]. One report implies that pines could produce about 230 m^3/ha of biomass in just eight years [7].

Depending upon where they are planted, pines are grouped into either exotic or indigenous. When pines are planted in the southern hemisphere, they are exotic and typically will grow faster than when planted in their natural range. For example, *Pinus radiata* might grow two or three times faster in New Zealand or South Africa when compared to the growth rate in its indigenous environment in California. There is much speculation as to why the growth rates are typically higher when pines are planted in the southern hemisphere; the answer may be due to different species of organisms in the soil. When *Pinus radiata* is planted as an exotic species in South Alabama, the rate of growth is typically not increased. This might be due to the presence of nematodes that are adapted to feed on pine roots. Although nematodes are present in the soil in New Zealand and South Africa, they are not adapted to pines. As a result, pines in New Zealand produce more foliage during the year and they typically end up with a higher leaf area index.

10.1.4 Energy Yield per ha per Year

The amount of energy captured by pines over a one-year period will vary with stand age, species and cultural practices. Pine trees that are less than three years old typically have a limited amount of foliage and, therefore, have not captured much energy (when compared to maize or perennial grass species). However, once pines have "captured the site" and are producing a high percentage of shade, the ability to capture energy increases. For species like *Pinus tadea* and *Pinus elliottii*, the amount of energy captured (i.e. stored as aboveground wood) in a given year typically peaks around ages 10–19 years. This peak may be around age 10 years when growth rates are high while lower growth rates may result in a peak near age 19 years. After this peak, the net energy captured in a year declines as the stand matures.

The amount of energy contained in one cubic meter of pine depends on the unextracted specific gravity, which changes with stand age. The specific gravity of a five-year-old *Pinus taeda* sapling may be 330 kg/m^3 (from stump to a height of 3 m) while that of a bone-dry, 3 m log from a 50-year-old stand may be 500 kg/m^3. In this example, the older log contains 50% more energy than an equal volume of the younger log. Therefore, it should not be assumed that the energy in a green tonne of 14-year-old pine logs will be the same as that contained in 28-year-old logs.

Sometimes the estimated energy per volume of wood varies by as much as 16% because wood shrinks when it dries. Therefore, one might overestimate the energy captured by pines if one overestimates dry mass productivity. Estimates of the dry mass per cubic meter could vary from 500 to 562 kg (Table 10.2) depending on if the volume is measured soon after the tree is harvested (i.e. green) or soon after the wood is removed from a drying oven. Therefore, overestimates may occur when specific gravity is determined using the oven-dry volume as the denominator.

Table 10.2 *Approximate mass (kg) per cubic meter of southern pine related to wood specific gravity (oven-dry mass divided by green volume) and moisture content (mass of water/dry mass of wood). It is assumed that volumetric shrinkage of wood is linear from 28 to 0% od moisture content.*

Tree age (yr)	Specific gravity (green volume)	Moisture content (od)					
		0%	10%	20%	30%	50%	100%
		(Kg/m^3)					
4	0.35	385	409	429	457	525	700
7	0.4	444	470	492	523	600	800
17	0.45	506	532	557	588	675	900
45	0.5	562	585	612	653	750	1000
90	0.55	639	665	687	718	825	1100
	Shrinkage For 0.55 SG	14%	9%	4%	0.5%	0%	0%

The amount of energy contained in a pine stand (aboveground biomass = 500 m^3/ha) might be 1150 MWh/ha (LHV) but this might end up producing only 250 MWh of electricity.

The greater value (1150 MWh/ha) assumes wood (25% od moisture content) will produce 2.3 MWh/m^3 when burned in a wood boiler (97% efficiency). The lower value (250 MWh) assumes the wood is used in a power plant to produce electricity (21% efficiency). Some wood-fired power plants may convert one Mg of waste wood into 0.8 MWh of electricity.

If the pine stand mentioned above was 25 years old, the yield would be 20 m^3/ha/yr or 46 MWh/ha/yr. Likewise, if it took 50 years to produce this volume, the yield would be cut in half (i.e. 10 m^3/ha/yr or 23 MWh/ha/yr). As a comparison, 23 MWh/ha is equivalent to 13.5 barrels of crude oil (in theory). A hectare of solar panels might yield about 990 MWh of electricity per year. As a comparison, it might take a year and 21 hectares to capture the same amount of wood energy with a pine plantation.

10.2 Cultural Practices

10.2.1 Nursery Production

To obtain seed, pine cones can be collected from natural stands, plantations or from intensively managed "seed orchards." For some species, the cost of collection and extraction (i.e. removing seed from the cone) is less than \$0.004 per seed. When kept at the proper moisture content, seed may be kept viable for several years. After the wing is removed, the shape of the seed is often conducive to sowing with either vacuum sowers or with other types of mechanical seeders.

Pine seedlings have been grown in nurseries for hundreds of years. For example, in 1664, John Evelyn described techniques for growing pine in containers and in bareroot nurseries. Over time, the ability to efficiently produce pine seedlings has improved. Now, as few as five persons can grow 30 million pine seedlings in a bareroot nursery (at a production cost <\$0.05 each). Some pines grown in containers on a large scale may cost less than \$0.15 each. The production of bareroot seedlings is more efficient when nursery soils are sandy (typically >75% sand). Therefore, in regions where soils are low in sand content, container nurseries are preferred. In regions where sandy soils are common, bareroot stock might be preferred, especially when container-grown stock costs two or three times that of bareroot stock. This partly explains why most pines in South Africa are produced in containers while most pines grown in the southern United States are grown in bareroot nurseries in the Coastal Plain.

Nursery managers in the United States are currently producing over 800 million pine seedlings a year, and this amount is sufficient to plant 0.7 million ha annually. Some predict a price of \$28 per green Mg (at the roadside) could increase the establishment of woody biomass crops to approach 5.2 million ha by the year 2017 [7]. This would require establishing over a million ha of wood biomass crops each year. Given notification at least two years in advance, nurseries in the United States would likely not be able to produce 0.6 billion Eucalyptus seedlings plus an additional 0.5 billion Populus cuttings in 2014. In contrast, there is a sufficient amount of pine seed in storage and enough fallow nursery land to meet this goal. However, a rapid expansion of biomass plantations in the United States would likely meet resistance from special interest groups, regulatory agencies, and, perhaps, even Congress.

10.2.2 Planting Season

In general, adequate soil moisture determines when pine seedlings should be planted. In the southern United States, wet and cool months are generally during the winter (January–March) and this corresponds to when most pines are planted. However, if soil moisture is adequate, pines may be planted in any month (especially when using container-grown stock). For example, pines have been successfully planted in the summer in both Florida and South Africa. However, when planted in the summer, bareroot seedlings have better survival when they are planted deep and the time between lifting and planting is less than three days. Most tree planters prefer to plant seedlings in cooler months. Therefore, in some temperate regions, planting in cool months is less stressful for both the pines and the tree planters. Also, bareroot pine seedlings may be stored in refrigerated coolers for several weeks if lifted after the winter solstice.

10.2.3 Planting Density

The recommended number of trees to plant per hectare varies depending upon the objectives of the landowner. In general, the number planted per hectare in Europe is higher than in New Zealand and the United States. Due to tradition, pines in Europe may be planted at 2500/ha and in the southern United States the number may be 1000–1400/ha; in New Zealand, the number may be 800–1000/ha [8]. When the delivered cost of pine logs is the same (per green tonne) for pulpwood and for fuelwood, then the economically optimum planting density (for a given species, location and discount rate) should be nearly the same.

When researchers establish a bioenergy pine plantation, they often plant more seedlings than would be recommended by an economic analysis. In one short-rotation experiment in Florida, *Pinus clausa* was planted at 26 900 seedlings per hectare [9]. Two factors that are often ignored are the cost of establishment and the cost of harvesting. In the southern United States, the cost of harvesting and transporting one tonne of pulpwood to a mill is about two-thirds the price paid at the mill. For example, a pulp mill might purchase green wood for $42 per Mg ($14 to the landowner, $10 for harvesting, and another $14 for transportation). Much of the time in harvesting is spent handling and processing each tree, so tree size is an important determinant in harvesting cost (Figure 10.1). For some planting densities, harvesting one green tonne might require less than 5.5 trees while planting 3000/ha may require cutting twice that many (Table 10.3). In many cases, the target planting density is selected without considering the economic impact of both establishment and harvesting costs.

10.2.4 Planting Row Configuration

10.2.4.1 Rectangular Spacing

Historically, many tree planting guides for pines recommend a square spacing. However, recent trends are in favor of a rectangular arrangement where the distance between the rows is greater than the distance between pines within the rows. In a few cases, the distance between rows is four times the distance between trees within a row. This planting configuration is especially useful in reducing establishment costs when trees are planted

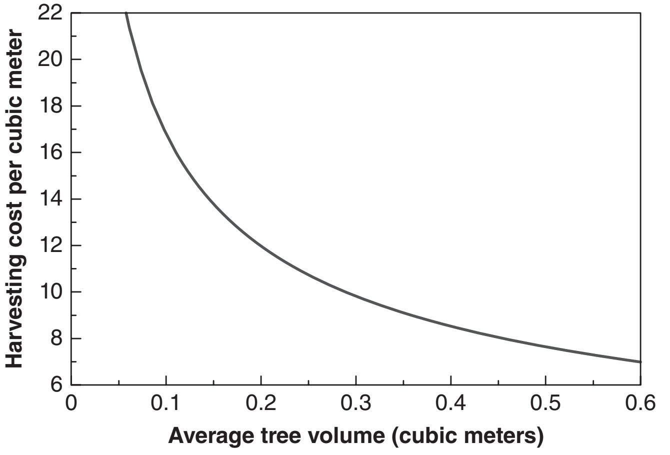

Figure 10.1 *The cost of harvesting trees is a function of tree size. The actual price to harvest trees that average 0.3* m^3 *will depend on equipment used, terrain, fuel costs, labor costs, year of harvest, exchange rates, and so on.*

with machines, on sites that have been ripped prior to planting, and in cases where herbicides are applied in bands (centered over each row of pines).

10.2.4.2 Hybrid System

The hybrid system (or FlexStand^{TM} System) is a way of growing pines for multiple markets. One such planting configuration involves a row of sawtimber crop trees next to a row of pines intended for bioenergy. For example, alternating rows of sawtimber crop trees (harvested after 24 years) may be planted between adjacent bioenergy rows that are harvested after 14 years (Table 10.4). In some cases, all seedlings in the plantation may be from the same genetic source while in other cases the genetics will vary by row [10]. For example, each row of sawtimber trees may be of one genotype (grown in containers) while alternating rows intended for bioenergy may be planted using less expensive bareroot stock (perhaps injecting them with paraquat two years before harvest [5]). Spacing for the biomass trees might be 2 m apart within the row while sawtimber trees might be spaced 3 m apart within the row. At some early age (perhaps 11–14 years) all of the biomass rows are harvested. On some sites this thinning might remove 100 green tonnes per ha of biofuel. After the biomass thinning, the remaining pines might be on a 10×3 m spacing.

10.2.4.3 Mixed Genus Configurations

Another planting configuration involves an intercropping system using wide rows of sawtimber crops that are interplanted with a biomass crop such as *Panicum virgatum*. The rows of pine are planted 6.1 m apart and pines are planted 1.5 m apart within each row. To capture the solar energy between rows, a biomass crop is established and harvested for fuel. This dual cropping system has an advantage in that some of the understory vegetation is

Table 10.3 *An example of the effect of planting additional pine seedlings (base level = 0/ha) on the added costs of producing, harvesting and delivering biomass (i.e. extra tonnes) to a biomass plant.*

Seedlings per ha	Yield of green biomass Mg/ha	Seedling cost $/ha	Hand planting cost $/ha	Standing value $/ha	Net present value at 5% $/ha	Average DBH cm	Trees per green Mg	Harvest cost per green Mg $/Mg	Net present value at roadside at 5% $/ha
500	111	30	60	3330	676	23.1	3.6	10.00	676
1000	155	60	120	4650	1286	19.8	5.3	11.60	1043
1500	179	90	180	5370	1578	17.8	6.9	13.10	1021
2000	184	120	240	5520	1567	15.5	9.0	15.10	555
2500	190	150	300	5700	1573	14.7	10.3	17.00	232
3000	193	180	360	5790	1531	13.2	12.4	20.40	−476

This example involves planting pine seedlings on a site index of 24 m (at 25 years) in the Coastal Plain, a 13-yr rotation, a 5% discount rate, an establishment cost varying from $1090/ha to $1540/ha, a price of $30/Mg for standing trees and $40/Mg for biomass at the roadside. In this example, the optimal planting density for biomass production for this rotation age is 1000 seedlings per ha when including harvesting costs and 1500 per ha when ignoring harvesting costs.

Table 10.4 *A comparison of a biomass only stand with a hybrid stand (all biomass rows (B) removed at age 14 yr; remaining sawtimber rows (S) harvested at age 24 yr) and a sawlog stand (wide row; thin at age 14 yr; harvest age 24 yr) All data were generated using Ptaeda3.*

		Hybrid stand		
Establishment	Biomass only	B Row	S Row	Sawlog
Row spacing (m)	2.4	2.4	2.4	4.6
Spacing within the row (m)	2.4	2.4	3.0	2.4
Ripping soil ($/ha)	250	250		133
Machine planting ($/ha)	170	170		91
Seedling cost ($/ha)	84	74		45
Herbicide – 2 m band ($/ha)	196	196		105
Total cost ($/ha)	700	690		374
Initial survival (%)	89	89		89
Stand characteristics at thinning				
Type of thin	—	Every “B”row		Remove small trees
Live trees at age 14 years before thinning	—	1243		739
Trees thinned	—	689		460
Basal area after thinning (m^2)	—	6.2		5.6
Average DBH – cm before thin	—	17.8		21.8
Average DBH – cm after thin	—	18.8		24.9
Average height – m before thin	—	14.7		15.7
gTonnes logs harvested (small + medium)	—	0		30 + 44
gTonnes of biomass chips harvested		118		0
gTonnes of branches and tops left on site	—	0		22
Stand characteristics at harvest				
Rotation age (years)	12	24		24
Average DBH (cm)	17.5	26.2		33.3
Average height at harvest (m)	12.8	21.9		25.0
Trees harvested per ha	1391	526		279
gTonnes of branches and tops	42 harvested	39 left on site		34 left on site
gTonnes/ha/yr (including branches)	15.6	16.0		15.4
dTonnes/ha/yr (including branches)	5.9	7.0		6.4
gTonnes large (sawtimber/ha)	0	47		193
gTonnes medium (chip-n-saw/ha)	46	131		3
gTonnes small (biomass chips or pulpwood/ha)	100	49		45
gTonnes removed/ha	188	227		241
Wood properties at harvest				
Average rings per cm (at groundline)	1.2	1.7		1.3
Specific gravity at harvest (at DBH)	0.42	0.46		0.46
Basal area in juvenile wood (at DBH) (%)	100	45		28
Moisture content – (od) (%)	138	117		117
Number of trees harvested per gtonne	8.2	2.5		1.3
Mass harvested (24-yr period)				
gTonnes of products (small + medium + large)	0	227		240
gTonnes of biomass per ha	374	163		0
Dry tonnes of biomass per ha	157	68		0
Value of harvested wood				
Biomass – year 12 ($/ha)	1692	0		0
Biomass – year 24 ($/ha)	1692	0		0
Biomass or Wood products – year 14 ($/ha)	0	1112		1067
Wood products – year 24 ($/ha)	0	4211		6182
Net present value at year zero: at 5% ($/ha)	377	1177		2081

Biomass and small logs = $9 per green tonne (gTonne); medium logs = $18/gtonne; large logs = $30/gtonne.

converted to a useful product (e.g. a liquid fuel). The company, Catchlight Energy, is currently working with the forest products company Weyerhaeuser in researching the opportunities for producing cellulosic biofuels from biomass crops in pine plantations.

10.2.5 Weed Control

Competition from herbaceous and woody weeds can slow the growth of pines and this can delay harvest by as much as seven years. For some pine species, experienced foresters will use fire (i.e., prescribed burns) as a way to control hardwoods. Prescribed burns may be used after harvest to prepare the site for planting and they can be used in developing stands once the pines are large enough to tolerate the fire. Some pines (e.g., *Pinus palustris*) are more tolerant of fire than others (e.g., *Pinus glabra*), so fire is only appropriate for certain pine species. The timing of fires is also important (both on an age basis and a time-of-year basis). Periodic prescribed fires are used in the southern United States to control woody vegetation and improve wildlife habitat, especially in areas where the plantation is far from residential homes.

Controlling woody weeds with herbicides is now a common practice in pine plantations throughout the world. Depending on the degree of hardwood competition, controlling all hardwoods during the first three years of stand development can result in shortening the rotation by 1–5 years (i.e., the same amount of pine volume can be harvested 1–5 years sooner). Similar gains may result when controlling all herbaceous weeds (on sites with no woody weeds). However, controlling herbaceous weeds on sites with lots of hardwood competition might not affect pine growth at harvest. This is because controlling herbaceous weeds might benefit hardwoods more than pines.

Applying herbicides after harvesting but before planting is desirable from a biological point of view. Injury to planted seedlings is less (especially when applying non-selective herbicides) and higher herbicide rates can be applied (when compared to applying herbicides soon after planting). In the United States, the tax system once favored waiting three or four years after planting before applying herbicides. The cost of herbicide application could then be expensed (instead of capitalized when applied the same year as transplanting). Effective control was less since the woody competition was larger and more resistant (when herbicide rate was comparable). Now, most landowners may deduct up to $10 000 per year in weed control costs from their income (before calculating taxes). In other countries, foresters may deduct all weed control costs in the year that it occurs.

Application of herbicides are either made from the air (often with helicopters) or from the ground. Broadcast applications are typically cost effective and are often used prior to planting seedlings. Ground equipment or hand labor is used when applying herbicides in bands (e.g. treating 50% of the area in alternating strips). Ground application may also be preferred in areas where the risk of damage by herbicide drift to adjacent landscape plantings or agricultural crops is high.

10.2.6 Fertilization

Fertilization of pine plantations can be categorized into four groups: natural (e.g. in rainfall), at planting, mid-rotation, and annual. In the southern United States, the majority of pine plantations are not fertilized but they receive a limited amount of nutrients when it rains. Nitrogen (N) rates in rainfall can vary from 1 to 5 kg N/ha/yr and the amount of phosphorus

(P) is often less than 0.5 kg of P/ha/yr. Over a 25-year period, a pine stand might receive 100 kg of N/ha in rain.

In some countries, pines might be fertilized at time of planting (sometimes in a circle around the planted tree or in a small pit about 20 cm from the seedling). The amount and types of nutrients that are applied will vary depending on the inherent fertility of the soil. In some cases, 50 g of N may be applied per seedling (equal to 100 kg N/ha when treating 2000 seedlings/ha).

By themselves, pines have a hard time extracting phosphorus from the soil. Fortunately, pine roots have developed a symbiotic relationship with certain fungi (i.e., ectomycorrhiza), which greatly increase the uptake of phosphorus. In most cases, growth of pines is very slow when pines do not form this ectomycorrhizal relationship. However, even when ectomycorrhiza are established, some soils are so low in available phosphorus that growth is dramatically reduced. These poorly drained soils are easy to identify and, therefore, foresters typically fertilize these sites with phosphorus prior to the time of planting.

Fertilization with nitrogen at planting may have either a positive or negative effect, depending on the degree of weed control. In some cases, applying nitrogen will increase growth of hardwoods and shrubs. This extra boost in weed growth might suppress the growth of the pines during the decade after planting. For this reason, many who apply fertilizers (before, during or after transplanting) also use herbicides to suppress weed competition. Although the use of fertilization at time of planting varies with ownership and fertilizer price, the amount of area treated might be 10–13% of the total amount planted that year.

On some sites, micronutrients may be limited and a deficiency will affect the growth of pines. On alkaline soils, uptake of iron (Fe) can occur and pine needles will turn yellow. For this reason, pines are typically not grown where the soil pH is greater than seven. On some sites, fertilization at planting with boron (B) or copper (Cu) have improved the growth of pines.

Occasionally, a few farmers have mistakenly killed pines by placing fertilizers directly into the planting hole. Pines will typically die when roots are “burned” due to direct contact with concentrated fertilizers. Slow release tablets are sometimes sold and are said to prevent roots from being “burned.” However, the cost of the fertilizer tablet is sometimes greater than the seedling and relatively high cost of nitrogen limits operational use.

Many pine plantations are fertilized after tree crowns have closed and roots from adjacent trees have overlapped. The decision to fertilize will depend on the nitrogen and phosphorus content of the needles. The response to fertilization is higher when nutrient content is below a target level. Historically, the price of fertilizer affects the decision to fertilize pines. In 2011, the inflation-adjusted price of nitrogen was four times greater than it was in 1960, and that of phosphorus was seven times greater.

Except for research studies (sometimes involving trickle irrigation or sewage effluent treatment) annual fertilization of pines is not practiced. Typically, pine stands are not fertilized or are fertilized once or twice during a 20+ year rotation.

10.2.7 Insects, Disease and Nematodes

Some diseases and pests of pines are native to the region while others are exotic (also known as introduced pests). A few examples of exotic pests include *Grosmannia huntii*, *Bursaphelenchus xylophilus* (Table 10.5) and *Sirex noctilo*.

Table 10.5 *An abbreviated list of pests of southern pines in the United States.*

Pest	Common name	Origin
Fungi		
Heterobasidion irregulare	Heterobasidion root rot	U.S.A
Cronartium fusiforme f. sp. fusiforme	Fusiform rust	U.S.A
Leptographium terebrantis	Blue stain	U.S.A
Fusarium circinatum	Pitch canker	U.S.A
Grosmannia huntii	Blue stain	exotic
Insects		
Rhyacionia frustrana	Nantucket pine tip moth	U.S.A
Ips avulses	Ips beetle	U.S.A
Pachylobius picivorus	Pitch-eating weevil	U.S.A
Dendroctonus frontalis	Southern pine beetle	U.S.A
Atta texana	Texas leafcutting ant	U.S.A
Hylastes salebrosus	Bark beetle	U.S.A
Hylobius pales	Pales weevil	U.S.A
Phyllophaga spp.	White grub – scarab beetles	U.S.A
Dendroctonus terebrans	Black turpentine beetle	U.S.A
Hylastes opacus	Bark beetle	exotic
Nematodes		
Tylenchorhynchus claytoni	Stunt nematode	U.S.A
Paratrichodorus minor	Stubby-root nematode	U.S.A
Bursaphelenchus xylophilus	Pinewood nematode	exotic

On a global basis, more pines die from stress and subsequent beetle infection than die from diseases [11]. Landscape-scale beetle mortality has occurred after stresses in Belize, Canada, China, Germany, Nicaragua and the United States. *Dendroctonus* spp. and *Ips* spp. are considered to be the most destructive insects of pines in North America. The risk of injury from these pests increases with age and stocking. Overstocked stands result in stressed pines that emit volatile compounds that attract beetles. Another beetle that may cause problems is *Monochamus* spp.

In some regions, regeneration weevils do not exist and, therefore, pines are planted just after the harvesting operation. However, in the United States and parts of Europe a delay occurs between harvesting and planting. This delay reduces the risk of injury from certain weevils (e.g. *Hylobius pales*). For a regime harvesting pines when 17-years old, a one year delay in planting reduces the amount of energy captured by about 5%.

In some cases, early growth rates have been increased by controlling certain insects. For example, reducing the level of weed competition can increase both the number of shoots per tree and the number of shoots that are affected by the insect *Rhyacionia frustrana*. Some believe that applying insecticides to pine plantations during the first two years will be economically beneficial (Table 10.6).

Nematodes (unsegmented roundworms) are present in nearly all forests but most soils in the southern hemisphere do not have species that are adapted to feed on pine roots. The growth of pine is affected by the stubby-root nematode (*Trichodorus christiei)* and the lance nematode (*Hoplolaimus galeatus*). Some nematodes (*Bursaphelencus* spp.) can kill pines when they are planted as exotics.

Table 10.6 *An example of the investments used to produce biomass in a loblolly pine plantation. This example involves a discounted cost of $700/ha (at 5% discount rate).*

Age Year	Month	Operation	Cost $/ha	Comment
0	Jan	Harvest	—	Remove all trees for biomass
0	Jul	Herbicide	163	Imazapyr
0	Oct	Ripping	222	Subsoiling before planting
0	Nov	Seedlings	64	1280 seedlings/ha
0	Nov	Planting	178	Machine planting
1	Mar	Herbicide	84	Sulfometuron
1	Apr	Insecticide	57	Permethrin
1	Jun	Insecticide	57	Permethrin
2	Apr	Insecticide	57	Permethrin
2	Jun	Insecticide	57	Permethrin
6	Jan	Fertilizer	166	250 kg/ha of DAP
12	Jan	Fertilizer	166	250 kg/ha of DAP
17	Nov	Harvest	—	Remove all trees for biomass

Production at age 17 years is 227 green Mg/ha. Discounted growing cost per green Mg = $3.08. DAP = diammonium phosphate.

Numerous fungi can affect the growth of pines. The most common disease of pines in the United States is *Cronartium fusiforme f. sp. fusiforme*, which can affect the stems and branches of several pines. In a few stands, over half of the trees are infected with this fungus.

10.2.8 Resin Management

The energy content of some pines can be increased by chemical treatment of stems two years before harvest [5]. The cost of the chemical (i.e., paraquat) is currently less than $0.004 per tree (does not include the cost of application). Injecting the chemical causes a wound response that increases the production of turpentine. The treatment also reduces the moisture content of the wood. As a result, the net energy yield of 20-year old *Pinus elliottii* logs may be increased by 13%. Organizations considering establishing bioenergy plantations with pines should consider this treatment because the reduction in moisture content should reduce the cost of transportation, since more logs can be loaded on a truck.

10.3 Harvesting

10.3.1 Harvest Age

The age when pines are harvested varies with the objective of the landowner. When the objective is based on economics (instead of biomass), rotations for pines in the southern United States are typically 20–35 years. Harvest rotations in Europe are typically longer and may range from 80–120 years [12].

When growing pines for biomass in research plots, the harvest age might be as short as 8–10 years [7, 13, 14]. However, the optimum economic rotation is determined by an economic analysis (Table 10.7). The economic rotation age for a biomass-only regime will

Table 10.7 An example of how the rotation age can affect the mean annual increment (MAI), the internal rate of return (IRR), and the equal annual equivalent (EAE). This example involves planting 1350 seedlings per ha, an establishment cost of $1000/ha and a price of $30/Mg for pine biomass.

Rotation age Years	Yield of green biomass Mg/ha	MAI Mg/ha/yr	Stand value at harvest $/ha	Internal rate of return %	Equal annual equivalent @5% $/ha/yr
10	99	9.9	2970	11.6	238
13	168	12.9	5040	13.3	284
17	253	14.9	7590	12.7	293
19	291	15.3	8820	12.1	289
20	307	15.3	9266	11.7	280
26	381	14.6	11430	9.8	224

be similar to that used for a pulpwood-only regime. This is because the cost per delivered green Mg of pine is similar for both pulpwood and biomass.

The "biological rotation" for pine is the point where the periodic annual increment (PAI) crosses the mean annual increment (MAI). Typically, the optimal economic rotation is shorter than the "biological rotation." The example given in Figure 10.2 illustrates why very short rotations of 5–10 years may not make sense in many cases. For example, when using a seven-year harvest rotation, two rotations of pine would capture less energy than one 15-year rotation. Because the costs for establishment and harvesting would be less, the final cost per MWh would be lower for the 15-year rotation. Some reports have incorrectly assumed the MAI for a 17-year rotation will be about the same as that obtained for an eight-year rotation. But according to the example in Figure 10.2, this flaw in logic would result in an 85% overestimation in yield.

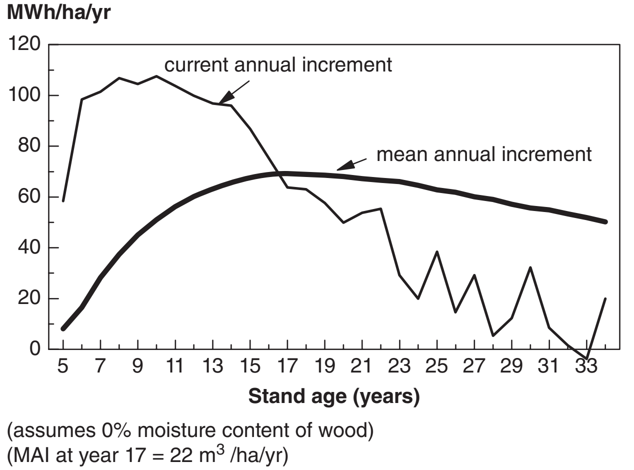

Figure 10.2 With a zero percent discount rate and a relatively high growth rate of pine, the optimal (biomass-only) rotation will be the age where the current annual increment (thin line) and mean annual increment (thick line) cross. When the economic discount rate is positive, and there is only one price per Mg for the harvested wood, the optimum rotation age will typically be shorter.

10.3.2 Harvest Season

In temperate and tropical zones, pines may be harvested by hand year-round. In some cases, this is an advantage when biofuel plants are operated on a continuous basis. When using heavy machinery the soil sometimes becomes saturated, which reduces productivity and increases the risk of damage to the soil properties. To avoid temporary harvest disruptions caused by inclement weather, stockpiling wood can be done with little loss of energy. In some high latitude zones, the impact of logging machinery on soil is reduced during the winter when the soil is frozen.

10.3.3 Clearcut Harvests

A "clearcut" harvest is used when all pines in the plantation are harvested. Bioenergy-only plantations will likely be harvested using a clearcut system. The harvesting costs (i.e., cost per MWh) are typically lower for a clearcut system than for a system that relies on one or two thinnings. This is because the time required to harvest one cubic meter of wood is typically higher when conducting a thinning, since the time required to move equipment to the location is doubled (one thinning) or tripled (two thinnings).

10.3.4 Thinning Harvest

In many countries, small and crooked pine trees are removed 5–10 years before the final harvest. The "thinned" trees are sold to pulp mills, oriented-strand board (OSB) mills or to energy plants. A "row thinning" occurs when every second, third, fourth (etc.) row is removed during the thinning. In cases where a hybrid stand has been established (where biomass rows are planted adjacent to sawtimber rows), each biomass row is removed at the first thinning.

10.3.5 Residue Harvest

In Sweden, timber is harvested and sent to the saw mill while branches and tops are placed in piles along the road. Tarps are placed over the pile to help keep the pile dry. After several months of drying, the piles are transported to a central heat plant. The dried pine residue is burned to produce steam and hot water. The hot water is then used in homes, reducing the need for residential hot water heaters.

In the United States, branches and tops are often left in the forest to decay. Once pine logs have been harvested for sawtimber and pulpwood, there are often 20–80 tonnes/ha of biomass remaining on the site. In some harvest operations, the branches and tops and non-merchantable stems are ground or chipped for use as energy. Crews with specialized biomass harvesting equipment process the pine tops, branches and non-merchantable hardwoods. The chips are then transported to a power company to produce electricity and heat. Some of the excess heat is used to dry chips prior to burning. In many cases, removing a residue of 60 tonnes/ha will reduce the cost of land clearing needed prior to establishing the next pine plantation. This savings could exceed $60/ha [14]. Currently, much of the fuel wood chips harvested in this manner in the United States are used by pulp mills to supplement mill residues and natural gas for cogeneration of steam and electricity.

10.3.6 "Hitch a Ride": Biomass Harvest

Most of the pine biomass used for energy in Europe and North America is first transported to pulp mills and lumber mills in the form of logs. After processing, the bark and sawdust compose a high proportion of the bioenergy produced in developed countries. In 2012, this "hitch a ride" method was the primary method of transporting wood fuel to power plants operated at pulp mills and OSB mills. The bark and wood "waste" is often burned for energy and, at some mills, the "waste" is sufficient to power the entire mill. Some mills that run on 100% wood fuel do not have to obtain any extra wood during the summer months. However, extra wood fuel (as bark or sawdust) may be required during the winter months when the "hitch a ride" system provides less energy than needed (due to colder temperatures outside). In contrast, some pines are harvested and sold to mills that produce wood pellets. Mill owners can increase the amount of this energy received by reducing specifications for top diameter and branchiness.

10.4 Genetic Improvement

Early work on provenances of pine was conducted by the Inspector General of the French Navy, Henri-Louis Duhamel du Monceau, from 1745 to 1755. About seven decades later, Phillipe André Vilmorin established provenance trials with *Pinus sylvestris*. During the 1920s, work on pines in North America began at the "Eddy Tree Breeding Institute" in California. As late as 1960, there were no genetically-improved pine seedlings available in nurseries in the United States. Today, essentially all *Pinus taeda* and *Pinus elliottii* seedlings grown in nurseries in the United States are genetically improved [15]. Customers can purchase various levels of genetic gain, which range from a mixture of genotypes from open-pollinated seed orchards to pure clones. In other countries, various pines (e.g. *Pinus banksiana*, *Pinus radiata*, *Pinus resinosa*, *Pinus sylvestris*, *Pinus patula*) have been selected for rapid growth.

Before undertaking a breeding program, it is important to select the appropriate species and provenance. The selection of species/provenance is very important to the economic success of a proposed bioenergy plantation. In some cases, failures have resulted because the species or provenance selected was not well adapted to the region. Sometimes, unimproved pine seedlings from the best provenance will grow more during the first eight years than "genetically improved" seedlings from other provenances.

Once the provenance has been selected, genetic gains can be made by selecting the best genotypes. In crops like *Zea mays*, the best genotype is determined by recording actual yields at the end of the growing season. However, for pines, it might take 13 years or more to determine the actual yields. Since "time is money," many tree breeding programs choose to make genotypic selections based on height growth at an early age (e.g. 6 years after transplanting). Therefore, realized gains from selecting the "best" genotype are rarely documented. Instead, estimates are made assuming greater height growth is equivalent to an increase in site productivity.

When purchasing *Pinus taeda* seedlings for use in a bioenergy plantation, there are various options. One option is to choose a mixture of selected genotypes that originated from an open pollinated seed orchard, which contains a range of genotypes from perhaps

20 or more "mother trees." This option typically has the lowest cost (about 4–5 cents per seedling). Another option is to use seedlings that originated from just one of the "mother trees." This option is commonly referred to as "family block planting," where seedlings have different fathers but the same mother. A third option involves "mass control pollination," where all seedlings (a.k.a. siblings) have the same mother and father (the cost might be as much as 14 cents per seedling). Finally, the clonal option is when all plants have the same genotype. In this case, clonal plants are produced by using cuttings, or from a process known as somatic embryogenesis. Clonally-produced pines are currently the most expensive option and may cost more than 40 cents each. Although higher volume production may be achieved with greater financial inputs, the amount of energy gained per dollar invested generally tends to diminish as investments increase.

To date, genetic selection of pines has generally not been carried out with the intention of increasing the heat of combustion (i.e. MJ/kg). Achieving relatively small increases in MJ/Kg is possible by increasing the lignin content. Lignin (23.3–26.6 GJ/Mg) has the highest energy per Mg of all wood constituents [16] other than resin. Some genotypes have higher lignin content than others. For example, some pine species may have 25% lignin content while others may have 30% (e.g. *Pinus palustris*). Genetic selections might be able to increase the lignin content of pine without reducing the total accumulation of biomass. If this is possible, perhaps the energy content of pines can be increased by about 4%. In contrast, the biochemical platform for liquid fuel production has emphasized the selection of genotypes with higher yields of cellulose rather than lignin to improve the conversion to simple sugars for fermentation.

10.5 Economics

Many landowners do not rely on economic equations (e.g. net present value, internal rate of return or equal annual equivalent) to determine the "optimal" rotation age or planting spacing when growing pines. Often, they ignore the time value of money and, instead, adopt objectives that overshadow profit motives. As a result, some use shorter rotations (e.g. 8-year) or plant more seedlings (e.g. >1700/ha) or spend more for intensive management than would be optimal for profit maximization (Figure 10.3). When economics is the primary objective, then the optimal rotation age will be a function of the desired interest rate. For example, when the interest rate charged by a financial company is 5%, the optimal rotation for pine biomass on some sites might be 17 years (Table 10.7). In contrast, a shorter rotation might be used when the landowner borrowed money at a 12% rate.

Landowners who are risk-adverse typically prefer short rotations over long ones. This might occur when the risk of losses due to fire, insects, disease or hurricanes is high. As a result, short biomass rotations might be attractive to some, especially when the expected return on investment is greater than 9%. Some landowners might be willing to accept a reduction of $9/ha/yr in equal annual equivalent (Table 10.7) if it resulted in reducing the risk of losing trees to beetles and disease.

In the cases where there is only one price per green tonne (regardless of tree size), the economic rotation is no greater than the age at maximum mean annual increment. Typically, the year when maximum mean annual increment occurs varies with site productivity. Sites high in productivity (e.g. >15 Mg/ha/yr) will achieve shorter "biological" rotations than

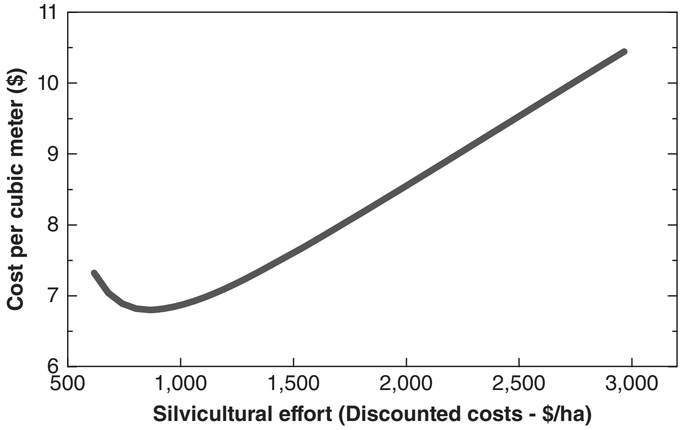

Figure 10.3 *Due to the law of diminishing returns, the discounted cost of producing a cubic meter of wood eventually increases with increasing investments in silviculture [17]. This is just one example and the shape of the curve depends greatly on the cost of silvicultural treatments selected.*

low productivity sites (e.g. <8 Mg/ha/yr). For example, some productive sites may result in a "biological" rotation of 19–20 years while the economically attractive rotation may be 13–17 years (Table 10.7).

Forest plantations are often on sites that generate lower rental rates for alternative land uses, such as crop agriculture or animal grazing. In addition, government policies that lower property tax rates for forest land or offer conservation payments offset potential rent from other land uses. As a result, the economic analyses of forest plantations seldom include annual rent as an input. The exclusion of market-based annual rent payment yields, on balance, longer economic rotations than when annual rent is included.

Although profits could be achieved for a landowner who sells biomass to a refinery that produces synthetic diesel fuel, the economic incentive is often greater when the grower is also the end user. For example, one green tonne of pulpwood may be worth $9 in the forest, $26 at the roadside, and $32 at the power plant. However, for a homeowner, the wood might be sufficient to offset $135 in fuel oil (2012 prices). Therefore, one green tonne of pine biomass is worth perhaps 12 times more to a landowner who burns wood as an energy source (to furnish heat to their business) when compared to a landowner who sells pine logs on the open market (to a pellet mill or a Biomass Fluid Catalytic Cracking (BFCC) plant).

Some landowners add value to their pine logs by splitting and drying the wood for use as firewood. In some regions of the United States, split, air-dried pine firewood is currently sold for $65/m^3. A landowner could either sell a green cubic meter of pines for $9 to a wood dealer or, after drying and splitting, could deliver it to homeowners for seven times that amount. Homeowners who purchase firewood do so because the cost of heating their home with wood is less than heating with fuel oil.

The least economical use of pine is as a substitute for coal, but one of the most economical uses is as a substitute for gasoline. During the Second World War, supplies of gasoline were limited and, therefore, many vehicles in Europe were converted to run on wood gas (also known as producer gas). In Sweden, there were over 70 000 of these vehicles at that time.

Figure 10.4 *In countries where gasoline was in short supply during the Second World War, people converted their vehicles to run on wood gas (also known as producer gas). Dr. South currently owns a 1989 truck that was modified to run on either gasoline or wood. This truck travels about 8.5 km using either a liter (0.72 kg) of gasoline or 2.4 kg of dry pine blocks (≈14% od moisture content) (© 2013, South).*

Currently, only a few individuals own vehicles that can be powered with wood gas. The senior author of this chapter actually owns a modified truck that can run on either gasoline or wood gas (Figure 10.4). This vehicle gets about 8.5 km per liter of gasoline or 2.4 kg of dry pine blocks (≈12% od moisture content). What is surprising is that the engine is more efficient when running on wood-gas. If one liter of untaxed gasoline costs $2 and one kg of dry pine block cost $0.06, then annual fuel costs (assuming 34 000 km) would be $8000 when using gasoline compared with a cost of only $240 when using wood gas.

10.6 Government Regulations

Globally, differences in governmental regulations can affect a landowner's desire to establish pine biomass plantations. Therefore, even when the price of coal is essentially the same in two countries, government policies can greatly affect the incentive for establishing plantations of pine. For example, policies regarding carbon dioxide have resulted in a decline in planting pines in New Zealand. In South Africa, policies regarding water limit the areas where pines may be established for energy (but establishing grasses for energy is permitted). Some regional governments have regulations concerning wood smoke pollution and the associated health effects.

10.7 Final Comments

In various countries, growing pines in plantations, for uses other than energy, is an economically viable enterprise. In addition, pine firewood and pine residue will continue to provide energy to homes and mills throughout the world. For example, bioenergy (from pine and other sources) provides more energy to Sweden than oil or hydropower or nuclear power. Although the technology to produce electricity and liquid fuels from pine is available, so far few pine plantations have been established solely for the production of bioenergy. This is partly because pine biomass can also be obtained from thinnings, mill residues, harvest residues and from pine scraps transported to landfills. However, the number of pine biomass plantations might increase dramatically if the prices paid (per Mg) by biomass plants skyrocket.

Claims about short-rotation woody biomass crops have been made for more than four decades. During that period, many predictions about prices, yields, and seedling planting rates have not been achieved. Therefore, we are hesitant to make any claims regarding the future extent of short-rotation pine plantations. However, those considering harvesting pines on an eigh-year rotation for bioenergy may wish to consider the following points:

- Some bioenergy reports have likely overestimated the expected yield/ha of short-rotation pine plantations (on average sites) harvested before the year 2030.
- Few (if any) landowners will invest $43 to grow and harvest a dry Mg of pine biomass when the price paid at the farm gate is only $40 per dry Mg.
- Most planting densities recommended for pine biomass are not the economically optimum for a landowner who sells harvested wood at the roadside and who wishes to maximize the land expectation value.
- Several studies that evaluate the optimum tree planting density do not consider any additional costs associated with harvesting small diameter logs.
- Unrealistic goals for the establishment of biomass plantations (of any species), will prove difficult to achieve.
- Some researchers have an inherent bias against pine, since there are few researchable bottlenecks for large-scale establishment of pine plantations.
- Some individuals have ignored the law of diminishing returns when stating that increasing silviculture intensity will lower the unit cost of producing pine biomass.
- In order to achieve 5.3 million ha of short-rotation plantations by the year 2022, it is first necessary to be able to produce a sufficient quantity of planting stock (perhaps 1 billion plants per year for energy crops plus an additional 0.9 billion seedlings for longer-rotation pines).

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11

Poplar

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11.1 Introduction

Populus consists of 25–35 species and among them hybridization is common. The genus itself has a large genetic diversity with some species growing 50 m tall with trunks of up to 2.5 m in diameter. All *Populus* species from family *Saliceae* are common in temperate climate zones but they are limited in tropical zones because the maximum temperature they can tolerate is approximately 30°C. Among the various species, *Populus alba* grows primarily in southern and central Europe, *P. tremula* in Europe and Asia (mainly in India), and *P. tremuloides* in North America with their northern border being Alaska. There are some reports concerning *Populus deltoides* growing in India [1], and although some *Populus* genotypes can be successfully grown on saline-sodic and alkaline soils, some tested clones could not survive those soil and climatic conditions in Uttar Pradesh province. In an age of globalization there is an increasing tendency for farmers, foresters, and owners of recreation areas to introduce different poplar species in non-native environments. Therefore, numerous *Populus* species are often found outside their natural borders. In Europe, for example, the most frequently grown poplar is hybrid *Populus* × *euroamericana* (*Populus deltoides* × *P. nigra*).

Berndes *et al.* [2] identified poplar short-rotation plantations (SRPs) as one of the most important sources of biomass for energy purposes, pointing out their energy and environmental soundness. In the United States, poplar species have been grown commercially for more than 100 years [3] and although, to date, business conditions have restricted their

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cultivation to specific geographic locations, those developments have provided proof of concept for growing short-rotation trees using intensive agricultural techniques. Therefore, looking to the future and to the great opportunity to develop a viable biomass energy feedstock supply, the poplar industry in many countries is well positioned to play a significant role in meeting global energy needs. Poplar species and their numerous hybrids are very productive genotypes due to their rapid foliar production, very high leaf area index and high photosynthetic rates. It was stressed [4] that the *Populus* genus, which contains more than 30 species worldwide, has remarkable clonal variation for both biomass production and distribution. Therefore, some species and clones are much more suitable for lignocellulose biomass production than others because they can allocate more biomass to aboveground plant parts than to roots. By understanding genetic variability among poplar species, Wullschleger *et al.* [4] pointed out that there is a starting point for future breeding programs aimed at obtaining clones of high and reliable yield level with a desirable distribution of assimilates in plant biomass.

Poplar is also one of the so-called energy crops that can, theoretically, improve relations between agriculture and environment. For example, studies on 12 poplar genotypes grown on marginal and agricultural soil in Hungary [5] confirmed wide genetic variability with average biomass yields of 27 Mg ha^{-1} ODM (oven-dry matter) and average energy yields of 309 GJ ha^{-1}. With regard to carbon, the authors reported that the balance was always positive (i.e. the amount of carbon emitted to the atmosphere as carbon dioxide during combustion was always less than the amount of carbon sequestrated in SRP poplar biomass) because of the high content of carbon in roots, litter and stools. Therefore, under Hungarian conditions, short-rotation poplar can be an effective carbon sink and source of renewable biofuel. Many other environmental benefits associated with growing poplar for energy have been presented from a United States perspective [6], with the prediction that in the United States growing poplar in short-rotation systems will link phytoremediation of contaminated soils with bioenergy production.

11.2 Cultural Practices

Soil demands of the genus *Populus* are similar to requirements of *Salix* because of the fact that poplar trees can grow very well on a very wide range of soils – sandy as well as loamy clay, but they cannot grow on sites without proper drainage. The optimal soil pH value for poplar is around 6.5.

The most critical limiting factor for poplar cultivation is water availability, and therefore it is considered to be common knowledge that dry areas should be avoided. The physiological reason for this response is a very high evapotranspiration rate – as high as 5 mm day^{-1} for each mature tree. Fortunately, there is substantial genetic variation for this important physiological trait. For example, water consumption by *P. balsamifera* and *P. nigra* is low and these species are considered to be relatively drought resistant compared to other species. On the other hand, the root system of *Populus* trees cannot be considered as flood resistant. Under conditions of permanent flooding (i.e. lasting longer than one month) several poplar species showed reduced photosynthetic capacity and other plant metabolism disorders, leading to lower growth [7,8].

Guidi and Labrecque [9] studied growth and performance of the hybrid poplar *Populus maximowiczii* × *P. nigra* in a pot study with very high (five times higher than field capacity) water supplies. Their focus was on assessing the suitability of poplar for purification of wastewaters from aquaculture and the chemical composition effects of drainage water. They found that evapotranspiration rates were higher in plants using wastewater. Overall, however, poplar biomass was severely reduced by high water supply because the conditions, which were similar to permanent flooding, inhibited root growth. Leaf and stem tissue nutrient levels were lower for the high water treatment compared to an optimal water supply. Therefore, although low nutrient content in drainage water confirmed that poplar can be suitable for removing nitrogen (N) and phosphorus (P) from wastewater, nutrient removal was more efficient when the trees were grown at an optimum water content. The overall conclusion of this pot study was that poplar could successfully remove nutrients from polluted water, provided an intensive selection program was used to find genotypes capable of growing under conditions with excess water. This confirmed previous field studies [10] using poplar as a vegetative filter that had suggested that irrigating short-rotation poplar plantations with pretreated wastewater could substantially improve wastewater quality before its release into surface waters, if the water contained sufficient nitrogen and phosphorus to meet plant demands.

The economic and energetic viability of growing SRP poplar in Northern Italy were investigated by Manzone *et al.* [11]. They obtained a SRP biomass yield of 10 Mg ha^{-1} $year^{-1}$ ODM for eight years using a high planting density of 6700 cuttings per hectare, a two-year cutting cycle, an intensive program of chemical weed control, nitrogen fertilization and a Class combine harvester. This resulted in a very high energetic efficiency coefficient of 13 – reflecting the relationship between output and input energy despite the energy required for the intensive agricultural inputs. Despite the very positive energetic balance, economic sustainability of SRP poplar will depend on political choices, including the price of wood chips and subsidies available for other fuels.

The potential of SRP poplar in Sweden was presented by Christersson [12]. Nine poplar plantations established beginning in the 1990s and their performance were reviewed. The author pointed out the necessity for proper selection of clones because, in some locations, *Populus trichocarpa* × *P. deltoides* hybrids did not survive, whereas *P. trichocarpa* clones performed very well. The other factor determining high productivity appeared to be spacing. It was stressed that in Sweden poplar plantations can be treated as multifunctional because only part of the trees were harvested for biomass energy while the rest remained for longer periods before cutting them for pulp or timber, thus resulting in best economic indices for combined energy and pulp plantations. The other function of poplar plantations in Sweden is their use in vegetative filters. There are several economically sound examples where sewage treatment plants use poplar plantations as the last stage of effluent purification, and farmers are paid by local sewage treatment plant for this service.

11.2.1 Establishment

When establishing commercial poplar genotypes, biomass productivity and pathogen tolerance or resistance are frequently used as primary selection criteria. Water consumption has traditionally been considered less important in breeding programs, since poplar production was traditionally restricted to areas with high plant available water. Furthermore, if potential negative consequences of global warming are considered and drought is projected as a more frequent occurrence, poplar breeders need to increase efforts focused on the genetic base for drought resistance [13]. This need was verified by modeling projected twenty-first century climate changes, with the conclusion that short-rotation forestry could be severely affected by water deficits and, therefore, some type of response action needs to be pursued in today's breeding programs [14].

Larchevêque *et al.* [15] reported that drought resistance of poplar hybrids can be improved considerably by including *Populus balsamifera* in breeding programs because this species shows stomatal control of photosynthesis that can overcome certain disadvantages of this species, such as higher resin content and dark colored heartwood. The authors concluded that hybrids with *P. balsamifera* can be very suitable for short-rotation plantation for energy purposes because they are able to grow even under a medium water stress, and even is a more severe drought occurs plants are able to resume growth when water is available again.

Some authors have mentioned other mechanisms of drought resistance within the genus *Populus*. Among them, the most effective seem to be decreased leaf area, leaf abscission, enhanced root growth rate and increased water use efficiency [16, 17]. It was stressed that the magnitude of the reduction in leaf area under conditions of water deficit was a good indicator of drought resistance within the studied clones. The main conclusion after screening 29 hybrid poplar genotypes was that there is a large potential for improving water use efficiency while maintaining high productivity [17].

Afas *et al.* [18] studied root characteristics of five poplar clones grown under conditions of short-rotation coppice and found that the vast majority of roots (in terms of both their biomass and total length) were located very near the surface (0–5 cm). They also identified a close and positive correlation between root biomass and aboveground productivity. Other authors have also reported significant and positive correlations between leaf area index (LAI) and root area index (RAI) – calculated as the sum of all root area per plot. Similar variability was found for root biomass as for aboveground biomass among the clones studied, with some showing high root density and high LAI and others a low density of fine roots and low LAI values.

In the United Kingdom [19], the high density of plant roots in SRP poplar was studied because of the possibility that introducing "deep rooting" trees to agricultural space could potentially disturb buried archaeological evidence that is protected by laws and regulations. To quantify both the rooting patterns and depth of rooting by various poplar clones, trenches were dug to expose the root systems of several stools growing on two different soil types. The trenches enabled researchers to observe the root systems and to make precise length and diameter measurements of individual roots. The study showed that the rooting habit of short-rotation poplar was influenced by several factors, including soil physical, chemical and hydrological properties as well as by silvicultural practices, such as cutting frequency, cultivation and fertilization. It also showed that between 75 and 95% of poplar roots were located in the Ap (30–40 cm deep) horizon. Although some roots were found at a depth of 1.3 m, their diameter was less than 10 mm. Furthermore, more than two-thirds of roots were less than 1 mm in diameter. The authors concluded that these results can help break the myth that "deep rooting" poplar will devastate drainage systems made with ceramic pipes.

Poplars are one of best examples of effective symbiosis between roots of higher plants and mycorrhizal fungi. Mycorrhizas in the case of poplar are very effective for many important physiological processes (e.g., enhanced nutrient absorption, protection against root diseases, drought resistance, and winter hardiness) that can be described as a reduction in genotype by environment interaction problems [20]. Wide variation among *Populus deltiodes*, *P. nigra* *P. balsamifera*, *P. trichocarpa*, *P. suaveolens* and 10 different hybrids was shown in response to colonization of their roots by mycorrhizal fungi. Of even greater significance was that whenever a lack of mycorrhizal symbiosis was recorded, the trees appeared to have both arbuscular mycorrhizas (AM) and ectomycorrhizas (ECM). Furthermore, only the *P. trichocarpa* × *P. suaveolens* hybrid had a higher number of AM than ECM. For the other 28 genotypes that were studied, ECM colonized the root systems more intensively (sometimes by a factor of five). However, there was no correlation between growth parameters (height and stem diameter) and mycorrhizal colonization, indicating it may have occurred at a very early growth stage. It was concluded that in some cases in Alberta, Canada, inoculating with mycorrhiza may be effective when introducing tree species into agricultural or disturbed lands where native mycorrhizal consortia are rather low. In those cases, co-inoculation of ECM and AM fungi with "helper bacteria" can be very effective for SRP systems [20].

Quoreshi and Khasa [21] evaluated mycorrhiza colonization of balsam poplar by inoculating seeds with different combinations of six fungal isolates plus helper bacteria and different rates of fertilizer. The bacteria alone were not effective. Seedlings with the highest mycorrhiza colonization were the most vigorous and after just 10 weeks those inoculated with ECM were taller and had significantly more dry matter than the controls. The nutrient content in seedling tissues was higher, however, only when the fungal species *Paxillus involtulus* and helper bacteria *Burkholderia cepacia* were included in the inoculum. High fertilizer rates usually inhibit mycorrhiza colonization of plants' root systems but, under the conditions of this experiment, one ectomycorrhizal species (i.e. *Pisolithus tinctorius*) was present as a symbiotic species regardless of the fertilizer rate. Plant biomass was always superior in seedlings with mycorrhiza than in the controls. The best results were found where less fertilizer (e.g. 67% of the standard rate) was applied in addition to the mycorrhiza. Generally, these results show that incorporation of ECM into poplar plantations is effective and can be treated as a standard management practice. Studies will be continued to compare performance of seedlings with and without mycorrhiza under field conditions. Successful artificial inoculation of poplar by ectomycorrhizal fungi was also observed in SRP under the semi-arid conditions of Spanish Andalusia, where it substantially increased drought survival and biomass production (Antonio Ramoz Fernadez, personal communication).

Natural mycorrhiza colonization in SRP poplar and willow were investigated by Hrynkiewicz *et al.* [22] in relation to cutting frequency of dedicated energy coppice systems. For the *Populus nigra* × *P. maximowiczii* hybrid, they found that mycorrhiza frequency and fungal species composition were significantly different for the three and six-year cutting cycles. They concluded that more frequent biomass harvesting promoted mycorrhiza colonization and assumed the response mechanism was based on chemical signals given off by the root system. The authors also highlighted the relationship between mycorrhiza frequency, fungal species and vitality of biomass production within short-rotation coppice systems.

Gunderson *et al.* [23] also studied effects of artificial mycorrhiza colonization of hybrid poplar (*Populus deltoides* × (*P. lauriflora* × *P. nigra*) cuttings by spores of two ECM fungi (*Pisolithus tinctorius* and *Rhizopogon* spp.) when used for phytoremediation of soils with diesel oil spills. It was reported [24] that among the 42 ECM species checked 33 were able to degrade at least one aromatic hydrocarbon and some species were able to degraded five different polycyclic aromatic hydrocarbons (PAHs). It was also found that ECM colonization was very effective in terms of poplar growth rate and increases in aboveground biomass production irrespective of soil contamination by diesel oil. Furthermore, plants with higher biomass accumulation also had more fine roots after artificial mycorrhiza inoculation [23].

11.2.2 Environmental Benefits

Poplar trees can also be grown to provide environmental benefits. For example, one option for managing sewage sludge, which is an unwanted by-product of the water purification industry, is its application on agricultural land as a soil amendment. Recently, because of the food chain contamination risk, there has been a tendency for banning agricultural sludge application in many countries. Therefore, it seems that non-food, non-feed energy crops could provide an alternative application site for sewage sludge from municipal water treatment plants. A high fertilizer value of sewage sludge was noted by Moffat *et al.* [25] in studies designed to evaluate the effect of sewage sludge application and wastewater irrigation on biomass production of two poplar genotypes. The three-year experiment showed that irrigation affected biomass yield more than sewage sludge application and that waste application at the rates used did not pose any risk for nutrient pollution of groundwater.

The special importance of riparian forest or stream buffer zones is understandable and, therefore, establishing buffer zones in forest or agricultural space is treated as a standard environmentally friendly practice in many countries [26]. Growing poplar in these systems is, therefore, a logical option for combining biofuel production with surface and groundwater protection. Furthermore, this would also increase biodiversity near water courses and their banks. Poplars, because of their physiological properties, are very well suited to have an important role in establishing riparian buffer zones. Henri and Johnson [26] suggested that social debate is needed to determine if riparian zones should be left as a “no touch” area or should be managed. They also evaluated options for managing such buffers and found that harvesting 50% of the area and selling biomass could provide both economic and environmental benefits. Fortier *et al.* [27] studied a multifunctional system of hybrid poplar riparian buffer in southern Quebec, Canada, and also found effective environmental and economic aspects. They stated that biomass produced in riparian buffers can be harvested for different purposes, especially with a multiclonal structure where some clones could be harvested for energy and some for pulp. When biomass productivity in buffers is considered, it is possible to achieve yields comparable to SRP poplar plantations and, since mineral nitrogen is often a limiting factor, the poplars also provide a very effective way to control nutrient flow to groundwater and surface water resources.

Agro-ecological zones have been used for global, national and regional evaluation of agricultural practices [28]. Recently this methodology was enhanced with digital geographic databases. This advanced technology was used to evaluate agricultural areas in Eastern Europe as well as North and Central Asia for their suitability to produce dedicated energy crops. A large variation in the potential for biofuel production was found among these countries, with the highest potential for poplar production being in the Czech Republic and Georgia, due to good soil conditions and a favorable climate. European energy use was estimated at 111 GJ per capita, with Latvia, Lithuania, Hungary and Estonia having the potential to produce more than 140 GJ per capita of bioenergy. The studies also identified some technical and non-technical barriers for bioenergy utilization, thus emphasizing the necessity for future research programs.

The economic soundness of poplar plantations for energy was also evaluated by Yemshanov and McKenny [29]. They constructed two scenarios: (1) "business-as-usual," where only the biomass has value; and (2) a "fibre + carbon" scenario, where benefits from sequestering carbon in silvicultural systems are included. Many factors were considered, with transportation costs appearing to play a very important role. When burnt for energy, the cost for 1 GJ from biomass ranged from \$4 to \$5 for scenario 1 and started at \$3 for scenario 2. Obviously, adding the benefits of carbon sequestration helped but, as the analyses show, biomass cost was still higher than the price of low-quality coal currently being used by power plants. Assuming the option of producing bioethanol from poplar biomass becomes feasible, the economics of biomass production will be substantially improved.

Several authors point out that the most important environmental effect of SRP poplar is the perennial nature, which promotes increased diversity and frequency of many soil organisms and the beneficial impact on soil organic matter [30]. The use of SRP poplar as a vegetative filter was also studied by Coyle *et al.* [31], who concluded that coppicing poplar was suitable for this purpose because of the extensive root system and high evapotranspiration rate. Poplar clones in their study were irrigated with leachate from municipal landfill and compared with control treatments receiving mineral fertilizers. Effects on soil meso and microfauna were also compared. They reported that microfauna (i.e., soil nematodes) as well as mesofauna (mainly insects) were more abundant in control treatments, while with the leachate, biodiversity among soil organisms was much higher. Based on these findings, the authors concluded that introducing phytoremediation technologies did not always lead to higher sustainability within the soil environment.

Studies on growth, biomass distribution and nutrient use by eight poplar (*Populus balsamifera* L., *P. trichocarpa* Hook) and hybrid poplar (*P. trichocarpa* Hook × *P. deltoides* Bartr.) clones in Sweden were conducted by Karačić and Weih [32]. The clones were chosen from Canada because its latitude is similar to that of Sweden. The objective was to evaluate genotype by environment interactions with a special focus on phytoremediation. All studied clones showed a high and positive response to irrigation. The results helped identify clones that were better suited for phytoremediation, which involves the application of as much water and nutrients as possible with minimum leaching from the system.

In California, U.S.A., irrigation water can have bad quality because of high selenium, boron, and/or sodium chloride concentrations. Research being conducted by Bañuelos *et al.* [33] is, therefore, focused on identifying plants that are resistant to elevated levels of these contaminants. Trees have an advantage over vegetative plants because they transpire large amounts of water, produce high amounts of biomass, live longer, have deeper roots, and, for many species, can re-grow after being cut. Poplar is one species that has all of these features and, therefore, this genus is widely used for phytoremediation. However, because of the wide genetic variation among species, hybrids and clones of this genus, screening experiments focused on the tolerance of the various genotypes are essential. Among the findings of this research were differences in the chloride and boron concentrations of both lower and upper leaves in poplar genotypes classified as susceptible or resistant to high concentrations of these micronutrients. The mechanism of resistance to high salt concentrations in the irrigation water was also identified as being early abscission of lower leaves containing a high concentration of chloride. Although the physiology of boron tolerance or toxicity remains to be determined, it appears that boron uptake is inhibited when irrigation waters contain elevated chloride concentrations although other resistance mechanisms may exist within the *Populus* genus.

Poplar grown in SRPs was also able to effectively degraded ethylene glycol, which is present in the environment because of its use as a coolant and deicing agent. Two mechanisms for removal of ethylene glycol (microbial degradation in the rhizosphere and uptake by the trees through evapotranspiration) have been identified [34, 35]. Based on these results, it is very probable that similar mechanisms can be effective for removal of other organic compounds. This was verified by Jordahl *et al.* [36], who reported that hydrocarbon degrading microorganisms were more common in the rhizosphere of poplar trees than in bulk soil.

Growth and survival of poplar clones at sites contaminated with hydrocarbons and at sites polluted by long-lasting industrial activity near Lake Michigan were investigated by Zalesny *et al.* [37]. In some spots, the pollution level exceeded 1% hydrocarbons per kilogram of soil. The average poplar survival rate was 67%, with the variation ranging from 56 to 100% and losses being higher for 60-cm cuttings than for 20-cm cuttings. The growth rate was the highest for commercial clones bred for SRP energy production.

To minimize bioaccumulation of toxic trace elements, Wang and Jia [38] proposed growing poplar or larch on contaminated soils. The reason for selecting these tree species for phytoremediation was the fact that deep roots are able to create microenvironments in the soil where immobilization or uptake of the metals can occur. The growth of two tree species in soil spiked with a mixture of cadmium, copper and zinc was investigated by Wang and Jia [38], who found that poplar could remove 56.2 g ha^{-1} of cadmium, 196 g ha^{-1} of copper and 1170 g ha^{-1} of zinc. Heavy metal transferring capacity from roots to aboveground organs was higher in poplar than larch, leading the authors to propose growing poplar on contaminated soils.

Poplar cannot be considered as a cadmium hyperaccumulator because it is able to take up only 10 mgCd kg^{-1}, whereas the known hyperaccumulator *Thlaspi caerulescens* can accumulate 100 mg kg^{-1}. However, because of the high biomass production in poplar plantations the total accumulation of cadmium is considerably higher per hectare and can actually reach 1000 gCd ha^{-1} for poplar compared to just 250 gCd ha^{-1} for *T. caerulescens*. Pietrini *et al.* [39] reported the results of studies on cadmium phytoremediaton potential of several poplar clones. They found high genetic variation among the 15 Italian clones that were studied. The most promising clones showed three desired strategies that could positively affect phytoremediation. Firstly, a relatively high cadmium accumulation level in wood parts; secondly, high leaf tolerance when measured as photosynthetic activity; and, thirdly, a very fast juvenile phase growth rate. The authors concluded that the best indicators of suitability of given poplar genotype for phytoremediation would be some chlorophyll fluorescence parameter.

Finally, a Life Cycle Assessment (LCA) approach was used to quantify the environmental impact of Italian poplar plantations [40]. Two types of short-rotation plantations (a 1- to 2-year cutting frequency and a medium cutting frequency of >5 years) were distinguished. All energy inputs and outputs were taken into account as well as other environmentally important aspects (acidification potential, eutrophication potential, global warming potential, ozone layer depletion, human toxicity potential, ecotoxicty potential, photochemical oxidation formation potential) in a life span of poplar plantations grown for energy purposes, from field preparation (in the first year) to field recovery (in 25th year). It was concluded that from the environmental aspect the best solution is to replace industrial fertilizers with cattle manure; this can reduce total energy use by 19.8%. The authors also concluded that future environmental soundness can be improved the by breeding of high-yielding clones of different poplar hybrids.

11.2.3 Disease and Pest Control

Leaf rusts are very common in poplar and they are caused by species of *Melanospora*. The genus *Melanospora* comprises several species that are able to infect trees from the genus *Populus*. Sometimes, heavy infections can lead to early leaf drop, delay of the flushing time of poplar in the next season and finally result in decrease of growing rate. Leaf rust is the most important disease of poplar [41]. Also, they are known many form of canker caused by fungi (*Septoria musiva* and *S. populicola* being the most pathogenic species); bacterial cankers have been frequently recorded, too (*Xanthomonas populi*). There is widely expressed opinion that *Melanospora* can cause economically important damages, particularly in the case when infection starts relatively early in the tree life, that is, during first ten years of tree life. When poplar is grown in a SRP system, rust can occur in seasons when weather conditions can favor fungus development but, so far, no fungicides are recommended for control of fungal diseases. There are two obvious reasons: the first is that energy crops in general should be treated as plantations of low-inputs in terms of energy, fuel and pesticides usage where environmentally benefits should be gained; the second reason is that even severe infection can cause substantial economic losses [41,42]. In contrast to agricultural or vegetable crops, where good appearance and lack of all symptoms of fungal or bacterial infection are of key importance as they are used as food or feed, in the case of bioenergy crops, where all aboveground parts of the crops are intended for use as energy biomass, fungal infection has marginal importance. There are reports that even total defoliation of poplar cause by rust in one growing season did not affect biomass yield in the following season [43, 44]. There is well-established opinion that disease control of poplar grown for lignocellulose biomass is based on breeding programs where resistance or tolerance of clones to leaf rust and canker are included in commercial genotypes [41–43]. What makes the process of breeding resistant clones a never ending activity is the fact that pathogens are able to evolve; there are many cases when pathogens successfully infected previously resistant clones, breaking clonal resistance [45].

On the other hand, within the genus *Populus* is almost a never ending genetic variability in each economically important trait, including resistance to diseases; therefore, the perspective for increasing resistance to rust and canker seem to be very good. Coyle *et al.* [42] warned against taking only one breeding criterion (most frequently biomass yield), which can result in establishing monoclonal plantations, with all the consequences of such a practice.

Leaf-eating insects occur on poplar in great variability, with gregarious poplar sawfly (*Nematus malanapis*), poplar shoot borer (*Gypsonoma aceriana*) and other larvae of Lepidoptera being the most common. As in any other crops, herbivorous insects have to be controlled only when the economic loss threshold is exceeded. It is pointed out that because of the fact that poplar plantations are functioning as nesting habits for many birds – including song birds, which are very scarce in the landscape where only typical agricultural crops are grown – chemical control of insects in SRP is not desirable. Sage [46] reports that 41 bird species were recorded in SRP and among them 30 song birds not found in another habitat in the vicinity. In many countries, poplar and willow SRP are treated as very good habitats for game animals, including pheasants, which are introduced by hunters' associations [47, 48].

Poplar grown in a SRP system can be particularly susceptible to infection by insects when re-sprouting starts in early spring after winter harvesting. Therefore, mechanisms of plant resistance should be studied and some conclusions have been drawn concerning the necessity of manipulating the chemical composition of leaf tissues; this can be achieved by proper selection of genotypes [49, 50].

11.2.4 Harvest Management (Cutting Height, Season, Frequency)

Optimum cutting cycle and plantation design were the focus for studies with three fast-growing clones at three locations in the United Kingdom. *Populus trichocarpa* was evaluated at two spacings (1.0 × 1.0 m and 2.0 × 2.0 m) and two- or four-year cutting cycles [51]. Annual yield of biomass was always higher in the longer cutting cycle and the 1 m^2 spacing generally had a higher biomass yield than the 4 m^2 option. The authors pointed out that all poplar cones gave higher yield at the site with the highest annual rainfall. They also suggested that the reason for better yields with the longer cutting cycle was a proper balance between root system and aboveground organ development. The authors also noted that a four-year cutting cycle is more economical due to lower harvest cost per unit dry matter.

di Nasso *et al.* [52] pointed out that plant spacing and cutting cycles are the most crucial factors for successful establishment and biomass production by short-rotation poplar. Their report summarizes results of long-term studies (12 years) designed to identify the most important production indices in relation to different cutting cycles (from annual to triennial). They found that the shortest cutting cycles resulted in increased stool mortality, making the shortest cutting cycle less efficient than the other cycles studied. The highest efficiency in terms of energy output was noted for a triennial cutting cycle. The authors stated that the energy balance was positive for all studied cutting cycles and that for short-rotation plantations good soil fertility plus low rates of fertilizer and pesticide application were important for making short-rotation poplar plantations a perfect example of sustainability in twenty-first century agriculture.

Fang *et al.* [53] also tested four planting densities and three poplar clones at three cutting frequencies. Each of the experimental factors significantly affected obtained biomass yield, with the highest annual production being obtained with a six-year cutting cycle. They concluded that, for China, a longer cutting cycle should be recommended because regardless of plant density biomass yield increased as cutting cycle length increased (i.e. from 10 to 13 Mg ODM ha^{-1} yr^{-1} when going from a four to six-year cutting cycle).

Guidi *et al.* [54] quantified the relationship between chemical composition of biomass obtained from SRP poplar and cutting frequency of plantations in order to answer the crucial question of "how to manage the plantation to achieve good quality of biomass for biochemical conversion into liquid biofuels." They concluded that different cutting cycles did influence the biochemical conversion rate of the poplar biomass, with the highest ethanol yield being associated with a four-year cutting cycle. This occurred because, at that age, the relative content of cellulose was much higher than in poplar biomass obtained from two-year cutting cycles, when the hemicellulose content was higher, or from six-year cycles, when the lignin content was greater because of the additional two years of growth.

11.3 Genetic Improvement

Genetic variation and genotype by environment interactions in SRP poplar were studied using growth and production of biomass as first-year selection criteria by Sixto *et al.* [55]. Investigations were carried out at several locations in Spain to identify the regions where production of biomass for energy would be most effective. Nine poplar clones that were commonly grown in Europe for timber as well as Italian clones specifically bred for SRPs were evaluated. An additional selection criterion of rapid juvenile growth was applied, since it can be very important if very short rotation periods (i.e. no longer than three years) are introduced. Clone stability was also taken into account using bi-plot analyses. Among tested clones, there was very high variability in juvenile production, ranging from 1.7 to 8.0 Mg DM ha^{-1}. The degree of interaction between genotype and environment was different among sites and led to the conclusion that along the shores of the Henares River in the middle of Spain and near La Tallada in northeast of Spain were the most suitable for poplar breeding programs because of the high variability among clones that was recorded.

Recognizing that there are large numbers of poplar clones growing in SRPs that need to be evaluated for their performance, Guo and Zhang [56] used cluster analysis with several easily measured indicators of survival rate and tree volume index to screen the suitability of poplar clones for their suitability for energy plantations. They assumed that maximum biomass production could be obtained if genotypes have a high survival rate and high productivity per plant. Deckmyn *et al.* [57] reported that the process-based model known as SECRETS (Stand to Ecosystem and EvapoTranspiration Simulator), which had been developed to simulate the growth of mixed forest species, could also accurately and realistically simulate the growth of poplar clones. They concluded that this model could be used to help in decision making and planning of biomass production of poplar on a regional scale, but the main advantage was the option of using it to identify management options for short-rotation poplar plantations.

11.4 Utilization

Poplar trees have been extensively cultivated in many countries and several different technologies for using their biomass have been implemented. Using wood obtained from SRP poplar as a fuel has energy, economic and environmental advantages when compared to coal and other fossil fuels. When used for direct combustion in heat and power plants, wood biomass has advantages over herbaceous biomass because of the lower quantity and higher quality ash that, in many cases, can be returned and applied as a soil amendment. The quantity of ash is related to chemical composition and bark content. Therefore, Guidi *et al.* [58] conducted studies to determine allometric relationships to predict fuel quality of poplar biomass before harvesting was undertaken. They found a significant relationship between bark content and main stem diameter at 130 cm (diameter at breast height, DHB) and pointed out that for DHB classes between 1 and 4 cm there was a rapid reduction in bark content compared to stems with a DHB of less than 1 cm. This indicated that it is more rational to harvest SRP poplar in three or four-year cutting cycles or to use poplar clones that do not produce a high number of low DHB stems.

Poplar wood can also be treated as a feedstock for production of second and third generation biofuels through conversion of lignocellulose into ethanol [59] and other fuels. However, it is important to recognize that lignocellulosic biomass is a complex matrix of hemicelluose, cellulose and lignin and, therefore, pretreatment (sometimes called prehydrolysis) is required before the biomass can be converted into liquid fuels. Authors studying different methods of *Populus nigra* biomass pretreatment (steam explosion and hot water pretreatment) have found that the former process gave better cellulose recovery when measured by enzymatic conversion of the biomass into bioethanol [60, 61]. In an extensive review, Huang *et al.* [62] also reported numerous technologies designed to provide the most effective pretreatment of lignocellulosic biomass and conversion into ethanol. They concluded that the best results have been achieved when complex methods (i.e., chemical, physical, and/or biological pretreatments) were combined. For enzymatic hydrolysis and fermentation, the most important and efficient method utilized cellulase produced by the commercially available fungus *Trichoderma reesei*.

Zhang *et al.* [63] presented an interesting but challenging approach to utilize the lignin and hemicelluloses in addition to the cellulose components. According to their citations, economically sound and environmentally friendly technologies for processing these components, once considered waste, have been developed and are being used to produce marketable products. Among them is the potential to replace phenolic compounds from the oil industry with lignin-originated products, while hemicelluloses, because of their less stable nature, can be converted to a mixture of monosaccharides.

Van Acker *et al.* [64] reported that by using biotechnology, poplar biomass can be converted into liquid biofuels without costly and energy consuming pretreatment. This can be achieved by reducing the amount of lignin in the wood biomass or by changing its composition to obtain forms that are more susceptible to chemical degradation, thus making saccharification more efficient. The key enzyme in the phenylpropanoid pathway for lignin modification is cinnamoylo-CoA reductase (CCR). Trees that have been genetically modified in terms of CCR regulation were originally produced for the pulp industry, but this trait appears to be even more suitable for processing of poplar wood into second generation biofuels, since saccharification was increased by 50%.

Klasnja *et al.* [65] compared the calorific value of willow and poplar biomass, with special attention given to a comparison between old and young stems of both species. Bark was separated from wood. The higher heating values of oven dry poplar wood (calculated for the whole tree with an adjustment based on the proportion of bark) ranged from 15 787 to 24 275 kJ kg^{-1} for one and two-year old clones of hybrid I-214, respectively. The authors concluded that the calorific value of wood is more favorable than that of bark, and the highest calorific values refer to two-year-old trees. Their other conclusion was that woodchips from young SRPs harvested biannually could be used as biofuel without the bark separation needed when using older stems.

11.5 Carbon Sequestration and Soil Response

Another function of fast-growing tree species such as poplar is their potential role as an effective carbon sink. Intensive management of SRP poplar for biomass energy could help to partially offset carbon dioxide emissions due to short-term turnover of fine roots and long-term accumulation and decomposition associated with larger roots and stumps. Rytter [66] provides calculations that are based not only on above and belowground biomass production data from field experiments, but also on fine root turnover, litter decomposition, and increased production levels from commercial plantations. Carbon accumulation in woody biomass, above and belowground, was estimated at 76.6–80.1 MgC ha^{-1} and accumulation of carbon in the soil at 9.0–10.3 MgC ha^{-1} over the first 20–22 seasons of plantation growth. The average rates of carbon sequestration were 3.5–4.0 MgC ha^{-1} yr^{-1} in woody biomass and 0.4–0.5 MgC ha^{-1} yr^{-1} in the soil. In each of his calculations, SRP poplar showed a higher carbon sink potential than for willow. Similar studies were carried out in China [67] where they also found that SRP poplar had higher carbon sequestration capacity than any annual cropping system in their country. They reported that carbon concentrations in poplar organs ranged from 459 to 526 gC kg^{-1} DM with the highest levels in stemwood and the lowest concentrations in coarse roots.

Jaoudé *et al.* [68] expressed doubts regarding the ability of poplar plantations to have a positive effect on carbon storage, arguing that if intensive management practices and commercial fertilizers were used, increasing emissions could reduce carbon storage in the soils. The processes for increasing carbon dioxide emission from short-rotation plantations were connected with soil respiration and included the following components: root respiration, heterotroph respiration (including microbial respiration of plant residues, turnover of soil organic matter, and rhizomicrobial respiration). It was found that coppicing increased carbon dioxide efflux from soil compared to the pre-coppicing period, but when nitrogen fertilizers were applied it caused a rapid and significant reduction of total soil carbon dioxide efflux by changing the metabolic pathways for both for hetero- and autotrophs.

The long-term effects of SRP poplar on soil properties is a matter of discussion in many countries, where some opponents of woody crop plantations have alleged that after 25 years of such management, soil nutrient levels are exhausted and special, long-lasting rehabilitation is needed. Recent studies in Germany [69] helped dispel this myth by providing data for sites where short-rotation poplar was grown for four rotations. The most important soil parameter (i.e. soil organic matter) was improved by 6.2 Mg ha^{-1} during the 12 years of poplar growth. Higher microbial activity was also recorded. There was some depletion in phosphorus and potassium but no negative yield effects and, furthermore, those nutrients can be easily supplemented with good management. With regard to soil physical properties, soil bulk density decreased and pore volume increased during the 12 years of short-rotation poplar growth.

Luo and Polle [70] evaluated effects of elevated atmospheric carbon dioxide concentrations on three poplar genotypes grown in SRPs to determine if the energy content would change. They found that changes in carbon dioxide concentration modified biomass composition more than nitrogen fertilizers. Long-term elevated carbon dioxide concentrations increased the quantity of lignin in the wood. Since lignin has the highest calorific value of all wood components, this suggests that elevated carbon dioxide could actually result in better poplar biomass if it is burnt directly as a fuel. The other important observation was that higher nitrogen rates were necessary for the poplar to utilize the additional carbon dioxide in the atmosphere.

Environmental benefits associated with converting arable land to short-rotation poplar were presented by Updegraff *et al.* [71]. With regard to potential greenhouse gas mitigation, they noted high differences in calculations of carbon content. Other benefits included a reduction in erosion and agricultural runoff that can lead to surface water protection. They also pointed out that short-rotation poplar plantations cannot be treated as conservation system because of the intensive agricultural practices that are used to sustain the plantations, but the management strategies and environmental benefits are attained by the site and growing conditions. Updegraff *et al.* [71] also considered the environmental benefits of converting arable land into SRP poplar by constructing three scenarios of 10, 20, or 30% conversion in Minnesota, U.S.A. They assumed two scenarios for utilization of the poplar biomass – wood production or energy generation – and included an assumption that an offset for carbon sequestration would be introduced. Modeling of the three scenarios gave results that had a very high level of uncertainty because of difficulty in quantifying the most crucial environmental benefit (i.e. carbon sequestration). They simply could not obtain an accurate estimate of belowground biomass and carbon dynamics. Therefore, they concluded that the benefits, when treated as offsets in monetary terms, could only be estimated with a very wide range of between \$44 and \$96 ha^{-1}.

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12

Development and Deployment of Willow Biomass Crops

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12.1 Introduction

According to the U.S. Billion Ton Update (BT2) [1]), a federal investigation into the feasibility of replacing 30% of petroleum feedstocks with renewable biomass, perennial energy crops are projected to provide as much as 61% of the potential biomass in the United States by 2030 under the most favorable set of scenarios (highyield, $60 a ton price, 4% energy crop yield increases). The objective is to grow these crops on marginal agricultural and abandoned land to minimize the impact on production of other agricultural crops and to provide landowners with alternative crops and income from these areas. The northeast United States is well suited to production of perennial energy crops because there are large amounts of marginal agricultural land and reclaimed land. Studies indicate that there are over 2.8 million ha of idle or surplus low-cost agricultural land [2] and 0.5 million ha of disturbed mine land available for deploying perennial energy crops in the northeast [3]. Both woody [e.g., willow (*Salix* spp.) and hybrid poplar (*Populus* spp.)] and herbaceous perennial energy crops [e.g., switchgrass (*Panicum virgatum*), *Miscanthus*] have been identified as potential perennial energy crops on this land base.

Interest in shrub willows as a perennial energy crop for production of biomass has developed in Europe and North America over the past few decades because of concerns with energy security, environmental impact associated with the current mix of fossil fuels,

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and economic challenges in rural areas. When deployed properly across the landscape, willow biomass crops can provide multiple environmental and rural development benefits [4–6], while providing a locally grown source of biomass that can be converted into a range of bioenergy, biofuels and bioproducts.

Initial trials with shrub willows as a biomass crop were conducted in the mid-1970s in Sweden and in the United States starting in 1986 [7]. Commercial expansion started in Sweden in the late 1980s and accelerated rapidly for several years because of favorable policies supporting biomass crop establishment. By the late 1990s, the acreage in Sweden had peaked at around 16 000 ha but since that time it has decreased slightly to about 14 000 ha of willow biomass crops [8–10]. An additional 18 500 ha of willow and poplar woody energy crops have been established in Germany, Italy and the United Kingdom [10].

Since the first research projects were initiated in upstate New York, U.S.A., in the mid-1980s, yield trials have been conducted or are underway in 15 states and six Canadian provinces, so that now over 500 ha of commercial scale willow biomass crops have been established. In addition to studies on potential yields of different varieties of willow across a range of sites, research has also been done on various aspects of the production cycle, including nutrient amendments and cycling, alternative tillage practices, incorporating cover crops into these systems, spacing and density studies, harvesting systems development, growth characteristics important for biomass production, use of willow plantations by birds, changes in soil micro arthropod communities under willow, changes in soil carbon, economics of the production system, and life cycle assessments of willow bioenergy systems. In addition, a breeding and selection program for shrub willows has been developed and is producing improved varieties of willow for both the biomass production and agroforestry markets [11]. Results from this and other initiatives in North America and Europe have provided a base from which to begin to expand and deploy willow biomass crops.

The most recent development in the commercialization of willow biomass crops in North America has been the establishment in 2012 of a biomass crop assistance program (BCAP) project area in northern New York State [12]. BCAP is a U.S. Department of Agriculture (USDA) initiative intended to promote wide-scale deployment of biomass cropping and utilization, established in the Food, Conservation, and Energy Act of 2008 (P.L. 110-234, Sec. 9011). Under this program almost 500 ha of willow biomass crops will be managed for at least ten years. This program provides cost share support from the USDA for the establishment of willow biomass crops and an annual rental payment for land that is used to produce these crops. Long-term agreements are in place for the sale of all of the biomass produced from these fields to an end user in the region that is generating electricity and heat using wood chips. This program addressed some key barriers to the deployment of willow, including reducing upfront costs associated with establishing willow biomass crops and providing a secure long-term market for the biomass that is produced.

12.2 Shrub Willow Characteristics

Shrub willows have several characteristics that make them an ideal perennial feedstock for the production of biofuels, bioproducts, and bioenergy: high yields that can be sustained in three to four-year rotations, ease of propagation from dormant hardwood cuttings, a broad underutilized genetic base, ease of breeding for several characteristics, ability to resprout after multiple harvests, and a chemical composition and energy content that is similar to other hardwoods. The similarity in the compositions of willow with other hardwoods allows these different sources of biomass to be blended together to provide a consistent year-round supply to end users.

A common misconception about willow biomass is that it makes a poor choice for the production of different forms of energy because its energy content is lower than other woody biomass and it has higher ash content. While the energy content of willow on a volume basis is lower than other hardwoods due to willow's lower specific gravity, on a weight basis willow is similar to other hardwoods. The energy content of three-year-old willow stems averaged 19.4 MJ kg^{-1} [13] compared to 19.4–19.8 MJ kg^{-1} for northern hardwoods [14]. However, the specific gravity of shrub willow is lower than most other hardwoods. The mean specific gravity of three-year-old stems of different willow varieties in three trials ranged from 0.40 to 0.43 g cm^{-3} [15, 16]. In both these studies there were significant differences in specific gravity among the willow varieties, with a range of 0.38–0.48 g cm^{-3}. Similar aged hybrid poplar stems had a specific gravity of 0.35 ± 0.02 g cm^{-3} [15]. In contrast, the specific gravity of northern hardwoods is typically in the 0.5–0.6 g cm^{-3} range [17].

Willow biomass crops are grown using coppice management that utilizes willow's natural ability to resprout. This results in biomass being produced and distributed across several stems. The number of stems produced and maintained in this production system varies among varieties and has ranged from 4.6 to 13.7 stems per stool after three years of regrowth following coppicing [18]. The production of multiple stems in this system results in the perception that the proportion of bark, and as a result the ash content, should be higher in willow biomass compared to other hardwoods. However, the bark on these smaller stems is thinner than on larger diameter stems, so the proportion of bark ranges from 4.2 to 6.6% on three-year-old stems [18]. Sampling procedures, age of plants, and stem diameter impact the proportion of bark such that other studies have reported that bark makes up 10–19% of the total biomass on two-year-old stems [19, 20]. The ash content of willow biomass is also relatively low, ranging from 1.3 to 2.7% across multiple clones at one site [15, 18]. When ash content was examined in trials planted with the same suite of varieties at two different locations, there were differences in ash content, both between varieties and sites, but the mean ash content across the 18 varieties at each site was only 1.14 ± 0.09 and $1.93 \pm 0.15\%$ [16]. Clearly, soil and site characteristics have an effect on ash content, but sampling protocols and laboratory procedures may also have an impact. Reported values for ash content in willow are at or below levels reported for other sources of woody biomass, such as whole-tree chips or forest residuals [13].

Determining the composition of willow biomass is important to understand the potential for using willow biomass as a feedstock for liquid transportation fuels. Recent studies have shown differences among willow varieties and across sites. Cellulose content among 18 willow varieties at one site was $42.3 \pm 0.3\%$, but was significantly lower ($41.0 \pm 0.2\%$) for the same suite of varieties grown at a second site. However, neither the lignin (22.1–22.3%) or hemicellulose (31.9–32.3%) content varied across the two sites. Other studies have found the ranges for cellulose (36–43%), hemicellulose (30–35%), and lignin (22–27%) to be slightly greater [16]. Further studies are underway to determine both genetic and site factors that may contribute to variations in biomass composition and its impact on energy production, particularly liquid transportation fuels.

12.3 Production Systems for Willow Biomass Crops

Willow biomass crops can be grown on marginal land using a coppice management system so that multiple harvests are generated from a single planting of genetically improved shrub willow varieties [21]. The system typically includes three-year rotations with one year of site preparation prior to planting. After the first growing season, the willow is coppiced and material is typically left in the field since first year production is very low, typically between 0.5 and 1.0 tons ha^{-1}. The willow resprouts the following spring and produces multiple stems on each plant. The willow is left to grow for three years and then harvested during the dormant season. After harvest the willows resprout and grow for another three-year cycle. Up to seven three-year rotations are currently projected before the willow stools spread out and limit access for harvesting and chip collection equipment. Following the final harvest, the willow can be killed with herbicide and stools ground down and incorporated into the soil [21].

Effective establishment of perennial energy crops like willow is essential to their biological and economic success, so conducting proper site preparation is essential. Site preparation should begin with control of existing weeds using a combination of chemical and mechanical techniques. These activities should begin in the fall before planting if the field contains perennial weeds, which is often the case with marginal land, or after crops are harvested if the land is currently being used for the production of an annual crop. It is essential to control competing vegetation and prepare the soil before willows are planted in the spring. Improper or incomplete site preparation often results in strong weed competition during the establishment phase and has frequently been noted as one of the main limitations to successful establishment of willow biomass crops [6, 9, 22].

Willows are planted as unrooted, dormant hardwood cuttings at about 15 000 plants per ha^{-1} as early in the spring as the site is accessible with mechanized planters attached to farm tractors. Over the years several versions of planters have been developed and two of them, the Step planter and the Egedal (Figure 12.1), are currently being used in the United States. With both machines, one-year-old stems are fed into the planter, cut at an appropriate length (15–20 cm) and either actively inserted into the ground (Step planter) or placed into a slit opened by the planter (Egedal). Both machines are capable of planting around 0.8 ha h^{-1} when site preparation has been done properly and ground conditions are appropriate.

The use of dormant cuttings allows planting of selected varieties of genetically improved willow. In North America, varieties are generally planted in individual blocks with several different genetic varieties planted across a field to maintain diversity. In parts of the United Kingdom, where pressure from willow leaf rust (*Melampsora* spp.) is stronger, studies have shown that planting random mixtures of different willow varieties can maintain or even increase yields [23, 24]. Differences in growth rates, stem form, canopy width and other characteristics among varieties may influence the effectiveness of this approach if some external pressure, such as a disease or pest, is not a major influence on the system. Research is underway in North America to characterize willow varieties and to explore the potential benefits associated with mixed random planting designs.

Current recommendations for planting designs and densities for willow in North America are based on the double row system developed in Sweden and research from Europe largely based on the growth of *S. viminalis* [25] and trials in North America [26]. Research in

Figure 12.1 *Planting willow biomass crops using one-year-old stems of select willow varieties in a (a) Step and (b) Egedal planter (Photo credit T. Volk and D. Rak © SUNY ESF).*

North America was based on a single variety, 'SV1' (*Salix dasyclados*), over multiple rotations with densities ranging from about 15 000 to 111 000 plants ha^{-1}. The current recommended spacing for a double row system allows 1.8 m between each set of double rows, 0.75 m between individual rows, and 0.55 m between plants along each row. This results in a planting density of about 14 600 plants ha^{-1}. However, recent studies with new willow varieties developed in New York suggest that their growth rate is rapid enough that there is no significant yield difference among planting densities ranging from 8800 to 17 500 plants ha^{-1} [27].

Following the first year of growth, the willows are cut back close to the soil surface during the dormant season to force coppice regrowth. This increases the average number of stems per stool from 1–4 to 8–13 depending on the variety [18] (Figure 12.2). After an additional three to four years of growth the stems are mechanically harvested during the dormant season after the willows have dropped their leaves so those nutrients are maintained in the system (Figure 12.3). In addition, most end users do not want foliage in

Figure 12.2 *Three-year-old coppice regrowth of shrub willow showing the multiple stems that are generated on each stool (Photo credit D. Angel © SUNY ESF).*

Figure 12.3 *Willow biomass crops are harvested during the dormant season after three or four years of growth. These shrub willows are four years old aboveground on a five-year-old root system and are ready to be harvested (Photo credit D. Angel © SUNY ESF).*

the biomass delivered to their facility because of its higher ash and nutrient content. The chipped material is then delivered to end users for conversion to bioenergy, biofuels and/or bioproducts. The plants will sprout again the following spring and are allowed to grow for another three or four years before being harvested. Projections indicate that the crop can be maintained for 7–10 rotations before the rows of willow stools begin to expand to the point that they are no longer accessible with harvesting equipment. At this point the crop can be replanted by removing the existing stools with herbicides after harvesting, followed by chopping using a heavy disk and/or grinding machine, and subsequently planting new cuttings that year or the following year.

Nutrient removal from willow biomass crops is limited because only the aboveground woody portion of the crop is harvested during the dormant season after the leaves have dropped and most nutrients have been translocated to the root system. Nutrients not translocated from the foliage are returned to the system in litterfall. For most soils in the region where willow is being deployed, the only nutrient addition that is recommended is nitrogen, which is typically added at the rate of about 100 kgN ha^{-1} once every 3–4 years in the spring after the crop is harvested. However, recent research has indicated that for a number of sites in the northeast there was no yield response when nutrients either in the form of commercial fertilizers or organic amendments were applied to willow crops [28, 29]. Marginal agricultural soils in the northeast United States are typically limited by poor drainage and wet conditions rather than nutrient supply. Additionally, tight nutrient cycling in these systems [30] and relatively low nutrient removal rates in the woody biomass [31] are other factors that may further reduce the need for fertilization on a wide range of favorable sites for woody crops in the region. If regular nutrient additions are not required, willow systems will reduce production costs and greenhouse gas emissions, improve the net energy balance, and preserve or improve water quality in natural streams and waterways when compared to annual cropping systems.

A rapid growth rate is one of the attributes that makes shrub willows an appealing biomass crop. Yields in research plots of fertilized [32] or fertilized and irrigated [31] unimproved varieties of willow grown for three years have exceeded 27 oven-dried metric tonnes (odt) ha^{-1} yr^{-1}. Due to costs associated with irrigation and the relatively low value for biomass, irrigation will not be used for most large-scale production operations. The exception with regard to irrigation is where willow biomass crops could be irrigated with wastewater as part of an overall nutrient management plan. Nonetheless, these studies set a benchmark for the potential production of willow biomass, with even higher yields being possible with improved genetic material from current breeding and selection programs.

First-rotation, non-irrigated research-scale trials across a range of sites planted between 1993 and 2007 with a range of willow varieties have produced yields of 6.9 odt ha^{-1} yr^{-1} [33]. Trials planted after 2005 that included new willow varieties developed in North America produced 9.2 odt ha^{-1} yr^{-1}, an increase of 33%. Many of these trials involved the testing of a wide range of varieties, some of which were later determined to be unproductive and were eliminated as potential commercial varieties. If just the top five varieties in each trial are included, then the reported yield is 9.2 odt ha^{-1} yr^{-1} in the trials with older varieties and 11.2 odt ha^{-1} yr^{-1} when new varieties were included, a 22% increase. Second rotation yields of willow are typically higher than first rotation yields because the plant's root system is already established and more of the carbon that is fixed by the plant in the second rotation can be allocated to aboveground growth. In one trial, second rotation yields increased by about 20% while third and fourth rotation yields were maintained and largely dependent on weather conditions [33].

12.4 Willow Biomass Crop Economics

Despite the wide array of benefits associated with willow biomass crops, expansion and rapid deployment of this system has been restricted by high production costs and, in some situations, a lack of market acceptance. The economics of willow biomass crops has been analyzed using a cash flow model (EcoWillow) that is publically available from SUNY-ESF (State University of New York-College of Environmental Science and Forestry) [34]. The model incorporates all the stages of willow crop production from site preparation and planting through to harvesting over multiple rotations, and transportation of harvested chips to an end user. The removal of the stools once the crop has expired at the end of seven rotations is also included in the model. The cash flow model is based on experience establishing and maintaining willow biomass crops in New York State. The model is flexible enough that it can be applied across the range of sites where shrub willow might be grown. Users can vary input variables and calculate cash flow and profits throughout the entire production chain from site preparation and crop establishment to the delivery of wood chips to an end user.

For the base case scenario in EcoWillow, a productivity of 12 odt ha^{-1} and a biomass price of \$60 odt^{-1} showed an internal rate of return (IRR) over seven, three-year harvest cycles (i.e., 22 years) of 5.5% [35] with profits of \$101 ha^{-1} yr^{-1} or \$10 odt^{-1}. The model shows that payback is reached in the thirteenth year with revenues from the third harvest neutralizing the project's expenses. Harvesting, establishment, and land rent are the main expenses associated with willow biomass crops over their entire lifespan making up 32%, 23%, and 16% of the total undiscounted costs. The remaining costs including crop removal, administrative costs and fertilizer applications account for about 29% of the total costs.

For willow biomass crops, harvesting is the largest single cost factor, accounting for just under one-third of the final delivered cost. Harvesting, handling, and transportation account for 45–60% of the delivered cost [34]. Harvesting operations have a significant impact on the final cost of production because it is the operation that occurs most frequently during the life span of the willow crop. If seven, three-year rotations are run for this system, harvesting operations need to be conducted seven times. Each of those operations requires a harvester and system of collection wagons or trucks. Since this part of the production system makes up such a large portion of the final delivered cost and the harvesting systems being used are relatively new, opportunities for cost savings are significant. Improving harvesting efficiency by 25% could reduce the delivered cost of willow by approximately \$0.50/MMBtu (\$7.50/ton). Research and development work is underway to reach these targets using a cut-and-chip harvesting system that is based on a New Holland forage harvester and cutting head (Figure 12.4) specifically designed for short rotation woody crops like willow and poplar. Recent field trials of this harvesting system have generated throughput rates exceeding 50 green tons h^{-1} [35].

Harvest costs are also significantly influenced by the field design. Missing or inadequate headlands can create costly delays when handling harvesting equipment. Furthermore, maximizing row length and, thus, reducing unproductive turn-around time is crucial. For instance, increasing row length from 200 to 400 m, *ceteris paribus*, increases the IRR by 11% [34].

Another approach for decreasing harvest cost is to reduce the number of harvests over the crop's lifespan. Increasing the production cycle to four years would result in five, four-year harvests instead of seven, three-year harvests, thus decreasing harvest costs per ton by about 14% and increasing the IRR for the entire system by about 11% [34]. This improvement in return is primarily associated with an increase in biomass at the time of harvest. However, this also assumes that mean annual willow growth does not decrease as rotation length increases and that the harvester can efficiently and effectively handle larger diameter stems.

Figure 12.4 Harvesting four-year-old willow biomass crops with a cut and chip harvesting system based on a New Holland FR self-propelled forage harvester and a New Holland FB 130 coppice header that was designed for woody crops like willow and hybrid poplar (Photo credit D. Angel © SUNY ESF).

Another alternative to reduce harvest costs is to use a smaller harvesting system that has lower capital and operating costs. One example is the NyVarra harvester, which could be used to harvest willow on a two-year rotation. This system is particularly appealing when biosolids are being land applied to willow fields and the producers are also generating some revenue from this operation. This has become more common in Europe in recent years. The limitations of a shorter harvest cycle and smaller harvesting system are that fewer tons are harvested in each rotation, so the fixed costs associated with both the harvester and chip collection system are spread over fewer tons and the rate of production of these systems is typically lower. Whether or not a smaller harvesting system and a more frequent harvest cycle is more economically attractive than a larger harvesting system is being explored further.

Willow biomass crop establishment is the second largest cost category in the production system, accounting for almost one quarter of the final delivered biomass cost [34]. The high upfront establishment costs are a barrier to the deployment of willow, especially since any return on these investments is not realized until the first harvest, which typically occurs four or five years after planting. Costs for planting stock typically account for over three quarters of the establishment expense for willow biomass crops. Current planting stock costs are in the range of \$0.12 to \$0.15 per cutting and with the current recommended planting density of 14 600 plants ha^{-1}, the cost of planting material alone is \$1752 to \$2190 ha^{-1}. There are two approaches to reduce costs associated with planting stock. One is to reduce the planting density and the second is to reduce planting material cost. As noted above, recent studies have suggested that the planting density could be reduced to 8800 plants ha^{-1} [27]. Furthermore, as willow biomass crops are expanded and demand for planting material increases, improvements in production of planting material in the nursery are anticipated to lower costs about \$0.10 per cutting. If both a lower planting density and lower stock cost were implemented, costs of planting stock could be reduced by 50–60%. This would have a significant impact on both establishment costs and overall returns from the system.

Improving yields will increase revenues from willow biomass crops and will improve returns. Yield improvement is a key focus of research efforts to overcome the economic barrier to commercialization of this system [16]. Increasing yields by 50% from 11.3 odt ha^{-1} yr^{-1} would improve the IRR from 5.5 to 14.6% [34]. As noted above, significant improvements in yield have already been made with the production of new willow varieties and additional improvements will occur with new genotypes and improvements in the management of willow biomass crops.

Willow biomass cropping systems are in their infancy in North America and there is potential for large gains in yield by optimizing production practices and through breeding. By addressing system components that have the greatest influence on costs, the overall economics of these systems can be improved so that they can be deployed across the landscape. As the knowledge base about how willow grows and the roles it plays expands, it will be deployed more effectively so that in addition to biomass, other landscape benefits derived from this system can be optimized.

12.5 Environmental and Rural Development Benefits

Willow biomass crops are being developed as sustainable systems that simultaneously produce a suite of ecological and environmental benefits in addition to a renewable feedstock for bioproducts and bioenergy [5, 6, 10]. The perennial nature of the willow production system provides a range of beneficial attributes, such an improved energy return in investment, reduced greenhouse gases, and changes to soil conditions and biodiversity.

A recent life cycle analysis of willow biomass crops in North America covered all the inputs and processes from the nursery through seven three-year harvest cycles. Establishment, harvest and delivery of the willow to an end user and removal of the willow stools after seven rotations were included. The study explored eight different scenarios based on differences in transportation distances to an end user (71 or 195 km), high or low-yield scenarios (11.8 or 9.2 odt ha^{-1} yr^{-1}) and, the use of 0 or 100 kgN ha^{-1} once every three years following harvest. In addition, uncertainty analysis was conducted using data on variations in leaf litter, yield, and belowground biomass. Across the eight scenarios, cumulative energy demand ranged from 446.5 ± 12.3 to 1055.2 ± 42.9 MJ odt^{-1} [36], which equates to an energy ratio of between 1:19 and 1:45 for willow biomass delivered to an end user. The largest fraction of energy demand across all scenarios was use of diesel fuel, of which 48–77% was used for transportation of willow chips from the field gate to the end user. Harvesting operations had a greater energy demand than other field processes due to the frequency of occurrence over the life of the crop and the size of the equipment that was used. A recent review of 26 studies of short-rotation willow and poplar systems found that net energy ratio across a range of scenarios ranged from 1:13 to 1:79 at the farm gate and

1 : 3 to 1 : 16 after delivery to an end user [37]. Results from the current study and those from a previous study in North America [38] are at the high end of this range because inputs to the willow system, such are fertilizer or fencing, are generally lower or non-existent, when compared to European recommendations.

Patterns similar to energy demand were also found for greenhouse gas emissions for willow biomass crops across all scenarios because fossil fuel use is the largest source of emissions in the system [36]. Among the eight scenarios, greenhouse gas emissions ranged from -138.3 ± 22.5 to -52.7 ± 14.7 kg CO_2-eq odt^{-1} (~ -6.9 to -2.7 g CO_2 eq MJ^{-1}). Carbon sequestration in the belowground portion of the willow system provided a large sink [39] that more than compensated for carbon emissions associated with crop production and management across all eight scenarios. As a result, the willow biomass crop system ended up being a carbon sequestration system, in addition to producing woody biomass that can be used to generate bioenergy, biofuels or bioproducts.

The perennial nature and extensive fine-root system of willow crops reduces soil erosion and non-point source pollution relative to annual crops, promotes stable nutrient cycling and enhances soil carbon storage in roots and the soil [39–42]. In addition, the crop is constantly in its rapid juvenile growth stage, so demand for nutrients is high, resulting in very low leaching rates of nitrogen even when rates of applications exceed what is needed for plant growth [43–45]. The period with greatest potential for soil erosion and non-point source pollution is during the first $1^1/_2$ years of establishment, when cover is often limited because weeds need to be controlled and the willow canopy has not closed. The use of a winter rye cover crop has proven to be effective at providing soil cover without impeding establishment of the willow crop [46] and trials with a spring planting of low growing white clover have also been effective [22]. Since herbicides are only used to control weed competition during the establishment phase, the amount of herbicides applied per hectare is about 10% of that used in a typical corn (*Zea mays*)–alfalfa (*Medicago sativa*) rotation in upstate New York [47].

Birds are one indicator of the biodiversity supported by willow biomass crops that have been studied in the United States. A study of bird diversity in willow biomass crops over several years found that these systems provide good foraging and nesting habitat for a diverse array of bird species [48]. Thirty-nine different species made regular use of the willow crops and 21 of these species nested in them (Figure 12.5). The study found that diversity increased as the age of willows and size of plantings increased, and also that birds have preferences for some willow varieties over others [49]. The number of bird species supported in willow biomass crops was similar to natural ecosystems, such as early succession habitats and natural, intact eastern deciduous forest ecosystems. The positive impact of willow on bird diversity was also supported in a recent assessment as part of a multidisciplinary study in Europe [10]. Instead of creating monocultures with a limited diversity across the landscape, willow biomass crops will increase diversity relative to open agricultural land or arable crop fields.

12.6 Commercial Development

Several key bottlenecks in the willow crop production system have been overcome during the past few years, making deployment on a large scale possible. One of those barriers has been availability of large quantities of shrub willow planting stock. Over the past few

Figure 12.5 *Cedar waxwings (Bombycilla cedrorum) nesting in three-year-old willow biomass crops in northern New York State (Photo credit R. Allmond © SUNY ESF).*

years a commercial nursery in western New York (Double A Willow) planted over 60 ha of willow nursery beds to meet the projected annual demand for millions of planting stock cuttings and several other nurseries are being planned.

Another significant bottleneck has been how to efficiently and economically harvest the crop and produce a consistent quality product that is acceptable to end users. Since 2004, Case New Holland (CNH) has been working with SUNY-ESF and other partners to develop a harvesting system for willow biomass crops based on a New Holland self-propelled forage harvester and a header that is designed to cut short rotation woody crops. Trials with the latest version of this system, based on a New Holland FR series self-propelled harvester and a 130 FB coppice header, indicate that for three or four-year-old willow biomass crops with the majority of stems <75 mm in diameter, consistent high quality chips (>95% of the chips being smaller than 37.5 mm) can be produced at a harvest rate of about 0.8–1.8 ha h^{-1}. Additional actions are being tested to further improve this machine [35]. As noted above, the improved production rates that are possible with this harvester will have a direct impact on the delivered cost of willow biomass.

12.7 Conclusions

In order to meet the projected demand for biomass for the production of bioenergy, biofuels, and bioproducts in the United States, perennial energy crops will need to be developed and deployed across millions of hectares over the next 25–30 years. Over the past few decades, research in Europe and North America has resulted in the development of a shrub willow production system. Thousands of hectares of shrub willow crops have been deployed in Europe, and the system is beginning to be expanded in the United States, but the future of it as a sustainable system will depend on continued research on biological, ecological and socioeconomic factors, development of a feedstock production and supply infrastructure, and supportive renewable energy policies.

Many characteristics of shrub willows, and the production system that has been developed, contribute to sustainability of the system. The perennial nature of willows, their extensive diffuse root system and the coppice management approach that has been developed, result in a crop that can be maintained and productive for more than two decades after it is planted. These characteristics create tight nutrient cycles and a permanent crop on the landscape that will improve soil and water quality as well as biological and landscape diversity relative to traditional annual agricultural crops. The potential of the system to sequester greenhouse gases and its high-energy return on investment are other key features that contribute to its sustainability.

Under existing policy structures, the economics of willow biomass crops are marginal because of the relatively high cost of establishment, low prices for woody biomass, and limited experience with the crop. In addition to optimizing the production system and improving yields, changes in policies to support commercial deployment of willow and other perennial energy crops in the near term are necessary to transition these crops to commercially viable systems. Recent development of the USDA BCAP project in northern New York is a positive step forward. As this and subsequent expansions occur, potential socioeconomic benefits associated with producing a marketable product from marginal agricultural land should begin to accrue to rural areas. Since biomass from shrub willow crops will be integrated with woody biomass from other sources, such as low-grade material from forests and residues from forest harvesting operations, there is potential for benefits to accrue to local communities from revitalization of those sectors as well.

The future challenges are to simultaneously optimize willow biomass crop production, increase interest from potential producers, and develop long-term markets for willow and other sources of woody biomass. To accomplish this and develop a sustainable system, strong links between researchers, potential producers, and end users are required. With these links in place, development of a vibrant willow biomass enterprise will play an important role in bolstering the farm and forestry sectors, while increasing energy independence, providing environmental benefits, and mitigating pollution problems.

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13

Herbaceous Biomass Logistics

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13.1 Introduction

Society collects raw materials using the following extraction activities: mining (which includes drilling for oil and natural gas), logging, farming, fishing, and hunting. Mining is a "point source" extraction of raw materials. Some geological event has deposited a high concentration of the desired raw material at a given location, and a mine is established at this location. Typically, a rail line, pipe line, or marine port is built to cost-effectively transport the raw material to distant utilization points.

Biomass is unique among the raw materials used by society in that it is a distributed resource. It must be collected from production fields/forests and accumulated for processing at a central location. This chapter primarily covers farming with some minor reference to logging. Fishing and hunting (relatively small in developed countries) are not covered.

This chapter is written to guide the reader through the thought process they will use if they are designing, or specifying, a logistics system for a bioenergy plant. Logistics systems have been designed for many agricultural and forest products industries. Thus, it is wise to use the lessons learned in these commercial examples. Each of these industries faces a given set of constraints (length of harvest season, density of feedstock production within a given radius, bulk density of raw material, various storage options, quality changes during storage, etc.) and the logistics system was designed accordingly. Typically, none of the existing systems can be adopted in its entirety for a specific bioenergy plant at a specific location, but the key principles in their design are directly applicable.

Our definition of biomass logistics is "a series of unit operations that begin with biomass standing in the field and ends with a stream of size-reduced material entering a bioenergy plant for 24/7 operation". (One example is shown in Figure 13.1.) All the required

Cellulosic Energy Cropping Systems, First Edition. Edited by Douglas L. Karlen.

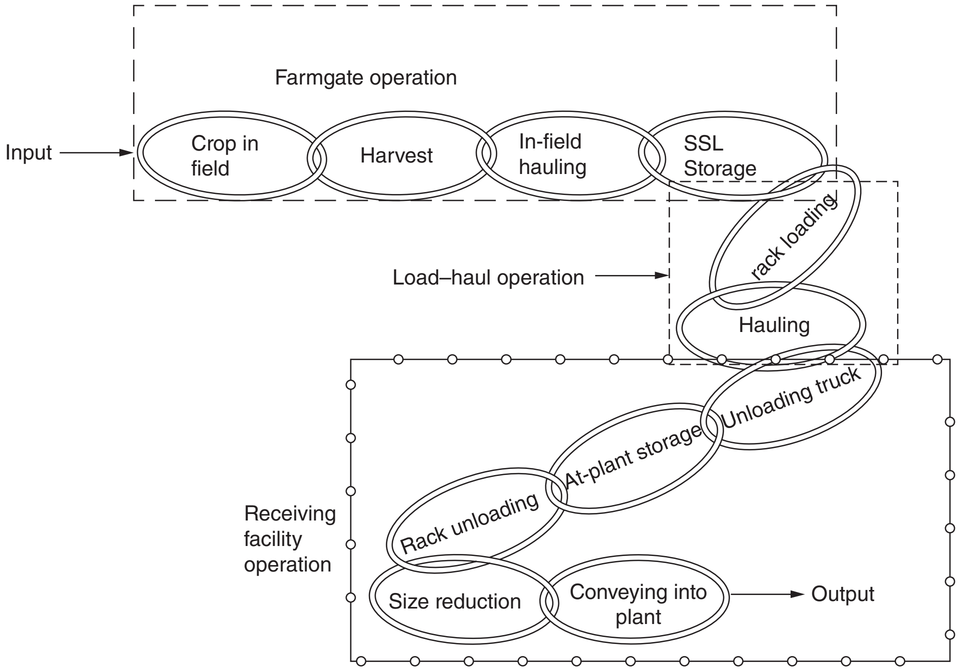

Figure 13.1 *Logistics chain for delivery of round bales to a bioenergy plant. (The dotted lines identify segments of the chain which are performed by different business entities).*

unit operations are linked together in this chapter. In general, it is not wise to end the analysis of a logistics chain when a truckload of raw biomass enters the plant gate, as is often done.

The term "feedstock logistics" is used to indicate that the focus is on the movement of raw biomass from the field to a bioenergy plant. This plant may be a "Regional Biomass Processing Depot" (RBPD) as outlined by Eranki *et al.* [1]. The depots (size range 100–1000 ton/d) are envisioned as locations where raw biomass is received and some preprocessing/pretreatment is done to create an intermediate product, or products, that are shipped to a large-scale biorefinery where the final processing is done. The term "biomass logistics" is reserved for the entire logistics chain from field to biorefinery, thus our use of the term "feedstock logistics" for the logistics from field to plant. Throughout this chapter, keep in mind that the "plant" can be an end user or a RBPD.

13.2 Typical Biomass Logistics Constraints

13.2.1 Resource Constraints

In this chapter, reference is made to production of the biomass (growing the plants) only in the context of (1) when during the year the biomass can be harvested, and (2) the properties at harvest, principally the moisture content. Any biomass crop that provides an extended harvest season has an advantage – remember, any business (not only bioenergy) wants to operate as many hours per year as possible. Herbaceous crops cannot be harvested during the growing season, thus storage is always a component in the logistics system design.

Two examples from opposite ends of the harvest-season spectrum are offered. In the Southeast, wood is harvested year-round. It is said to be "stored on the stump". Weather conditions in the Southeast are such that few harvest days are lost in the winter due to ice and snow. At the other end of the spectrum, consider the harvest of corn stover in the Upper Midwest. The grain harvest is completed in the fall and then the stover is collected. In some years, there are less than 15 days between the completion of the grain harvest and the time when the fields are covered with snow and no stover can be collected. All feedstock required for year-round operation of a bioenergy plant using only corn stover must be harvested in a two- to five-week period – a significant challenge for the logistics system.

13.2.2 Purchaser Constraints

Any purchaser of biomass is interested in the cost of the material as it enters their plant. The plant can be burning the biomass directly to produce heat and power, or it can be using the biomass as a feedstock for some more complex conversion process to produce a high-value product. In this chapter, the term "feedstock" is used to refer to any raw biomass before its chemical structure is modified by a conversion process, be it direct combustion, thermochemical, or biological.

Feedstock cost ($/dry ton) is defined as the cost of the stream of size-reduced material entering the *reactor* at the bioenergy plant for 24/7 operation. (The reactor is defined as the unit operation where an initial chemical change in the feedstock occurs.) The reason for choosing this end point for the biomass logistics system is twofold:

1. The plants that can operate continuously, 24/7, have an advantage. Maximum production (tons/yr) per unit of capital investment gives a competitive advantage in the market place – the cost to produce the product is lower.
2. Some logistics systems do size reduction with the harvesting machine, while some reduce size at a transfer point between in-field hauling machines and highway hauling machines (perhaps as a prerequisite to a densification step), and some reduce size at the entrance to the processing plant. In order to compare the several systems, it is necessary to have a consistent end point for the system analysis.

The reader should be aware that many studies in the literature select a different analysis end point than used here. A typical end point is the cost of feedstock when a truckload of raw biomass enters the plant gate. This end point is favored because of tradition. Some agricultural (and forest product) industries still pay the producer when the raw material is delivered to their plant. Other industries have moved away from this model.

13.3 Linkage in Logistics Chain

It is helpful to visualize the various unit operations in a logistics system as a chain with the links as the unit operations. The example in Figure 13.1 shows a logistics system to move round bales from Satellite Storage Locations (SSLs) to a bioenergy plant. The dotted lines show various segments of the chain that are assigned to the several entities in the business plan. In this example, the segment identified "Farmgate operation" is performed by the feedstock producer, the segment identified "Load-haul operation" is included in the operations performed by a load–haul contractor, and the segment identified as "Receiving Facility" is performed by the bioenergy plant.

The division shown by the dotted lines in Figure 13.1 is arbitrary; several other options are used in commercial practice. Three examples are given to show the reader the range of these options.

13.3.1 Model Systems in Commercial Practice

- *Traditional model* – The producer grows, harvests, stores, and delivers raw material (biomass) in accordance with a contract with the processing plant. Deliveries are made to ensure that the plant has a supply for continuous operation during the processing season, which for most agricultural industries is only part of the year.
- *Cotton model* – The producer grows, harvests, and stores the raw material (seed cotton) in modules at the edge of the field (Figure 13.2). The gin (processing plant) operates a fleet of trucks to deliver the modules as required for operations during the ginning season. Farmers are paid for the seed cotton that crosses the scale at the gin. The gin operates a warehouse and stores bales of ginned cotton for periodic delivery to its textile mill customers throughout the year.
- *Sugarcane (Texas) model* – the producer grows the crop. The sugar mill takes ownership of the crop in the field and harvests and delivers it for continuous operation during the processing season. (Sugarcane must be processed within 24 hours of harvest, so storage is not part of the sugarcane system.)

The advantage (or disadvantage, depending on perspective) of the traditional model is that all quality issues reside with the producer. There is no question who is responsible

Figure 13.2 *Module hauler picking up a module stored at the edge of a field. (Photo credit J. Cundiff © 2013).*

if a quality standard is not met. Business people planning the operation of a bioenergy plant tend to prefer this model, though they typically balk at paying a feedstock price that adequately compensates the producer for their additional risk.

The advantage of the cotton model is that the specialized equipment needed for hauling the modules is owned by the gin. The producer does not have to own equipment that will be used only a few times per year. The gin uses its module haulers many more hours per year, thus the hauling cost ($/ton) is less than can be achieved by an individual producer. Typically, gins haul modules in the order they are "called in" by the growers. Module storage time in the field, and any subsequent losses are not dealt with in the grower–gin contract. The grower is paid the contract price for the mass of cotton fiber (and co-products) that the gin produces from a particular module.

The advantage of the Texas model is that the producer does not have to own any harvesting or hauling equipment. The disadvantage is that the producer does not have control over the time of harvest. Sugar content peaks in the middle of the season and a producer who has cane harvested early, or late, sells less sugar. Fortunately, this issue is addressed in the producer contract.

13.3.2 Assigning Unit Operations to Various Business Entities

The Figure 13.1 example introduces a very significant point for the design of the logistics system. *The business plan can have equal, or greater, impact on delivered cost of feedstock than the technical issues.* The technical issues are defined as the functionality (tons per hour handled) and cost ($/h) of individual pieces of equipment in the logistics chain. The business plan specifies "who will do what"; it assigns the various unit operations to the several business entities.

Ma and Echoff [2] compare a commodity model (current grain industry) with a contract model (plant contracts with farmers to grow feedstock). They state, "Based on commodity pricing, the producers/suppliers who are farther away from the refinery will realize less profit since they have to pay more for transportation; therefore, it is less attractive for them to participate in the project. Even with contract pricing, it is less attractive to sign contracts with more distant producers." In the presence of this reality, the remaining discussion in this chapter envisions that the load–haul activities will be done by the bioenergy plant (or its contractor). Then, all highway hauling cost to move biomass from SSLs to the bioenergy plant is borne by the plant, and all farmgate contractors get the same opportunity for profit, no matter their distance from the plant. Ma and Eckhoff [2] state that biorefineries can achieve a lower unit production cost for liquid fuel using the contract pricing method rather than the commodity pricing method.

One main reason that the assignment of the business entities in the logistics system is so important is that it establishes the capitalization requirements. Generally, the plant is in a better position to obtain capital than the small business owner (producer). The next key economic factor is how many hours-per-year (and thus tons-per-year) can be handled by the purchased equipment and facilities. This factor has always been a major issue for agriculture. Most field equipment is used a relatively few hours (200–400) per year, thus the ownership cost per operating hour is high.

Suppose a logistics system is designed using the traditional model – the producer must deliver the raw biomass to the plant. The plant needs year-round deliveries, so it schedules the producers to deliver certain days of each week for 47 weeks of annual operation. During the planting and harvesting seasons, the farmers are working dawn to dusk on their field operations, thus they do not have time to make deliveries. The plant will receive no deliveries during those periods, thus it will need a large inventory in at-plant storage.

If each farmer is assigned only a few delivery days each month, the total tons delivered is too low for them to afford to invest in equipment required to make the delivery cost efficient. Consider the delivery of round bales as an example. They will choose to use the equipment they have – gooseneck trailer pulled by a pickup truck or perhaps a flat-bed truck – and the plant must now deal with a situation shown in Figure 13.3. Note the different type of trucks lined up to deliver grain to a buying point. A bioenergy plant would end up with a similar situation. There would be no uniformity in the loads received, and the plant would have to unload what comes through the plant gate. It is a challenge for a receiving facility at a bioenergy plant to operate cost effectively in this manner.

Now consider an option that emulates the cotton model. In this model, the deliveries are done with specialized transport equipment (module haulers). Each load is the same when it arrives at the plant. Now the receiving facility can be organized to receive the maximum loads per unit time. The time a truck waits in the queue to unload is minimized, thus the truck cycle time is minimized, and the truck cost ($/ton) is minimized.

An additional benefit of uniform deliveries is realized by the bioenergy plant. Each unit of equipment in the receiving facility handles more tons per unit of operating time, thus the

__Figure 13.3__ Line of trucks in queue at grain storage facility. (Illustration shows the situation when the configuration of each delivery unit is not uniform). (Photo credit J. Cundiff © 2013).

unload cost ($/ton) is less. For example, suppose the cost to operate a forklift is $50/h and, on average, it handles 50 ton/h throughout the workday. The cost is then

$$\frac{\$50/\text{h}}{50\ \text{ton/h}} = \$1/\text{ton}$$

If this same forklift has to wait for trucks to arrive and thus averages 25 ton/h over the workday, the cost is

$$\frac{\$50/\text{h}}{25\ \text{ton/h}} = \$2/\text{ton}$$

This simple example illustrates a very important principle in calculating the cost for a unit operation. Cost, ownership plus operating, for a commercial machine is defined by standard methods [3] used to calculate that cost. (An example calculation for a forklift is given in Appendix 13.A.) When this machine is used in a logistics system in such a manner that tons handled per operating hour is maximized, then cost ($/ton) is minimized.

There are studies in the literature that seek to define an optimum cost for a single unit operation in the logistics chain, or, more typically, a series of unit operations that define one segment of the total logistics chain. There is nothing wrong with this approach; however, this author has observed that if an attempt is made to optimize one unit operation in isolation, then the cost of the unit operation immediately upstream, or downstream, is increased such that the overall solution, in this case, the average delivered cost of feedstock for 24/7 operation, is higher. The reader is admonished to watch for this potential problem as they “design” a logistics system for a specific application.

13.4 Plant Size

Investors want to build a plant as large as possible because processing cost (per unit of product) typically goes down as plant size increases. Overend [4], Jenkins [5], and others more recently have shown how the average delivered cost of feedstock increases as plant size increases. The reason is that, as the feedstock consumption increases, the size of the production area increases, and hauling cost increases with average haul distance. Two factors are important:

1. Density of feedstock production – the percentage of total land area within a given radius of the plant that is attracted into feedstock production.
2. Feedstock yield – the tons of biomass harvested per unit of production land.

The two terms are sometimes lumped together into the term “feedstock density”. The influence of feedstock density is shown in Figure 13.4. Average hauling cost increases with plant size for all densities. Note, however, that the cost increase is much less for the higher density curves. A plant owner seeking to obtain an economy-of-scale benefit by building the largest plant possible will want to locate where the maximum number of surrounding land owners sign up to grow feedstock.

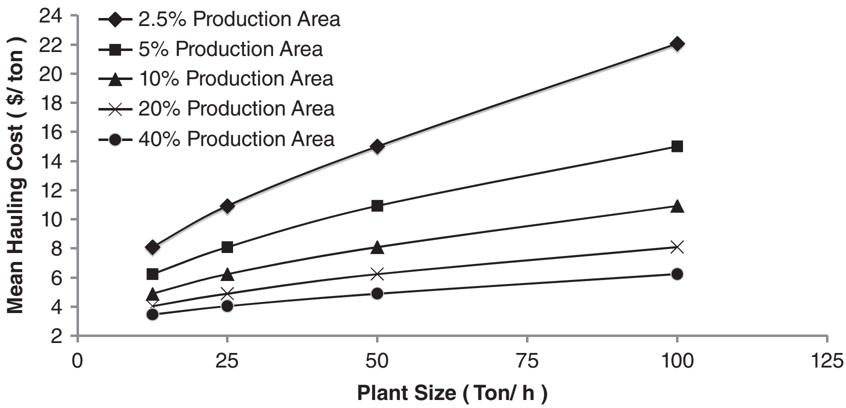

Figure 13.4 *Influence of plant size on mean hauling cost. Production area percentage is the percentage of the total land area attracted into feedstock production.*

13.5 Harvesting

Harvesting of cellulosic biomass, specifically herbaceous biomass, is done with a machine, or more typically a set of machines, that travel over the field and collect the biomass. These machines are designed with the traction required for off-road operation, thus they typically are not well suited for highway operation. Therefore, the transfer point between "in-field hauling" and "highway hauling" is critical in the logistics system. In-field hauling is defined as the operations required to haul biomass from the point a load is created in the field to a storage location chosen to provide the access needed for highway trucks. This hauling includes hauling in the field plus some limited travel over a public road to the storage location.

13.5.1 Coupled Versus Uncoupled Systems

Harvesting systems can be grouped as *coupled* systems and *uncoupled* systems. Ideal coupled systems have a continuous flow of material from the field to the plant. An example is the wood harvest in the Southeast United States; wood is harvested year-round and delivered directly to the processing plant. Uncoupled systems have various storage features in the logistics system.

Sugarcane harvesting is an example of a coupled system for an herbaceous crop. (The sugarcane harvest season in South Florida is 140 days, not year-round as with wood throughout the Southeast.) The harvester cuts the cane into billets about 15-in long and conveys this material into a trailer traveling beside the harvester (Figure 13.5). The harvester has no on-board storage – a trailer has to be in place for it to continue to harvest. The trailer, when full, travels to a transfer point where it empties into a truck for highway hauling (Figure 13.6). Each operation is coupled to the operation upstream and downstream. If the truck is not there for the trailers to dump into, they cannot return to the harvester, and the harvester has to stop. It requires four tractors, trailers, and operators to keep one harvester

Figure 13.5 *Sugarcane harvester delivering material into a dump trailer for delivery to the edge of the field. (Photo by Sam Cooper, courtesy of Sugar Journal, P.O. Box 19084, New Orleans, LA 70179; SugarJournal.com).*

Figure 13.6 *Transfer of sugarcane from in-field hauling trailers to highway-hauling trucks. (Photo credit J. Cundiff © 2013).*

operating. The trucks have to cycle on a tight schedule to keep the trailers moving. One breakdown delays the whole operation.

A “silage system” can be used to harvest an herbaceous crop for bioenergy. With this system, a forage harvester chops the biomass into pieces about one inch in length and blows it into a wagon beside the harvester. This wagon delivers directly to a silo, if the field is close to the silo, or it dumps into a truck for a longer haul to the silo. All operations are coupled – a wagon must be in place to keep the harvester moving, and a truck must be in place at the edge of the field to keep the wagons cycling back to the chopper. It is a challenge to keep all these operations coordinated.

A coupled system can work very efficiently when an industry is integrated like the sugarcane industry in South Florida. There, the sugar mill owns the production fields surrounding the mill and the roads through these fields. The mill controls everything: harvesting, hauling, and processing. Because sugarcane has to be processed within 24 hours after harvest, the need for an integrated industry is obvious.

An example of an uncoupled system is the cotton industry using the new cotton harvester that bales cotton into 7.5-ft diameter by 8-ft long round bales of seed cotton (Figure 13.7). This system was developed to solve a limitation of the current module system. With the module system, in-field hauling trailers, given the rather quaint name “boll buggies”, have to cycle continuously between the harvester and the module builder at the edge of the field. The best organized system can typically keep the harvester on the row harvesting cotton only about 70% of the total field time. Harvesting time is lost when the harvester has to wait for a boll buggy to get into position beside the harvester so the bin on the harvester can be dumped.

The round bale cotton harvester is designed to form a bale, wrap it in plastic, and eject it without stopping the harvester. A new bale is begun while the current bale is being wrapped and ejected. (Current round balers for hay have to stop, wrap the current bale, and eject it before beginning the next bale.) The round bale cotton harvester, because it is uncoupled from the in-field hauling operation, can achieve a 90% field efficiency. This means the harvester is actually harvesting cotton for 90% of the in-field time compared to 70% for the

Figure 13.7 *Round baling of seed cotton. (Photo courtesy of Deere & Co.).*

Figure 13.8 In-field transport of round bales by the cotton harvester. (Photo courtesy of Deere & Co.).

current harvester in the module system. Repeating a principle stated earlier, more tons/hour through the harvester means the $/ton harvest cost is less.

Techniques have been implemented to improve the in-field hauling of round bales of seed cotton. As shown in Figure 13.8, the harvester can carry a completed bale and drop it at the edge of the field to facilitate direct loading onto highway hauling trucks.

13.6 Highway Hauling

The quickest way to communicate the key issues in highway hauling is with a simple analysis. The cost factors used in this example are representative, but they will be different in different local economies.

Truck cost is well defined by a mature trucking industry. Ownership cost plus operating cost (routine maintenance, driver labor cost, insurance, license, taxes, fuel) are known for short-haul operations. A truck can be used to haul gravel, logs, or hay bales and the short-haul cost ($/d) is approximately the same. The way to minimize truck cost ($/ton) is to maximize truck productivity (tons hauled per day, per week, or per year). Two issues are significant:

1. Tons per load.
2. Truck cycle time – time required to load, haul, unload, and return for the next load.

Hauling cost is defined here as loading cost plus truck cost plus unloading cost. The reader can quickly grasp the interaction of these three operations by considering the following example.

13.6.1 Truck Cost

Suppose it takes 40 minutes to load a truck and this truck travels 25 miles at an average speed of 45 mile/h. (This is a reasonable average speed for short hauls over rural roads.). It takes 40 min to unload the truck (no waiting in a queue) and then it returns 25 miles at 45 mile/h. The cycle time is 146 min = 2.4 h. In a 10-h workday, this truck can haul four loads.

Suppose the cost for the truck (ownership + operating) is $450/d and the cost of fuel is $3.50/gal. The truck averages 4 mile/gal, which is typical for short-haul operations. Fuel cost per load is:

$$(25\ \text{mile} \times 2)/(4\ \text{mile/gal}) = 12.5\ \text{gal} \times \$3.50/\text{gal} = \$43.75/\text{load}$$

The truck hauls four loads per day, thus the fuel bill is:

$$\$43.75/\text{load} \times 4\ \text{loads/d} = \$175/\text{d}$$

Total truck cost is:

$$\$450/\text{d (ownership + operating)} + \$175/\text{d (fuel)} = \$625/\text{d}$$

If the load is 12 dry tons, the cost per dry ton is:

$$\frac{\$625/\text{d}}{4\ \text{loads/d} \times 12\ \text{dry ton/load}} = \$13/\text{dry ton}$$

Now suppose this same truck, hauling the same dry ton per load over the same distance, can be loaded in 10 min, not 40 min, and it is unloaded in 10 min, not 40 min. Now the cycle time is 86 min = 1.43 h and the truck can haul seven loads in a 10-h workday. (This comparison is an idealization – no travel delays are allowed, which is not realistic in a real-world situation. Also, the assumption that the truck never has to wait to be loaded and unloaded is unrealistic.)

The truck hauls seven loads per day, thus the fuel bill is:

$$\$43.75/\text{load} \times 7\ \text{loads/d} = \$306/\text{d}$$

Total truck cost is:

$$\$450/\text{d(ownership + operating)} + \$306/\text{d (fuel)} = \$756/\text{d}$$

The cost per dry ton is:

$$\frac{\$756/\text{d}}{7\ \text{loads/d} \times 12\ \text{dry ton/load}} = \$9/\text{dry ton}$$

Truck cost has been reduced from $13 to $9/dry ton, or 31%, by just loading the truck more quickly and unloading it more quickly.

Fuel cost ($306/d) is 40% of the truck cost. Fuel cost ($/dry ton) is a key parameter in the entire biomass logistics chain, not only truck cost, and it increases whenever the world market for transportation fuel produces a price increase. This linkage, more than any other single factor, limits the distance that raw biomass can be hauled, cost effectively, by truck.

13.6.2 Interaction with Bulk Density

Now suppose the bulk density of the load is increased by 20%. The load is increased from 12 to 14.4 dry ton, and the cost per dry ton (10 min load, 10 min unload) is reduced from \$9 to \$7.50.

We are now ready to address a very important issue in logistics system design. It is obvious that increasing bulk density increases dry tons per load. (The volume of the truck is fixed by highway regulations.) But what is the cost of increasing the bulk density? In this example, suppose the cost of increasing the bulk density is \$2.75/dry ton, and no cost benefit is assigned in loading or unloading operations for the higher bulk density material. The reduction in truck cost is only \$9.00–7.50 = \$2.50/dry ton. This means that \$2.75 has been incurred in densification cost to save \$2.50 in truck cost, thus the total delivered cost *increased* by \$0.25/dry ton. It is better, just considering truck cost, to haul the raw biomass without densification.

13.6.3 24-h Hauling

Now suppose the same truck in the above example hauls the same dry ton per load over the same distance (10 min load, 10 min unload) and operates continuously 24 h/d. The truck can now haul 16.7 loads in a 24-h workday as compared to seven loads in a 10-h workday. (It is acceptable to use the 16.7 loads, since the truck is operating continuously. It can *average* 16.7 loads/d over some chosen time period.) The labor cost increases because operators must be hired for three 8-h shifts plus the maintenance cost per day increases due to more miles traveled per day. Use \$800/d as the cost for the truck.

The truck hauls 16.7 loads per day, thus the fuel bill is:

$$\$43.75/\text{load} \times 16.7\ \text{loads/d} = \$731/\text{d}$$

Total truck cost is:

$$\$800/\text{d(ownership} + \text{operating)} + \$731/\text{d (fuel)} = \$1531/\text{d}$$

The cost per dry ton is:

$$\frac{\$1531/\text{d}}{16.7\ \text{loads/d} \times 12\ \text{dry ton/load}} = \$7.64/\text{dry ton}$$

The truck cost has been reduced from \$13 to \$7.64/dry ton, or 41%, by operating 24 h/d rather than 10 h/d.

Why not design logistics systems to operate 24 h/d? The issue in feedstock logistics is not the unloading at the receiving facility – the plant operates continuously so the receiving facility can certainly operate continuously. The issue is loading the trucks. No one has devised a system to load trucks at night at some remote location. An example will be shown later for trailers loaded during the day and pulled during the night, so that the same truck tractor is used for 24-h hauling.

The issue of trucks operating on rural roads at night is unresolved. This may be accepted, or it may not; there is little experience to establish a precedent.

13.7 Development of Concept for Multibale Handling Unit

13.7.1 Modulization of Bales

Individual handling of bales (round or square) is not cost effective; it takes too long to load and unload the truck. Several concepts for a multibale handling unit are under development, and much of this development is still proprietary.

Permission was received to present a concept that was far enough along in development that second-year field tests were carried out in the 2012 fall–winter harvest season. The concept was developed by a consortium led by FDC Enterprises (K. Comer, personal communication) and is shown in Figure 13.9.

The self-loading trailer loads six stacks of six bales, referred to as "six-packs", for a total load of 36 large rectangular bales ($3 \times 4 \times 8$ ft). The length of the load is $6 \times 8 = 48$ ft and the height is $3 \times 3 = 9$ ft. The width is $2 \times 4 = 8$ ft. The trailer built to implement the concept (Gary Kelderman, personal communication) is shown in Figure 13.10. Estimated load time is 5 min, about the same load time as the cotton module shown in Figure 13.2. In fact, the multibale unit emulates the cotton module system. The 36-bale unit can be

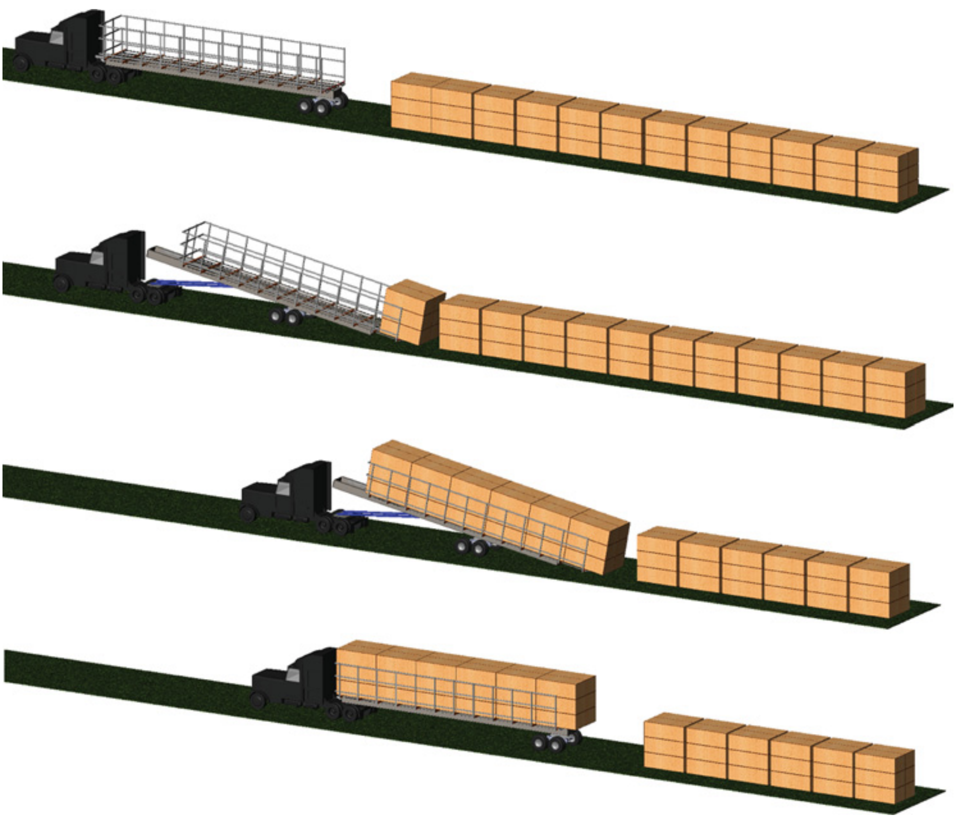

Figure 13.9 *Multibale handling unit concept developed for 3 × 4 × 8 large rectangular bales by an FDC Enterprises-led Consortium. (Reprinted with permission, K. Comer, personal communication).*

Figure 13.10 Self-loading trailer built by Kelderman Mfg. to implement multibale handling unit concept for 36-bale stack of 3 × 4 × 8 ft rectangular bales. (Image courtesy of Kelderman Mfg. Reprinted with permission, K. Comer, personal communication).

off-loaded by the truck directly onto the conveyor into a bioenergy plant, or it can be set on the ground in at-plant storage to be used later, just as is done with cotton modules at a cotton gin.

13.7.2 Receiving Facility

A reasonable goal for design of a receiving facility for any bioenergy plant is:

1. weigh and unload a truck in 10 min, and
2. move material into, and out of, at-plant storage to support 24/7 operation.

The second most significant cost benefit of a multibale handling unit, after the improvement of truck productivity, is the improved cost effectiveness of receiving facility operations. Design of a logistics system must be integrated with the design of the receiving facility.

13.7.3 Farmgate Contract

Creation of a multibale handling unit will require specialized equipment, thus it is not offered as a practical option at the "farmgate" level. As an example, the rack system concept [6] envisions a farmgate contract whereby the contract holder grows the crop, harvests in round bales, and places these bales in single-layer ambient storage in an SSL. The contract holder owns the SSL and is paid a storage fee for each unit of feedstock that is stored. *The biomass is purchased by the bioenergy plant in the SSL.* All agricultural operations are now "sequestered" in the farmgate contract, which gives those seeking a farmgate contract a well-defined body of work to prepare their business plan.

13.7.4 Hauling Contract

The multibale handling unit system concept envisions that the hauling contractor will invest in the industrial equipment needed for year-round operation. Because the hauling contractor is hauling year-round, they can (1) afford to invest in higher capacity industrial-grade equipment designed for up to 5000 h/yr (or more) operation, and (2) their labor force will develop expertise at the operations, and the tons handled per unit of equipment investment will be a maximum. These two factors together create the potential to minimize hauling cost ($/ton).

13.7.5 Application of Information Technologies

The inclusion of a hauling contractor in the business plan provides the best opportunity for all of the technology developed for other logistics systems to be applied to feedstock logistics. The "information technologies" applied include a Global Positioning System (GPS) unit in every truck, a bar code on every multibale handling unit, data entry over the cell phone network at every SSL load-out site, data entry (load mass and time stamp) for each load across the receiving facility scales, and a data entry when each multibale handling unit is unloaded in the plant. The data collected is used to optimize asset utilization in real time; it will also feed needed data into the bookkeeping software to pay the farmgate and hauling contracts.

It is expected that the collected data will be presented, in real time, to a "Feedstock Manager", perhaps as a map display showing the location of all assets updated at a programmed time interval. The goal is to provide an opportunity for the Feedstock Manager to make optimization decisions in real time. Examples are: trucks rerouted to avoid traffic delays, assets redeployed during breakdowns, at-plant inventory increased when inclement weather is forecast, and a turn-down of plant consumption when a delay in feedstock deliveries cannot be avoided.

Some perspective of the logistics complexity, as presented to the Feedstock Manager, can be gained from the following "example" parameters. This example presumes that operations will be in the Upper Southeast United States where switchgrass is harvested over an eight-month harvest season, August through March. (The switchgrass is left to dry standing in the field and harvested when field conditions are satisfactory throughout the winter.) Suppose the supply area has 199 SSLs within a 30-mile radius of the plant, and each SSL has a different amount of material stored. (The visualization shown in Figure 13.11 will help the reader understand the complexity.) The farmgate contractors all want to fill their SSLs at least twice during the harvest season in order to minimize per-ton SSL investment. The Feedstock Manager's job is to coordinate load–haul operations such that each farmgate contractor is treated fairly. Suppose there are five SSL load-out operations under contract and each of them wants the same opportunity to earn income (total tons hauled per year). The Feedstock Manager's job is to treat all contractors fairly – not a simple task.

The example can be complicated further. Storage losses increase with time in storage. If the bioenergy plant requires farmgate contractor A to store for a longer period than farmgate contractor B, then contractor A will have higher storage losses and should be compensated. Contractor A filled its SSL on time – it is not their fault that hauling was delayed. One can expect that days-in-storage will be a factor in the farmgate contract.

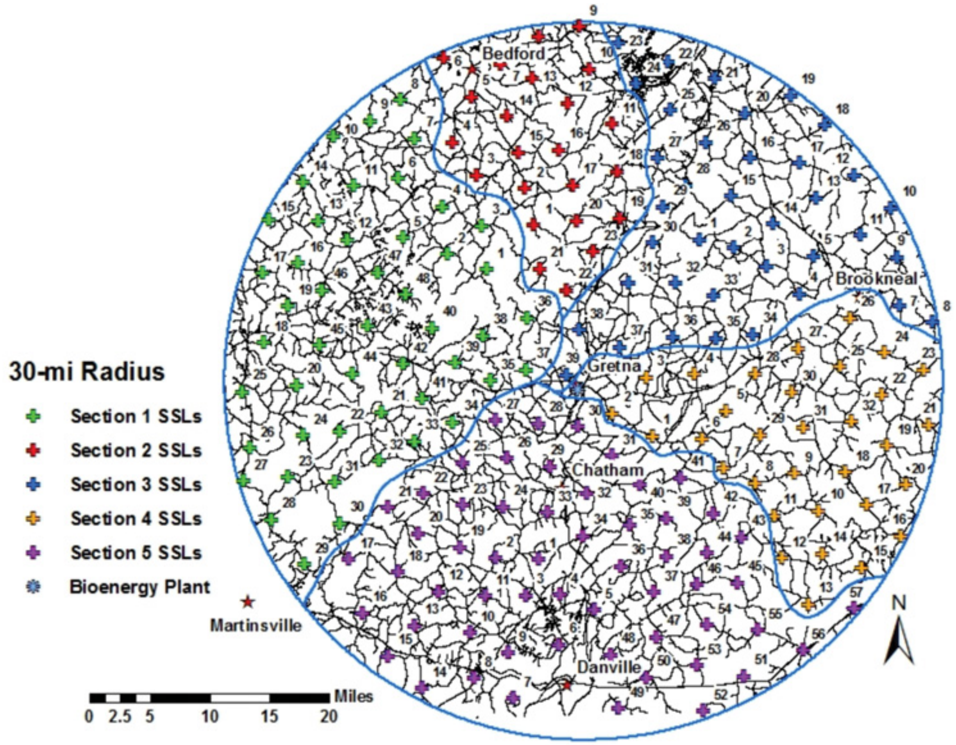

Figure 13.11 Example of Satellite Storage Locations (SSLs) located over a 30-mile radius around a chosen bioenergy plant location. (The plant is located in the center of the circle. Each cross represents an SSL location with access to a public road. The smallest SSL stores biomass from 60 acres of production fields and the largest stores biomass from 1200 acres of production fields).

13.7.6 Storage

The complete system described in this example has three storage features. Round bales, because the rounded top sheds water, can be left in the field for a short time (days) before in-field hauling. This in-field storage provides the advantage of uncoupling the harvest and in-field hauling operations, and thus provides an opportunity for improving the cost efficiency of both operations. The farmgate contract holder has the opportunity to bale when the weather is right and haul later – there is no requirement to delay baling for in-field hauling to catch up.

The second storage feature, satellite storage (SSL), provides the needed transfer point between in-field hauling and highway hauling. The system in this example envisions that the SSLs will be located so that the ton-mile parameter for each SSL will be not more than two miles. (This means that, averaged across all tons stored at that SSL, each ton will be hauled less than two miles from the production field to the SSL.) This constraint gives the farmgate contact holder an upper bound for their in-field hauling cost.

The third storage feature, at-plant storage, provides the needed feedstock buffer at the plant. Those building a bioenergy plant would like to operate with just-in-time (JIT) delivery

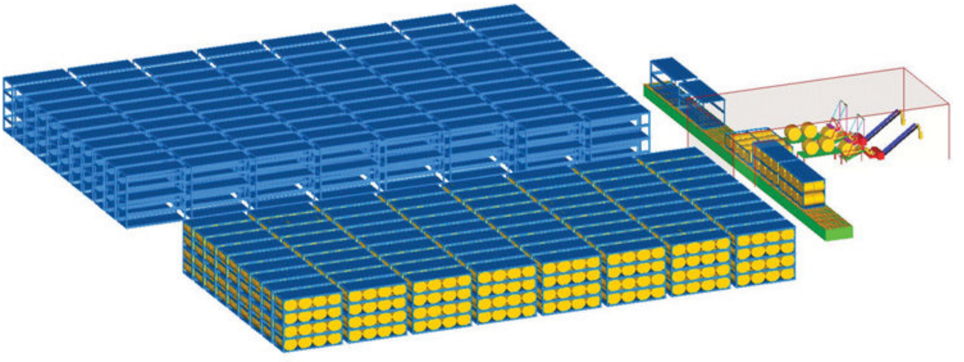

Figure 13.12 *Illustration of at-plant storage for a Rack System Concept.*

of feedstock, as this gives them the lowest cost for receiving facility operation. If JIT is not possible, they want the smallest at-plant storage for cost-effective operation of the plant. There is obviously a trade-off in the logistics system design between the higher cost to purchase JIT delivery, and the cost of at-plant storage operations.

13.7.7 At-Plant Storage

In a "real-world" setting, it will be very difficult to achieve JIT delivery of any raw material for 24/7 operation. All multibale handling unit concepts, must include some at-plant storage. Even when known quantities of feedstock are stored in a network of SSLs, and a Feedstock Manager is controlling the deliveries, there will always be random delays.

To give a frame of reference, an initial decision was made to include 2.5 days of at-plant storage in this example. This minimum may work in the Southeast United States where ice and snow on the roads is not typically a significant problem for winter operations. In the U.S. Midwest, more days of at-plant storage will be required.

A visualization of at-plant storage for the rack system concept is shown in Figure 13.12. The number of racks shown is not part of the "cost analysis" example given later.

The bale remains in the rack until processed – there is no individual bale handling at the plant. *This is a very important aspect of any multibale handling system.* This reduction in bale handling not only reduces cost, but also reduces damage to the bales. The integrity of the bales must be maintained. The reader should visualize a multibale lift of large rectangular bales when the strings on one of the bales "pop" and the whole lift comes tumbling down. The same problem exists when the wrap on a round bale fails.

13.8 Functionality Analysis for Rack System Concept

The "Rack System Concept" envisions that round bales will be loaded into a rack in the field or at a Satellite Storage Location (SSL). This rack is off-loaded at the plant, emptied when the bales are needed to supply the plant, and then returned to be refilled. It is cycled multiple times each week within the closed logistics system operated for a specific plant.

When reading this specific example, the reader should understand that others are implementing the feedstock logistics principles in a different way because they are dealing with a different crop in a different region with a different harvest season. Also, the farming culture is different in different regions, and this can have an influence on logistics system design.

All the different options cannot be discussed here; however, a specific example is needed to help the reader "think through" an entire logistics system. *The selection of the Rack System Concept for this example implies no criticism for the other ways of implementing the multibale handling unit concept currently being developed.*

In this example, cost to grow, harvest, and store in an SSL is covered in the farmgate contact. The analysis begins with round bales in single-layer ambient storage in the SSL and ends with a stream of size-reduced material entering the bioenergy plant for 24/7 operation.

To understand this example, it is appropriate to summarize the "baseline"constraints:

1. The rack and trailer design must conform to the standards for highway transport.
   (The rack used for this example holds 16 5-ft diameter × 4-ft long (5 × 4) round bales. With two racks on a truck, a truckload is 32 round bales. Other rack designs are being investigated.)
2. The bales will be pre-loaded into the racks while the trailer is parked at the SSL. When a truck arrives, a trailer with two empty racks is dropped, and the trailer with two full racks is towed away. The goal is to exchange trailers in 10 minutes, or less.
3. At the bioenergy plant, the racks are unloaded from the truck and placed on a conveyor to be conveyed into the plant for immediate use, or stacked two high in at-plant storage. The goal to unload the trailer should be 10 minutes, or less.
4. The plant will operate with a minimum of 2.5 days of storage. All at-plant storage is bales in racks.
5. Hauling will be done 24 h/d. Truck drivers will work five 8-h shifts per week and operations will be continuous for a 6-day work week. The rack loading crew at an SSL will be organized such that each worker will work a 40-h week. SSL operations will proceed such that racks are loaded six 10-h workdays per week.
6. The example assumes that the plant processes one bale per minute. A bale at 15% moisture content weighs 900 lb = 0.45 ton. The dry ton per bale is:

$$0.45\ \text{ton/bale} \times (1 - 0.15) = 0.3825\ \text{dry ton/bale}$$

Assuming one bale is processed per minute, the processing rate is:

$$0.3825\ \text{dry ton/bale} \times 1\ \text{bale/min} \times 60\ \text{min/h} = 23\ \text{dry ton/h}$$

(For comparison, 23 dry ton/h = 552 dry ton/d. This size is in the 100–1000 dry ton/d range recommended for Regional Biomass Processing Depots by Eranki *et al*. [1].)

The processing of racks is:

$$\frac{60\ \text{bale/h}}{16\ \text{bale/rack}} = 3.75\ \text{rack/h}$$

$$3.75\ \text{rack/h} \times 24\ \text{h/d} \times 7\ \text{d/wk} = 630\ \text{rack/wk} = 315\ \text{truck loads/wk}$$

13.8.1 Operation Plan for 24-h Hauling

The plant will operate 24/7, but the receiving facility will be open 24 hours per day for six days. At 0600 Sunday morning, there will be enough feedstock accumulated in at-plant storage for the normal 2.5-day buffer (60 h). Hauling operations begin again at 0600 Monday morning. At-plant storage is decreased to a 1.5-day buffer (36 h) to supply the material for weekend operation.

To discuss the 24-h-hauling concept, it is convenient to consider two SSL operations, a "day-haul" operation and a "night-haul" operation. For the day-haul operation, the racks are hauled as they are loaded.

For the night-haul operation, the required number of empty racks, enough for one day's operation, are pre-positioned at the SSL. (Cost of pre-positioning the racks is not considered in this example.) The SSL crew loads these racks during their 10-h workday, and they are hauled during the night. Each truck arriving during the night leaves a trailer with two empty racks and hauls a trailer with two full racks. The next morning the loading crew will go to work on the empty racks delivered during the night and fill them during their workday.

13.8.2 Operational Plan for Receiving Facility

A forklift (10-ton capacity) will operate continuously at the plant. This machine will unload full racks from trucks and place them onto a conveyor into the plant for direct processing, or stack these racks in at-plant storage. It will then load empty racks onto the truck for return to the field. Empty racks will be removed from the conveyor and stacked in the storage yard until they are loaded onto trucks.

The operational plan calls for two forklifts at the plant, identified as a "work horse" and a "backup". The workhorse will operate continuously and the backup will operate during the day when trucks are backed up in the queue. Key point – the system must have a backup forklift because, if a forklift is not available to handle racks, all operations cease.

The handling of the racks emulates the handling of bins at a sugar mill in South Florida. (The Rack System Concept is actually an adaptation of the successful commercial technology used for sugarcane.) In the bin system, a truck has three bins, two on the first trailer and one on a "pup" trailer. The bins are side-dumped if material is needed directly, or they are off-loaded and stacked two-high on the storage yard for nighttime operation. (A bin system is also used for the sugar industry in Texas. Figure 13.13 shows bins being off-loaded at a sugar mill in Texas, and Figure 13.14 shows bins being stacked on the storage yard at this mill.) When the bins are dumped directly, it takes 3 min to unload a truck. For normal operation, one truck hauls 10 loads (30 bins) a day. At 37 tons/load, each truck hauls 370 ton/d. Sugar cane is 80% moisture content, so 370 ton = 74 dry ton/d/truck. The reader is asked to record this figure for later comparison.

The receiving facility operates 6 d/wk, thus, on average, the daily delivery will be:

$$\begin{aligned} \frac{630 \text{ racks/wk}}{6 \text{ d/wk}} &= 105 \text{ racks/d} \\ &= 53 \text{ trucks/d} \end{aligned}$$

For this example, plant size (23 dry ton/h) was chosen to optimize the operation of the two forklifts at the plant. One forklift is expected to unload full racks and load empties

Figure 13.13 *Bins being side-dumped at a sugar mill in Texas.*

at the rate of one truck every 27 minutes averaged over the 24-h day. The design of the storage yard has to facilitate this operation. A larger at-plant storage will lower the forklift productivity (ton/h) because average cycle time to move an individual rack is greater.

13.8.3 Size of At-Plant Storage Yard

As an example, maximum at-plant storage for a three-day supply is calculated as follows.

$$3.75 \text{ racks/h} \times 72 \text{ h} = 270 \text{ racks}$$

Racks will be stacked two high in "units" with two rows of 24 spaces each, thus there are 48 storage spaces in each unit. Each unit stores 96 racks. Three units are required for a 270-rack storage.

If a seven-day at-plant storage is required, the total number of racks required is 630, or seven 96-rack units. This implementation of the rack system is not believed to be a cost effective choice. The rack system competes best when the racks are filled and emptied as

Figure 13.14 *Bins being stacked in at-plant storage at a sugar mill in Texas.*

many times as possible in a given time period, not when they are used as storage units. Other multibale handling units (Figure 13.10) are more suitable for a larger at-plant storage.

13.9 Cost Analysis for 24-h Hauling Using Rack System Concept

The costs given in this section are presented without supporting detail. They were calculated using the procedures given in the ASABE Machinery Management Standard [3]. They are "best estimates" given current cost parameters. It is unlikely significant $/h cost reductions can be achieved for the various machines. All costs are given on a $/dry ton basis for operation of a bioenergy plant consuming 23 dry ton/h. The real challenge is to find a way that machine productivity (tons/operating hour) can be increased.

Some additional detail on the functionality of the various unit operations in the rack system logistics chain is given in Appendix 13.B. This detail will benefit those who want a better understanding of the opportunities for improved productivity in individual operations.

13.9.1 Truck Cost Excluding Fuel

The assumed truck cost (tractor and trailer for hauling the two racks) is $630/d for a 24-h workday, which includes ownership plus operating cost, plus labor, but excluding fuel.

Truck cost, excluding fuel, is:

$$\frac{\$630/\text{d}}{11.5\ \text{loads/d} \times 12.2\ \text{dry ton/load}} = \$4.49/\text{dry ton}$$

13.9.2 Truck Fuel Cost

Fuel cost for the 25.4 mi average haul distance is

$$(25.4\ \text{mile} \times 2)/(4\ \text{mile/gal}) = 12.7\ \text{gal} \times \$3.50/\text{gal} = \$44.45/\text{load}$$

$$\frac{\$44.45/\text{load}}{12.2\ \text{dry ton/load}} = \$3.64/\text{dry ton}$$

13.9.3 Total Truck Cost

Total truck cost is:

$$\text{Ownership and operating} + \text{Fuel} = \text{Total}$$

$$4.49 + 3.64 = \$8.13/\text{dry ton}$$

13.9.4 Load, Unload Operations

1. Handling racks at plant – 1.93 (workhorse forklift) + 1.02 (backup forklift) = $2.95/dry ton
2. SSL operation – 3.66 (telehandler) + 0.98 (extra trailers) = $4.64/dry ton
3. Rack cost – cost of 230 racks = $1.80/dry ton
4. Storage yard at processing plant – $0.13/dry ton
5. Conveyor entering plant – $0.28/dry ton.

13.9.5 Size Reduction

Unroller-chopper – $5.76/dry ton

The costs given in Table 13.1 are grouped as follows:

Rack cost – All costs associated with the ownership and maintenance of the racks.

Loading cost – All costs associated with the loading of bales into racks. These costs are referred to as “SSL operation costs”.

Table 13.1 Total cost for hauling, receiving facility operations, and size reduction for Rack System Concept example – 24-h hauling.

Operation	Cost ($/dry ton)
Racks	1.80
Loading at SSL	
Telehandler	3.66
Extra drop-deck trailers	0.98
Truck cost	8.13
Unloading at plant	
Workhorse forklift	1.93
Backup forklift	1.02
At-plant storage (Gravel lot with lighting)	0.13
Conveyor into plant	0.28
Unroller-chopper (Initial size reduction)	5.76
Total	$23.69

Truck cost – All costs associated with the ownership and operation of the trucks.

Receiving Facility cost – All costs associated with the unloading of racks from trucks, placement of racks onto conveyor (or placement in at-plant storage), conveyor operation, operation of at-plant storage, and removal of racks from at-plant storage and placement on trucks for return to SSL.

Size reduction – All costs associated with the unloading of bales from the rack, operation of conveyor for single file delivery of bales to a size reduction machine, and operation of machine for initial size reduction.

Costs are as follows: truck (34%), SSL operations (20%), receiving facility operations (14%), size reduction (24%), and racks (8%). It is clear why the Rack System Concept was organized to maximize truck productivity – truck cost is the largest cost component. Truck cost plus SSL operations are $12.77/dry ton, or 54% of total cost. The receiving facility cost is $3.37/dry ton, only 14% of total cost. As with all other multibale handling system concepts, the Rack System Concept provides an opportunity for minimizing cost between the plant gate and the size reduction unit operation.

The total cost shown in Table 13.1 does not include the farmgate contract cost (production, harvesting, in-field transport, storage in SSL, profit to producer). The farmgate contract cost can be estimated from local data for production, harvest, and ambient storage of round bales of hay. In the Southeast United States, the key issue relative to the hay cost comparison is the difference in yield – switchgrass will yield about 4 ton/acre as compared to traditional hay species that yield about 2 ton/acre.

13.10 Summary

The key decision points for the design of a logistics system for a bioenergy plant operating 24/7 year-round are summarized as follows:

1. A complete logistics system is defined as one that begins with the biomass standing in the field and ends with a stream of size-reduced material entering a bioenergy plant for 24/7 operation. Optimizing one unit operation in isolation may increase the cost of an "upstream" or "downstream" operation such that total delivered cost is increased.
2. Herbaceous biomass is harvested only part of the year, thus storage is always a part of the logistics system. A cost effective logistics system provides for efficient flow of material into, and out of, storage.
3. Just-in-time (JIT) delivery of feedstock provides for a minimum at-plant storage cost and is preferred by plant designers. Since JIT delivery is not practical for typical biomass logistics systems, there is always a cost trade-off between the size of at-plant storage and the other design parameters needed to insure a continuous feedstock supply. Having known quantities of biomass in SSLs provides a Feedstock Manager an opportunity to minimize the at-plant storage cost.
4. Farmgate contracts that require a winter harvest must compensate for the loss of yield incurred by the delayed harvest.
5. Uncoupling of the unit operations in the logistics chain can provide an advantage.
   (a) Baling uncouples the harvesting and in-field hauling operations. When the harvesting operation is not constrained by in-field hauling, both unit operations can proceed at maximum productivity.
   (b) When truck loading is uncoupled from hauling, the loading crew never has to wait for a truck to arrive and the truck never has to wait to be loaded.
6. Truck cost is the largest component of total cost in most logistics systems, thus it is essential to maximize truck productivity (tons hauled per unit time) by increasing tons/load and loads/day. A 10-min load time and a 10-min unload time is a desired goal for increasing loads/day.
7. The multibale handling unit was developed to solve the rapid load, rapid unload challenge.
8. Twenty-four-hour hauling can minimize truck cost ($/ton). The challenge is to find a way to load the trucks at night at a remote location.
9. The design of the receiving facility, because of the need to unload trucks quickly, is critical in the design of a complete logistics system.
10. Assigning different unit operations to different entities in the business plan can lower average delivered cost. For example, it is more efficient to pool all farmgate activities into a farmgate contract and have a hauling contractor handle all load–haul activities. This division is defined as a division between "agricultural" and "industrial" operations. One key benefit achieved is in the capitalization of the equipment. Load–haul contractors can afford to invest in industrial-grade, high-capacity equipment designed for year-round operation as compared to farmgate contractors who will use their equipment 400 hours (or less) per year.
11. A biomass logistics system must be structured such that information technologies (GPS, bar codes, entry of data over cell phone network) and optimization routines developed for other logistics systems can be used to optimize asset utilization in real time.

Appendix 13.A Cost to Operate Workhorse Forklift (Example for Equipment Cost Calculations)

Machine selected for this study: Taylor Model TX 360M

Purchase Price:	\$154 400
Design life:	15 000 h
Annual use:	24 h/d, 7 d/wk, 47 wk/y = 7896 h
Interest rate:	8% $r = 0.08$
Insurance rate:	\$0.80/\$100 value/y
	$\frac{154{,}000}{100} \times 0.80 = \$1232/\text{y}$
	(This is equivalent to (1,232/154,000) × 100 = 0.8% of purchase price)
Tax rate:	1%
Repair and maintenance factor (R/M)	\$3.00/h
Fuel use:	12 l/h
Fuel cost:	\$0.925/l
Labor cost (including benefits):	\$20/h
Expected service:	
	$n = \frac{15{,}000\ \text{h}}{7896\ \text{h/y}} = 1.9\ \text{y}$
Salvage value	10% $S_v = 0.1$

Ownership cost:

Ownership cost percentage [3]:

$$C_o = \frac{1 - S_v}{n} + \frac{(1 + S_v)r}{2} + K_2$$

where

C_o = ownership cost percentage (dec),
S_v = salvage value (dec),
n = machine life (y),
r = interest rate (dec), and
K_2 = factor for taxes and insurance (dec).
$K_2 = 0.01 + 0.008 = 0.018$

$$C_o = \frac{1 - 0.1}{1.9} + \frac{(1 + 0.1)(0.0625)}{2} + 0.01$$
$$= 0.474 + 0.034 + 0.018$$
$$= 0.526$$

Annual ownership cost (\$):

$$\$154,400 \times 0.526 = \$81{,}004$$

Annual ownership cost ($/h):

$$\frac{\$81{,}004}{7896} = \$10.26/\text{h}$$

Operating Cost ($/h):

$$\text{R/M} + \text{Fuel} + \text{Labor} = \text{Total}$$
$$3 + 12 \times 1.02 + 20 = \$34.10/\text{h}$$

Total cost ($/h):

$$\text{Ownership} + \text{Operating} = \text{Total}$$
$$10.26 + 34.10 = \$44.36/\text{h}$$

Total cost ($/dry ton):

$$\text{Plant averages 23 dry ton/h}$$
$$\frac{\$44.36/\text{h}}{23 \text{ dry ton/h}} = \underline{\underline{\$1.93/\text{dry ton}}}$$

Appendix 13.B Operational Plan for "Rack System" Example

B.1 Operation Plan for SSL Loading

Ideally, the rack-loading operation at the SSL can load 16 bales in a rack in 20 minutes. This is a design goal which has not yet been attained with actual equipment. Discussion of how it might be achieved is presented later.

In a workday with 10 productive hours (600 min), a 20-min/rack operation can theoretically load 30 racks, or 15 truckloads. An actual operation, given the reality of field conditions, cannot sustain this productivity. For this analysis, it is reasonable to assume that a mature operation can average 70% of the theoretical productivity. The number of loads/day/operation used for this analysis is $15 \times 0.7 = 10.5$ loads/d. The number of loading operations required is then

$$53 \text{ loads/d required at plant} = 5 \text{ operations averaging } 10.5 \text{ loads/d}$$

This means that loading operations will be operating at five different SSLs for each workday and each will load, on average, 21 racks/d. Time to move the loading operation from one SSL to the next is not dealt with in this analysis, so the 21 racks/d productivity, averaged over an entire year, may be optimistic.

There are several options for a rack design. For this example, we chose the Side-load Option. It assumes a telehandler with special attachment will pick up two bales per cycle (Figure 13.B.1) and load these bales into the side of the rack while it remains on the trailer. We use the assumption that the average productivity that can be achieved under production conditions is 34 min/rack. Time required to load the two racks on a trailer is 68 min. *Remember, this is the assumed average load time for year-round operation.*

SSL operations – the loading of the trucks – is the most difficult challenge in the design of a cost-effective biomass logistics system. It is difficult to reduce the cost of these operations because the labor productivity (tons handled per worker per hour) tends to be low.

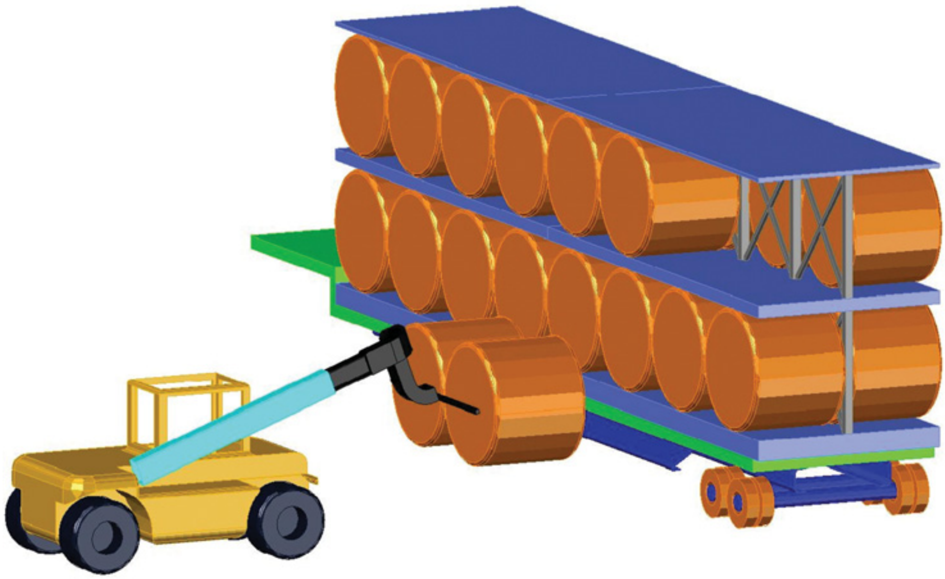

Figure 13.B.1 Concept for side loading bales into rack on trailer.

We choose to *uncouple* the SSL loading and hauling operations. This means we want a system where the truck does not have to wait for racks to be loaded in order to pick up the trailer. Also, the SSL crew does not have to wait for a truck to arrive to have a trailer with empty racks to fill.

The day-haul operations are uncoupled by providing two extra trailers at the "day haul" SSL, and the night-haul operations are uncoupled by providing nine extra trailers at the "night haul' SSL. Each truck tractor then has a total of 11 *extra* trailers in the system. This is probably not an optimal (least cost) approach, but it does provide a reasonable starting point for this example.

B.2 Influence of SSL Size on Rack Loading Operations

It is necessary to give the reader some additional perspective on SSL operations. If the yield of switchgrass in a commercial-scale operation averages 4 ton/acre, this equates to approximately 9 bales/acre. It is specified for this example that the minimum size SSL is 60 acres = 540 bales, and the maximum size SSL stores 1200 acres = 10 800 bales. If 70% of the theoretical loading of 30 racks/d is achieved, the contactor will load 21 racks × 16 bales/rack = 336 bales/d. The minimum size SSL will be loaded out in about 540/336 = 1.6 days. The maximum size SSL will be loaded out in /10 800/336 = 32 days.

Cost of the SSL operations at the smaller SSLs will be higher because of the mobilization charge to move equipment in for a relatively few days of operation. It is probable that the load-haul contract offered by the plant for each individual SSL will consider both the haul distance and SSL size, thus the per-ton payment will be different for each SSL.

B.3 Total Trucks Required – 24-h Hauling

To achieve 24-h hauling, the truck drivers will work 8-h shifts and the trucks will run continuously from 0600 Monday to 0600 Sunday, a total of 144 h/wk. The total racks processed each week is 630, equal to 315 truckloads. If a uniform delivery is assumed, the average truck unload time is

$$315 \text{ trucks}/144 \text{ h} = 2.2 \text{ trucks}/\text{h}$$

or about one truck every 27 min. This productivity is well within the Rack System design goal of a 10-min unload time.

As previously stated, the 24-h hauling concept envisions that the loading crew will leave a supply of loaded racks on trailers at the SSL when they finish their 10-h workday. These racks will be hauled during the night. The next morning the loading crew will go to work on the trailers with empty racks delivered during the night and fill them during their workday.

The key variable in hauling is the truck cycle time. To calculate cycle time for this example, we need an average haul distance. An actual database was developed for a proposed bioenergy plant location at Gretna, Virginia and was used to calculate an average haul distance.

An analysis was done for a 30-mile radius around Gretna to identify potential production fields based on current land use determined from current aerial photography. Using a conservative assumption, about 5% of the total land base could be attracted into switchgrass production. SSLs were established at 199 locations (Figure 13.11), and the existing road network was used to determine the travel distance from each SSL to the proposed plant location at Gretna. Some loads were hauled two miles and some were hauled over 40 miles. A weighted ton-mile parameter was computed and found to be 25.4 miles. This means that, averaged across all 199 SSLs, each ton travels 25.4 miles to get to the plant.

Truck cycle time is calculated using the 25.4-mile average haul distance, a 45 mile/h average speed, 10-min load time, and 10-min unload time. Theoretical cycle time is 1.46 h. In 24 hours of operation, one truck can haul

$$\frac{24 \text{ h}}{1.46 \text{ h}/\text{load}} = 16.4 \text{ loads per truck per day}$$

Assuming that a truck can average 70 % of the theoretical capacity, the analysis uses $0.7 \times 16.4 = 11.5$ loads per truck per day. Remember, since the trucks run continuously, a decimal number of loads can be used as the *average* achieved per-day productivity.

It is not practical to use the each-contractor-runs-their-own-trucks assumption for 24-h hauling. The way to maximize truck productivity is to have the Feedstock Manager be able to send any truck to any SSL where a trailer with full racks is available. This greatly facilitates the hauling at both day-haul and night-haul SSLs.

Total trucks being controlled by the Feedstock Manager are:

$$\begin{aligned} 53 \text{ loads}/\text{d required at the plant}/\ 11.5 \text{ loads per truck} &= 4.6 \text{ trucks} \\ &= 5 \text{ trucks} \end{aligned}$$

B.4 Total Racks Required – 24-h Hauling

Since the only time deliveries are not being made is the 24-h period, 0600 Sunday to 0600 Monday, the amount in at-plant storage can be reduced. It was decided to use 1.5 days as the minimum at-plant storage, so the total hours of capacity required in at-plant storage at 0600 Sunday, when deliveries are ended for the week, is:

$$24 \text{ h (actual)} + 1.5 \text{ d} \times 24 \text{ h/d (at-plant storage)} = 60 \text{ h}$$

$$3.75 \text{ racks/h} \times 60 \text{ h} = 225 \text{ racks}$$

Total trailers are calculated as follows. Each truck has one trailer connected, two parked at a "day-haul" SSL and nine parked at a "night-haul" SSL for a total of 12 trailers. The total racks on trailers is calculated as follows:

$$5 \text{ trucks} \times 12 \text{ trailers per truck} \times 2 \text{ racks/trailer} = 120 \text{ racks}$$

Ostensibly, total racks required is calculated as follows:

$$\text{At-plant} + \text{On 60 trailers} + \text{Reserve} = \text{Total}$$

$$225 + 120 + 5 = 350$$

The actual number of racks required is calculated by subtracting the racks on parked trailers from the rack total (empty + loaded) at the plant. Potentially, 60 loaded trailers can be parked at the plant when hauling ends for the week at 0600 Sunday. In order for this procedure to work, the racks on most of these 60 trailers have to be returned to SSLs during the period 0600 Sunday to 0600 Monday so that they will be in position for operations to begin at each SSL at 0600 Monday. This requires some empty back hauls. Cost for these empty back hauls is a level of detail that must wait for a more sophisticated analysis.

When racks on trailers are counted as part of the at-plant storage, the minimum number of racks is:

$$\text{At-plant} + \text{On 60 trailers} + \text{Reserve} = \text{Total}$$

$$(225 - 120) + 120 + 5 = 230$$

Average number of cycles per rack is

$$29\,610 \text{ racks processed per year}/230 = 129 \text{ cycles/y},$$

or about 2.7 cycles per week for 47 weeks of annual operation.

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14

Woody Biomass Logistics

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14.1 Introduction

The economics of using woody biomass as a fuel or feedstock for bioenergy applications is often driven by logistical considerations. Depending on the source of the woody biomass, the acquisition cost of the material is often quite low, sometimes near zero. However, the cost of harvesting, collection, processing, storage, and transportation from the harvest site to end users can be quite expensive. In many cases, the combined cost of logistics will exceed the delivered value of the resource by a substantial margin. Therefore, it is highly important to the economic success of any bioenergy project that the logistics of bringing the woody biomass to the consuming facility be optimized to the greatest extent possible.

Optimizing the logistics for woody biomass fuels and feedstocks can best be accomplished in the planning stages of the project. If the consuming facility is improperly located with respect to the geographic distribution of the woody biomass resource, the project will likely suffer a continuing economic burden in the form of excessive transportation costs. Furthermore, the design of any woody biomass-consuming operation is generally best served by providing for as much feedstock flexibility as the operation's core conversion technology permits. That is to say that a wider range of feedstock species, form, particle size, ash content, and moisture content will be preferable from an economic standpoint. Increased feedstock flexibility expands the usable resource base, which in turn will serve to reduce risk and uncertainty in feedstock supply. Diversified feedstock supply chains may also reduce procurement costs by avoiding competition for biomass with other users, such

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as pulp mills and pellet manufacturers. Investments at the consuming facility in storing, processing and drying the woody biomass to the extent required by the conversion technology can offset the logistical disadvantage of performing these functions in the field.

14.2 Overview of the Woody Biomass Supply Chain

The woody biomass supply chain varies by region and land ownership type. The primary sources of woody biomass are federal, industrial, state, and private forests managed for a variety of objectives. Ownership and management objectives affect the availability, volume, and quality of biomass harvested, as do forest age, the type of woody biomass being harvested, tree species present in the forest, and the type of harvesting system. For example, short-rotation hybrid poplar energy crops, pre-commercial thinnings in pine plantations, wood utilized from fuels-reduction treatments to reduce the risk of catastrophic wildfires, and logging residues from industrial silviculture all produce different yields and quality of woody biomass. Moreover, the details of the supply chain depend heavily upon the material specifications of the final, delivered product for a particular end use or conversion process. For example, some drop-in liquid biofuel conversion processes that rely on digestion are well suited for delivery of high moisture content materials, while other processes, such as densification to pellets or briquettes, may require both low ash content (e.g., $<1\%$) and low moisture content (e.g., $<12\%$). Thus, to some extent, the specifications of the end product dictate the nature of the supply chain, including: (1) the characteristics of the raw material, (2) the number and types of preprocessing steps required to meet feedstock specifications, (3) the cost effectiveness of alternative transportation modes, and (4) the area of the procurement region needed to supply the facility.

14.2.1 Sources and Scale of Temporal Variability

The theoretical temporal variability associated with three biomass supply options is shown in Figure 14.1, representing conversion to densified biomass from multiple rotations of a dedicated short-rotation woody crop, two intermediate thinnings from a stand grown primarily for sawlog production, and logging residues utilized only during final harvest in a sawlog production system.

From Figure 14.1, it should be evident that there is an interaction of temporal and spatial variability at play in utilizing woody biomass from forestry activities that may be less relevant for agricultural crops. In particular, woody biomass from stand thinning operations and logging residues from an intermediate or final harvest may be spaced as much as an entire rotation length (25–100 years) apart at any fixed point on the landscape. Thus, in order for woody materials from logging residues to adequately supply annual demand for a depot or conversion facility, spatial rotation of management activities between the stands that make up an estate ownership or management area is needed. Accurate characterization of the frequency of treatments performed, types of woody biomass available, spatial pattern, and transportation network associated with projected annual utilization within a draw region is critical for long-term supply planning.

Two common ways to manage long-term supply planning in well-regulated, managed forests are *area control* and *volume control*. Strict area or volume control are most easily applied in even-aged silvicultural systems growing a single cohort of trees from the

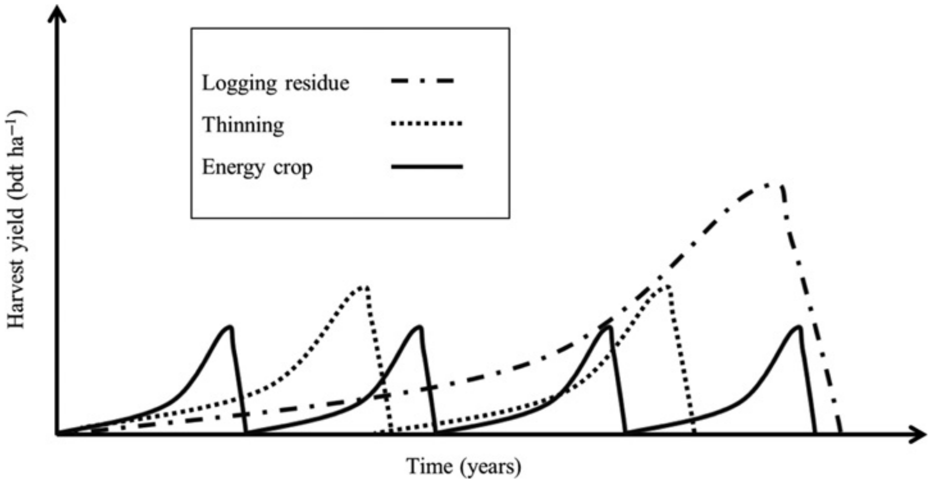

Figure 14.1 *Comparative relationship between harvest yield and time for three different woody biomass sources.*

regeneration phase to final harvest, it is the harvesting of the primary sawlog crops that result in logging residues utilized for woody biomass. Area control is realized when, for a given estate area of size A hectares and a stand rotation length of N years, A/N hectares are harvested each year. *Volume control* refers to the case in which a fixed target sawlog volume, (V + G)/N, is harvested over the rotation length, N, from all standing timber volume (V) plus growth (G) over that time period. For example, in the inland northwestern United States, it is assumed that the yield of useable woody biomass from terminal harvest logging residues falls between 0.5 and 1.5 bone dry tons (BDT) per 1000 US board feet, or 2.4 m^3, of sawtimber volume. Depending on regional variability, a typical mature stand might have between 15 000 and 25 000 U.S. board feet (15–25 MBF) per acre (0.4 ha) or more. At moderate residue concentration, in a productive and mature stand in the inland northwest, approximately 25 BDT of logging residues might be available for every 0.4 hectares of sawlog volume harvested, or 61.75 BDT per hectare. Thus, yields from harvesting potential available woody biomass are considerably larger, more spatially variable, and less frequent than yields from agricultural crops on a per unit area basis.

14.2.2 Preprocessing in the Woody Biomass Supply Chain

As will be evident in Section 14.4, there are a large number of established and emerging equipment options for harvesting and in-woods preprocessing of woody biomass. The level of preprocessing that occurs and the point at which it occurs in the supply chain have important impacts on supply chain efficiency because transportation costs, whether from stump to landing, landing to depot, or over long distances by rail or barge, are affected by the energy and mass density of the material. In general, supply chains that reduce the particle size, ash content, and moisture content of woody biomass close to the harvest location have the greatest transportation efficiency. This is because more densely packed densified, dried biomass contains the highest energy content per unit volume or mass (BTUs m^{-3}, BTU ton^{-1}). To address this characteristic of the woody supply chain, a number of specialized harvesters and forwarders have evolved that process, comminute, and densify biomass in the woods, immediately after harvest, to varying degrees. These include, for example, slash bundler forwarders, self-feeding chipper-forwarders, and even mobile depot units that dry, grind, and densify regional woody biomass supply at tactical scales (e.g., 3–4 years within a draw area) before moving to another location. Some of the more common harvesting and combined harvesting and processing equipment types currently available are described briefly and generally in Section 14.6.

Most woody biomass currently used or being actively studied in the context of biofuels and bioenergy development is derived from three major source categories: dedicated short-rotation woody crops (SRWCs), thinning materials, and logging residues.

14.3 Woody Biomass from Dedicated Energy Crops

Woody biomass from purpose-grown energy crops offers the opportunity to positively affect logistics costs in several ways. One of the most obvious is the opportunity to reduce transportation costs by geographically concentrating the source of the material, in the form of plantations, close to the consuming facility. Secondly, and even more impactful, would be the higher productivity of the energy plantations versus wood derived from natural stands. Producing more biomass per acre means less acres required to sustain operations, resulting in shorter haul distances for the woody biomass fuel or feedstock. Therefore, it can be seen that highly-productive energy plantations, grown in close proximity to the consuming bioenergy facility, offer an excellent opportunity to minimize the logistical complexity and cost of sourcing the woody fuel or feedstock.

Dedicated woody energy crops currently represent only a minor source of biomass for energy, although it is expected that energy plantations will become an increasingly important source in the future. Harvesting systems for woody biomass from energy plantations remain somewhat developmental and will need to be adapted to the specifics of the regime being considered. Specifically, the number of stems, spacing and tree size are important determinants of feasible harvesting solutions, production, and costs.

Short-rotation woody energy crops from genera such as the willows (*Salix* sp.), pines (*Pinus* sp.), poplar (*Populus* sp.) and Eucalyptus (*Eucalyptus* sp.) provide important SRWC crops. SWRC crops differ from pulp or sawlog stand thinnings and logging residues as biomass sources in that the sole purpose of intensive energy crop plantations is biomass production. By contrast, thinning materials and logging residues from silvicultural treatments in forestry are a secondary product, after sawlogs or pulp. Poplar energy wood crop rotations are short, from 7 to 15 years [1], and stands are established primarily through cuttings. Willow rotations may be even shorter (3–4 years). Because poplar and willows can also be regenerated well in coppice systems, coppice regeneration systems can also be deployed for both crops. Coppice systems are those in which stump sprouts or "suckers" re-sprout from stumps to establish the new stand of woody crop following harvest.

The systematic row-crop spatial location and small diameter of short rotation woody energy crops are conducive to agriculture-style harvesting with short-rotation woody harvesters. These purpose-built machines are forage harvesters with harvesting heads that can handle woody stems, typically less than 5 inches (12.7 cm) in diameter at breast height (DBH). A major advantage of using short rotation woody harvesters is that the resulting material delivered to roadside is a chip that is ready for transport without further preprocessing, that is, a single pass system. A further advantage of short rotation woody crop harvesters over the equivalent, conventional timber harvesting equipment (e.g., small excavators with harvester heads), is that they are able to conduct continuous travel harvesting, rather than stop-and-go felling of individual stems [2].

Although dedicated SRWC harvesters are the most promising emerging modern equipment for woody energy crops, a variety of conventional logging equipment has been evaluated in the context of woody biomass. Feller-bunchers and single-grip harvesters designed for sawlog production have been evaluated, as have a variety of forwarding systems. Mobile harvester-chipper-forwarders with knuckleboom harvester arms, chipper-forwarders, slash forwarders, slash compactors, and slash bundlers all have potential use with short-rotation crops. However, these systems tend to have either lower overall hourly production or higher hourly logging costs compared to modified swath harvesters because they require multi-stage processing. The many harvester-chipper-forwarders now available for woody biomass tend to be designed for larger diameter stems than are achieved in short rotation crops, and are better designed for intermediate thinning treatments in stands being grown for pulp or sawlog production. Unlike SWRC harvesters that have evolved from forage harvesters, the harvester-chipper-forwarder style machines tend to be designed for single approach harvest. That is, they have a harvester head mounted on a knuckleboom arm that is used to fell one or more stems, and the stems or bunch of stems are fed into the conveyor-feed mouth of an internal chipper. They are not able to perform continuous travel harvesting, but instead must stop intermittently.

14.4 Woody Biomass from Stand Thinning

In contrast to SRWC biomass, woody biomass from stand thinning is obtained from intermediate treatments in forest stands managed for sawlog or pulp production, or managed for non-market values like recreation and wildlife habitat that may be enhanced or protected by thinning treatments. In forestry, thinning operations are partitioned into *pre-commercial* and *commercial* thinning. Pre-commercial thinning incurs a cost, typically requiring investment of \$100–150/acre (\$247–371/ha), but generally results in better growth and higher production for the stand over the rotation. In addition, pre-commercial thinning is often used to reduce fire risk or manage insects and disease, regardless of impacts on long-term commercial output. Commercial thinning treatments are deployed in even-aged silvicultural systems, when feasible, 10–20 years before a terminal harvest. At this point in stand growth, stems are large enough to yield at least one small diameter sawlog, and revenue from the sale of merchantable sawtimber outweighs the logging costs associated with operations. At some critical threshold price, or under certain financial incentives, markets for woody biomass may help to further offset logging costs and help to make commercial thinning financially viable in stands where it otherwise might not be through supplemental revenue.

A number of supply chain pathways have been explored for thinning materials to be used for biofuels or bioenergy that are low in both ash and moisture content. In southern pine plantations, thinned stems are typically harvested with wheeled feller-bunchers that are able to proceed through plantation rows in alternating fashion, removing a stem from the left, then one from the right, and so forth. Pre-bunched stems may then be collected by a grapple skidder or forwarder. Or, in order to reduce the moisture content of stems for subsequent processing, pre-bunched stems may undergo in-woods drying before being removed for processing. Efforts to reduce the ash content of woody materials from thinning operations have evaluated extraction methods that fully support stems using forwarders or wheeled loaders, minimizing dragging and resulting soil contamination associated with grapple skidding.

In the western United States, a major potential source of biomass is thinning materials removed from fuel treatment operations on national forests. Frequently these types of treatments result in net costs, with relatively low value material removed from treatment units. Recent analysis of U.S. national Forest Inventory and Analysis data [3] using the BioSum model has shown that fuel treatment costs in the western United States range from very moderate (e.g., \$100/acre) to infeasible (>\$10 000/acre) on the landscape, depending on logging system used, topography, and transportation distance to utilization facilities. Remote stands on steep slopes that require cable logging or specialized equipment for treatment tend to be prohibitively expensive to treat.

14.5 Logging Residues

In most cases, woody biomass derived from the forest for energy applications today comes from either roundwood timber or forest residues recovered in conjunction with conventional harvesting activities. Certain bioenergy applications, including energy pellets, require or prefer clean fiber feedstock with very low bark content and soil contamination, which results in low ash content of the final product. Also, certain biofuel conversion technologies, specifically certain biochemical platforms, are best adapted to narrowly specified clean fiber feedstocks, often of a single species or species group. When clean fiber is required, conventional harvesting and debarking systems for pulpwood and other small diameter timber are commonly employed. These could include conventional longwood systems for delivering tree-length material to the conversion facility or in-woods chipping operations. In the former case, the timber would typically be debarked and chipped at the conversion facility. In the latter case, debarking would occur in the forest, usually by means of a flail debarking system, close-coupled to the chipper. In this case, clean chips are normally blown directly from the chipper outfeed into a chip van for delivery to the plant.

Logistics associated with utilizing woody biomass from slash, tops, and unmerchantable stem portions produced as a by-product of logging operations depend on the type of harvesting method used. The majority of logging in North America uses ground-based harvesting systems, with a variety of skidder or forwarder types. However, on steep slopes (>40%), cable logging is required. Industrial forest ownerships in the western United States and Canada most commonly require a mix of ground-based and cable logging. The difference in systems has important implications for the cost of extracting woody biomass. In general, cable logging operations are both more expensive and less productive than ground-based logging operations. Landing sizes tend to be smaller due to the steep terrain, and logging roads are more difficult to navigate with conventional chip trailers. In particular, curve radii engineered for conventional log trucks in the western United States may not be suitable for possum-belly chip trailers. A variety of emerging options to productively transport biomass on low volume forest road networks designed for roundwood transport are described in Section 14.7. In this environment, it is rarely cost effective to handle logging residues using cable systems.

14.5.1 Whole Tree Versus Cut-to-Length

As mentioned in the previous section, the distinction between cable and ground-based logging affects the production rate and cost of woody biomass utilization from logging residues. Within ground-based systems, feasibility of biomass extraction, production rates, and costs are further affected by the type of harvest and processing system in use. Whole tree harvesting that involves felling of stems with a feller-buncher, followed by grapple skidding or shovel logging to forward whole trees (including branches and tops) to roadside or a centralized landing, is, by design, paired with a processing method that accumulates loose woody biomass at the roadside. Processing with a grinder or chipper step at a landing or a concentration yard is then required, prior to subsequent transport. By contrast, in cut-to-length harvesting systems, stems are bucked into sawlogs in the woods by a feller-processor that delimbs and tops trees immediately after felling, at the location of the stump. Piled sawlogs are loaded by a log forwarder, which advances them to the landing. This process leaves the majority of logging residue in the woods following the initial harvesting and processing step (Figure 14.2), and thus requires an additional, separate slash bundler, slash forwarder, chipper-forwarder, or other equipment option to collect and move slash to the roadside. If slash is forwarded without processing, or is bundled and compressed for forwarding, it must then be ground or chipped at the roadside, a landing, or a concentration yard before transport. Figure 14.3 shows a small number of the many possible systems and equipment configurations available for moving logging slash from the woods to a conversion facility in whole tree and cut-to-length harvesting operations. From the figure, it is evident that there are various points at which comminution may occur, and the number of pieces of equipment that handle materials along the supply chain can range from very few to very many (Figure 14.4).

Figure 14.2 *Logging residue piled by an excavator. (Photo: © Keefe, 2013).*

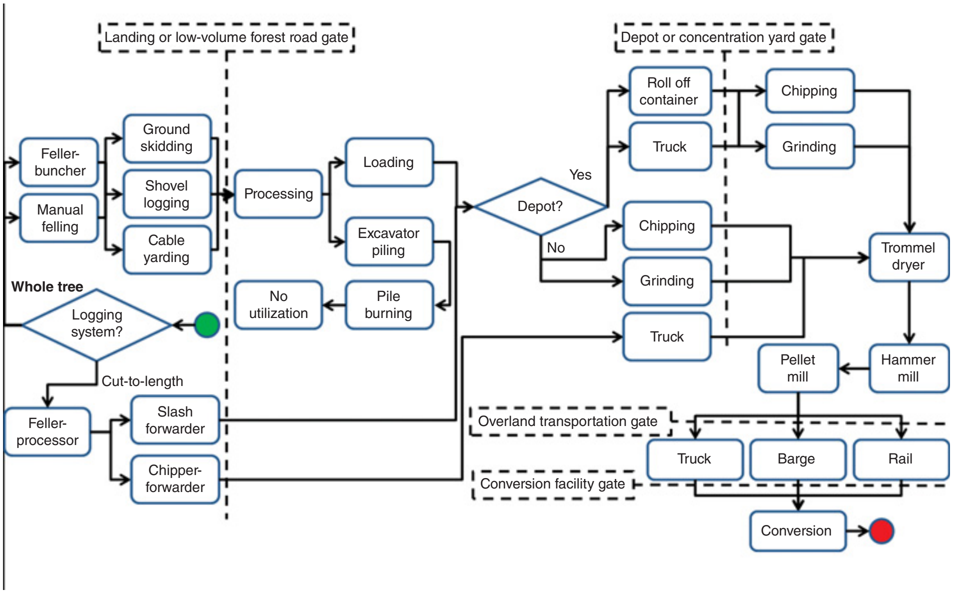

Figure 14.3 Some examples of possible primary woody biomass supply chain alternatives for logging residues from conventional whole tree and cut-to-length mechanized industrial logging operations with a single, localized concentration yard and a depot to densify uniform feedstock woody biomass.

Figure 14.4 An end dump semi-trailer used to haul slash to a concentration yard. (Photo: © Anderson, 2013).

When in-woods residues are collected by a self-feeding chipper-forwarder, then, depending on the system, they may be off-loaded directly from the chipper-forwarder to a chip van for subsequent transport. Open top ‘roll-off’ and hook lift containers are another useful option for advancing loose logging residues, either as a forwarder to advance residues to the roadside in cut-to-length operations, or to advance residues from the roadside to centralized concentration depots in whole-tree harvesting. Following a grinding or chipping step at the roadside or concentration depot, chips or hog fuel may be conveyed directly onto a chip trailer for transport to a processing facility (as part of the step, e.g., via equipment outfeed), or it may be piled and loaded at a later time. For example, a large chip trucking contractor in Idaho has developed specialized, large capacity wheel loader buckets for loading hog fuel onto chip trucks with higher production rates than could be achieved with a conventional loader.

14.5.2 Effect of Source on Feedstock Quality

Because logging residues are often laid or piled on disturbed, exposed soil during harvesting and processing, either in-woods or at the roadside, and may also be dragged along skid trails during extraction, the ash content tends to be high and affects the quality and value of this feedstock source. It is especially important that machine operators know if logging residues are going to be used as biomass rather than burned for disposal because they can work to minimize contamination in piling, especially on the landing. A number of post-harvest methods for reducing ash content in order to meet quality specifications of different biofuel and bioenergy processes exist. The most common methods are: (1) using rotary trommel screens to reduce the percentage of fine, inorganic materials that damage mill dies and increase ash content, and (2) downstream blending of feedstock from different material sources to meet quality specification standards. For example, if ash content of a residue feedstock is 5% and needs to be at or below 2% ash to meet quality specs for a particular conversion process, blending of 20% logging residue with 80% cleaner feedstock (for example, a one-pass agricultural residue, or clean pulp chips in pre-processing) can achieve a blended fuel with quality specification of 1.8 % ash content, though using higher quality feedstock in blending is likely to drive up costs.

Regulating moisture content of woody biomass feedstock from logging residues is an important research and development area. Depending on the season of the year, local climate, time between harvest and delivery, timing of processing, and species, the moisture content of cut slash and tops may vary from 12 to 50%. High or low moisture content may be desirable in final material specifications, depending on the conversion process. For example, aviation biofuels produced with a wet, thermochemical process are ultimately digested at high moisture content. For this reason, wetting dry feedstocks after transportation may be desirable for some conversion processes. In contrast, densification of uniform feedstock biomass into energy pellets requires dry material. Dried, ground biomass that is stored for subsequent use may actually regain moisture from ambient air prior to conversion, necessitating proper storage. Reduction in moisture content tends to reduce per unit transportation costs for biomass and may increase its value if end users pay for feedstock on a dry basis. From a technical standpoint, developing logistic supply chains that deliver feedstock with appropriate moisture content requires development and validation of predictive models that integrate tree and wood physiology (e.g., evapotranspirative drying as a function of local climate) with forest operations to consistently deliver a final product at required quality standards to meet conversion requirements. However, it may be more economically efficient to meet narrow feedstock specifications by centralized processing and drying at the facility rather than trying to meet them in the field.

14.6 Harvesting and Processing Systems and Equipment

There are a variety of harvesting systems in use in conventional forestry and short-rotation woody crop operations. This section describes the equipment used in conventional sawlog production operations from which thinning or logging residues may be derived, as well as short-rotation woody crop production equipment. When evaluating these equipment options working in sequence in biomass operations, the convention for establishing cost and production rates of equipment most commonly follows traditional *machine rate* methods, in which the hourly costs of equipment ownership and operation are partitioned into fixed and variable costs. Production functions are estimated using regression relationships developed from work sampling and time and motion field studies, with production in volume or mass per hour expressed as a function of stand (e.g., mean tree diameter, species, trees per hectare), site (average slope), equipment (machine payload capacity, horsepower), and operator variables as predictors. Logging costs for alternative supply chain components and equipment combinations are estimated by dividing machine rates, whether individually or summed over several machines, by the total production achieved in a specified time period. The result is cost per volume ($\$\ m^{-3}$), or cost per unit mass ($\$\ t^{-1}$). For example, if a feller-buncher has a machine rate cost of US$140 per hour to own and operate, and averages felling and bunching of 10 cubic meters per hour, then the total logging cost is estimated to be $\$140/10 = \$14\ m^{-3}$.

14.6.1 Harvesting

Though manual felling has largely been replaced by mechanized harvesting in many regions where gentle topography allows, it is still common on steep slopes in the western United States and other countries with mountainous terrain, where most mechanized single-grip harvesters and feller-bunchers in use are slope-limited (e.g., cannot operate on slopes >45%). Manual felling is also common when residual tree spacing is close enough to limit access and handling by large felling machines, in countries where forest operations are labor intensive rather than capital intensive, and as a component of cut-to-length operations focused on extraction of high value hardwood sawlogs and veneer, where poor bucking decisions can be extremely costly.

14.6.2 Single-Grip Harvesters

Single-grip harvesters ride on tracked, excavator bodies and have a hydraulic arm capable of felling, and usually processing, individual stems. The harvester may have a chainsaw felling head, a disk-like rotary cutting head that is variable speed or continuous (i.e., a "hot saw"). If the harvester is a feller-processor, it acts like a danglehead processor with hydraulic feed rollers that are capable of feeding the entire stem, horizontally, back and forth, in order to delimb the tree and buck it into sawlogs immediately following harvest. Feller-processors are commonly paired with forwarders, a woods machine with a hydraulic loader that carries multiple, fully supported sawlogs on a large trailer, as part of cut-to-length operations.

14.6.3 Feller-Bunchers

Feller-bunchers are similar to single grip-harvesters, but have the additional capacity to hold stems while additional felling cuts are made. The development of hydraulic accumulator arms that act like mechanical fingers on the felling head gives these machines the ability to hold one or more stems in place while a second or third is cut. Furthermore, this gives feller-bunchers the capacity to pre-brunch stems for a skidding or forwarding machine, without stopping harvesting.

14.6.4 Short-Rotation Woody Crop Harvesters

Short rotation woody crop harvesters, also called swath harvesters, are forage harvesters that are modified to harvest small diameter woody energy crops. These machines are typically able to harvest stems less than five inches in diameter. Stems are harvested and chipped, ground, or shredded, and fed through an auger to a trailer that is either pulled by the harvester or pulled by a second tractor driving in parallel.

14.6.5 Ground-Based Skidding and Forwarding

There are a variety of types of skidding and forwarding machines used to move whole trees, slash, or chips from the woods to a landing or roadside location in forestry. In the subsequent sections, traditional ground-based skidding and forwarding equipment types are described briefly, as are some specialized forwarders for woody biomass.

Ground-based log skidders may be tracked or wheeled machines. Log skidders are capable of working on moderate slopes (<40%) and may be configured as either cable or grapple skidders. Cable skidders have a large hydraulic winch on the back, which log ‘chokers’ are attached to, allowing multiple stems to be winched to the machine and elevated off the ground prior to skidding to the landing. Grapple skidders have a large hydraulic grapple on the rear of the machine that lifts logs off the ground for skidding (Figure 14.5). Cable skidders thus have the advantage of being able to pull felled trees out of areas that may be difficult for the machine to navigate, or preferable to avoid, such as streamside management zones (SMZs), while grapple skidders must be able to back up directly to bunched logs where they lay. Working under similar conditions, grapple skidders have higher production rates than cable skidders, and are more common. On the west coast of the United States (Oregon and Washington), shovel logging has largely replaced the use of skidders for ground-based yarding in industrial forest operations. However, skidders are still used commonly in the inland northwest and in the eastern United States.

14.6.6 Slash Forwarders and Chipper-Forwarders

There are several types of commercially-available slash-forwarders that are purpose built to forward woody logging slash and tops from in-woods locations to a landing or roadside pickup for subsequent processing or transportation. These machines include simple

Figure 14.5 Conventional grapple skidder releasing a turn of small diameter logs. (Photo: © Keefe, 2013).

forwarders with bunks for transport of loose logging residue, machines with inverted hydraulic grapples that compress slash in order to increase payload capacity, and forwarders with mechanisms for wrapping slash into large bundles.

Alternatively, a variety of self-feeding chipper-forwarders now exists that are able to pick up and chip logging residue in the woods. Slash is picked up with a hydraulic arm and grapple, self-fed to an in-feed conveyor or feed roller mechanism, chipped, and carried in an internal container to the landing. Because chipper-forwarders densify biomass from logging residues in the woods prior to transport, these machines tend to have higher production rates than slash-forwarders [4].

14.6.7 Shovel Logging

Shovel logging is the term used to describe a type of log or whole-tree forwarding in which a "shovel", "swing machine" or long reach hydraulic loader built for forestry advances stems toward roadside using a series of 2–3 "swings". Figure 14.6 shows a shovel logging system in which Douglas Fir stems are being advanced to a log landing using a shovel logging machine on moderate slopes, alongside a cable logging operation on steeper terrain.

14.6.8 Chippers

Wood chippers may be disk or drum machines and are available in a variety of sizes, from small, trailer-mounted models able to handle small diameter branch material, to mobile, whole-tree chippers that can process large diameter stems with high throughput in industrial operations. Whole-tree chippers may be paired with a separate loader or may

Figure 14.6 *Shovel logging to advance whole trees to the landing on moderate slopes near a standing skyline cable yarding operation in western Washington. (Photo: © Keefe, 2013).*

be self-loading. Tracked machines are able to work in the woods in order to minimize slash forwarding with a forwarder or excavator. Stationary machines work at a landing or concentration yard. Figure 14.7 shows a full mobile chipping unit processing commercially thinned stems at a log concentration yard in north Idaho. In general, chipping tends to work most efficiently when stems have high moisture content (i.e., "green" wood).

Fuel chips are most commonly used for thermal applications, such as boiler fuel, and for power generation. The presence of bark and foliage in the chips is generally not problematic in these applications, assuming that the presence of inorganic material can be controlled to reasonable levels. In addition, certain biofuel conversion technologies can utilize fuel chips, notably the thermochemical processes that gasify biomass or utilize some form of pyrolysis to convert the solid material to a liquid or gas.

14.6.9 Grinders

Unlike disk and drum chippers that slice and chunk wood into smaller particle sizes through cutting knives that slice fiber, grinders separate wood through a mashing and tearing or fibers. Thus, grinding may be more effective at lower moisture contents. Horizontal grinders such as that shown in Figure 14.8 have a rectangular open top for loading, with a conveyor and feed roller infeed that forces residues against the grinder, and then ejects hog fuel along an in-line conveyor outfeed. Vertical grinders, more commonly called "tub" grinders, have a large, cylindrical open top in which residues are loaded, and rely on gravity to feed the grinder.

Figure 14.7 *A complete mobile chipping unit processing de-limbed small-diameter logs from a commercial thinning operation into clean chips in north Idaho. The chipping is located at a concentration yard 2–3 miles from where the trees were harvested. (Photo: © Keefe, 2013).*

Figure 14.8 *A loader feeds a horizontal grinder, which in turn fills a high walled dump truck being used to haul biomass over a low volume forest road to a concentration yard. (Photo: © Anderson, 2013).*

Grinders, both of the tub and horizontal varieties, have an important place in the current infrastructure for woody biomass processing. The quality of the product resulting from grinders is generally of lower quality than a chipped product. Grinders tend to be more forgiving of soil and other contaminants, with the result that a higher proportion of these undesirable materials typically find their way into the product. Material processed in grinders is most often suitable for boiler fuel, in part because large biomass boiler systems tend to be less sensitive to ash content. Grinders are better adapted to locations where cut-to-length logging is common. In these operations, logging slash tends to be dispersed throughout the logging site. Logging residues are generally forwarded to the roadside or other locations where they can be accessed by the grinding equipment. Grinders are paired with a knuckle-boom loader and the outfeed discharges into a chip van of some sort. The ground product tends to be inconsistent in size and shape, and thus is not a preferred fuel or feedstock.

The choice of tub versus horizontal grinder is largely dependent on the type of material being processed. Tub grinders are better adapted to odd-shaped pieces, such as stumps, short bole sections, and the like. Horizontal grinders are more efficient at processing material with a more linear configuration, such as tree-length material or long tops and limbs. Horizontal grinders are capable of very high throughputs, making them efficient options where the product is acceptable.

14.6.10 Portable Conveyors

Most equipment for primary harvesting and extraction in forestry has been designed for handling sawlogs or whole stems, which are single or multiple large, heavy objects. Relative to sawlogs, the material properties of woody biomass are very different, including small particle size and bulkiness. For this reason, use of portable conveyors for in-woods biomass handling applications, such as forwarding, have received some attention. Portable belt conveyors and continuous loop cable systems have important advantages over conventional skidding and forwarding equipment options. The continuous material flow properties of conveyors make it possible for high production rates to be maintained, regardless of turn distance [4, 5]. This differs from the production function for most skidding and forwarding equipment, which tends to decline with increasing turn distance. Set-up costs, or total equipment costs, tend to offset production gains associated with deploying conveyors for primary extraction to a landing or roadside. However, an additional advantage of conveyors is that many are able to handle bulky biomass in a variety of raw or comminuted forms, including, for example, chips, hog fuel, and unprocessed slash and tops. This flexibility makes it possible for portable conveyors to function as part of a variety of different system and equipment configurations.

14.6.11 Combined Harvesting and Processing Equipment

In addition to chipper-forwarders, there are now commercially available machines capable of harvesting, self-feeding, chipping, and transporting woody biomass. Though not commonly in use, these machines have the advantage of performing "single pass" utilization of thinned materials, when larger diameter (e.g., >5-inch DBH) must be processed.

14.7 Woody Biomass Transportation

Along with harvesting and processing costs, transportation costs are a major determinant of the delivered cost of woody biomass. Even after communition or compaction, woody biomass tends to be bulky and difficult to transport efficiently. The preferred approach, when possible, is to maximize net payload by using the largest trailer possible. For example, high-capacity chip tractor–semi-trailer combinations, also called chip vans, can exceed 19 m in length, 45 000 kg in gross vehicle weight, and 30 000 kg in net payload. Large payloads distribute the fixed costs of transportation over a larger amount of material and generally, though not always, result in greater input/output efficiency in variable costs, such as fuel consumption. Larger payloads also reduce operational delays associated with the loading and unloading of many small trucks compared to loading fewer large trucks. Though ideal from an operational standpoint, a number of factors constrain the use of these vehicles in woody biomass logistics.

14.7.1 Regulatory Considerations

In most places, regulations govern on-road trucking and limit vehicle dimensions and gross vehicle weight (GVW). Different laws may apply to different road segments along a route depending on local, state, provincial, and federal jurisdictions. For example, in some US states maximum GVW may be set at 45 360 kg, but vehicles greater than 36 290 kg are prohibited from traveling federal interstate highways, requiring smaller payloads or sub-optimal truck routing onto high GVW roads. Overweight and over-dimensions exemption permits are generally available but many jurisdictions bar such permits for cargo that can practically be divided into smaller loads, such as biomass. Even if overweight permits for divisible cargo are allowed, permit fees and transaction costs may exceed added revenue associated with larger payloads. In addition to GVW restrictions, seasonal road closures related to mud and snow conditions can limit transportation at certain times of the year. In general, these types of regulations have a direct influence on transportation options for both individual harvest sites and facility-specific transportation logistics systems.

14.7.2 Operational Considerations

There is also a close link between transportation options and material handling capabilities. At the harvest site, large open-topped chip van trailers can be loaded evenly by a conveyor, overhead hopper or front-end bucket loader. Closed trailers and box trucks, as well as trailers that cannot be approached from the side due to terrain or road conditions, must be loaded from the back. Depending on the particle size of the material and ejection range of processing equipment, it may be difficult to fill long compartments uniformly to maximize payload. Similarly, grapple loaders must have sufficient room to maneuver to efficiently load roundwood or compacted bundles onto long trailers. Unloading is discussed in more detail later in this chapter, but similar constraints apply to unloading biomass. Self-unloading configurations, including walking floor (Figure 14.9), side dump, end dump and belly dump trucks and trailers, carry smaller payloads than long, possum belly semi-trailers, but may be required if the end user does not have a hydraulic truck dump system on site. For

Figure 14.9 The back of a walking floor trailer that allows for automatic unloading of comminuted biomass. (Photo: © Anderson, 2013).

roundwood, self-loading log trucks equipped with a hydraulic grapple arm may be required if the log landing does not have a loader or forwarder on site.

Regulations and handling constraints apply broadly to all biomass supply chains but the forest sector is unique in the extent to which transportation logistics are dictated by harvest site characteristics. Plantations and native forests located on flat topography close to end users and accessed over high-speed, wide, paved roads with high GVW are obviously ideal for minimizing transportation costs. However, forested sites are frequently accessed over gravel or native soil low-standard forest roads that are steep, narrow and winding with limited turn-out locations for passing and turning around. In many cases, forest roads were designed for stinger steered log trucks and are inaccessible to the long, low clearance, high-volume tractor-semi-trailer combinations that maximize transportation efficiency for woody biomass. Road improvements can widen curves, flatten rough roads and reduce steep grades, but can rarely be justified by biomass extraction objectives alone and may be limited by regulation or forest management objectives. Recent innovations in stinger steering and rear axle modifications that allow a tighter turn radius than traditional fifth wheel semi-trailers with fixed axles have improved access to difficult sites by large semi-trailers. Such trailers are commercially available but cost more than conventional equipment. Short chip van tractor-semi-trailer configurations are also used to haul woody biomass on low-standard forest roads. Under especially challenging road conditions, shorter, higher clearance, and more maneuverable box trucks, dump trucks, roll-off bins, or tractor-trailers are an option. However, the smaller payloads carried by these vehicles typically translate to higher per unit transportation costs, which are intensified by long on-highway travel distances. In addition, if biomass has received some field drying before processing, smaller truck configurations tend to reach maximum volume before they reach maximum GVW. This is suboptimal from a logistics standpoint because it further reduces payload and increases per unit costs.

14.7.3 Concentration Yards

It is possible to combine the maneuverability of small trucks with the long-haul efficiency of large semi-trailers by using a concentration yard to improve logistics [6]. Concentration yards, also known as sort yards for roundwood, are intermediate transfer points where material is collected. In the forest sector, they typically serve to improve logistics in transportation, processing, storage and marketing. For sites that are inaccessible to large chip vans, smaller trucks can be used to transport material over forest roads to a site with better road access. Biomass can then be transferred to large trucks with higher payloads to cover long on-road distances to end users. Similarly, when harvest sites are widely dispersed, difficult to access, and have relatively small amounts of material to process, it is costly to move processing equipment from site to site. In this case, logging residues and roundwood can be transported from harvest sites to a central location, stockpiled, and then processed in large volumes, which increases processing efficiency. This logic can also be applied to pretreatments, which are discussed in more detail later in this chapter. In some cases, processing and pretreatment equipment cannot be transported to harvest units due to poor road conditions or design limitations, making a concentration yard necessary. In both cases, gains in transportation and processing efficiency must be balanced against added handling costs, with concentration yards requiring additional unloading, handling, and re-loading components. In general, the costs of double handing low-value material like woody biomass are very difficult to recover by improving transportation efficiency, unless transportation costs are extremely high.

Concentration yards can also provide off-site storage of raw material, either in its raw or processed/pretreated form. This may be an attractive option in areas affected by seasonal road restrictions that limit access to material at harvest sites for part of the year. In addition, though less relevant for woody biomass than for high value roundwood products, concentration yards can be used to improve efficiency in product marketing by separating aggregate deliveries of logs from harvest sites into fuelwood, pulpwood, and different grades of sawlogs for shipment to different facilities [7]. Typically, this is done on the log landing or at a facility that uses its log yard as a sort yard, shipping loads of logs to other facilities, but there are some conditions where it may make sense to incorporate this approach into woody biomass logistics. As with the storage and processing aspects of concentration yards, the added costs must be weighed against added revenues of product sorting and marketing. Though they are used in road-based logistics systems, concentration yards are a necessity when woody biomass is going to be transported by rail or ship. Though extremely rare because of its unfavorable economics, biomass removals by helicopter also require a concentration yard. For railroad transportation, rail-side concentration yards allow material to be stored on site and transferred efficiently into rail cars and shipped after sufficient material is stockpiled.

14.8 Pretreatment

14.8.1 Mechanical and Chemical Pretreatments

Communition of woody biomass through chipping, grinding and shredding increases its bulk density, which improves transportation efficiency by allowing trucks to carry heavier payloads. Such processing also improves handling and storage by reducing particle size and increasing homogeneity, allowing material to be more efficiently handled by loaders, conveyors and other equipment. In the context of woody biomass logistics, pretreatment generally includes additional processing that further improves the transportation, handling, storage and end use characteristics of biomass feedstocks beyond typical communition methods. Physical, chemical and thermal pretreatments are all technically possible but vary significantly in their operational characteristics and commercial potential.

When end users of woody biomass have feedstock specifications that are outside traditional parameters for chips and hog fuel, additional drying, milling, chipping and screening can be used as pretreatments. For example, many distributed scale gasification systems require clean, dry, microchips as a preferred feedstock (e.g., low ash, bark-free chips less than 3 cm in size and 10% water by weight). The equipment to produce this high quality of feedstock from woody biomass is commercially available and widely deployed in industrial settings. More intensive debarking, chipping and screening are easily accomplished on a log landing, though these steps obviously incur additional costs. In-woods pelletization has also been explored as a pretreatment option, but remains difficult to do efficiently at distributed scales. Similarly, chemical pretreatments are widely used by cellulosic ethanol operations to reduce lignin content and improve sugar yields, but these techniques are not easily mobilized for field applications and typically involve liquid waste management and reprocessing that is almost impossible to do efficiently away from a large-scale facility. In contrast, there has been growing interest in using mobile thermal pretreatment technologies close to the harvest site to further improve transportation efficiency and produce renewable high-value bioproducts that can be shipped efficiently to distant markets, especially in areas characterized by long transportation distances. Though discussed here as a pretreatment option, thermochemical pretreatments can also be classified as biomass conversion technologies, especially when deployed at larger centralized facilities (Chapter 2).

14.8.2 Thermal Pretreatments

Among thermal pretreatment options, torrefaction, or pyrolysis of biomass in the 200–300°C temperature range, is closest to widespread commercial use [8]. Torrefaction produces a devolitalized, hydrophobic, high-carbon content product often referred to as torrefied wood. Several characteristics of torrefied wood make it more efficient to transport and store than untreated biomass, including lower water and oxygen content, higher energy density, hydrophobicity, resistance to decay, grindability, and relatively homogenous particle size. Torrefied wood is generally considered a solid fuel product suitable for combustion applications, including utility boilers and co-firing with coal, but may also be used in gasification and bioproducts manufacturing. Much attention has been paid to using torrefied wood as raw material in the manufacture of fuel pellets because low water content and high energy density are desirable for most energy applications. The sequence of processing can also be reversed, with wood pellets serving as the feedstock for torrefaction. However, this configuration is not a viable in-woods option due to the difficulty in efficiently down-scaling pellet manufacturing, which is strongly subject to economies of scale in production, handling and transportation. In most torrefaction systems, once pyrolysis is initiated with an application of heat, the process is exothermic and self-sustaining, meaning the chemical reactions required to produce the end product will proceed without net additions of energy, such as heat from combustion of propane, natural gas or combustible gases produced by the reaction itself. This provides a deployment advantage for log landings that are close to the harvest site and typically distant from infrastructure. Another advantage is that torrefied wood can typically be handled by the same equipment used to handle and transport processed biomass, though initial cooling and additional dust control measures may be required.

Pyrolysis of biomass at higher temperatures (300–700°C) produces recalcitrant charcoal as well as volatile gases, a fraction of which can be condensed into liquid pyrolysis oil, also called bio-oil. Mobile pyrolysis systems have been examined as a pretreatment option for woody biomass but are not yet widely used in the forest sector [9]. The charcoal produced has most of the same favorable properties as torrefied wood and can be used in its raw form as solid fuel or as a feedstock for the production of other products, including chemicals, pellets, activated carbon and soil additives. The charcoal output of pyrolysis of biomass is commonly called biochar when it is used as an additive to improve the bulk density and nutrient and water holding capacity of soils. Pyrolysis oil can be used in its raw form as liquid fuel. However, because of its high oxygen and water content and low chemical stability, it is generally considered a crude product to be used in the production of refined (i.e., upgraded) biofuels and industrial chemicals.

Pyrolysis in this temperature range often produces residual tars, which can provide fuel for conversion, be sold as a commercial output, or handled as an undesirable waste by-product, depending on production objectives, equipment capabilities, and markets. Systems operating at the low end of this temperature range may be exothermic, similar to torrefaction systems, but fast pyrolysis units operating at higher temperatures are characteristically endothermic and require net additions of energy to sustain the thermochemical reaction due to their high heating rate and the relatively short residence time of the feedstock. Often this energy can be provided by combustion of producer gas generated by the system, which is generally composed of carbon monoxide, hydrogen, carbon dioxide, methane and other non-condensable gases. Because of the high temperatures and smaller feedstock particle size, which facilitate rapid heat transfer, the pulverized charcoal from fast pyrolysis systems can require significantly different handling than wood chips or torrefied wood – most often a cooling phase followed by containerization in drums, closed trailers, or large industrial bulk bags. Compared to biomass, pyrolysis oil is energy dense, and thus has the potential to improve transportation efficiency, but as a liquid product it adds material handing requirements that are unusual for most forest operations, including on-site liquid fuel storage, specialized trucking needs, and fire and spill containment preparations.

14.8.3 Locating Pretreatment Operations

As a component of woody biomass logistics, pretreatment can occur close to the harvest site, at intermediate processing and storage facilities such as concentration yards, or prior to use at the conversion facility. The location and timing of necessary pretreatment is highly dependent upon the end use and other components of the supply chain. However, several general considerations are worth mentioning here. In any logistics configuration, the value of pretreatment is likely to depend on the cost of the pretreatment weighted against the cost savings associated with increased transportation efficiency and the difference in delivered price between the treated and untreated materials. For example, when compared to green chips, torrefied wood produced from green chips at a harvest site may be cheaper to deliver on a cost per ton basis and may also command a higher delivered price attributable to its higher energy content. However, if the cost of the torrefaction operation is greater than the sum of transportation cost savings and new revenue, then the torrefaction preprocessing option is unlikely to be commercially viable.

Balancing the scale of operations is also important. Many existing pyrolysis and torrefaction technologies that can be deployed to forest settings have much lower material throughput (e.g., 1 t h^{-1}) than grinding and chipping systems, which can produce up to 50 t h^{-1}. When forest operations are bottlenecked through lower productivity preprocessing, gains in transportation and revenue may be erased by operational delays in the harvesting and processing components of the system. This is especially true of batch systems, where equipment may be idle during preprocessing periods. In addition, some technologies (e.g., refinery operations) benefit from clear economies of scale and cannot be effectively down-scaled for deployment to in-woods and concentration yard environments. Many of these challenges can be overcome with effective engineering, operations planning and logistics management, but others reflect the realities of preprocessing technology deployed in difficult operating environments.

14.9 Handling and Storage

Processed woody biomass is unloaded in different ways depending on the transportation method and capabilities of the concentration yard or facility to which it is delivered. High-volume operations, such as large combined heat and power boiler systems and electric power plants, typically use hydraulic truck dumps. These systems raise conventional tractor-semi-trailers vertically and use gravity to dump the contents of their trailers into a transfer bin, pit or bunker, or onto a ground-level pad. Once dumped, the biomass can be moved from the unloading area by drag chains, conveyors, wheeled front-end bucket loaders, or similar handling equipment. Paired with large-volume chip vans, truck dumps are an extremely efficient unloading system. However, they are costly to install and maintain, so they are generally found at facilities requiring hundreds of thousands of tons of feedstock per year. For smaller volume operations, such as distributed heating systems, self-unloading trailers are preferred. These trailers generally discharge onto a pad, where the material is moved by a rubber-tired front-end bucket loader. A variety of belly, side and end dump trailers are available for different truck and tractor configurations. However, walking floor (or live floor) self-unloading semi-trailers are a good option to maximize payload when a truck dump is not available or when the truck must unload in a covered

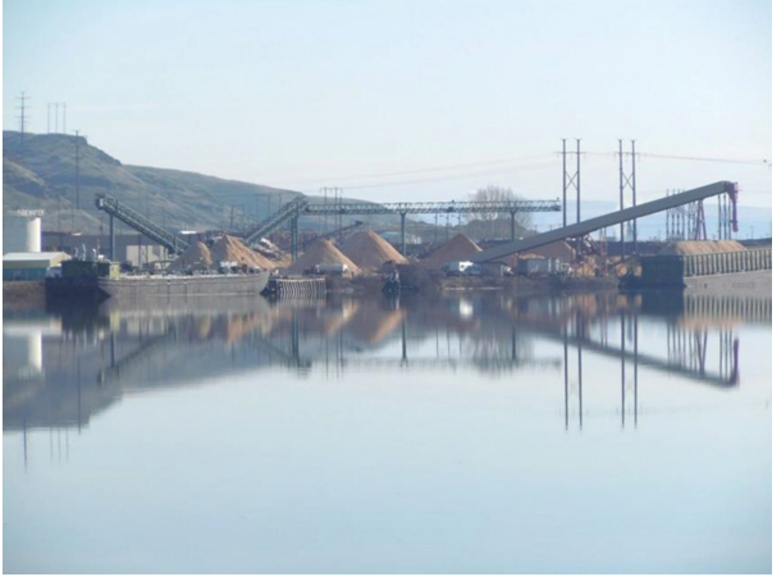

Figure 14.10 Woody biomass piled outdoors and loaded onto barges using a series of conveyors, prior to long-distance transport downriver. (Photo: © Keefe, 2013).

storage area or bunker with low overhead clearance that limits the use of side and end dump trailers.

Chipped or ground woody biomass can be stored in piles that are open to the weather (Figure 14.10). Obviously, moisture content is not a problem for conversion technologies that use wet chemical and biochemical processes, but even for thermochemical conversion processes where dry material is preferred, biomass harvested from green trees or logging residues that have received some field drying is unlikely to increase much in moisture content from precipitation when stored in piles outdoors. However, in most cases piles with high moisture content should be rotated to avoid degradation, which can change its physical and chemical properties, resulting in loss of energy content. Spontaneous combustion of green and wet chips can also occur if piles are allowed to remain outdoors without rotation for extended periods. This phenomenon is the result of microbial activity that produces heat, which can build up and cause combustion under some temperature, oxygen and moisture conditions. Regular rotation dissipates heat and changes pile conditions to make combustion unlikely.

Some woody biomass, especially residue from solid wood products manufacturing, has low moisture content as a result of kiln drying prior to final processing. In some cases, green woody biomass is dried prior to use, as in most fuel pellet manufacturing operations. Drying wood is expensive but elevates the recoverable energy content and value of the material. As a result, dry woody biomass should be kept in a dry condition using proper storage and handling procedures, which often include covered storage and short storage duration before use. Though spontaneous combustion and degradation are less of a concern with dry materials, dry biomass may require additional dust control, typically in the form of collection and exhaust systems that minimize fire, environmental and health risks. In general, the smaller the particles, the greater the need for such management systems.

For bioenergy facilities using roundwood delivered on log trucks or flatbed trailers, there are a variety of conventional options for unloading, handling, and storing wood. Log trucks can be unloaded by crane, either rotary or portal varieties, and easily stored in tall piles in a log yard. Unloading and storing wood in this fashion is an efficient option for high-volume operations and is commonly employed at conventional forest products manufacturing facilities. Grapple loaders and rubber-tired front-end log loaders can also be used effectively, although a larger land area is required due to the limited reach of the equipment. Log yards often employ both cranes and log loaders to stack and store roundwood. Low volume operations are unlikely to prefer roundwood as feedstock but can opt for grapple loading log trucks and a tractor or skidder to manage logs in the yard before processing.

14.10 Logistics Management

14.10.1 Delivered Cost and Woody Biomass Logistics

For facilities using woody biomass as a fuel or raw material, a central objective of logistics management is to reduce the delivered cost of the material. For woody biomass, delivered cost generally includes three core components: stumpage, forest operations costs, and transportation costs. Stumpage is the term used in the forest sector to denote the fee paid to owner of the raw material, typically the landowner. Stumpage costs are highly variable and regionally specific, but biomass generally has the lowest stumpage cost of any material removed from the forest. In contrast, operations costs for biomass, especially logging residues, can be quite high compared to large diameter roundwood. Operations costs include all on-site harvesting, handling, and processing, as well as handling and processing at intermediate transfer points, like concentration yards. Operations costs can be accounted for using a marginal costing approach, where biomass is considered a by-product of the production of high-value products that support most of the operations costs, or a joint product costing approach where biomass is considered a co-product and operations costs are proportionally allocated among all products, including biomass [10]. Transportation costs most often cover a single motor carrier transporting material from the harvest site to the end user, but may include multiple trucking segments, depending on logistics. If a short-haul transportation segment is required to bring slash or processed biomass from the harvest site to a nearby concentration yard, short-haul transportation costs may be included in operations costs, especially if the short haul is conducted by the logging contractor. In general, if the total costs of delivering woody biomass to a facility exceed the price that the end user is willing to pay, the material is left to decompose or burned on site to reduce fire risk and open growing space for regeneration. In some cases, the net costs of woody biomass utilization may be offset by revenues from higher value products if biomass use is uneconomical but desirable for other reasons. For example, utilization may be used as an alternative disposal method in situations where open burning is prohibited.

Different logistics costs may be borne by different organizations along the supply chain, or by a single firm in a vertically integrated operation. In locations where biomass supply chains are characterized by independent firms specializing in land investment, forest management, harvesting, transportation, and conversion, the details of cost structure are typically proprietary because efficient operations are a competitive advantage for competing firms. In this context, firms along the supply chain typically interact on price (e.g., stumpage price or gate price for delivered material). However, a number of different sources of information can be used to guide logistics management with regard to costs. The most important and reliable form of cost information is transaction evidence, or records of costs and prices from previous market transactions. In addition, in well-developed biomass markets individual firms are often surveyed by public agencies or industry organizations that aggregate market information, especially prices, into stumpage reports and other similar market data reports, which are available for free or for a fee. Government land management agencies sometimes have publicly available data and methods that characterize the value and costs of forest products from public land, including fuel wood and biomass. For forest operations, a large body of research is devoted to quantifying and improving the cost structure of woody biomass harvesting and processing. These data can be compiled to provide delivered estimates for a certain size and type of facility in a specific location.

14.10.2 Spatial Analysis of Woody Biomass Logistics

Many of the variables that determine the delivered cost of woody biomass have spatial attributes. Transportation distance is often cited as a critical constraint on the financial feasibility of biomass utilization but in a heterogeneous landscape the distribution, quality, ownership, management and accessibility of forestland also have spatial dimensions that influence biomass supply. The following section discusses the tools and approaches that are used to perform spatial analysis of feedstock supply to inform logistics. Though the techniques can be complex, their broad purpose is to help estimate how much biomass can be supplied to a specific facility at a given cost.

14.10.3 GIS

Facility managers typically take a large number of factors into consideration to build an optimal procurement plan to minimize woody biomass cost. In practice, those plans vary in detail from expert opinion and trial-and-error [11] to metaheuristic solvers that are incorporated into a geographic information system (GIS) [12]. While expert opinion is often used to minimize costs for an individual operation, it tends to produce substantial uncertainty when a supply chain is complex and compared to alternative operations occurring across vast landscapes over long periods of time. In that light, forest management, which typically covers large areas, has multiple objectives, delivers raw materials to many destinations, and utilizes long time horizons, often relies on building logistical costs into a GIS that can be used to compare multiple scenarios in a spatial and temporal manner.

In simple terms, a GIS is a collection of software procedures and data that use geometry as a primary relationship among records [13]. GIS data reside in a relational database structure that link records with one another based on primary keys and topological relationships. Within a GIS, real objects such as roads, harvest units and mills are symbolically represented as table records in either vector or raster form. Each record within a table stores descriptive information of each object (attributes) such as size, length, area, and cost along with a collection of coordinates that depict shape and location in the form of points, lines, polygons, or raster cells. Moreover, because an object's geometry (shape and location) is stored, spatial relationships such as proximity to, touching, adjoining, within, and containing can be used to relate attributes of neighboring objects to one another.

In the context of managing woody biomass supply chains, these objects represent the base components that can be attributed costs. For example, a polygon that symbolizes a 40 hectare harvest unit on a gentle slope located next to a primary road can be allocated costs related to the weight of the biomass collected, a skidder harvesting system, and primary road access. Allocating cost across a landscape within a GIS is straightforward and can be accomplished by defining a clear set of rules that constrain cost to specific locations based on a combination of spatially explicit factors. These rules are typically defined by setting lower and upper bounds (i.e., thresholds) on transportation distance, the types of equipment that can be used, and the amount of material that can be removed from a given location. Thresholds can be based on a wide range of factors including regulations, policy, management objectives, the physical limitation of equipment being used, transportation infrastructure, and the characteristics of the landscape, and should be derived in a manner that represents yes or no outcomes in terms of supply. Records or spatial locations meeting the defined thresholds can then be attributed a designated cost and mapped appropriately.

Commonly, logistics costs are based on rates such as dollars per unit of distance, area, or weight. While rates can be easily attributed to specific objects (e.g., harvest units), it can be helpful to convert rates to an absolute value when aggregating different sources of cost for an activity. For example, plotting total cost against total amount can provide useful supply curves. Again, within a GIS this process is straightforward, as long as there are estimates of distance, area, and weight for each of the different cost types. Common tables developed to store these kinds of estimates include vector and raster data sets that spatially depict woody biomass stocks, topography, road and stream networks, receiving facilities, and treatment units.

One of the most common ways to generate the geometry of objects within these tables is to use "heads up digitizing" and image interpretation where a technician manually converts maps and other imagery into a digital format that can be used in GIS [14]. For larger landscapes, though, this tends to be cost prohibitive. In those situations, remote sensing techniques are often employed to automate the creation of GIS data. Regardless of how an object's geometry is created, once it is defined it can be attributed with the base information needed to calculate absolute cost and biomass yield.

14.10.4 Estimating Biomass Stocks Across a Landscape

Estimating woody biomass feedstock across a landscape consists of three basic steps: (1) quantifying estimates of forest characteristics, such as basal area, trees, and woody biomass tons per acre across a landscape; (2) using those estimates to help determine where to apply actual or hypothetical silvicultural prescriptions; and (3) combining estimates of woody biomass with prescriptions to calculate potential treatment residues that can be utilized for fuel or raw material. Quantifying existing forest characteristics can be a substantial endeavor. Generally, this process consists of sampling areas on the ground and recording tree measurements, such as species counts, diameter at breast height (1.37 m), total height, live crown ratio, age, and percentage cull and breakage [15]. From these tree measurements, estimates of standing volume and weight are calculated using allometric equations. These measurements and calculations are then summarized based on sampling design to describe multiple aspects of a forest on a per acre basis. A common classical approach to quantifying existing forest characteristics uses stratified random sampling to relate summarized values to polygons within groups (strata) of similar forest types, stockings, and canopy cover [16]. With this approach, polygons and strata are generally created and labeled through manually defining boundaries of similar forest cover types, percentage canopy cover, and topographic position derived from aerial and satellite imagery. For larger landscapes where manual interpretation is impractical, image classification techniques are used to develop appropriate strata. Once strata have been defined, a random sample of polygons within each stratum is selected, visited, and sampled to derive mean estimates of forest characteristics for that stratum. Mean strata estimates are then attributed to each polygon within each stratum.

While this basic approach is still used in many analyses, mean estimates relate to the stratum as a whole and do not account for spatial variations within a given stratum. Furthermore, the coarse grain nature of this type of estimate may not be suitable for fine scale projects that utilize only small portions of strata. To address this issue, recent analyses have developed spectral and textural relationships between remotely sensed data and field measurements [17–19]. Using these relationships, estimates of biomass can vary as spectral and textural values change, thereby maintaining the spatial heterogeneity of forest characteristics at fine spatial resolution across the landscape.

After forest characteristics have been quantified for polygons or cells, they can be used to help determine where silvicultural prescriptions are applied across a landscape. The process of allocating these prescriptions to forested areas can be done in a similar manner as allocating logistical cost. Specifically, rules can be developed and applied using the attributes of spatial objects to identify polygons, portions of polygons, or cells that meet defined thresholds. Once allocated, these prescriptions can be combined with quantified forest characteristics to provide spatially explicit estimates of potential total woody biomass that can be removed from a given location. Finally, depending on the efficacy of the harvesting system and the merchandizing of the trees, treatment residues can be calculated for a given location. These residues represent the amount of potentially available woody biomass that can be utilized for energy and incorporated into potential woody biomass flows.

14.10.5 Estimating Transportation Costs Across a Landscape

Transporting woody biomass represents another important spatial aspect of logistics costs. Typically, these costs are derived as a series of rates relating to factors such as road speed, fuel consumption, machine hours, and payload. When combined with other costs, these rates can be converted to an absolute value based on hauling distance or time (trip) and the total number of trips required to transport the material. Within a GIS, hauling routes that minimize travel distance and time can be estimated for a route from a starting location (source of biomass) to an ending location (facility) using a road network, source and delivery points, and road network routing [20]. The total number of trips required to transport woody biomass from a given location can be estimated from the total amount of woody biomass available at that location, the associated densities of the woody biomass, and the payload of the truck-trailer configuration. Moreover, trip distance or time and number of trips can be tied together based on the spatial relationship between the source of woody material and the road network.

Minimizing travel distance and time between the source of biomass and a delivery site is straightforward within a GIS. However, on a forested landscape there are many potential sources of biomass for which to determine optimal routes to delivery sites. In this situation, it is easier to think of loading points along a transportation system that can be attributed a minimized trip distance and time. From loading points on the road network, polygons can be created that define the areas closest to each individual loading point, in an automated fashion (Thiessen polygons). Each Thiessen polygon can then be attributed with the transportation costs of its point on the road network, which can be efficiently related to estimates of biomass using spatial relationships.

14.10.6 Estimating Harvest Costs Across a Landscape

Similar to determining transportation costs across a landscape, harvesting costs are derived from rates such as fuel consumption and machine hours. Additionally, absolute costs derived from harvesting rates depend on the total amount and density of standing biomass. While the amount and density of biomass is typically quantified for polygons or a raster surface, the boundaries of those polygons or cells of the raster surface may not represent boundaries of areas that will be harvested. A separate spatial table that defines harvest unit boundaries is often needed to account for management objectives and the logistics of harvesting.

In practice, predicting the location of a harvesting unit boundary is difficult prior to its actual creation. However, within a GIS rules can be created that generalize harvesting policy, management objectives, and stochastic events to create potential harvesting units across a landscape. These rules can quickly become complex and can incorporate a wide range of factors, such as topography, proximity to streams, available tree biomass, maximum harvest unit size, proximity of harvest units to recently harvested land, fire mortality and beetle kill. Often, due to the complexity of building rules for harvest unit boundaries and the reliability of the outputs, a surrogate boundary table such as the Thiessen polygons described in Section 14.10.5 is used to represent harvesting units.

Once harvest unit boundaries are defined, rules and thresholds based on factors such as topography and soil condition can be used to determine the appropriate harvesting system. In addition, total woody biomass, densities, and residues can be calculated for harvest boundaries by spatially relating the geometry of each harvest unit to the estimates of biomass stocks. Absolute costs for the harvest unit are then calculated using the cost rates associated with the selected harvesting system and the weight of the residuals calculated from a treatment.

14.10.7 Planning

After determining harvest and transportation costs across a landscape, the two can be linked to one another through overlay analysis [21]. Specifically, absolute harvesting costs can be combined with absolute transportation costs based on estimates of woody biomass residues for a given harvest unit and the spatial proximity of that harvest unit to the closest loading area. These combined costs are attributed to the harvest unit and compared in relative fashion across the landscape (cost per acre or weight of material). Furthermore, estimates of available woody biomass residues for the harvesting unit are used to represent potential flow of material from that location. Using these costs and potential flows, questions such as how much woody biomass is available across a landscape, where are the least expensive areas to procure woody biomass, from which locations is it profitable to market woody biomass, and are there timing components related to harvest locations that can reduce logistical costs, can be answered in a relatively quick and easy manner.

When utilizing base data and rules to derive cost and potential woody biomass flows from a landscape, it is important to consider the scale and the level of precision needed to answer these types of questions. Base data and rules that are too coarse may not provide an adequate level of detail to properly estimate woody biomass and flows. On the other hand, too fine a scale may present issues related to finding and developing complete data sets, digital storage space requirements, and total processing time and memory it takes to perform spatial analyses for the landscape of interest. Once defined for harvesting units, these costs and potential flows can be used to plan harvesting schedules across both space and time for a given landscape. Multiple simulations depicting various policies, objectives, and conditions can be compared to evaluate the impacts of decisions made based upon the constraints of those criteria. Moreover, if objectives and constraints can be spatially represented in a relative fashion they, can be optimized across the landscape to minimize logistic costs and maximize woody biomass flows. Such analysis can help reduce biomass supply costs, especially in complex procurement environments.

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15

Economic Sustainability of Cellulosic Energy Cropping Systems

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15.1 Introduction

Cellulosic energy cropping systems can be sustained when economic incentives remain positive for each participant in the system. In other words, profit from an energy cropping system must equal or exceed profit from available alternatives for each component of the system. This chapter includes an overview of economic principles applied to sustainable energy cropping systems. Capital investment and risk are addressed in addition to recurring revenue and operating costs. Sustainable policy issues and non-market issues such as environmental protection, resource conservation and energy security are also presented. Implications of the comparative profitability requirement are presented for each link in the energy cropping supply chain. The interaction of prices and quantities supplied and demanded is a primary focus for each of the goods and services affected by sustainable energy cropping systems.

Economics is the study of resource allocation to maximize the welfare of people. Applications range from (1) specific choices by individuals, to (2) decisions by a variety of business entities, (3) local, regional, national, and global market behavior, and (4) government policies. In many economic applications, people are perceived to maximize their personal welfare or utility through their choices to invest, produce, save, or consume. People's choices are constrained by the quantity of resources they have and by the level of available technology. Technology is defined here as the capacity to convert resources to goods and

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services valued by people. As simplifying restrictions are relaxed, economic models are expanded to include optimization over time and to include risk and uncertainty. These basic ideas are applied to sustainable energy cropping systems in the following sections.

Sustainable systems are defined conceptually here as systems that are economically competitive, that are not dependent on excessive consumption of scarce resources, that are not dependent on excessive levels of detrimental emissions to the environment, and that are generally socially acceptable. Absolute thresholds for these definitions are not proposed here. Economic concepts of the trade-off between marginal changes in absolute thresholds and other determinants of human welfare are raised in this chapter.

15.2 Economics of Crop Production

Crops of all types are typically produced for profit by a producer. Profit can be defined as the value of products produced minus the value of inputs used in production:

$$\pi = p_y \cdot q_y - p_x \cdot q_x \tag{15.1}$$

where π = profit, p_y = price of product, q_y = quantity of product, p_x = price of input, and q_x = quantity of input.

Producer behavior is often represented as profit maximization in economic models. The amount of profit that producers can make is limited by several constraints and exogenous variables. Constraints include technology and quantities of resources or inputs available to the producer. Exogenous variables include prices for inputs and outputs on which the producer's decisions have no significant market effect. Exogenous variables also include inputs such as temperature, sunlight, and rainfall that have no price, are beyond the control of the producer, and can have large effects on production and profit. Control variables (those affected by the producer's decisions) include which type and variety of crop to produce and what quantities of variable inputs to use (area of land, machinery use, seed, fertilizers, crop protection and other chemicals, irrigation water, labor, management, insurance, other risk management aids, fuel and lubricants, other supplies, custom services, and others). Control variables also include intermediate and long-term variables, such as the type and quantity of land to own or rent, the type and capacity of machinery to own or lease, the type and amount of debt to incur, the type of human capital to acquire and maintain, and others. Included among control variables, too, are management decisions such as planting and harvesting dates that do not have specific prices attached but can have large effects on production and profit.

The Profit Maximizing Crop Producer's Objective Function is:

$$\text{Maximize: } \pi = \sum_{y=1}^{Y}(p_y \cdot q_y) - \sum_{x=1}^{X}(p_x \cdot q_x) \tag{15.2}$$

Subject to: $q_y \leq f(q_x)$ the technology constraint
$q_x \leq q_x^*$ constraints on the availability of some inputs
$p_y = p_y^*$, $p_x = p_x^*$ prices determined exogenously

where π, p, and q are profit, price, and quantity as in Equation 15.1, $\sum$ is the summation over all products (y) or over all inputs (x), $f(q_x)$ is a function of quantities of inputs (x)

used that defines the maximum amount of product (y) that can be produced with current technology, and q^* and p^* are fixed quantities and prices that are exogenous to the producer.

The technology constraint embodies the biological relationships that define crop growth and product yield. Genetic stock of the plants, via seed, determines the maximum growth and yield possible. Most plants and animals are limited in their growth and yield by insufficient supply of one or more of the inputs or conditions for optimal growth. Much of modern agriculture and silviculture is dedicated to identifying those deficiencies and correcting them. Examples include various fertilizers, irrigation water and drainage, chemicals for plant protection from disease and weeds and pests, mechanical treatment of soils, and temperature and light control in greenhouses. Another important part of modern agriculture and silviculture is dedicated to development of genetically superior plants and animals. Sustainability in crop production is inseparable from production decisions and is discussed in a subsequent section.

15.2.1 Crop Enterprise Budgets

A widely used tool for evaluating the potential costs, revenues, and profit from crop production is the enterprise budget. Crop enterprise budgets are typically customized to local production conditions. The Ag Risk and Farm Management Library [1] provides links to a variety of enterprise budgets and most United States state agricultural extension services have sample crop budgets available [2]. Budgets for non-traditional crops may be more difficult to find and may be based on smaller samples of actual production data.

Each enterprise budget represents a single point on a profit function (Equation 15.2). A specified quantity of product and a specified quantity of each included input are multiplied by specified prices, respectively, and summed to obtain estimates of revenue, cost, and net returns to excluded inputs and profits. Most published enterprise budgets are not intended to predict costs, revenues and profit for each or any producer. Instead, they are intended as a somewhat typical guideline and as a starting point for use by producers to adapt to their own production and market conditions. Enterprise budgets may embody generally recommended practices and input levels to produce the optimal yield of a selected crop in a selected location for a specific year or season. Farms vary widely in terms of area farmed, topography, soil type, crop mix, machinery complement (age, capacity, equipment type), labor availability, managerial expertise, weather and other factors. Management decisions are likely to deviate from initial plans as weather, markets, and other variables deviate from "normal" during the growing period. Lazarus [3] provides an example of an enterprise budget for a single season crop: corn for grain and for corn stover.

Several characteristics of enterprise budgets are notable. The revenue section of the budget lists each of the products of the crop that generate revenue, such as grain and stover. The cost section of the budget lists each input with quantities, prices, and cost. The cost section may separate costs of single use inputs (seed, fertilizer, chemicals, custom services, etc.) from costs of owning machinery and equipment and from costs of labor, management, and land. The single use inputs are typically cash expenses for farmers while the other inputs may be owned and contributed, shared with other crops, financed with borrowed money, or residual claimants on net revenue. The net returns section of the budget lists the balance after costs have been subtracted from revenue. Net returns equates to profit if all costs have been subtracted or it may represent a net return to inputs that have not been included as costs: typically management and land. In order to facilitate analysis of profit maximizing decisions, enterprise budgets should accurately portray the quantity and price or value of each product and of each input used to produce the crop.

Olson [4] provides a thorough overview of farm management issues and methods.

15.2.2 Stover as a Co-Product of Corn Grain

Cellulosic energy crops can be categorized as co-products or dedicated crops and as single season (e.g. corn) or perennial (e.g. switchgrass) or multiseason crops (e.g. trees). Corn stover is a single season, co-product crop. The revenue from a co-product must meet two conditions for economic feasibility. Firstly, the sum of revenues from all co-products of the crop must exceed the sum of costs of production. Secondly, the revenue from each co-product must exceed the additional costs of producing that co-product. In the example from Lazarus [3], the revenues from stover as a co-product of corn grain are $126 per acre (at $70 per ton) and marginal costs are $89 per acre, including $33 for fertilizer, $41 for machinery with labor, and $14 for transport, generating a net return of $37 per acre. The addition of a profitable co-product can increase the profitability and competitiveness of an existing crop.

15.2.3 Perennial and Multiseason Crops

Costs and revenues for perennial and multiseason crops occur over several seasons so additional calculations are needed to represent annual costs and returns. A separate enterprise budget is prepared for the establishment period of the crop. The establishment period may be one or more seasons, during which the crop is planted and allowed to grow to sufficient maturity that harvesting can begin. Total cost minus any revenues during the establishment period is calculated. The net cost of establishment is then amortized as an annual expense over the productive period of the crop. North Carolina State University (NCSU) [2] provides an example of an enterprise budget for switchgrass, including an establishment budget and a line on the annual budget listing amortized establishment cost. A life cycle accounting approach may be applied to perennial or multiseason crops such that costs or benefits of restoring land to its original productive state can be assessed and distributed backwards on an annual basis to the crop.

15.2.4 Crop Production Functions

Important production decisions are assumed to have been made prior to assembling enterprise budgets. How much of each input to use, when to plant and harvest, which land to use, and many other control variables are treated as fixed in enterprise budgets. A crop enterprise budget is a "snapshot" or single point representation of a complex set of production possibilities. Usually, the crop enterprise budget portrays the profit maximizing or recommended set of practices and expected yield. Economists employ production functions to represent the physical and biological relationships inherent in crop production. Physical and biological scientists study the relationship between various input levels and management decisions and the resulting plant growth and yield characteristics of a crop. Economists are interested in analyzing which combination of inputs and management decisions results in the most

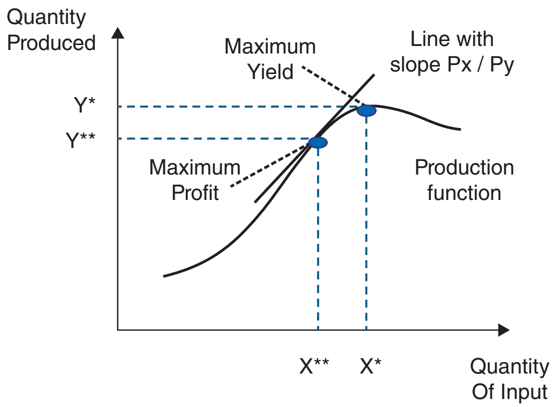

Figure 15.1 *Production function with profit maximum versus yield maximum.*

profit. Figure 15.1 illustrates a simple production function with quantity produced on the vertical axis and quantity of input used on the horizontal axis. The curved line represents the quantity produced as a function of the quantity of input used. Maximum yield y^* occurs when input quantity x^* is used. Profit maximizing yield y^{**} occurs when input quantity x^{**} is used. Profit maximizing quantities are defined by tangency of the line with slope p_x/p_y to the production function. This tangency is derived from a condition of profit maximization stated as Marginal Cost = Marginal Revenue.[1] In other words, at the profit maximizing level of input use, change in total cost equals change in total revenue. At this point on the production function, any additional use of input increases cost more than it increases revenue. Similarly, at the optimum point, any reduced use of input reduces revenue more than it reduces cost. A second order condition for this point to be a profit maximum is that the slope of the production function is declining. This characteristic reflects declining marginal yield response to additional input use as maximum yield is approached. An important general point is that the profit maximizing level of input use and yield is generally below maximum yield unless the input is free.

The identification of a profit maximizing set of inputs for a specific crop is very difficult. Many inputs and interaction between inputs cause the simple input–output relationship depicted in Figure 15.1 to become a complex multivariate function. The relationship between control variables and other independent variables, such as prices, climate, and soils, further complicates the farmer's decision problem. A sustained program of agricultural research and extension education combined with the practical experience of farmers has allowed United States agriculture to achieve very high and increasing levels of agricultural productivity. Yields of many crops have increased steadily over time while input use has remained constant or fallen. It is important to note that production cost per unit falls as yield increases as fixed and quasi-fixed costs are spread over more units of production. The link between productivity and sustainability is discussed in a later section.

[1] Mathematically, the profit maximizing condition is stated $p_y * \Delta q_y = p_x * \Delta q_x$. Rearranging terms, the profit maximum is expressed in terms of the slope of the production function being equal to the ratio of input price to product price: $\Delta q_y \div \Delta q_x = p_x \div q_y$.

15.2.5 Crop Rotations and Long Run versus Short Run Land Allocation

After approximating how much profit can be expected from each of several crops that could be grown, farmers must decide how much of their land and which land to allocate to which crops. Farmers may prefer to rotate crops on each field. For example, they may prefer to plant corn on a field one year and soybeans on the same field the next year. Yield and input cost may be conditional on rotation. Repeated planting of the same crop or the same class of crops on a field may result in increased pressure from disease, weeds and other pests. Increased disease and pest pressure may result in lower yields and increased rates of pesticide use. Rotating crops may allow use of a wider variety of control products and practices over time, resulting in higher yields and lower pest control costs. In dry climates, a fallow period may be included in the rotation to increase soil moisture and allow increased pest control. Crop rotations may include two or more crops being produced on the same field in a single year. Prolonged periods of temperatures above freezing and prolonged periods of absence of extreme heat and drought are conducive to more than one crop being produced on the same field in a year.

In each planting period, farmers' crop selection decisions may be further constrained by availability of seed and other inputs. Farmers may deviate from their usual rotation when potential profit from a crop or input constraints suggest a crop mix different than their longer term crop rotation.

Multiseason and perennial crops require farmers to make a longer-term decision about land allocation. Expected profit from a perennial crop over a 3–5 year period may be compared to several single season crops and other multiseason alternatives. The importance of time in farm decision making is emphasized by perennial crop decisions.

15.2.6 Economies of Size and Scale

Cost per unit produced (bushel, ton, etc.) of a crop may fall with increased farm size or scale. Economies of size and scale arise from costs that do not increase proportionately to the area of land being farmed or the quantity of the product being produced. For example, a tractor driver operating implements 20 feet in width may cost the same per hour as a driver operating similar implements 40 feet in width. The cost of the driver per acre or hectare is far less for the driver pulling 40 feet wide implements. Similarly, the purchase price of many implements, tractors, and structures may increase at a fraction of the rate of increase in their capacity. Therefore, the ownership cost per unit of work completed may be lower for the larger machinery when both sets of machinery are used to capacity. Economies of scale can be seen in enterprise budgets for differing field sizes and underlying farm sizes for the same crop in the same location.

Diseconomies of scale also exist. As farms and other businesses become larger, the required quantity of management increases. Additional people may be employed and additional layers of management may be required to coordinate activities.

Economies of scale also exist in acquisition of inputs and selling products. Average price per unit purchased may be reduced for large volume orders that reduce the selling costs incurred by suppliers. Smaller-scale farmers may achieve the benefits of economies of scale by working with other farmers or by hiring custom services to employ specialized equipment or oversized equipment without owning it. Marketing associations and buying clubs allow groups of farmers to acquire benefits of large volume transactions.

15.3 Risk and Uncertainty

Discussion to this point in the chapter has largely ignored risk and uncertainty. Crop production is inherently risky and uncertain due to the effects of weather, biological factors including disease and pests, and markets. The actual quantity produced and the price received for a crop may differ considerably from levels expected by the farmer at planting time. Economics of sustainable cellulosic feedstock for biofuels must include consideration of risk and uncertainty. Economists distinguish between risk and uncertainty. Risk is defined here as the possibility of two or more outcomes to an action or decision where the probabilities of occurrence of each outcome are known. Uncertainty is defined here as the possibility of two or more outcomes to an action or decision where the probability of each outcome is unknown. The economic implications of risk in crop production are critical to farmer decision making. A failed crop or sharply reduced prices for the crop result in financial losses for the farmer. A series of financial losses may result in financial collapse and loss of the farm business. A cellulosic energy production system is also vulnerable to risk where loss of feedstock supply or adverse variation in prices may bankrupt processors and other businesses in the supply chain.

15.3.1 Yield Risk

Yield risk is defined here as the risk that the yield of a crop may differ from that which was expected at planting time. Crops are subject to many types of damage. Weather affects yields in many ways. Inadequate supply of water at critical points in the growth of the plant reduces yield and extreme drought can kill the plant. Excessive heat or frost can damage or kill plants. Severe storms can damage or kill plants by hail, wind, or flooding. Fire, whether started by lightning or other cause, poses a risk to crops. Biological factors also affect yields. Disease, fungus, insects, weeds, birds and other animals all can reduce crop yields in terms of quality and quantity.

Yield risk can be quantified in several ways. By recording yields in different fields each season, a frequency distribution can be assembled for each type of crop. Historical frequency distributions can be adjusted for trends in average yields to estimate probability distributions for the coming crop season. Crop insurance underwriters may estimate probability distributions for crops to determine what level of yield to insure and what premium to charge for insurance. Note that yield is conditional on many factors. Distinct yield probability distributions may be estimated for the same crop grown under different conditions. Locational factors, such as soil type and climate, affect historical yield frequency distributions as well as estimated probability distributions. Managerial factors, such as seed variety or genetic type, particularly in relation to planting date and days required for crop maturity, can affect the estimated probability distribution. Similarly, irrigated crops can have very different yield probability distributions than dryland crops of the same type.

Figure 15.2 illustrates three yield probability distributions. The horizontal axis indicates yield and the probability of occurrence is indicated on the vertical axis. Each of the curved

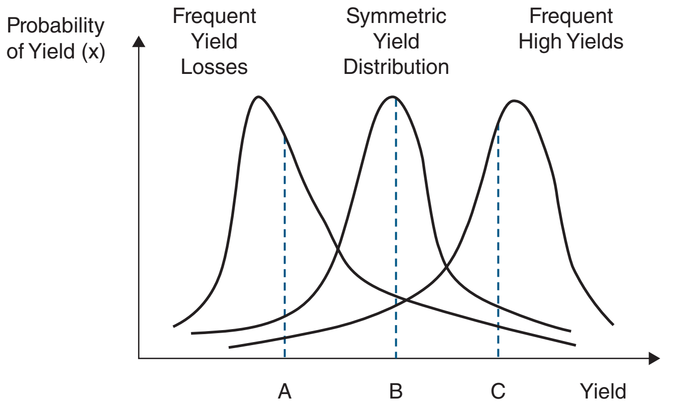

Figure 15.2 *Three yield probability distributions with mean values.*

lines represents a different yield probability distribution. The middle curve represents a symmetric distribution with similar probabilities of yields above and below the mean or average (point B). The curve with higher probabilities of lower yields and a long tail of declining probability to the right has mean labeled 'A' and represents a crop that seldom achieves its potential and often suffers reduced yields. This probability distribution can represent a crop being grown in adverse conditions. Conversely, the curve with a long tail of declining probability to the left and higher probabilities of high yields with mean 'C' represents a crop that frequently achieves near maximum yields. This probability distribution may represent a crop that is being grown in favorable conditions and could represent an irrigated crop. A general observation from this example is that crop yield probability distributions may differ both with respect to their mean or expected yield as well as the probability of various degrees of yield loss below the mean.

The economic effects of yield risk are many. Farmers incur routine costs to prevent or reduce risk of yield loss. Herbicides, pesticides, and fungicides are examples of inputs that are not used directly by the plant for growth but that reduce the frequency of losses due to pests. Irrigation and fertilizers provide inputs used by the plant and affect both average yield and the probability of yield loss. Farmers also incur costs of excess input use when yield is reduced or crops fail. For example, fertilizer may be applied at a rate sufficient for the expected yield or for a higher yield that is quite possible. When a lower yield is realized, the value of excess fertilizer is wasted. In other words, had they known the yield would be so low, the farmer could have applied less fertilizer and saved some input cost. Conversely, if a farmer applies only enough fertilizer for the average or expected yield and conditions occur that would have supported a higher yield, the farmer loses the value of foregone yield net of the additional fertilizer cost. The purchase of crop insurance is a common method of mitigating the financial effects of yield risk.

15.3.2 Stochastic Production Function

The production function discussed previously in this chapter was deterministic. Risk was not considered in that function. A stochastic production function is a more general presentation of the same concept. Rather than a single output quantity being associated with each input quantity or set of input quantities, the stochastic production function has a probability distribution of output quantity associated with each input quantity or set of input quantities. This specification of a stochastic production function allows input quantities to affect not only the mean yield but also the probability of various degrees of loss (or gain) relative to the mean. In other words, the quantity of inputs used can affect the mean, variance, skewness, and kurtosis of the yield probability distribution. The farmer's decision problem may be more realistically portrayed by a stochastic production function. The additional complexity introduced by the stochastic production function may also be more representative of the decision challenges faced by farmers. Not only must they consider the effects of numerous inputs on expected yield but also their effects on the probability of various degrees of yield loss or gain relative to the average yield.

15.3.3 Price Risk

Price risk for crops arises from changes in market conditions during the crop production period. Prices for both inputs and outputs can change from the time the farmer decides to plant the crop until the time the crop is sold. This statement is true for single season crops as well as perennials and multiseason crops. Shocks to supply of a commodity can arise from many sources, including widespread weather events such as drought or an unusually favorable growing season over a wide area. Shocks to demand can also occur due to a range of factors, including reduced supplies of a competing product such as petroleum with respect to biofuels. Unexpected loss of processing capacity due to damage or financial failure can also shock the demand for an intermediate product such as cellulosic biomass. International trade disruptions and changes in currency exchange rates can affect the prices of many goods and services as well. Crop farmers have experienced very substantial volatility in prices for seed, fertilizer, fuel, and crop products over the past decade.

15.3.4 Effects of Risk on the Profit Maximization Decision Framework

A simple deterministic profit function was presented in Equation 15.2. The introduction of risk creates a more general expression of the farmer's decision problem. Instead of all profits, prices and quantities being represented by single values, some are represented as probability distributions. In particular, quantity produced and price of product may be expressed as probability distributions with a known or predicted mean value and, at least, a known or predicted variance. In other words, some of the constraints to Equation 15.2 become stochastic, including the production function and some of the price constraints. The presence of stochastic variables on the right-hand side of the equation means that profit (the left-hand side variable in Equation 15.2) is also stochastic. Rather than maximizing profit, the farmer is now said to maximize expected profit. That is, the farmer chooses inputs to maximize the mean or expected value of profit rather than actual profit.

Consideration of risk caused economists to consider even more general representations of the farmer's decision problem. Rather than maximizing expected profit, the objective function can include terms for variance of profit or the probability of losses or gains relative to expected profit. Decision makers who are risk averse may prefer to forego some expected profit in exchange for reduced probability of losses below the expected value. A simple objective function that incorporates risk has the left hand side of the equation include expected profit minus some coefficient multiplied by variance of profit. A larger coefficient on the variance of profit term indicates greater risk aversion by the decision maker and a greater willingness to exchange lower expected profit for reduced variance of profit. A zero coefficient on the variance term means the decision maker is risk neutral and will maximize expected profit regardless of variance of profit. In general, this farmer objective function in the presence of risk suggests that two farmers faced with the same yield and price distributions may choose different input quantities solely due to their differing preferences for risk. Risk management comes into focus as an important aspect of farm management.

15.3.5 Time and Risk

As the discussion here has shifted from deterministic models of production and profit to stochastic models with risk, the dimension of time was made explicit in the crop production process. The time between the crop planting decision and the sale of the crop was identified as a source of risk. Time is a critical dimension of biological processes. Longer periods between the planting decision and final sale of the product may allow for increased risk. More shocks to production and to markets may occur over a longer period of time. Therefore, decisions that commit farmers' resources over a longer period to production of a specific crop may entail more risk. A subsequent section examines risk mitigation. Time is also an important underlying factor in the finance of inputs, including operating inputs such as seed and fertilizer, as well as longer-term assets such as machinery and land.

15.3.6 Finance, Risk, Debts and Assets, Bankruptcy

Operation of a farm or any business requires financing input purchases and asset utilization. Farmers may borrow large amounts of money or invest their own money to buy land. Agricultural land is an appreciating asset typically valued at many times the annual rent it can generate from agricultural use. Farmers also invest and may borrow money to buy machinery, such as tractors, trucks and equipment, and buildings, such as grain storage. Machinery and buildings are depreciating assets that may provide needed services over a number of years and may have a smaller resale value through time. Farmers also invest their own money or may borrow money to purchase operating inputs, such as seed, fertilizer, chemicals, and fuel, or to rent equipment or hire services during the growing period. The money used to finance the purchase of operating inputs is referred to as operating capital.

All capital used in the farm business comes at a cost. The cost of capital is time dependent. Interest is charged at some rate per period of time for borrowed capital. Interest is foregone on money invested by the farmer in the business. The interest paid to lenders is visible as a cash expense while interest foregone on owned capital is an opportunity cost. Owned capital could be used to pay off other loans and avoid interest costs or it could be invested in interest-bearing accounts.

Capital is a limiting resource for businesses. Without capital, farmers are unable to acquire inputs needed for crop production. Lenders typically require security for the amounts they lend. Non-depreciating assets such as land are preferred collateral. Depreciating assets such as machinery and buildings may also have value as collateral. Lenders may accept an ownership interest in the growing crop as partial collateral for operating loans. Other assets, such as other real estate and savings accounts, also serve as collateral for borrowed money. Interest on capital appears in the enterprise budget both as an operating expense for operating capital and as a component of the amortization of investments in machinery and buildings.

The net worth of any business, including farm businesses, can be defined as the total value of assets minus the total value of debt. An important implication of risk in agriculture is that crop losses reduce the net worth of the farm business. When losses exceed net worth, the farm business may no longer be viable and may be foreclosed upon by lenders, may enter bankruptcy, or may simply be unable to finance new production. Farmers with smaller net worth relative to the size of their farm may find it more difficult to borrow money and may have to pay higher interest rates. Such farmers may also select less risky crop mixes or less risky input combinations in order to reduce the probability of financial collapse. Acquisition of new machinery to produce a new crop or the allocation of land to a new unproven crop may impose capital costs and risks that are unacceptable to low net worth farmers.

15.3.7 Product Market Risk and 'Thin' Markets

Another type of risk faced by farmers is the risk that there may be no place to sell their crop once it is harvested. The farmers are then forced to pay substantial transportation costs to deliver to a distant market or they may have no outlet at all for a very specialized crop. The term 'thin markets' is used to describe the case where there are few buyers or few sellers. Two problems arise from thin markets. Firstly, there may be no one willing to buy or no one willing to sell at various times, such that both sellers and buyers may incur additional costs. Secondly, the loss of a buyer or seller due to financial failure or other causes may impose severe losses on other sellers or buyers. Such risks must be overcome when new markets are being established, as in the case of cellulosic feedstocks.

15.4 Risk Mitigation and Management

A variety of instruments and methods are used by farmers to manage risk. The use of production inputs to limit yield risk was discussed in a previous section. Insurance is a traditional instrument used to mitigate risk by pooling a large number of independent risks, collecting premiums from each, and paying benefits to those suffering losses. Crop insurance is available in many countries and is often underwritten or re-insured and subsidized by governments. In the United States, the national crop insurance program requires a history of at least three years of production yield in a given location before offering insurance. Pilot programs for new crops may provide coverage until a larger program is established. Crop insurers may also offer crop income insurance where a degree of price risk mitigation is included with yield risk mitigation in the insurance contract. Collaboration with crop insurers on establishment of a new crop insurance program can provide an important risk mitigation alternative for farmers.

Futures markets and options provide an important price risk management instrument for buyers and sellers of large volume commodities. Futures and options contracts are standardized contracts traded on central exchanges. The futures contracts specify date, location, quantity, and quality of a commodity to be delivered. By taking an offsetting position (called a hedge) in the futures markets, buyers and sellers can essentially lock in the price they will receive or pay for the commodity. Costs of using this instrument include transaction fees paid to brokers and the maintenance of a margin account with the brokerage. The margin account is a cash reserve that buyers and sellers must maintain with the exchange to ensure that they will honor their obligations under the contract. A large amount of capital may be required to maintain margin accounts. Most futures contracts no longer allow actual delivery and are cash settled instead, based on a specified spot market price. In either case, the price that a buyer or seller receives locally may differ with date, location, and quality from the price used to settle the futures contract. The difference between cash price and futures price is called basis. Basis is variable over time, so it is a remaining source of risk for futures contract hedgers, albeit considerably smaller than overall price risk. Options contracts are derivatives of futures contracts that are also traded on central exchanges. Commodity producers and consumers can buy options to establish a minimum or maximum price that they will receive or pay. They pay a premium to purchase the option contract. As option buyers they do not have to maintain a margin account. If prices move adversely, they can sell the option and recover the difference between the floor or ceiling price established with the option and the current price of the underlying futures contract. These contracts are unlikely to be available for new small volume commodities but are available for large scale crops, including wood products, and can be established for new crops when the volume becomes large enough.

Production contracts and marketing contracts are used widely in agriculture, particularly for specialty crops. Marketing contracts are also used where buyers and sellers seek to avoid marketing and procurement costs by establishing longer-term contracts for delivery and pricing. Marketing contracts may establish the schedule for delivery, the terms for pricing, and penalties, bonuses, and courses of action for various circumstances that may arise. Production and marketing contracts are also used for commodity agricultural products where buyers desire specific qualitative traits in their purchases and those traits are more costly to measure than to acquire through contract. Production contracts may include terms where the buyer provides some inputs such as genetic stock, provides harvesting or transport of the crop, and acquires all product from the crop. The production contract may provide a specified price with quality adjustments to be paid by the buyer to the seller upon collection of the product.

Marketing contracts and production contracts help mitigate many of the ongoing risks in agricultural production. Such contracts still leave the farmer or the buyer subject to risk of contract failure. Financial failure or other inability or unwillingness of the other party to meet their obligations under the contract may leave the remaining party in severe financial difficulty; particularly if there are no other processors or suppliers of feedstock nearby. Parties to contracts should have plans for contract failure in place before the contract is signed.

Strategies for managing financial risk include the use of fixed rate debt, diversification of crop mix and other agricultural enterprises, maintaining a large cash reserve or diversification of investments in unrelated assets. Taking on partners or shareholders to provide more equity capital is another common strategy to manage financial risk. Using contracts and insurance to limit the probability and severity of financial losses helps limit risk of financial failure.

15.5 Supply, Demand and Prices

The combined effect of many farmers' decisions about which crop to plant and how to produce it is a supply function for each crop. The supply function is defined as the schedule of the quantities of a commodity that will be produced at various prices for that commodity; all else held constant. Typically, as prices rise, producers are willing to produce more of that commodity. Increased production may be achieved by increasing the amount of various inputs and possibly reducing the production of other commodities. The supply function can be shifted up or down by factors other than the price of the product. For example, increases in the price of a competing product may cause farmers to reduce production of one crop to increase production of the competing crop. The supply function of the original crop would shift up and to the left such that a higher price would be required to maintain the same level of production. Changed prices of inputs are another factor that can shift supply functions. Lower input prices mean farmers are willing to use more inputs and supply more of the crop at the same product price. In other words, the supply function shifts down and to the right with lower input prices. Technological improvement has been a major shifter of supply of agricultural commodities over the past several decades. Technological improvement is characterized by yield increases with declining levels of input use and hence lower cost per unit yield. Technological improvement of cellulosic crops can thus be a major driver of sector growth.

Supply of cellulosic crops may take many forms and may be location specific. Where the cellulosic crop is a lower valued co-product (e.g., corn stover), the supply may be driven largely by the supply of corn and the marginal costs of harvesting and delivering stover and the cost of replacing any soil nutrients exported with the stover. Where the cellulosic crop is a stand-alone crop, such as any of the perennial grasses, in a cash market setting the supply may conform to the classical description above with quantity being driven by price and relative profitability versus other crops. Where the supply is restricted by contracts to a fixed acreage, then price may have limited effect on quantity supplied except to the extent that variable inputs are used or not used to enhance yield. A thorough overview of bioproduct feedstock supply in the United States is provided in the Billion Ton Study Update [5]. A demand function for cellulosic crops may be defined as a schedule of the quantities of cellulosic feedstock that will be demanded at various prices, all else held constant. As prices rise, the quantity demanded would fall as purchasers find substitute feedstocks or simply reduce the quantity consumed. Shifters of demand for a specific cellulosic feedstock may include the price of a competing feedstock. As the price of a competing feedstock falls, buyers shift to the competing feedstock and demand less of the current feedstock. The demand curve shifts down and to the left as a lower quantity is demanded at the same price. Similarly, an increase in the price of the end product (e.g., fuel) may shift the demand function upward and to the right as buyers are willing to bid more for the same quantity of feedstock.

Longer term, demand for commodities may be expected to increase as the global population becomes larger (e.g., from 7 billion to 9.1 billion by 2050) and particularly as income rises (by 135% by 2050). Population and income are important demand shifters for many goods and services. Furthermore, declining stocks of non-renewable inputs such as petroleum and phosphorus may result in reduced supply and higher relative prices for such commodities. Reduced supply may increase the demand for substitutes and increase incentives for technological change that reduces use of those commodities.

15.5.1 Derived Demand

Intermediate products such as cellulosic feedstocks face a derived demand function. That is, the demand function they face is derived from the retail market for the end products and translated through the profit functions of each handler and processor involved in transforming the feedstock at the farm to the products at the consumer outlets (biofuel, other biochemicals, etc.). In addition to the retail prices for end products, derived demand functions are shifted by prices and quantities of inputs used from farm to retail. Capital, labor, and energy are important inputs in converting cellulosic biomass to end products. Because of their bulkiness, the costs of transporting and storing cellulosic feedstocks are important shifters of the derived demand function at a specific farm. That is, the farm price at which a specific quantity is demanded may fall with distance from the initial processing location. Some processing operations offering contracts with transport included may restrict contract offers to farms within a specified radius around the processing location (e.g., 30 or 50 miles).

Again, technological change can result in an upward shift in derived demand. More efficient conversion of feedstock to end products allows processors to bid more for feedstock. Historically, the farm to retail margin for bioenergy products has been less variable than the retail price of biofuels and other fuel. In other words, most of the volatility in farm prices for biofuels feedstock crops can be traced to volatility in retail fuel prices.

15.5.2 Equilibrium: The Interaction of Supply and Demand

Prices for commodities arise from the interaction of supply and demand. The point where the supply function intersects the demand function reflects the price at which quantity supplied equals quantity demanded. Given the myriad relationships affecting supply and demand, market clearing prices may be continuously changing. Artificially set prices may quickly become obsolete. The stochastic nature of prices links directly to the profit function of the farmer and of each supplier, handler and processor participating in the supply chain.

Logistics are very important in cellulosic crop to product systems. The costs of transport were mentioned previously as affecting demand or price over distance. Storage costs may similarly affect price or demand over time. If a crop is only harvested once per year and processed throughout the year, then almost all of the crop must be stored over periods ranging from a few days through to an entire year. Similarly, if the crop is harvested over several months and processed throughout the year, then the quantity processed outside of the harvest period must be stored from a few days up to the full length of the period. Costs associated with storage include investment in storage structures, handling costs of loading material into and out of the storage facility, interest on operating capital invested in the stock in storage, value of commodity lost to shrinkage in quantity and quality, and costs of managing risk for the stored material.

Demand, supply, and prices are usually contingent on quality. Typically, the concentration of the desired components in the feedstock is an important measure of quality. Price per gross unit of quantity of the feedstock may increase with higher concentrations of desirable compounds and decline with higher concentrations of undesirable compounds.

Value of co-products can be important for feedstocks. If co-products of a cellulosic chemical have value, processors may bid more for the feedstock and still generate profit. In effect, derived demand is increased.

15.5.3 The Derived Demand for Land

A puzzle for many who develop pro-formas for cellulosic crop to chemical systems is what amount to budget for land. This puzzle arises from the endogeneity of land rent in the supply and demand functions of crops. In other words, when demand for a new crop is introduced to an existing equilibrium in agricultural crop markets, the use of land to produce that crop reduces the supply of land available to other crops. Reduced supply of an input reduces the supply of those crops. The new equilibrium price for those crops is higher as reduced supply interacts with constant demand. With higher crop prices and all else held constant, farmers bid up the demand for land. Land rents increase and if land rents are sustained at a higher level, the sale price of agricultural land rises. Developers of new crop-to-chemical systems should anticipate paying at least current land rents to start and perhaps higher land rents to sustain supply through time.

15.6 The Start-Up Barrier

Start-up of a new crop-to-fuel system poses difficult challenges. Farmers unfamiliar with a crop and uncertain of the longevity of the only market for that crop may be willing to risk very little on such a venture, particularly if the crop is a perennial that generates little revenue in the first two years of cultivation. Processors may be unwilling to invest a lot of money in a new facility if feedstock supply is uncertain. In this case, a collaboration between farmers, the processor, and interested government agencies is likely required. Long-term marketing or production contracts are required to satisfy farmers and processor that their needed market outlet and feedstock supply will exist. Some degree of establishment cost-share may be required to enable farmers to commit land and other resources to the project for years before any revenue is generated. This may be in the form of a loan that could be repaid over the life of the contract if the venture survives. Work to establish scientific support programs for the crop, as well as regulatory programs to permit chemical use and enable crop insurance coverage, must be completed very early in the process. Farmers and the processor should have adequate equity financing to carry them through the first few years of establishment and provide a subsequent sound basis for ongoing production. Product marketing contracts for major co-products are needed to assure market outlets for the processor unless they are selling into a very large market with many buyers and sellers. Even in the latter case, contracts that provide some degree of price assurance would be constructive. Terms for renewing contracts and re-negotiating terms are critical to good contracts.

In the case where the crop is an annual, farmers may be more willing to enter contracts with limited start-up investment. If the crop is an abundant co-product such as corn stover, contracts may not needed or they may be single season contracts with emphasis on timing of delivery, storage, transport, and pricing. In either case, the processor must have realistic expectations of what prices will be necessary in which locations to acquire the necessary supply. Contracts can determine such prices prior to planting.

15.7 Elements of Sustainability

The production function and profit function presented previously in this chapter make no explicit mention of resource, environmental, and social dimensions of sustainability. The profit maximization model implies reward for efficient use of resources. Similarly, rewards for efficient use of inputs provide disincentive for waste and related environmental emissions. The expected profit maximization and variance minimization model makes explicit the trade-offs between input use, expected profit, and variance of profit. Input use and implied waste may be increased or decreased to affect variability of profit. Various terms can be added to the expected profit maximization model to explicitly incorporate sustainability conditions and incentives. Explicit restrictions can be placed on the crop production function to limit the amount of nutrient loss to surface and groundwater. Such constraints raise the cost of production if they are binding. Emissions restrictions may represent regulatory limits or sustainability conditions imposed by the processor or the farmer. Incentive payments can be added to the income portion of the function reflecting payments received for attaining sustainability criteria. Such terms could represent income from a watershed nutrient trading program or from credits from a carbon capture and retention program.

Outside of the expected profit maximization model, footprint and life cycle analysis based measures of performance can be included in contracts and farmers along with the processor and input providers can apply existing standards for sustainable production to set practices and procedures. Third-party certifying agencies can be employed to audit procedures, monitor progress, and suggest avenues for improvement. Such efforts can inform ongoing technology development efforts within the system.

Markets for traditionally non-market goods and services include markets for nutrient discharge permits or reduction credits, markets for carbon emission reduction credits, markets for renewable energy credits, and others. In addition, some manufacturers may sell branded or certified sustainable products at a premium to capture consumers' willingness to pay for sustainability attributes. Some corporate retailers impose sustainability criteria on their suppliers and incorporate the increased cost of procurement into their product pricing. Such retailers may differentiate their products by highlighting the sustainability criteria in advertising campaigns.

15.8 Policy

Policy can have profound impacts on the economic sustainability of cellulosic-based biochemical systems. Renewable fuel standards can create guaranteed markets for specified quantities demanded of wholesale or retail products. Direct costs are passed on to consumers if the constraint is binding, although reduced demand for other fuels may create some offsetting savings for consumers. Tax credits and deductions can reduce the after-tax cost of investments in facilities and start-up costs. Governments have been willing to give up tax revenue in the short run to create jobs and income and tax revenue over the longer term, particularly in economically depressed areas. Cost-share payments for crop establishment have been made by governments to farmers who sign contracts with new crop-to-fuel systems. Loan guarantees to new processors have also been used to reduce investor risk. Energetic discussions take place around the sustainability criteria and implications of government programs.

15.9 Summary

Economic sustainability of cellulosic energy cropping systems requires that cellulosic feedstock production is a profitable alternative for farmers, as well as other suppliers, handlers, and processors in the supply chain. Crop production is a risky proposition for farmers. Various types of risk including yield risk, price risk, risk of financial collapse, and contract risk must be addressed when considering cellulosic energy cropping systems. A variety of risk management and risk mitigation alternatives are available for farmers and processors. Longer-term commitments by farmers and commitment to single outlet markets by farmers are likely to require more start-up cost sharing and risk mitigation through contracts. Adequate profitability in realistic projected budgets, adequate equity to survive start-up and shocks, product contracts to assure energy product prices through the first few years, and strong scientific support for crop development are important components of a successful start-up and economically sustainable system. Explicit criteria for resource, environmental, and social sustainability can be incorporated into the expected profit maximization model. Sustainability incentives and criteria can be included in contracts and standard operating procedures. Continued investment in technological improvement to increase yields, reduce resource use and environmental emissions, and generally reduce the cost and increase profitability and stability of the enterprise are critical to long-term sustainability.

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Environmental Sustainability of Cellulosic Energy Cropping Systems

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16.1 Introduction

All forms of energy extraction/production/use have environmental footprints, most of which have not been thoroughly analyzed. The U.S. Energy Independence and Sustainability Act (EISA) and the European Union Renewable Energy directive establish goals for bioenergy but the EISA is unique in establishing specific sustainability goals with the regulations. The national United States bioenergy system goals, or RFS2 goals, focus on transport fuels and have numerous requirements related to sustainability. Because of the thorough environmental analysis of RFS2 that has been done by the USEPA, there is a clearer understanding of how cellulosic bioenergy crops can meet RFS2 goals. This analysis will also be relevant to other types of energy systems (non-liquid fuels), such as the use of cellulosic biomass for heating pellets. This chapter focuses on the types of systems described in Chapters 1–12 and includes an examination of woody crops and perennial herbaceous crops. Issues related to environmental sustainability of crop residue removal for cellulosic feedstocks have been covered in Chapter 7, Crop Residues. Also not addressed is the environmental sustainability of annual winter cover crops grown for cellulosic feedstocks because the expectation is that those crops would be grown on existing croplands and with only minor inputs of water, nutrients, and pesticides.

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Future United States bioenergy production as mandated by the RFS2 provisions of the EISA is an unique enterprise in that regulations have been developed that define the required greenhouse gas (GHG) reductions relative to gasoline and diesel fuel from fossil fuels. In the United States, this is the first national regulation to evaluate direct and indirect GHG for any product – GHG life cycle emissions. This is done through an accounting that has been developed by the USEPA and has undergone rigorous peer review [1]. For the first time, biofuels must meet new GHG reduction thresholds to qualify as "Renewable Fuel" or other EISA specified categories of fuels. In addition, only feedstocks produced from certain types of lands will be considered renewable biomass, and thus eligible to be used in production of a "renewable fuel". In general, the feedstock/conversion/fuel systems that meet RFS2 standards will be considered environmentally sustainable, largely because of the factors taken into account in the greenhouse gas reduction analysis. To qualify as a "renewable fuel" [1], the fuel must:

"Be produced from 'renewable biomass' as defined in the rule and demonstrated by reporting and recordkeeping requirements of the rules and qualify based on fuel type, feedstock, and production processes specified in Section 80.1426(f) [or qualify byway of an alternative pathway petition]; "Renewable Biomass means:

1) *Planted crops and crop residue harvested from existing agricultural land cleared or cultivated prior to December 19, 2007 and that was nonforested and either actively managed or fallow on December 19, 2007.*
2) *Planted trees and tree residue from a tree plantation located on non-federal land (including land belonging to an Indian tribe or an Indian individual that is held in trust by the U.S. or subject to a restriction against alienation imposed by the U.S.) that was cleared at any time prior to December 19, 2007 and actively managed on December 19, 2007.*

These provisions of the RFS2 rules are generally aimed at environmental sustainability and recognize that if renewable fuels are produced on lands that are cleared of forest or other native vegetation, there are impacts due to both loss of habitat and loss of ecosystem functions as well as the need to account for a large carbon debt (the carbon stored in biomass and soil, [2]).

Environmental sustainability analysis of cellulosic bioenergy necessarily models industries that do not yet exist (e.g., cellulosic ethanol and renewable diesel) [1, 3]. The cellulosic feedstocks assumed to meet total EISA goals of 16 Bgal (ethanol equivalent liquid fuel) by 2022 are: dedicated energy crops 7.9 Bgal; agricultural residues 5.7 Bgal; corn (*Zea mays*) stover 4.9 Bgal; urban waste 2.3 Bgal; sugarcane (*Saccharum officinarum*) bagasse 0.6 Bgal; and other sources (wheat (Triticum *aestivum*) residue, sweet sorghum (*Sorghum bicolor*) pulp, forestry biomass) 0.3 Bgal. Assuming adequate biomass availability, these projections are consistent with the "Billion Ton Study" conducted by the USDA and USDOE [3].

The environmental sustainability of feedstock production systems will depend on several factors, including their effects on GHG emissions, soil and water resources, wildlife, and whether the feedstock is a potentially invasive species or can harbor them. These direct effects are generally determined based on direct land use change from annual crops, managed perennial vegetation (e.g., perennial pastures, industrial or non-industrial forest plantations), or other types of perennial vegetation (i.e., natural forest or grassland). Although conversion of natural grasslands or forests to bioenergy crops may occur, both the USDA regulations concerning conversion of natural grasslands and stated policies for biomass sources are meant to avoid conversion of native vegetation. Most of the direct environmental effects of cellulosic biomass production will come from existing agricultural land (pasture and row crop), existing forest plantations, or previously harvested forest land.

International land use change is often a large part of the GHG life cycle analysis when food crops such as corn or soybean [Glycine max (L.) Merr.] are used for biofuel. For cellulosic bioenergy crops such as switchgrass (*Panicum virgatum*) that are not likely to directly displace food crops, it will generally be a smaller component of the GHG life cycle analysis (LCA) because less international land conversion is forecast per unit of bioenergy produced [3]. Although indirect international land use change effects are considered to be an aspect of sustainability for bioenergy feedstocks, it will not be covered in this chapter. Rather, readers are referred to others [4–6] for different perspectives on this issue.

Direct land use effects are based on our understanding of the changes in field, landscape and watershed attributes when dedicated feedstock crops replace other land uses or covers. Direct effects (all of which can be either positive or negative) include GHGs, soil quality (including but not limited to soil carbon), water quantity and quality, invasive species, and wildlife habitat. Some of these factors can lead to direct effects on adjacent ecosystems and some can lead to larger effects at the watershed or landscape scale. The effects will also be dependent on where bioenergy crops are produced. For instance, there may be net environmental benefits (especially GHG and soil/water benefits) from conversion of cropland to warm season grasses (WSG) or to short-rotation woody crops (SRWC) but for conversion from forest, managed for saw timber production, to biomass there may not be any net benefits. The scale of benefits also depends on the land converted with the general idea being that the less productive and more marginal the land, the greater the benefit from conversion to perennial cellulosic biomass crops [7, 8].

The global potential to produce bioenergy [9] indicates that as much as 59 million ha of abandoned agricultural land may be available nationwide in the United States alone [3]. There are abandoned and under-used croplands in many parts of the United States and in other agricultural regions. The western United States has areas with the largest amount of available abandoned agricultural land but in many cases these areas are not irrigated [1]. Midwestern states, including typical Corn/Soybean Belt states such as Iowa, Illinois, and Ohio, have approximately 1–2 million ha of abandoned land, all likely to be more productive than more arid areas in the West [1]. In a study of marginal lands in 10 Midwestern states, Gelfand *et al.* [10] estimated that about 11 million ha of marginal lands would be available for cellulosic biofuel feedstocks.

16.2 Greenhouse Gas Effects

Life cycle GHG emissions from a fuel source refer to the aggregate GHG production from both direct and significant indirect sources. The definition of life cycle greenhouse gas emissions established by the USEPA states that:

> The term 'life cycle greenhouse gas emissions' means the aggregate quantity of greenhouse gas emissions (including direct emissions and significant indirect emissions such as significant emissions from land use changes), . . . related to the full fuel life cycle, including all stages of fuel and feedstock production and distribution, from feedstock generation or extraction through

the distribution and delivery and use of the finished fuel to the ultimate consumer, where the mass values for all greenhouse gases are adjusted to account for their relative global warming potential [3].

Greenhouse gas emissions are expressed in mass of CO_2 equivalent emissions per unit of fuel energy (typically kg CO_2 eq per mmBTU), and are generally compared to a gasoline or diesel baseline scenario. This explains the "well to wheel" GHG reference within the RFS2 regulations, and is the reason approved biofuels must achieve at least a 60% GHG reduction compared to baseline scenarios. For cellulosic based biofuels, life cycle GHG emissions include those associated with growing, transporting, and converting feedstocks, as well as effects due to indirect land use changes and changes in soil carbon. Because cellulosic-based processes are just coming on-line in 2013 as this chapter is being written, the best projections for the United States are based on environmental analyses prepared by the USEPA [1] for the RFS2 mandate. Based on this analysis, switchgrass had net GHG emissions of −110% or −72%, for biochemical or thermochemical conversion, respectively. By comparison, corn stover had net GHG emission reductions of −129% or −92%, for biochemical or thermochemical conversion, respectively. Overall, a reduction in net GHG emissions of greater than 100% means the entire system will store carbon. Compared to the 2006 baseline, diesel from a Fischer–Tropsch process had net GHG emissions of −71% for switchgrass and −91% for corn stover. Estimates were made by the USEPA only for these two feedstocks because there was insufficient data for other cellulosic feedstock sources.

Although net GHG emissions of other crops are not as well understood as switchgrass, estimates have been made for other perennials that may be used for cellulosic feedstocks. In a study of 10 Midwestern states, Gelfand *et al.* [10] estimated that about 25% of the RFS2 mandated supply of liquid biofuels could be produced on 11 million ha of marginal and under-utilized land by growing successional mixes of herbaceous plants or hybrid poplar (*Populus* spp.) plantations. Both crops had net GHG emissions of −105% or less. Modeling of these areas indicated that enough feedstock could be grown within 80 km of potential biorefineries to produce these fuel amounts using secondary succession vegetation. Using marginal agricultural lands that are not in current crop production or which have low yields for conventional crops reduces both the carbon debt and the indirect land use effects of conversion of land use to cellulosic bioenergy crops [10].

In many cases, net GHG reduction depends on the type of energy sources used in the conversion facility. For instance, ethanol production from switchgrass can emit fewer GHGs by combusting the lignin component to produce the facility's steam and electricity needs and thus eliminating the need for external energy sources [11, 12].

16.3 Soil Properties

Conversion of cropland to WSG such as switchgrass can increase infiltration and improve soil structure over time with measurable changes generally taking place over 6–15 years [13, 14]. Changes in soil hydraulic properties under warm season bioenergy grasses will depend on grass species, soil type, climate, and management [7]. In a study of both hybrid poplar plantations and switchgrass plantings in north-Central Minnesota, Coleman *et al.* [15] showed that a combination of variable native soil organic carbon (SOC) levels and slow rates of SOC change made it difficult to verify soil carbon sequestration in the first

12 years of short-rotation poplar plantations. Conversion of cropland to short-rotation poplar only led to increases in soil carbon on poorer soils that were marginal for agriculture [15]. It is likely that SRWC plantations will only change SOC over multiple rotations as the influence of larger structural roots on SOC becomes more important [16].

The use of buffers can enhance environmental sustainability of row-crop systems [17,18], and may be a source of bioenergy feedstock because of the perennial characteristics of the species generally recommended for these buffers. Furthermore, while streamside and other riparian buffers may not be appropriate places for bioenergy crops because of the frequency of harvest, bioenergy plantations would likely require smaller buffers than annual crops [19].

Concern about soil erosion in biomass production systems dates back at least 25 years and is likely the greatest threat to sustainability of soil resources on which cellulosic bioenergy feedstocks generally depend [20]. Soil erosion may be reduced by as much as an order of magnitude in SRWC, compared to annual crops, although the establishment phase of the woody crops may leave considerable bare ground until a canopy and leaf litter layer are established [21]. Establishing SRWC with cover crops reduced erosion by 35–64% compared to SRWC without cover crops [22], with better erosion control for winter annual ryegrass (*Lolium multiflorum*) than for perennials fescue (*Festuca arundinacea*) or lespedeza (*Lespedeza cuneata*). During the first year of establishing SRWC, a poplar planting without a winter cover had higher erosion than either poplar with a fescue cover or no-till corn [21]. Nyakatawa *et al.* [23] found similar high erosion rates early in the establishment of sweetgum (*Liquidambar styraciflua*) plantations. Even in the first year of establishment, sites in the southern United States showed lower erosion from poplar plantations than from conventional tilled cotton (*Gossypium hirsutum*) and corn [21, 24]. After the establishment phase, well-managed WSG and SRWC species can be managed to provide year-round cover and reduce soil erosion compared to annual crops [7, 25]. As with woody crops, the establishment phase of WSG is critical to soil erosion. Management is also critical for WSG in that they should not be harvested at heights below 0.1 m in order to retain erosion control and soil building benefits [7].

There is a general consensus that conversion of cropland to perennial bioenergy crops (SRWC or perennial WSG) will result in an increase in soil carbon sequestration, but the conversion of grassland may not be as beneficial [26, 27]. Soil carbon concentrations will not increase indefinitely, as eventually a new, higher carbon equilibrium will be achieved, although it is not clear how long this process will take [28]. Assessment of SOC changes under perennial bioenergy crops for a range of soils, climates, and management practices should be a research priority because of the importance of soil carbon accumulation on the potential net greenhouse gas measures of bioenergy crops [7].

16.4 Water Quantity and Quality

Large scale expansion of crop production for bioenergy would lead to a large increase in the amount of transpired water that is used for human purposes, perhaps equaling the present amount used by the end of the twenty-first century [29]. Globally, commercial bioenergy production is projected to consume 18–46% of the current agricultural use of water by the year 2050 [29]. Increased bioenergy production will strain water resources in all continents but the challenges will be most pronounced in Asia and Africa [30]. By 2075, water use for the production of bioenergy could push some important agricultural countries, including the United States and Argentina, from a condition of no water stress into a condition of incipient national water stress [29]. U.S. agriculture uses both blue water (water from aquifers and surface supplies) and green water (water stored in soil transpired by plants) [31]. U.S. agriculture is the second largest consumer of blue water [32, 33] and it, along with forestry, are the major industries using green water. The supply of blue water is dependent on effective precipitation (EP), which is defined as the part of rainfall that reaches streams or recharges groundwater. The future biofuels production industry will create major new demands on the quantity of water used by agriculture and production forestry in the United States. New research and new tools are needed to account for these water demands as the nation implements sustainable biofuels production, because in many parts of the United States the agricultural sector already face water shortages. In the west, agricultural withdrawals account for 65–85% of total water withdrawals [33]. In the east, irrigation supplies are under pressure from competing uses, especially in periods of drought. Although overall water withdrawals in the United States have decreased since 1980 and irrigation efficiency improvements are still possible, the amount of both green and blue water needed for a biofuels-based energy supply is much greater than for the historic, fossil fuels based economy.

Comparisons of perennial bioenergy crops (both woody and herbaceous) have shown higher evapotranspiration (ET) and less EP than either annual crops or natural ecosystems. Simulations using the Environmental Policy Integrated Climate (EPIC) model showed the potential for 12–30% more ET from switchgrass than either corn or winter wheat in the Midwest [34]. Water balance measurements for pine plantations in the southeast showed 30% higher ET than natural pine forests [35]. At this point, watershed research has not shown that these increases in field scale ET will affect streamflow discharge for areas of perennial bioenergy crops expected in most watersheds. Modeling studies have examined the effects of conversion to perennial bioenergy crops, especially switchgrass, on water quantity and quality.

Simulations using the Soil and Water Assessment Tool (SWAT) in Minnesota showed only a small decrease in streamflow when 27% of the watershed was put into switchgrass instead of conventional crops [36]. Conversely, applying SWAT to the Delaware river watershed in Kansas and assuming 43% of the watershed was converted to switchgrass estimated that surface runoff would decline by 55% with large reductions in edge of field erosion, sediment yield, and nitrogen export. Reduction in nitrogen export depended on the fertilizer level assumed for the switchgrass [37]. Modeled results from the United Kingdom showed that EP was lower for both *Miscanthus* × *giganteus* (*M.* × *giganteus*) and short-rotation coppice (SRC) willow (*Salix* spp) [26]. The decrease was greater for SRC willow than for *M.* × *giganteus*, generally reflecting the lower water use efficiency in C_3 plants (willow) than in C_4 plants (*M.* × *giganteus*). On a watershed basis, the effects on EP will depend on both the fraction of the watershed in perennial biofuels crops and the precipitation. Modeled decreases in EP were greatest in areas below about 600 mm annual precipitation [26].

Vanloocke *et al.* [38] used a plant growth and ET model to estimate that *M.* × *giganteus* grown in the Midwest United States would use more water than the agro-ecosystems it might replace. The model showed that substantial increases in water evaporated to the atmosphere and potential decrease in EP to streams and groundwater would only occur when the *M.* × *giganteus* fraction cover for a watershed exceeded 25% in dry regions and

50% in nearly all of the rest of the Midwest. Conversion to woody biomass may also lead to reduced streamflow compared to non-forested watersheds. Farley *et al.* 2005[39] estimated that in arid areas where streamflow was 10% or less of rainfall, afforestation could eliminate most streamflow and that in areas where streamflow was 30% of rainfall, streamflow could be cut in half by afforestation of shrublands or grasslands.

Direct measurements of water quantity and quality effects of perennial biomass grasses are rare. McIsaac *et al.* [40] showed that nitrate leaching was very low beneath unfertilized *M.* × *giganteus* and switchgrass primarily because drainage water was reduced, especially under *M.* × *giganteus*. They estimated that in the tile-drained Midwest, *M.* × *giganteus* could reduce streamflow by as much as 32% compared to conventional corn/soybean rotations. Experimental studies of bioenergy feedstock crops generally give results that show the complex interactions among fertilizer regimes, crops, and development of perennial cropping systems. For instance, in north Alabama, coppiced sweet gum had much lower nitrogen and phophorus losses in runoff than corn, but switchgrass had phosphorus losses similar to corn and only in the final two years of a five-year trial were NO_3-N losses lower [23]. In addition, there were high erosion losses for sweet gum unless it was grown with a cover crop.

Although runoff and erosion should be less from fields in perennial bioenergy crops than in annual crops, meaningful comparisons will depend on management of both cropping systems. Conservation tillage generally reduces runoff and erosion and may have lower rates than under perennial crops, especially during the establishment phase of the bioenergy crops. Furthermore, the high cost of perennials may lead to low establishment rates and more bare soil than with annual cropping systems.

Sustainability issues related to water will help determine the types of cellulosic feedstocks grown. For instance, due to higher biomass production, greater leaf area index, and longer vegetative growing season, *M.* × *giganteus* requires more water during the growing season than switchgrass or corn [40, 41]. Consequently, water availability strongly influences *M.* × *giganteus* yields, and the crop is thought to be best suited to locations that receive at least 30 inches of precipitation per year. In contrast to *M.* × *giganteus*, switchgrass yields are most strongly influenced by nitrogen availability [42]. This means that in areas like the Midwest where rainfall is generally adequate, but high nitrates in drain tile are an issue, *M.* × *giganteus* would be a better choice for producers than switchgrass. In drier areas of the country, where water is limiting, but groundwater quality is not an issue, adequately fertilized (i.e., 50–100 lbN/acre or 56–110 kgN/ha) switchgrass may produce higher amounts of biomass [42].

16.5 Invasive Species Effects/Mitigation/Enhancement

Invasive species are any "alien species whose introduction does or is likely to cause economic or environmental harm or harm to human health" [43]. Valery *et al.* [44] clarify the concept of "alien" at the ecosystem scale, rather than at the scale of geopolitical boundaries (e.g., switchgrass is native to grasslands of the central United States, but alien to California grasslands). Biomass production for bioenergy has the central aim of maximizing harvestable dry mass per unit land area, labor and input expense. As bioenergy crop candidate species have been evaluated for their ability to fulfill these production criteria, a suite of traits characterizing a bioenergy crop ideotype has been identified. Ideal bioenergy crops feature a C_4 photosynthetic system, long canopy duration, perennial life history, no known pests or diseases, high relative growth rate to suppress competing vegetation, sterile seeds, storage of nutrients in underground organs prior to biomass harvest, and high water use efficiency [42]. As noted in Raghu *et al.* [45], with the exception of sterile seeds and perennial life history, all of these traits are risk factors associated with increased likelihood that a plant species will become invasive when introduced into favorable habitats beyond its native range.

Many scientists have expressed concern about the invasive potential of bioenergy crops over the past five years [45, 46–52]. To date, such reports have largely approached the issue in one of three ways: literature reviews providing background on species being considered as potential bioenergy feedstocks [51]; bioclimatic envelope models to determine potential ranges for introduced crops [46, 53]; and qualitative analyses of risk using expert decision support systems, such as the Australian Weed Risk Assessment (WRA) or adaptations thereof, tailored to specific locales [47, 52]. Such approaches are a necessary beginning for evaluation of invasive potential of bioenergy crops, but the power of inferences made with these methods is limited by the lack of empirical evidence from within proposed areas of introduction, and further limited by variation in expert opinion driving these tools [54]. For those bioenergy crops nearing deployment, quantitative risk analysis based on field studies in the proposed production area will provide site-specific information on invasive potential [50]. A small number of such experiments have begun to appear in the scientific literature [55, 56], hopefully providing a more comprehensive understanding of invasiveness in coming years.

Impacts of invasive plants in their new habitats can range from modest effects on community composition to wholesale reorganization of ecosystem structure and function [57, 58]. For example, invasion of montane forests in Hawaii by the fire-adapted grass *Schizachyrium condensatum* resulted in a more than fivefold increase in fire frequency and severity, altering species composition and nutrient flows [57]. The estimated combined economic impact of invasive species worldwide is in the order of $190 billion annually in lost revenues, ecosystem services and cleanup efforts [59]. Among current perennial bioenergy crop species, several are already known as invaders within the continental United States. These include *Arundo donax* [60], *Miscanthus sinensis* [51], *Phalaris arundinacea* [61], *Phragmites australis* [62], and *Triadica sebifera* [63]. The choking rhizomatous mats of vegetation produced by *A. donax*, *P. arundinacea* or *P. australis* in riparian corridors displace native vegetation and make lavish use of water resources [64]. Potential impacts of invasions by bioenergy crop species on wildlife populations are difficult to predict, since such studies are few and most draw conflicting inferences depending upon crop species, wildlife species and habitat of concern [65–67]. In addition to the scenario of bioenergy crops becoming invaders themselves, there is also the possibility that they will facilitate the invasion of other organisms. One such scenario includes augmentation of agricultural pest populations by providing them with over-winter habitat. For example, *M.* × *giganteus* has been found to serve as an alternate host for the Western corn rootworm (*Diabrotica virgifera virgifera*), thereby creating the potential for increased severity of outbreaks of this insect pest and exacerbated crop yield losses [68].

The amount of biomass necessary to meet renewable energy goals is enormous and will, therefore, require huge land areas [69]. Pilot projects are already underway to develop biomass production potential, such as the initiative to grow *M.* × *giganteus* on marginal arable land in the Midwest United States, sponsored by the Biomass Crop Assistance

Program of the USDA Farm Services Agency [70]. This project calls for four 20 000 ha areas to be planted to *M.* × *giganteus* in Arkansas, Missouri, Ohio and Pennsylvania. Current qualitative evaluations of *M.* × *giganteus* traits suggest that it has low invasive potential in California and Florida [52, 53]. However, even if the probability of a given bioenergy crop species becoming invasive is low, if it is greater than zero there will likely be escapes when production is fully scaled up by 10^5–10^6 ha, and 10^9 plants are involved.

Reducing the frequency and impact of biological invasions resulting from bioenergy production is essential to the sustainability of the enterprise. Three complementary types of actions are necessary to prevent and ameliorate bioenergy crop invasions: (1) germplasm screening; (2) production best management practices; and (3) containment. Most pre-introduction screening of bioenergy crop cultivars to date has been accomplished using variants of the Australian WRA [47, 48, 52]. Following such initial screens with an empirically-based demographic modeling approach in planned areas of introduction will likely provide much more robust inferences on how much of a threat different crop cultivars are likely to be [50]. Such a system would be helpful not only for evaluating existing crop germplasm but would also help to define non-invasive crop ideotypes to guide breeding efforts [71].

When scaling up biomass production from test plots to production fields, best management practices for plantation design, production and harvesting should all contribute to lower risks of invasion. A basic ground rule for siting plantations is that rhizomatous perennial grasses, which are easily dispersed by water, should not be planted adjacent to riparian areas [60, 62]. Quantitative knowledge of dispersal processes of the crop species is critical to designing effective buffer areas for production fields. A buffer strip surrounding the bioenergy crop should be sown to a turf or agronomic crop species for which weed management practices are well-characterized. This will form a containing perimeter for the bioenergy crop that is easily maintained as a pure stand and for easy monitoring of possible escapes. The width of the surrounding buffer area should be estimated as the product of the annual rate of vegetative spread of the crop and the number of years a production field will be maintained, possibly increasing the buffer area by some margin of error. If the bioenergy crop species has viable, wind-dispersed seed, as with *Miscanthus sinensis* [51, 56], it may be safer to embed a smaller biomass production area within a larger matrix of agronomic crop to form a barrier against seed dispersal. Such a design will help to provide containment of the bioenergy crop species even if monitoring efforts fail in some years.

Monitoring is essential for any containment strategy and should be performed annually along the entire perimeter of the bioenergy crop production field. Escapes should be flagged and terminated, and revisited for several years thereafter to ensure complete eradication [72]. For wind dispersed species, monitoring efforts will need to extend beyond buffer areas into surrounding habitats that are likely to allow establishment of the bioenergy crop species [73]. Such efforts will be aided at a local scale by empirical data on potential establishment of bioenergy crops in various types of non-arable lands, and at regional and larger scales through the use of climate-matching models [53].

16.6 Wildlife and Biodiversity

At least two approaches are possible to produce cellulosic bioenergy without having detrimental impacts on wildlife: produce bioenergy crops from lands already in crop production and use land use practices that are compatible with wildlife to produce them [74]. In the case of cellulosic biofuel crops there are limited studies showing that perennial grasses such as switchgrass and *M.* × *giganteus* can have some benefits for bird species. In a modeling study, Murray *et al.* [75] projected that bird species which were management priorities in Iowa would be increased by converting row crops to switchgrass but that other, more common birds that depended on annual crop fields would be diminished in population. Similarly, in a field study of *M.* × *giganteus* and row crop fields in the United Kingdom., Bellamy *et al.* [76] showed that recently planted *M.* × *giganteus* fields had higher populations of breeding birds but speculated that these advantages would be lost as the *M.* × *giganteus* matured and, especially, as weed populations decreased. Tilman *et al.* [77] postulated that low input, high diversity grasslands for biomass production would be beneficial because higher diversity would be favorable for insects and wildlife. Furthermore, compared to annual crops, limited use of pesticides on perennial bioenergy crops will also benefit wildlife.

Unlike most annual crops, there will be possibilities for multiple harvests and variable timing of harvest for many of the perennial cellulosic bioenergy crops. Wildlife benefits from bioenergy grasses will only be achieved if harvests are scheduled to avoid local nesting or rearing seasons. Biomass cropping systems that include multiple harvests during the summer months will provide little benefit to wildlife [78]. Standards for harvesting of Conservation Reserve Program (CRP) perennial grasses to benefit wildlife may be applicable to bioenergy grasses in the parts of the country where there is substantial land in CRP grasses. Stubble heights are critical to wildlife when harvesting herbaceous vegetation and leaving higher stubble can result in much better nesting success for grassland nesting ducks and other waterfowl. Higher stubble can also trap more snow, shade the soil, and decrease evaporation [78]. Of course stubble left in fields is unharvested biomass and experiments are needed to determine how much biomass is needed for wildlife and what the economic cost is. Recommended harvest heights for perennial bioenergy grasses should be examined based on wildlife needs as well as biomass harvest goals. The best harvest scenario on a landscape scale is one that provides a mosaic of harvested and unharvested fields, but this has to be economically feasible [74].

Wildlife effects of land conversion to SRWC will depend on the type of land converted and the landscape in which the conversion takes place [79]. In general, conversion of annual cropland to SRWC will increase biodiversity but conversion of mature grasslands or forest to SRWC will likely result in a decrease in wildlife biodiversity [80, 81]. Compared to corn, or other row-crops, conversion to either SRWC (poplar or pine) or conversion to perennial grasses has a positive effect on bird biodiversity. Management practices that increase landscape heterogeneity, reduce chemical input, and delay biomass harvesting until after bird (or mammal) breeding will help increase biodiversity [80].

16.7 Conclusions

"The emerging bioeconomy is likely to result in the single largest reconfiguration of the agricultural landscape since the advent of industrial agriculture. This change includes a large-scale shift toward perennial plants, increased appropriation of net primary production for biomass relative to food, and intensification of crop production on marginal, previously fallowed lands" [71]. In most of the developed world, the current system of agriculture has grown over the last 150 years with accelerating changes for the last 65–70 years. The

biofuels revolution in agriculture and forestry could be largely complete in 10–15% of that time (2005–2022) if RFS2 goals are met. Even with delays in meeting these goals, which now seem inevitable, changes are likely to be largely completed in 25–30 years. To both assure that mandated sustainability goals are met and that bioenergy resources are available into the future, new knowledge and new tools are needed to evaluate the sustainability of this revolutionary change in the modern societal role of agriculture and forestry. The most appropriate means to analyze options for sustainability of the bioenergy based economy is to focus on net energy from a combined feedstock production/conversion technology and to determine the environmental costs per unit of net energy [35]. Minimizing the environmental cost per unit of net energy will help meet both short and long-term economic and environmental goals for bioenergy. It is likely that investments and policy decisions that do not seek to minimize the environmental cost per unit of net energy will decrease the long-term sustainability of bioenergy. Although in the short run other policy and technical considerations may drive investments in less sustainable directions, "footprint" evaluations based on net energy from a given final fuel product are needed to establish the right mixes of feedstocks and fuels for every region.

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17

Social Sustainability of Cellulosic Energy Cropping Systems

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17.1 Introduction

Social sustainability is the capacity to create personal, social, political and economic environments that facilitate healthy human existence as part of the entire global ecosystem [1]. As cropping systems are changed to produce cellulosic energy crops, there will often be accompanying changes in land use, personal, group and community opportunities. Moving crops or cropland from food to fuel use means creation of new value chains that have implications not only for the individuals involved but also on the interactions among individuals within the surrounding communities. These changes will likely have differential impacts on human communities depending upon their magnitude and implementation strategy. Interactions among individuals, which are crucial for mutual support, will ultimately determine social sustainability and acceptance of these new systems. Incorporating cellulosic energy crops into traditional cropping systems faces many physical, economic, and environmental challenges, as outlined in other chapters. But perhaps an even more important challenge that is often overlooked is how these new systems are organized and operated. Paying attention to these social implications is crucial for increasing the sustainability of healthy social structures in ways that will encourage humans to embrace and act on the goal of having a sustainable, well-functioning planet.

Social sustainability operates on many levels – the individual, the family, the community, ethnic and racial groups, politics, the economy, and local, national and international

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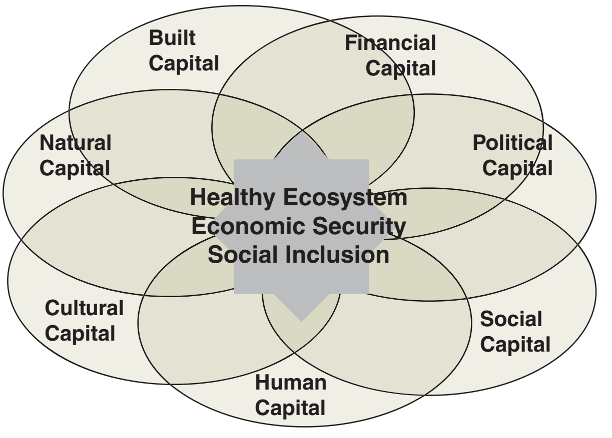

Figure 17.1 *Community capitals and sustainability.*

spheres. Social justice concerns play an important political role in the development of sustainability standards used by governments, private firms, and civil society [2–4]. As the market for cellulosic energy is global, standards are increasingly being set and enforced by international bodies, such as the International Standards Organizations, the International Financial Corporation, and private certifiers (e.g. Roundtable on Sustainable Biofuels). In contrast to past endeavors, these standards are generally based on the process of production, not just observable qualities of the product.

Social sustainability does not mean that everything in a community remains the same, but implies balanced change and adaptation. Social resilience is the ability of a system to sustain itself in terms of human communities through adaptation and transformation. By looking at the potential impact of cellulosic energy cropping systems on human communities in terms of community assets and their interactions, the potential impacts can be anticipated. Using the community capitals framework [5], the potential of a variety of cellulosic energy cropping systems is analyzed in terms of their impacts on the stocks, flows and interactions of seven community capitals – natural, cultural, human, social, political, financial and built – and how those impact the community in terms of ecosystem health, economic security and social inclusion (Figure 17.1). This approach has been used in ex-post evaluations of a variety of interventions [6–8]. In this chapter, the impacts are analyzed based on potential interactions, as few studies have been made of social impacts of bioenergy cropping systems to date.

17.2 Standards for Social Sustainability

From the perspective of Civil Society Organizations (CSOs), the adoption of sustainability standards is a tool that can help promote social protection in an era of global free trade [9]. Examples of these standards in which CSO agendas are embedded include labor standards to prevent sweatshop and child labor and standards for social justice and equitable compensation of small-scale producers and indigenous communities. Some scholars have declared this proliferation of sustainability standards to be the rise of a new “NGO–Industrial Complex” [10].

Sustainability standards are based on the process of production, not necessarily observable qualities of the product [11]. Biomass for biofuels, such as corn stover, switchgrass, and wood, can be produced in a variety of ways, some very disruptive to social sustainability, particularly when there are changes in land use and land tenure. Such changes have important implications for vulnerable populations, particularly indigenous peoples. Indigenous communities holding land in common and small-holders find it difficult to gather together the resources necessary to certify small lots, and certification of cultural integrity is often not amenable to conventional measurement [12].

Tightly integrated value chains in biomass used for energy are highly visible. Thus, production processes of biomass for energy are likely to be monitored by social justice organizations [13]. Activists have found that in tightly integrated supply chains, it is easier to link abusive practices in the production process with their consequences for workers, producers and communities at the production end, versus open markets where "[f]ragmented supply chains conceal the social relations and exploitative practices of production" [14: 5]. Exposés of social injustice in bioenergy crop production have had serious implications for sales and stock values of companies involved. And if the driver of the biomass energy value chain is a government, the legitimacy of that government program, and therefore its continued public support, is in jeopardy. Furthermore, if lenders require social sustainability standards to be in place, there is a much higher likelihood that they will be implemented throughout the value chain.

However, large-scale producers are advantaged over small and marginalized producer-groups in certification, even if they do not necessarily contribute more to social sustainability. Their size and scale increases their ability to pay high certification costs and deliver large and consistent volumes of products at a constant quality. Certification benefits large corporate downstream firms by allowing them to control and switch between certified, substitutable suppliers. Suppliers unable to conform to the wishes of the buyer are ultimately excluded from the chain [15]. Thus, social sustainability requires standards that are not too burdensome for small scale producers to implement, as social equity is enhanced by multiple producers rather than a single supplier.

While governments once regulated working conditions and protected land tenure, the global sourcing of biomass for biofuels has shifted certification of all types of sustainability to third party certifiers [16]. The shift to market-driven regulation has created a fundamental paradox of globalization. On the one hand, major corporations have become increasingly powerful and have assumed greater market dominance. At the same time, many of these corporations are confronted with a growing assortment of stakeholder concerns about how their products are produced, their social impacts, and the overall sustainability of the system.

Governments, such as those in the United States, Australia, and the European Union, are major investors and eventually major users of biofuels for military transportation. They also set emission standards for all fuel users in their geographic jurisdictions. Attention to social sustainability can help avoid public pressure against biofuels being seen as socially detrimental.

17.3 Forest-Based Biofuels

The forestry and timber sector provides a good case study on the dynamics of competition between various sustainability standards and certification systems. It also provides a background for the emergence of the Roundtable on Sustainable Biofuels. The decline of social sustainability standards as part of certification for forest sustainability suggests potential pitfalls in the inclusion of social sustainability standards for biomass energy production and value chains.

Public concerns over deforestation in the tropics, loss of biodiversity, and the perceived low quality of land management in developing nations, from which energy biomass is often sourced [17, 18], led to discussion among civil society organization (CSOs), transnational corporations (TNCs) and governments around securing adherence to sustainability standards in forest management. As a spin-off from these international discussions, the private Forest Sustainability Council (FSC) was successfully established in 1993. A decade later, the FSC had certified more than 53 million hectares of forest in 78 countries.

The FSC was the primary certification system for much of the 1990s and early 2000s. Yet by the second decade of the twenty-first century, its privileged position in the sector had been challenged. As of 2005, a least 23 different national, regional, and global standards competed with the FSC. One competitor, the Programme for the Endorsement of Forest Certification (PEFC), was established in 1999 by forest owners and the timber industry as an umbrella scheme for national standards. By mid-2002, the PEFC had become the world's largest forest certification scheme in terms of certified forest land [17]. PEFC requires that local stakeholders be involved in both standard-setting and decision-making before a system can be endorsed [19].

The marginalization of the FSC and the widespread support for the PEFC and other programs originating from within the industry has disappointed many environmental groups, which see the industry initiatives as inherently weaker. For example, unlike the FSC, the PEFC does not rely on independent on-the-spot inspections, demand annual inspections, or implement regular checks. This should be no surprise, however, as competing forestry standards allow for producers and suppliers to choose from the standards systems that best fit their needs, reduce their costs, and maximize their profits [20].

In contrast, the management practices required by PEFC include several social sustainability criteria, including ecosystem services that provide habitats and shelter for people and wildlife, offer spiritual and recreational benefits, protection of workers' rights and welfare, encourage local employment, and respect indigenous people's rights. The PEFC conducted a stakeholder dialogue on Sustainable Biomass and Forest Certification in November of 2012 in conjunction with the International Energy Agency's Bioenergy initiative. The goal of the meeting was to explore sustainability issues related to expanding use of forest biomass for energy and other industries. Addressing the added pressures on communities caused by forest-based biofuel production is necessary, as sustainable forest management may not be enough to ensure social sustainability, as those standards may not adequately address specific intensified production and harvesting methods related to forest fuels [21].

17.4 Biofuel Social Sustainability Standards

Civil society organizations (CSOs) are questioning the impact of biomass production for energy on land use changes, greenhouse gas emissions, environmental impacts including soil erosion and water quality, and food prices [22]. In addition, with hunger and food insecurity rising, some have questioned the morality of shifting land use, especially in developing countries, from food production to fuel production for consumers in the global North [23].

Biofuel-specific social sustainability standards were able to build on older movements that used the standards to increase market share for sustainably raised products, particularly those that took an ecosystem-based approach. Forest sustainability schemes often include criteria addressing environmental preservation, labor relations, occupational health and safety, resource use rights, fair employment, extent of forest resources, forest health and vitality, productive functions of forests, biological diversity, protective functions of forests, socioeconomic benefits and needs, and legal, policy and institutional frameworks [18]. Of the three general aspects of sustainability (economic, social, and environmental), the social dimension, such as issues of worker welfare and impacts on local communities, receives the least attention [24,25]. However, since biofuels for biomass require considerable investment in the infrastructure for conversion, social sustainability requirements of government lenders, such as the USDA/Rural Development and the International Finance Corporation of the World Bank, provide additional incentive for adherence to social sustainability standards.

USDA/Rural Development has no social sustainability standards for biofuels. The World Bank does. Its eight standards include labor and working conditions, community health, safety and security, land acquisition and involuntary resettlement, indigenous people, and cultural heritage. Furthermore, the first performance standard, assessment and management of environmental and social risks and impacts, includes social sustainability issues by requiring effective community engagement through disclosure of project-related information and consultation with local communities on matters that directly affect them. And even Performance Standard 6, biodiversity conservation and sustainable management of living natural resources, states that where residual impacts remain, to compensate/offset for risks and impacts to workers [26].

17.4.1 Plantation Cropping Systems

It is not just trees as biomass for fuels that threatens forests and communities that depend on them. Many of the land acquisitions by foreign firms in Tanzania, for example, take land from traditional land holders and refugees for biofuel plantations [27]. The existing and proposed crops include jatropha, sugarcane, and white sorghum as well as oil palm and *Croton magalocarpus*, native to Burundi, Democratic Republic of Congo, Kenya, Malawi, Mozambique, Rwanda, Tanzania, and Uganda. The schemes that involved sugarcane and jatropha, an introduced species, acquired the most land. Sugarcane requires relatively productive land, while jatropha grows on marginal lands.

In the case of palm oil, land is often cleared for plantations of the export crop. As a result of concerns not only about ecosystem health but indigenous rights, particularly related to traditional communal land tenure, the Roundtable on Sustainable Palm Oil (RSPO) was developed. Of particular concern in land rights, which are part of all biomass fuel cropping systems, is that many of the issues revolve around who represents the impacted communities and exactly how to involve local stakeholders.

The implementation of RSPO standards has been fraught with challenges. The RSPO's approach is pragmatic, as the diversity of actors and divergence of interests has necessitated a gradual, step-by-step approach to implementing change. Tensions exist between developing country producers and developed country processors and retailers. Where standard-less market channels are still available, producers see no need to implement the very sustainability standards that they helped design as part of the RSPO process. NGOs criticize the pragmatic, stepwise approach and argue for more fundamental discussions regarding sustainability [28]. The legality and legitimacy of the RSPO is dependent on the inclusion of a wide variety of stakeholders and consensus-based decision making. However, pragmatic compromises often lead to a perceived undermining of the principles of sustainability. The resulting sustainability standards are less stringent. When NGOs feel like the key tenants of sustainability have been excluded, they refuse to endorse the standard, hence decreasing its legitimacy. This, in turn, compromises the legitimacy of the RSPO standard in the eyes of concerned external observers and the public [28].

As with many sustainability standards that involve resources on indigenous land, the RSPO strategy refers only to Free, Prior and Informed *Consultation*, despite continuing demands from indigenous peoples that only by adopting Free, Prior and Informed (FPI) *Consent* will fair and non-coercive negotiations between investors and affected communities be possible. FPIConsent is currently under consideration in the ongoing formulation of the International Finance Corporation of the World Bank (IFC) Performance Standards strategy, and cannot be part of the palm oil strategy until this process is completed. Norman Jiwan of Indonesian NGO SawitWatch points out that "the IFC is a member of the RSPO, which recognizes FPIConsent, but the new strategy refers only to FPIConsultation. This is effectively a breach of the RSPO code of conduct by the IFC, and means there will be far less incentive for IFC-backed companies to comply with the principles and criteria of FPIConsent" [29]. The difficulties of enforcement and the willingness of some signers of the RSPO to deviate from the principles and criteria undermine the legitimacy of these sustainability standards, despite the massive efforts that have been put into developing them.

17.4.2 Roundtable on Sustainable Biofuels

Of the 12 Principles of the Roundtable for Sustainable Biofuels, six are clearly social (Legality, Planning, monitoring and continuous improvement, Human and labor rights, Local food security, and Land rights), while parts of the other criteria include social justice aspects. For example, small feedstock producers are exempt from greenhouse gas emissions, Criterion 3c. Biofuels' contribution to climate change mitigation shall be improved over time. However, given the expenses involved in measuring and implementing climate change mitigation, exempting small producers makes sense. All the conservation criteria (Principle 7) take into account local communities as well as ecosystems. Principle 9, Water, includes "respect prior formal or customary water rights". Principle 11 includes specific concern for the people place. "The use of technologies in biofuel production shall seek to maximize production efficiency and social and environmental performance, and minimize the risk of damages to the environment and people."

A number of scholars have attempted to specify the criteria to be used to indicate social sustainability. Table 17.1 provides examples of potential social criteria proposed by Markevičius *et al.* [24] for the development of liquid biofuel standards. Much of biomass

Table 17.1 *Potential social criteria for liquid biofuels.*

Criterion No.	Criterion Name	Criterion Explanation
1	Compliance with laws	Complies with all applicable laws and internal regulations like certification principles, countering bribery
2	Food security	Enough land locally available for food production, preference of marginal sites for energy crops
3	Land available for other human activities	Enough land locally available for housing, energy (e.g. firewood), recreation, and other resource supplies
4	Participation	Stakeholders included in decision making; facilitation of self-determination of stakeholders
5	Cultural acceptability	Consider spiritual values, local knowledge
6	Social cohesion	Migration and resettlement, wealth distribution, fair wages, intergenerational equity, charity
7	Respect for human rights	Health services, liberty rights, security, education
8	Working conditions of workers	Worker health, work hours, safety, liability regulations, exclusion of child labor
9	Respecting minorities	Recognition of indigenous peoples' rights, gender issues
10	Standard of living	Public service support, access to energy services (e.g. electricity lifeline tariffs)
11	Property rights and rights of use	Land and resource tenure, dependencies on foreign sources (e.g. financial investments, knowledge) fair and equal division of proceeds, customary rights
12	Planning	Stating clear objectives, a management plan is written, implemented, and updated as necessary

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for fuels is transformed into liquid fuels. These criteria are focused on the sustainability of local populations, and do not lend themselves to plantation systems.

Table 17.2 provides examples of social criteria proposed by Lewandowski and Faaij [30] for the development of biomass/bioenergy standards.

17.4.3 Importance of Context

The domestic political economy influences the degree to which social sustainability can be implemented. As seen in the case of land grabs, which are often done for biomass production for fuels [23, 31, 32], national governments will often make deals that ignore local and customary land rights. Bartley [10] points to several key factors. Firstly, the nature of the relationships between the business and state will impact the readiness of firms to see value in quickly shifting to sustainability standards. Secondly, the clarity of legitimacy of property rights and their administration will affect the harmonization of domestic conditions with transnational regulations. Thirdly, the nature of the national political regime and its openness to non-business agendas will influence the incentives for international and domestic actors to pursue private arenas of rule-making in that context. These three areas of consideration highlight why vast differences may exist in the conceptualization of sustainability standards in the affluent democracies of Europe and North America compared to the on-the-ground implementation of sustainability standards in developing countries [10].

Table 17.2 *Social criteria for sustainable biomass production and trading.*

Areas of Concern	Criteria
Labor conditions	• Freedom of association and collective bargaining • Prohibition of forced labor • Prohibition of discrimination • Least minimum wages • No illegal overtime • Equal pay for equal work • Regulations to protect the rights of pregnant women and breastfeeding mothers
Protection of human safety and health	• Protection and promotion of human health • Farmers, workers, etc. are not unnecessarily exposed to hazardous substances or risk of injury • Safe and healthy work environment: machine and body protection, sufficient lighting, adequate indoor temperature, fire drills • Availability of documented routines and instructions on how to prevent and handle possible near-accidents and accidents • Performance and documentation of training of all co-workers; training ensures that all co-workers are able to perform their tasks according to the requirements formulated for health protection and environmental benign management or resources
Rights of children, women, indigenous peoples and discrimination	• Elimination of child labor: minimum age and prohibition of the worst forms of child labor • Children have access to schools; work does not jeopardize schooling • Indigenous peoples' and tribal rights respected • Recognizing and strengthening the role of indigenous peoples and their communities • Women are not discriminated against; their rights must be respected • Spouses have the right to search for work outside the entity where the partner works
Access to resources ensuring adequate quality of life	• Farmers are content with their social situation • Access to potable water, sanitary facilities, adequate housing, education and training, transportation, and health services • Promotion of education, public awareness and training • Market access for small-scale farmers and producers • Equitable access to forest/farm certification among all forms of forest/farm users and tenure holders • Establishment of a communication system that facilitates the exchange of information
Food and energy supply safety	• Availability of enough food of sufficient quality • No severe competition with food production and the shortage of local food supply • Energy supply in the region of biomass production should not suffer from biomass trading activities
Capacity building	• Local organizations, institutions or companies involved in the process, through control and certification • Marginalized social groups should play an equitable role in certification processes • Jobs should be generated • Trade-related skills development and social justice oriented capacity-building are facilitated through learning exchanges between trading partners • Building and use of local labor and skills

Table 17.2 *(Continued)*

Areas of Concern	Criteria
Combating poverty	• The activity should contribute to poverty abatement
Democratic participation	• Stakeholder involvement in the decisions that concern them
Land ownership	• Avoidance of land tenure conflicts • Land ownership should be equitable • Tenure and use rights shall be clearly defined, documented and legally established • Projects should not exclude poor people from the land in order to avoid leakage effects
Community (institutional) well-being	• Farms must be "good neighbors" to nearby communities and a part of the economic and social development • A basis is created for strengthening the mutual confidence between business and the society in which they are active • Involvement of communities into management planning, monitoring and implementation
Fair trade conditions	• Transparency and accountability of negotiations • Direct and long-term trading relationships • Fair and equal remuneration – all supply-chain partners are able to cover costs and receive fair remuneration for their efforts through prices that reflect the true value of the product. Risk sharing mechanisms are actively encouraged. • Communication and information flow – supply-chain partners communicate openly with each other showing a willingness to share information
Acceptance	• Acceptance of the production methods by producer and consumer • The activities do not lead to disadvantages for the local population like losses of jobs or food shortages • The activity carries advantages for the local population
Long-term perspective	• Long-term commitments, contracts and management plans
Strength and diversification of local economy	• The activity should contribute to strengthening and diversifying the local economy • Local labor and skills should be used • Professional and dedicated human resources are enhanced
Reliability of resources	• Minimization of supply disruptions • Supply security for the biomass consumer • No over-dependencies on a limited set of suppliers should be created
No blocking of other desirable developments	• The activity should not block other desirable developments
Landscape view	• Increase and improvement of the variation of the landscape • Conservation of typical landscape elements
General Compliance with laws and international agreements	• Activities have to comply with national laws and international agreements • All applicable and legally prescribed fees, royalties, taxes and other charges shall be paid • In signatory countries, the provisions of all binding agreements, such as CITES, ILO Conventions, etc., shall be respected
Traceability	• Biomass has to be traceable • Biomass from non-certified resources cannot enter the trade chain • A chain-of-custody control system is in place

(*continued*)

Table 17.2 (Continued)

Areas of Concern	Criteria
Avoidance of leakage effects	• (Negative) leakage effects should be avoided • People should not involuntarily be driven from their land • The biotrade activity provides local people with income opportunities that are at least equivalent in quality and quantity to the baseline situation (i.e., situation without biomass trade activity)
Strengthening the role of non-governmental organizations	• The role of non-governmental organizations should be strengthened
Improvement of conditions at the local level	Generation of jobs Generation of education opportunities Capacity building Support of infrastructure development Enhancement of democratic development Increase of (farmers) income Improvement of environmental management at the local level

Not only do national political economies matter but the actors embedded within those contexts significantly influence the shape of transnational governance mechanisms. As Geisler [33] points out, on the African continent African governments and elites subordinate African needs to offshore interests. For example, in Mozambique the production of biofuels has resulted in poorer groups losing access to the land on which they depend, with major negative effects not only on local food security but also on the economic, social and cultural dimensions of land use, in part because of the late implementation of planning and monitoring tools to ensure social sustainability [34].

The emergence and adoption of multiple, dynamic sustainability standards is influenced by key initiators and stakeholders such as TNCs, NGOs, development agencies, and others. The position of the standard-setters and adopters within global value chains, national business and institutional contexts brings greater understanding to the proliferation and convergence of diverse sustainability standards, how multiple actors in value chains influence the proliferation, variation, and evolution of sustainability standards within a certain industry [35]. Firstly, leading buyers, by responding to their target consumers, affect the transmission of selection of sustainability standards in producer countries through the communication of preferences to suppliers. Secondly, producer size and type differentiate the types of standards adopted in a particular country. Thirdly, national exporters and traders play an important role in transmitting standards on behalf of clients through facilitating and overseeing the process of implementation and certification.

17.4.4 Roundtables

Roundtables are a type of multistakeholder partnership for sustainability standard-setting that has gained prominence in recent years. As a specific form of private governance, such collaborations focus on improving sustainability within one specific commodity chain or sector. As with other multistakeholder partnerships, roundtables include actors from private businesses as well as NGOs. Representatives from government agencies might participate by consulting and observing, but have no decision-making role. Roundtables go beyond merely creating niche markets and instead aim to transform entire commodity chains towards more sustainable practices. The current generation of roundtables – such as Roundtable on Sustainable Palm Oil (RSPO), Round Table for Responsible Soy (RTRS), Better Cotton Initiative (BCI), Better Sugarcane Initiative (BSI) and Roundtable for Sustainable Biofuels (RSB) – trace their conceptual origins to the multistakeholder initiatives of the forest and marine stewardship councils (FSC and MSC) [28]. Roundtables connect commodity chain actors from around the globe. These actors come from diverse locations, occupy various roles within the commodity chain, and hold different belief systems regarding sustainability. The legitimacy of their collective actions is based on the justification for why they are the right actors to govern the commodity chain, and the creation of a common understanding about what and how they desire to govern [28]. The establishment of shared goals and common activities are the basis for the working relationship.

17.4.5 Council on Sustainable Biomass Production

The Council on Sustainable Biomass Production (CSBP) is a multistakeholder organization established in 2007 to develop voluntary sustainability standards for the production of second generation, cellulosic biomass and its conversion to bioenergy. "CSBP has generated broad, multistakeholder consensus guidelines for sustainability that will serve as the foundation for a certification program for sustainable biomass and bioenergy production. This effort will set the emerging cellulosic bioenergy industry on a course of continuous improvement with support from growers, all sectors of industry including refineries, and social and environmental interests" [36]. It is an institution based in the United States that includes as members U.S. industry, environmental, biophysical research institutions, such as the Energy Bioscience Institute at the University of Illinois and the Institute of Renewable Natural Resources at Texas A&M University. Of the 20 CSBP members, only The Great Plains Institute addresses parts of social sustainability in its mission and has farm organizations as partners. CSBP has developed sustainability standards while the industry evolves, rather than retrofitting the industry to the standards.

CSBP has developed a biomass to bioenergy sustainability standard in two phases. The first is from field to energy production facility entry gate (biomass producer standard)' the standard that was released on 12 June 2012. The second is for energy production facilities (biomass consumer standard). CSBP is working on an auditing and certification process.

Of the nine principles, Principle 6 addresses social sustainability directly.

Socioeconomic Well-Being

CSBP embraces a tripartite vision of sustainability, focusing on practices and products that are environmentally, socially, and economically sound. This Principle speaks to the need for sustainable distribution of socioeconomic benefits to the various participants in biomass and bioenergy production systems. A sustainable commercial model benefits from the support of wealth creation in local communities.

PRINCIPLE 6: *Biomass and bioenergy production take place within a framework that sustainably distributes overall socioeconomic opportunity for and among all stakeholders* *(including land owners, farm workers, suppliers, biorefiners, and the local community), ensures compliance or improves upon all applicable federal and state labor and human rights laws, and provides for decent working conditions and terms of employment* [37].

Specification of this principle mainly addresses labor relations.

Compliance with Labor Laws

Ensure that human rights and labor laws are respected in biomass production fields for both employees and contractor employees.

Fair Labor Standards Act

Participants demonstrate employee protection that is compliant with or exceeds the Fair Labor Standards Act (FLSA) and all other federal and state labor laws.

IMPLEMENTATION: Participants demonstrate employee protection concerning minimum wage and overtime pay; health, retirement, and leave benefits; equal opportunity hiring; safety and health in the workplace; fair youth employment; and union rights, among others, unless state law requires greater employee protection. Participants' contracts with contractors or contracting agencies require they abide by or exceed the employee protection requirements stipulated in the FLSA and all other applicable federal and state labor laws.

Fair Treatment of Workers

All workers and contractors shall receive fair treatment.

Grievance Procedures

Participants with 10 or more full-time employees, including seasonal workers, have a management policy that provides a mechanism for employees to raise concerns, safety issues, or grievances without fear of termination or any other reprisal, and inform workers of the policy at the time of hire or adoption of the policy.

IMPLEMENTATION: Participants demonstrate a system for the operation that provides a platform for employee grievances without fear of reprisal. Participants' contracts with contractors or contracting agencies require comparable grievance procedures.

Employment Contract

Participants provide workers with a written agreement describing the terms of hire.

IMPLEMENTATION: Participants demonstrate a written agreement (e.g. employment contract) regarding hiring, firing, working hours, and vacation time. Participants demonstrate compliance with local, state, and federal labor contract laws. Participants' contracts with contractors or contracting agencies require written agreements describing terms of hire.

Workplace Improvements

Participants provide opportunities for employees to make suggestions for workplace improvements.

IMPLEMENTATION: Participants demonstrate a system to provide an opportunity for employee suggestions and a sample of suggestions in the previous year.

Freedom of Association
Participants respect the right of workers to associate freely in the workplace and, if desired, organize among themselves to negotiate working conditions.

IMPLEMENTATION: Verified through private interviews employers and/or employees, or written policies and procedures.

Environment, Health, and Safety
Participants ensure that biomass production activities are conducted in a manner that protects the health and safety of employees. Table 17.3 represents an assessment of social sustainability for the crops discussed in this volume. This is done based on general literature and is not a case-by-case examination on the ground.

Compliance with Laws and Regulations
Participants maintain and provide documentation of compliance with federal, state, and local occupational health and safety laws and regulations.

IMPLEMENTATION: Participants demonstrate compliance with OSHA and applicable federal, state, or local laws or regulations. Participants' contracts with contractors or contracting agencies require compliance with OSHA and applicable federal and state health and safety laws.

Training
Participants and Participants' contracting agencies maintain and provide documentation that employees are trained for health and safety in the workplace.

IMPLEMENTATION:

- All employees, including seasonal employees, receive health and safety information, in a language they understand.
- All full-time employees receive health and safety training and get updated training at least every five years.
- All employees using potentially dangerous chemicals and machinery have received appropriate training.
- Supervisors are trained in emergency procedures and all provided information about who to contact in case of emergency and location of emergency kits.
- Participants' contracts with contractors or contracting agencies require comparable training and documentation for workplace safety training.

Hazardous Materials Protection
Participants and Participants' contracting agencies provide, and employees use, adequate protective clothing, appropriate safety equipment, and filtered air respirator systems and/or positive pressure cabs for workers handling highly toxic chemicals.

IMPLEMENTATION: Participants document the purchase of Hazardous Materials Protection for employees or identify the location of the equipment on the premises evidence of

Table 17.3 *Potential for selected social sustainability criteria for crops in this volume.*

Crop	Potential for farmer displacement 1 = high 5 = low	Fuel does not displace food Yes = 1 Never = 5	Inclusive of small and collective producers Never = 1 Always = 5	Potential to generate local enterprises None = 1 High = 5
Miscanthus	3	4	4	4 Propagation is labor intensive; custom harvesters
Napier grass	2 Large-scale production	4 Leaves can be used for forage	2	3
Sorghums and other annuals	1	4 Not if grown in rotation	4	4
Corn stover	3 Corn monoculture contributes to land concentration	5 If the grain is used for feed or industrial food inputs	3 Since there are advantages to scale, it is not likely to be inclusive	3
Wheat straw	4	5	3	3
Eucalyptus	1	2 Can graze cattle on eucalypus plantations	2	3 Tree harvesting services
Pine	4 If raised on plantations	4 Depends on if raised in plantations	4	4 Collecting and initial processing residue from sawmills
Poplar	2 If raised on plantations	3	3	3 Tree harvesting services
Willow	2 If raised on plantations			
Herbaceous crops	4 assuming not raised in plantations	3 Depends on what part of the crop baled	4	4
Sugarcane	2 If raised on plantations	4 Juice can be used for sugar, bagasse for biofuel	3 Small producers raise sugar cane in Mexico and Andean countries	3 Collecting and transporting the bagasse could be local
Energy cane	2 Lends to plantation cultivation	1	2 Requires high inputs and shifts in cultivation practices	2 Some harvesting and perhaps pre-processing
Woody crops				
Switch grass	4 Can be integrated into existing cropping systems on marginal land	4 Not if grown as conservation buffers	3	4 Value chain could be through decentralized platforms, with local units of production and processing delivering a high value product

worker education. Participants' contracts with contractors or contracting agencies require comparable protective equipment and clothing for the use of hazardous materials.

Accidents and Injuries
Participants and Participants' contracting agencies are prepared to handle injuries and chemical spills.

IMPLEMENTATION:

- Employees have access to well-stocked first aid kit at each work site.
- Employees are trained in emergency response procedures.
- Appropriate to the size of operation, procedures, materials, and training to address spills of hazardous materials are maintained.

Sanitation
Participants or Participants' contracting agencies provide clean drinking water and sanitary services.

IMPLEMENTATION: Participants provide records that document employee access to sanitation devices and clean drinking water for employees. Participants' contracts with contractors or contracting agencies have assurances to provide workers with clean drinking water and access to sanitation.

Insurance against Workplace Injury
Participants and Participants' contracting agencies provide workers compensation for all full-time employees.

IMPLEMENTATION: Participants provide evidence of insurance policies documenting the purchase of insurance products to cover workplace injury situations. Participants' contracts with contractors or contracting agencies require the purchase of workman's compensation insurance [14–16, 37].

In addition, Principles 7 and 8 address the key social areas of legality and transparency and Principle 1 requires integrated resource management planning.

17.4.6 Limits of Sustainability Standards

Sustainability standards and certification systems have been criticized for creating entry barriers and adding burdens to small-holders. The demanding, knowledge-intensive technical requirements and the certification process itself can exclude small-holders who are not given adequate extension service support or training in how to adapt to new standards [15]. The high financial, time, and opportunity costs of implementation can cause additional burdens, resulting in income loss and market access restrictions for small-scale farmers and enterprises, particularly those considered among the poorest [11, 25]. Sometimes the extra investment and effort needed to gain certification status does not pay off in terms of price premiums gained for certified products. Existing developing country suppliers might lose their position in global market chains as rising standards create new challenges [11]. If and when a standard becomes widely accepted, it could become *de facto* purchasing criteria. Buyers may be less willing to pay extra premiums for standards compliance, thus leaving producers to bear the burden of higher production and compliance expenses but with no direct financial incentive apart from market access [11]. When expected benefits do not materialize in the short term, the hidden costs of compliance undermine effective and cohesive collective action by cooperatives or associations designed to take advantage of certification systems [11].

Sustainability standards and certification systems have also been criticized for exacerbating inequalities in commodity chains. Even when producers receive some benefits, power relations remain unaltered when producers are non-participants in the decision making processes that affect them [11]. Downstream actors such as retailers can set higher consumer prices due to the value attached to symbolic attributes of the products; yet these higher prices do not always yield higher producer prices. Therefore, the inequalities of value distribution within different stages of certified chains are often higher for certified chains compared to conventional chains [15]. Moreover, sustainability standards and certification systems may enhance product quality and environmental outcomes for export-oriented production, giving the appearance of success, but fail to create incentives for sustainability in domestic markets, hence creating additional difficulties for companies wanting to produce for both markets.

Observers have further criticized sustainability standards for their failure to recognize and uphold certain social criteria for sustainability. For example, the Ethical Trading Initiative (ETI) fails to address gender-specific concerns of female workers and farmers arising from their domestic and household responsibilities [38]. Furthermore, the degradation of social well-being for populations in producing countries is one implication of uneven, unequal standards-induced employment and income in these areas. Some scholars go as far as to question the democratic legitimacy of sustainability standards, noting that "What private food governance does not foster and, in fact, tends to worsen, however, is the aspect of the social sustainability of the global agrifood system" [25].

The national context in which sustainability standards are implemented greatly influences the success or failure to reach compliance and enhance sustainability. Indonesia, where sustainable forestry standards conflict with local land tenure arrangements, provides a good example. The logic of certification does not adapt well to the political economy of land use in Indonesia. Certification systems rely on evaluations occurring in specific forest units, but the system of forest governance in Indonesia does not respect the integrity of such units [10]. Certification requires clearly defined forest boundaries and clear classification of forest types. Such clarity, however, does not exist in Indonesia, as 90% of state forest land has ambiguous legal status. Ambiguity results from conflicting interpretation of land rights and land use practices between the central government and customary, community-based land rights (*adat*). Land reforms to address these issues have stalled.

Social sustainability is often ignored by national governments who choose not to respect local land rights by leasing land directly to TNCs. The resulting predicament runs counter to FSC principles. FSC principle 2.2 says, among other things, that ". . . local communities with legal or customary tenure or use rights shall maintain control, to the extent necessary to protect their rights or resources, over forest operations unless they delegate control with free and informed consent to other agencies . . .". FSC principle 3 includes that ". . . the legal and customary rights of indigenous peoples to own, use and manage their lands, territories, and resources shall be recognized and respected . . .". Despite these FSC principles, the

Indonesian Ministry of Forestry has often granted timber concessions to large firms in areas where communities claim land use rights or where the legal status of the land is still unresolved [10].

Pressures to implement social sustainability standards will be based on the vigilance of CSO and the major buyers, including the U.S. government and major transportation companies, such as airlines. Pattberg [39] claims that effective market-based systems for governance toward sustainability outcomes must meet two basic conditions. Firstly, demand for eco-labeled products must be sufficiently high and steady to affect changes in production processes and business practices beyond temporary, "hot topic" public relation campaigns that are acted on in the media. To meet this condition, the champions (such as civil society organizations) of standards and certification systems must adequately inform consumers about existing choices. Secondly, effective private governance requires an adequate and consistent supply of certified products. When new systems are unable to provide a consistent visible presence in the market, they lessen their credibility, reduce their market share, and face difficulties in rivaling the non-certified products of competitors.

One shortcoming of sustainability standards and certification systems is their tendency to undermine social sustainability by marginalizing small-scale producers, enterprises, and retailers. Forest certification can also marginalize small-scale private forest owners and producers in developing countries. Certification adds cost to the production process, costs that are more heavily felt by small-scale producers who are unable to spread costs out across a larger operation. The result is loss in market share as they fail to cost-effectively meet market demands for certified timber and forestry products [18].

17.5 Summary and Conclusions

Social sustainability is not a result of the cropping system but in the way that the crop is grown by whom and where. Any biomass, including switchgrass, miscanthus, wheat straw and corn stover, can be grown in ways that contribute to the social sustainability of the producers, workers and local community, or in ways that limit the access of those stakeholders to natural, cultural, human, social, political, financial and built capital. When social sustainability is ignored, and fuels from biomass are viewed as simply a technical problem, it is likely that social inequality and social displacement will occur with serious societal repercussions. Managing investments may be more important for social sustainability than managing cropping systems. Since production of biofuels from biomass requires vertically integrated value chains, attention to land grabs and speculation by those at the end of the value chain to control the feedstock supply can have serious social consequences that impact not only social sustainability but ultimately environmental sustainability as well.

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18

Commercialization of Cellulosic Energy Cropping Systems

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18.1 Overview

In the United States during the mid-1970s, numerous cellulosic bioenergy research and development activities were conducted by U.S. Department of Energy (DOE) and U.S. Department of Agriculture (USDA) scientists and engineers, as well as many private sector companies and investors. Unfortunately, most of those efforts waned because obstacles to commercialization were not overcome. This chapter provides a perspective on developments since that time from the viewpoint of an active biomass conversion facility and examines five major challenges facing the emerging bioenergy industry. These include land availability, crop selection, financing, agronomic challenges, and risk management. Despite these challenges, it appears that public interest, political will, engineering and agronomic advances have now achieved a level where successful commercial operations can be developed.

18.2 Introduction

The processes and technologies required for producing, handling, and converting lignocellulosic biomass to energy have been key focus areas for research and development activities throughout the last decade. Universities, federal agencies and laboratories, private companies and foundations have all invested heavily to bring a biomass-based energy sector to reality for the United States. Early on, research focused on processes by which biomass could be converted to energy. Success was achieved utilizing both biochemical and thermochemical pathways. The next stage in the development of the industry focused on the

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development and production of a variety of biomass sources. From crop residues to dedicated energy crops, agricultural and forest-based biomass resources have been identified as the primary source of these materials. Biomass development and production research has focused on utilization of biotechnology and traditional plant breeding to improve existing crops with increased yield and conversion efficiencies, introduction of exotic plant species (e.g., *Miscanthus giganteus*), and development of appropriate agronomic production practices for each of the differing types of systems. Additional efforts have been directed toward development of logistical systems associated with moving, handling, and storing large volumes of biomass for energy production.

All of these efforts have significantly advanced the developing biofuels industry. Increased biomass yield per acre, decreased cost per ton at the farm gate, and increased gallons of ethanol, butanol or other fuel per ton of biomass have all improved when compared to their baseline values [1, 2]. As conversion technologies near commercialization, increased emphasis has been placed on commercial scale biomass production. Producing hundreds of thousands of tons of a given crop for a single facility is an industrial supply chain challenge that involves many players, including landowners, farmers, harvesting equipment manufacturers, truckers and logistical firms. All are dealing with a product that is different than any traditional agriculture or forest product, both in format and scale. Therefore, to be successful, commercial scale biomass supply chains must achieve a sustainable environmental and economic balance while overcoming several logistic and other obstacles. This chapter highlights five key areas of concern when commercializing dedicated energy crop biomass supply chains. Regardless of the scale of the required biomass production, many of these issues remain key.

18.3 Land Availability

As an industry that relies upon the growth of plant material, the basic denominator of all supply chains is availability of suitable agricultural land. Land is also the foundation for most other agricultural industries, including forage and grain for beef, swine and poultry production as well as the commodity or row crops. Competition for land will be one of the primary challenges to overcome in achieving commercial scale biomass production [3]. However, developing a sustainable feedstock supply chain is much more complicated than simply finding available land. Commercializing dedicated energy crops requires not only finding land but also recruiting landowners to use their land for biomass production. Recruiting landowners is a difficult task that must address several factors, including out-of-pocket costs, return to land and labor, competing land uses and existing relationships on the land.

It is often said that "marginal" land will be used for production of energy crops. But what is marginal land? Is it abandoned agricultural land? Fallow land? Land used simply for grazing or pasturing of animals? The definitions are broad and challenging and no two people can agree on a sound definition. It is safer to say that the use of agricultural land will be determined by its owner, who is guided by several factors: financial return, existing relationships (lease holders), and their farm management skills. For any available land to be enrolled in energy production, it must provide the right value to the farmer, both financially and as it fits with the landowner's management objectives. There is no argument that some land areas are more suitable for certain types of biomass production, while other areas are either not suitable or simply unavailable. In a perfect world, each acre of agricultural land would undergo a rigorous evaluation to determine its highest value and best use. In reality, though, there are many other factors that influence decisions made regarding land use.

When landowners make decisions regarding how to use their land, the current use, current and projected level of management, and several community-oriented issues all influence their final determination. However, the most influential factor and what usually finalizes the decision is whether or not a particular land use will be profitable to the landowner [4]. When commercializing energy crop production, landowners and farmers typically think about the cash flow of their operations in annual terms. Operating capital outlays offset by harvest season income is the common *modus operandi* for commodity row crops. However, when planning financial operations related to dedicated energy crops, the timeframe between outlays and income is much more extended and no longer fits with traditional agricultural operations. To willingly invest in in biomass production for cellulosic bioenergy operations, landowners and farmers must understand and be comfortable with this key difference and know how to plan accordingly. Simply comparing the current year's return from a crop like soybeans to the possible return from the same acre with switchgrass would not be a valid or accurate comparison. Similarly, comparing the current year's annual return on hay production to that from an energy crop on the same acre would not be accurate either. In both cases, many other factors can impact the annual return.

For row crops, annual returns are impacted by weather, global demand, and many other factors. Over the last three to four years, a variety of these factors have convened to make commodity prices for corn and soybean reach record levels [5]. These current high commodity prices make producing corn and soybeans on less productive acres more attractive. As a result, many agricultural areas have seen an expansion of these crops onto land where row crops have traditionally not been grown, as farmers can afford to take a lower yield per acre and still achieve a break-even or profitable return on investment with the current market. This expansion of row crops into less productive areas will impact land availability for energy crop production. Likewise, forage markets are significantly driven by annual weather patterns. During 2012, there was an intense drought throughout the central portion of the United States and, therefore, prices for hay moving out of the southeast reached near record levels. To compare these one-year returns to energy crop production on similar acres, the landowner and/or farmer must evaluate long-term benefits.

Energy crop production can bring a significant multiyear benefit to the landowner or farmer. In most cases, it is envisioned that long-term (5–10 year) contracts will be utilized to reduce risk for both the conversion facility and the producer. These long-term contracts will guarantee price stability over the contract period. Given that most dedicated energy crops' drought tolerance is greater, yield variation due to weather will be minimal compared to traditional row crops, thus resulting in more consistent yields over time. Consistent yields lead to more consistent returns in long-term contracts. As landowners and farmers evaluate energy crop production, they should compare returns from the previous 10 years of competing land use against potential 10-year returns from the selected energy crop. Only then can a clear decision be made based on financial returns per acre of land.

18.4 Crop Selection and Contracting

Selecting the appropriate crop for energy production for a given area is critical to commercial scale success. The choice is fundamentally determined by the product of two primary factors, adaptation and intended use. Firstly, the species must be adapted to the local climate. For example, tropical species such as Napier grass will have limited application in more northern climates, while species like miscanthus are more adapted to those areas. Extensive research and development has produced production guidelines for many biomass crops and data are readily available to producers [6–8].

The second factor (i.e., use) will be determined by the end user's specifications. Bioenergy crops will not be planted at large scales unless there are markets available for those crops. Those markets will be developed by biopower, biofuel, and bioproducts manufacturers. Some technologies are feedstock agnostic and can consume a wide array of feedstocks. Other technologies, most commonly biochemical platforms, are more selective and may have a more narrow specification for the species and types of feedstocks they accept. Either way, the biomass producer must ensure they are growing an acceptable type and quality of feedstock for the consumer.

An additional facet of crop selection is the determination of perennial versus annual energy crops. Most energy crops are perennial in nature. Species such as switchgrass, miscanthus, and energy canes can all have lifespans exceeding 10–15 years [6]. Woody crops, like poplar and willow, can extend 15–20 years depending on the desired rotation [9]. However, there are some energy crops that are annual in nature. Biomass sorghum, sweet sorghum, and grain sorghum all can be used as energy crops. These annuals offer flexibility in land utilization and farmer adoption.

Perennial bioenergy crops are desired for a range of reasons, mainly their low input and management intensity compared to other crops [10]. Annual crops, like sorghum, function more like traditional row crops and typically require higher levels of inputs. Yet these crops may be attractive to some landowners. Flexibility in contracting with both perennial and annual crops would allow an energy crop supply chain manager to offer both long-term (perennials) and short-term (annuals) contracts to attract landowners of differing interests and management goals. Having multiple types of contracts will truly increase the pool of available agricultural land.

Contracting with farmers for production of energy crop biomass can take many forms as well. The choice between perennial and annual crops will significantly determine contract attributes [11]. For perennial energy crops, long-term contracts (5–10 years) will likely be the norm. These longer-term contracts will be required to allow for recovery of the higher up-front establishment costs. Additionally, they provide more security and lower risk to the end user, whose project financing will require as much guarantee around feedstock supply as possible. In contrast, however, selection of an annual energy crop such as sorghum would allow for more short-term contracting and may attract landowners and farmers who have different approaches to land management. Those landowners and farmers would typically not participate in long-term contracts as they make more decisions on an annual basis. From a processor's perspective, being able to contract for cropping systems that combine annuals and perennials will provide the most flexibility regarding the type of contract and type of landowner/farmer they can recruit.

Undoubtedly, contracts will likely vary substantially from farm to farm. Commercial biomass entities need to be prepared with a base level contract that spells out the specific criteria that must be met (e.g., who is performing the management, what is the floor price, what are the materials specifications, etc.). Some landowners and farmers will want to self-perform all management activities while others will prefer to have custom operators fulfill those duties. There will not be one single type of contract used for commercial applications.

There will also be multiple types of contracts to address the many different farm situations that exist.

18.5 Financing Establishment

The choice of which energy crop to grow has a significant impact on production economics, especially establishment costs and how they are treated. Many farmers are accustomed to growing annual crops whose production systems require a more basic annual operating capital scenario, under which establishment costs are financed through a credit line or out of cash reserves. The return comes in the same operating year when the annual crop is harvested. Due to weather, market, and other risks, annual crop production is a high but short-term risk scenario.

Managing establishment costs for perennial crops is somewhat different. With a perennial, the producer must pay establishment costs up front, similar to an annual. However, the producer's return that will repay those establishment costs may come over a long period of time (e.g., ten years or more in some cases). This high up-front cost without quick recovery can be a barrier to many producers.

Programs such as the United States Department of Agriculture's (USDA) Biomass Crop Assistance Program (BCAP) and other incentives have sought to overcome this hurdle by providing producers cost-sharing assistance during the establishment year. BCAP repays producers for 75% of the establishment cost (www.fsa.usda.gov/bcap). Some states are evaluating methods by which they can create programs to assist with feedstock establishment and production costs. The challenge is that the long-term viability of incentive programs like BCAP and state incentives has yet to be proven. Furthermore, incentives such as these may become rarer in the current governmental fiscal climate and will likely be subject to political discourse. Nonetheless, to ensure development of a viable bioenergy industry, additional methods of overcoming these costs must be found.

One potential model is to have the biomass consumer, the conversion facility, include costs of establishing perennial biomass crops as part of the overall project financing package. As an incentive to recruit landowners and farmers to produce biomass, the production facility could offer establishment assistance by cost sharing or by providing inputs such as seed at no charge. The biomass consumer would like get a lower feedstock price for a defined period of time in return. However, the assistance from the downstream user mitigates risk to the landowner as well as the facility by making it easier to enroll land into energy crop production.

18.6 Agronomic Efficiencies and Management

Once the dedicated energy crop has been chosen and established, the supply chain must have a robust agricultural infrastructure to support it. The selection of dedicated energy crop species and mix will impact the agricultural infrastructure required to economically and sustainably operate the supply chain. Some energy crops require little to no modification of existing planters, harvesting equipment, and transport systems, while others will require improved or new technologies to improve the economics of the supply system. Crops that are planted using rhizomes or other rooted stock matter are a good example of this. Traditional planting of crops like miscanthus have required significant labor and time.

Recent advancements, however, have shown automated planters not only reduced the cost of establishment but in many cases actually improve establishment success rate. Many herbaceous crops can be harvested with existing hay and forage equipment that is generally available throughout most agricultural communities. However, some crops may require more specialized and less common harvesting equipment. One example of this is sweet sorghum, which requires cane-type harvesters.

Biomass consumers will require their feedstocks to meet certain specifications, including cost, moisture, delivered form, and particle size. The consistency in delivered feedstock will be critical, not only to the operation of the conversion facility, but also to the cost of the feedstock. For example, facilities will not be designed to allow farmers to deliver different bale sizes to a singular processing line. Biomass preprocessing equipment will likely be designed for specific feedstocks and to prepare the required delivery format. Variation from that format could cause a disruption in the supply chain.

In this new industry, the first few commercial scale cellulosic-based facilities will require tightly managed and highly efficient supply chains to minimize feedstock costs. In most cases, it is envisioned that these supply chains will be managed by the facility itself, an independent third-party operator, or producers, in the form of cooperatives. Commercial scale facilities will likely require significant investment in agricultural equipment that would make it difficult for individual producers to participate in the initial phases. Facilities that require round bale package formats may be more suitable to smaller producers as the capital cost of equipment is relatively small and similar to their current forage management operations. Facilities requiring a large square bale format or a chopped form from a forage harvester would probably prevent smaller producers from operating on their own, as the capital cost for equipment could be anywhere from three to ten times higher than that for conventional round bales. In these scenarios, third-party custom operators or operators employed by the conversion facility itself would be required to meet all required feedstock specifications. Additionally, not all land recruited for bioenergy crop production will be actively farmed or have owners that have the capabilities to conduct the operations for energy crop production and, therefore, custom operators will be required in those scenarios.

In commercialized supply chains, it is likely that some energy crop production will be carried out by farmers while some will be carried out by custom operators. Each has its benefits. Individual farmers tend to have more focus on their particular production acres, leading to more timely attention to production issues. Working with many individual farmers also has its challenges. Maintaining consistency, particularly in harvest, of crop conditions and packaging is made increasingly difficult with more operators and different pieces of equipment. Custom operations, however, create certain levels of efficiencies that are required to reduce cost in feedstock production. They also provide consistency in operations across a broad portion of the land being used to produce energy crops. Fewer machinery operators can lead to improved ability to train and reduce variation between operations. The consistency in quality and delivery package is of utmost importance to end users. A commercial scale biomass supply chain must be designed to minimize variation so that processing of biomass feedstock can be optimized. Additionally, landowners who have no interest in performing management tasks on their own land will also require custom operations.

Commercial scale energy crop systems must be able to deliver consistent quality. Consistency in delivery format and condition is critical, especially for first-generation commercial operations. Biomass conversion facilities will require as little variability as possible, whether that be in the feedstocks' form of packaging or composition characteristics of the incoming feedstock.

18.7 Identifying and Addressing Risks

At its core, the primary challenge with commercializing energy crop production for bioenergy is minimizing risk. This includes risk to the producer, risk to the biomass conversion facility developer, and risk to the institution(s) financing the project. Understanding and mitigating these risks are a part of the commercialization process. There are three primary areas of risk with energy crop commercialization. They are:

- Land recruitment.
- Establishment and supply ramp up.
- Annual yield risk.

As discussed earlier, recruitment of land is critical to all other aspects of the commercial scale supply chain. If a project is unable to secure the required amount of land in a given area, the entire project could fail. Addressing this risk begins with adequate planning. Finding a qualified partner to conduct a feasibility study on land recruitment will be critical. Feasibility studies will allow for the evaluation of many aspects of a given area's land use, agricultural infrastructure, and willingness of farmers and landowners to participate. A feasibility study will help identify potential issues with a given location prior to the start of a project and/or enable better site selection processes.

Recruitment risk can also be reduced through incentive programs, like BCAP, that reduce cost and risk to landowners and farmers. Particularly with perennial crops, reducing the up-front cost to landowners though such a program or by covering a portion of establishment costs through the project will enhance the project's ability to recruit land.

Significant risk is also associated with crop establishment and ramp up in yields to meet the demands of the biomass conversion facility at start-up. With perennial crops, the maximum yield of the crop is not reached until three years after establishment. This extended maturation of the plant requires commercial biomass supply chain developers to carefully plan establishment activities with the construction and subsequent start-up of additional biomass conversion facilities. Regardless of how well establishment is planned, several factors could disrupt the process and delay biomass supplies. Establishment of crops like switchgrass and miscanthus is not an easy task. As discussed in other chapters, precipitation, weed control, and other factors can make establishment difficult. If an acre of biomass crop is not successfully established and must be replanted, there will be an automatic delay in maturation of the crop by one year; this will thus affect anticipated delivery of biomass to the conversion facility.

To reduce establishment risk in energy crops, several best management practices should be employed. Firstly, areas with high populations of weed species known to compete with the target crop should be avoided. For all land types, site preparation in advance of planting can improve the likelihood of success significantly by reducing potential weed issues before they occur. Utilizing quality planting stock from reputable sources is also important. Seeded species require high germination rates for success and rhizome-type planting materials need to receive good care through rhizome harvesting and storage to enable adequate planting success. Finally, establishment-year management must be diligently carried out. Addressing competition issues and other field-by-field management concerns in a timely manner will significantly increase the likelihood of success. Additional tools, such as an increase in availability of applicable herbicides, will aid in management success.

The final key risk category is year-to year-variation in energy crop yield. While dedicated energy crops are more resistant to drought and other climactic factors, they are still susceptible. A drought that would wipe out a corn or soybean crop may reduce perennial energy crop yields by 20–30% [12]. Generally there will still be an adequate harvest and the stand will survive, but biomass yield will be reduced. There are also risks for pests and diseases that may impact the yield of dedicated energy crops. Planning to mitigate risk for this variation in yield, regardless of the source, will be difficult. As biomass conversion projects develop, energy crop production will be carefully monitored to match the annual volume of material required to operate a facility. Due to land and crop establishment costs, many projects will not have the ability to "overplant" a buffer supply to mitigate variation in yield from year to year. Therefore, planning to carry inventory over from year to year to buffer feedstock shortfalls is one method of addressing the risk. Identifying and planning conversion facilities for alternative feedstocks to augment primary supplies is another method. Developing a diverse portfolio of feedstocks is a broad, impactful tool to help ensure long-term success for commercial energy crop systems.

Additional risks, those that may not be directly tied to energy crop supply chains, exist and can dramatically impact the overall biomass-based industry. These risks include the stability or lack thereof in state and federal policies related to bioenergy. Policies, such as the Renewable Fuel Standard (RFS), can successfully generate market demand for biomass and subsequent products. However, as of 2013, the RFS and other biomass related programs, such as BCAP, continue to be a controversial mandate in the political arena. The policy climate presents significant risk to the industry as a change in the policy or even discussion about changing the policy can impact capital investment availability and markets for existing facilities. Additionally, some sectors of the biomass-based conversion industry are operating or planning to operate technologies that remain relatively unproven in the market place. Inherent risk is associated with using new technologies at a commercial scale. With the reliance of some biomass-based industries on perennial energy crops, the failure of a conversion technology may leave a large island of biomass energy crops stranded without a significant market for use. Creating multiple markets and outlets for the biomass will significantly reduce risk associated with policy and technologies by providing biomass producers with alternatives.

Biomass conversion facilities that have the ability to accept multiple types of feedstocks will have inherently lower feedstock risks. This is a key method of risk mitigation. Fewer acres of each individual crop will reduce yield variation and production risks. An ability to use other feedstocks when a particular one falls short on supply provides adequate back up to keep the conversion facility in operation. A diverse feedstock supply can also reduce feedstock costs by decreasing storage and other production system costs. Without any question, management strategies that accommodate diverse feedstocks are the primary method for reducing risk in energy crop supply chains.

The second overarching method to reducing risk in commercial dedicated energy crop supply chains is improvement in energy crop genetics. These improvements will be critical, just as they have been for corn and soybean. Significant yield gains have been made in the last 10 years through genetic resistance to drought, disease, and other pests affecting those crops. Similar improvements are now being incorporated into energy crop production and additional, significant improvements are expected in the next several years. Improvements in yield alone will reduce risk from all factors. Less land will be required to produce the same amount of biomass while fewer acres planted reduces establishment and annual variation risk. Other genetic traits and factors, such as herbicide resistance and improved nutrient use efficiencies, will also help reduce establishment and yield risk.

To successfully commercialize the energy crop supply system for a given consumer, project participants, financiers, and others will all be evaluating risk throughout the system. Careful thought and pre-planning of the energy crop supply chain can mitigate a significant amount of problems downstream.

18.8 Conclusion

Commercializing dedicated energy crop supply chains is not an easy task. Significant hurdles must be addressed to be successful. The good news is that a broad array of research and development (R&D) efforts have been and are underway. Government agencies, universities, and private companies have all made significant investments in developing systems by which energy crop supply chains can be commercialized. Significant research and development activities have occurred and are occurring in herbaceous energy crops and dedicated woody crops in all sectors of the United States and abroad. These R&D activities have generated a strong base of knowledge and expertise that commercial entities are now beginning to utilize at the commercial scale. It is projected that the United States could produce over one billion tons of biomass between 2025 and 2030 [13]. To produce that much biomass in a sustainable manner will require planning, a broad array of skills, and sound risk management, as well continual improvement of the entire supply chain during the next decade. As the first few commercial scale projects begin operation in 2014 and 2015, all of the knowledge and skills developed will be put to the test. With the extensive work that has gone on in the past decade, we are well positioned to make the commercialization of dedicated energy crops a great success, a success that will benefit generations to come.

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19

Selected Global Examples of Cellulosic Cropping System Trends

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19.1 Overview

Plant biomass has been recognized globally as an important link to a sustainable energy future because it can be grown universally and converted into liquid transportation fuels or other material through biochemical, thermochemical, or catalytic conversion processes. However, those potential benefits must be viewed in the context of other global societal needs (i.e., food, feed, fiber, potable water, carbon storage in ecosystems, and preservation of native habitats and biodiversity) that must also be met by plant biomass growing on a finite amount of arable land. The development of cellulosic feedstocks for biofuels and other bioproducts must be accomplished in an economically viable, environmentally benign, and socially sustainable manner. This task is feasible throughout the world, as illustrated by examples from Brazil, China, and India.

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In Brazil, the primary cellulosic feedstock will be the straw and bagasse from the sugarcane industry. Traditionally, the straw was burned prior to harvest but increasing public concern has resulted in a phasing out of burning throughout the main sugarcane-growing regions of the country. Efforts to develop economically viable second generation ethanol production using these materials have been supported by investments from the Brazilian government through new research institutions, such as the Brazilian Bioethanol Science and Technology Laboratory (CTBE) and Embrapa Agroenergy. National and state research funding agencies as well as the Brazilian Bank for Economic and Social Development have also provided support for these endeavors.

In China, mandates that bioenergy production must not compete with food or feed production and must not inflict harm on the environment are key drivers in the development of this new industry. Crop residues and some plantation agriculture on marginal land are being explored but currently sweet sorghum has been identified as the best candidate for biofuel production. Similarly, in India, where 70% of the population depends on agriculture for its livelihood, bioenergy production must not have any negative impacts on food supplies or the overall economic welfare of Indians.

Undoubtedly, many similar and perhaps some divergent examples could be given by including perspectives from other countries, but that was beyond the scope of this book. The important perspective from this work is to recognize that Cellulosic Bioenergy Cropping Systems have both universal and site-specific characteristics that need to be fully vetted and understood to have truly sustainable food, feed, fiber, and fuel production throughout the world.

19.2 Cellulosic Ethanol in Brazil

19.2.1 Feedstocks

In Brazil, sugarcane-derived bioethanol is one of the most successful examples of large scale biofuel production, distribution and use. The use of ethanol in transportation and for the production of electricity from sugarcane residues accounts for nearly 16% of the total energy supply [1], making it the second primary source after oil. Current ethanol production is based on first generation (1G) technology, fermenting sugars extracted from sugarcane stalks. However, sugar only represents approximately one third of the energy content of sugarcane. The other two thirds are composed of straw that is either burned on the field or left as mulch, and bagasse, the fibrous material left from the juice extraction process, which is mostly used as fuel for process heat and electricity generation at the mill. Cellulosic ethanol, also known as second generation (2G) ethanol, can be produced from what is currently considered agricultural and industrial residues (straw and bagasse).

Bagasse is readily available at the plant site without collection and transportation costs, in the shredded form and with low ash content. However, two trends might put pressure on bagasse availability for cellulosic ethanol production: the declining fiber content of new sugarcane varieties – a target of most crop breeding programs – and the increase in surplus power generation, especially in the new mills. On the other hand, there are commercially available technologies to reduce process steam consumption – the main energy demand at the plant – thus reducing bagasse consumption and increasing its availability for cellulosic ethanol production.

Pre-harvest burning has been a conventional practice to facilitate sugarcane manual harvest. Due to environmental and socioeconomic reasons, there are ongoing burning phase out programs in the main sugarcane-growing regions in Brazil, with the gradual replacement of manual harvest with burning by mechanized harvest without burning leaving 10–20 tons (dry matter) of straw per hectare on the field. This lignocellulosic material has also been considered as a feedstock for cellulosic ethanol production in Brazil. However, the task of collecting, transporting and pre-treating this material presents important challenges that need to be overcome before it can be used on a commercial basis. The low mass and energy density, and the distribution throughout extensive land areas are limitations due to transportation costs. Collection methods such as bailing can deteriorate the quality of the feedstock by increasing the ash content to a level that requires a pretreatment to bring the values to acceptable levels [2]. There is ongoing research to develop mechanical harvesters that can efficiently handle both sugarcane stalks and straw, being capable of separating and conditioning the straw with sufficient load density for low-cost transportation as well as maintaining adequate quality for industrial use.

There are also potential benefits of leaving crop residues on the field, such as protection against erosion, nutrient cycling, soil carbon sequestration, weed suppression and soil moisture retention. On the other hand, considering the large quantities of residue generated and their high carbon-to-nitrogen ratio and fiber content, it is likely that removing part of the straw will still secure most environmental and agronomic benefits. Those benefits are site specific, so the amount of straw that can be removed sustainably should be calculated considering climate, topography, soil, and crop variables.

Sugarcane is a semi-perennial crop with a plant crop and successive regrowth crops, known as ratoons. After five or six harvests on average, it is necessary to replant the crop, and there is usually a period of a few months in which there is a fallow period or cover crops, usually legumes. Sweet sorghum (*Sorghum bicolor* L. Moench) has been evaluated as feedstock for both first and second generation ethanol production [3]. Currently, there is preliminary research in Brazil for cropping sweet sorghum in the short period between sugarcane cycles, providing supplementary feedstock for ethanol mills in a period of low sugarcane availability.

The growing interest in bioenergy crops led to the development of cane varieties with high stalk and leaf fiber and lower sucrose content, called "energy cane" [4]. Since the primary energy content per unit of cropped area is higher than with conventional sugarcane, energy cane has the potential to become another alternative feedstock for cellulosic ethanol production in Brazil.

19.2.2 Conversion Technologies

A fundamental advantage for integration of cellulosic ethanol into current first generation ethanol production from sugarcane in Brazil is the availability of lignocellulosic material (bagasse) at the plant site and the feasible alternative to also use sugarcane crop residues (straw). Regarding this, it is fundamental to consider optimization strategies for first generation ethanol production, aiming at energy savings and, thus, more surplus lignocellulosic material for second generation ethanol production. Cellulosic ethanol production in Brazil may also benefit from sharing part of the infrastructure where first generation ethanol production takes place (for instance juice concentration, fermentation, distillation, storage and cogeneration facilities). In addition, potential fermentation inhibitors generated in the lignocellulosic material pretreatment may have a minor effect on fermentation yields, since the hydrolyzed liquor may be fermented mixed with sugarcane juice, diluting these inhibitors.

Due to the high potential of biomass for the production of fuels and chemicals, research in Brazil has focused on the hydrolysis of sugarcane bagasse and/or straw for cellulosic ethanol production. Furthermore, the production of liquid fuels through the use of pyrolysis/gasification has also been seen as a promising alternative.

Second generation ethanol production involves basically four steps: pretreatment, enzymatic hydrolysis, fermentation and ethanol recovery. In recent years, pilot and demonstrattion scale plants have been built in Brazil and worldwide. However, enzymatic technology still faces numerous obstacles and is not yet mature enough for full commercialization. Some major challenges faced are the high cost of the pretreatment step and the low efficiency of the enzymatic saccharification of polysaccharides to sugars, as well as the high cost of enzymes.

Owing to the large impact of the pretreatment step on all the other operations in the process, research efforts have been made to find efficient, fast and affordable pretreatment methods which primarily aim at making biomass accessible to enzymatic attack. Several pretreatment methods have been studied in Brazil, usually involving high temperature and pressure, such as in hydrothermal and steam explosion pretreatments. These processes may be performed at different pH (acidic, basic or neutral), depending on the addition or absence of catalysts; also, the use of organic solvents in these processes is quite usual. Common to all of them is the need to integrate the process, including energy and water consumption and reagent recovery, in order to obtain high cellulosic ethanol yields at reasonable costs and low environmental impacts.

These pretreatment methods need to be further improved in combination with enzymatic hydrolysis and fermentation, as improved enzyme mixtures may lead to less severe pretreatment conditions and, thereby, to lower enzyme costs and reduced formation of inhibitory compounds, while more robust fermentation organisms can tolerate more toxic hydrolysates.

Regarding enzymatic hydrolysis, studies have shown that reducing the cost of cellulase enzyme production is an essential step to make enzymatic hydrolysis more economically feasible. In-house enzyme production, using part of the pretreated bagasse as substrate, emerges as a potentially attractive alternative technology. Another important factor to be considered is the increase of enzyme effectiveness that can be achieved through the development of more efficient enzymes and enzymatic complexes with higher activity.

19.2.3 Progress Towards Commercialization

Evaluations of integrated versus stand-alone cellulosic ethanol production from sugarcane bagasse/straw [5] demonstrated that some scenarios for the integration of first and second generation ethanol production in Brazil present better economic results than optimized first generation ethanol production. Integrated scenarios can increase up to about 40% ethanol production per unit of sugarcane processed and increase the internal rate of return by about 2% per year in comparison to optimized first generation ethanol production. These results show that the ethanol average cost from an integrated first and second generation ethanol production can be cost competitive with first generation ethanol and gasoline at current oil prices, if the projected process performance is achieved. The current challenge regarding cellulosic ethanol production lies in gaining a competitive and sustainable scale for achieving the consolidation of industry standards of production. Naturally, having the best conditions in relation to the cost and availability of raw materials are essential factors for the success of this strategy, and Brazil presents several advantages considering the favorable environment for integration of second generation ethanol in the efficient and well established first generation ethanol production chain.

The internal market for ethanol in Brazil has steadily increased, driven by the government mandates of 18–25% ethanol in gasoline, as well as the widespread use of flexible fuel vehicles, which can run on any fuel mix between gasoline and pure hydrated ethanol. It is expected that the existing storage, blending and distribution infrastructure of 1G ethanol will benefit the commercialization of cellulosic ethanol in Brazil.

Regarding the potential external demand for cellulosic ethanol, current trends might foster production of 2G ethanol in Brazil. In the United States, the revised Renewable Fuel Standard (RFS2) puts emphasis on both advanced biofuels and cellulosic biofuels. First generation sugarcane ethanol is classified as advanced biofuel, since it meets the threshold of 50% reductions in greenhouse gas emissions compared to fossil fuels displaced. Under the RFS2, cellulosic biofuels will have an increasing share of the biofuel market in the United States, reaching 16 billion gallons by 2022. The current trend in the European Union for reduced reliance on conventional biofuels that could potentially compete with food or fiber, and to substantially increase the share of cellulosic biofuels from crop residues, waste, woody material, can also provide incentives for growth of cellulosic ethanol production in Brazil.

19.2.4 Enabling Government Policies

Over the past few years, the Brazilian government has invested on research, development and innovation regarding cellulosic ethanol production, with the creation of new research institutions, such the Brazilian Bioethanol Science and Technology Laboratory (CTBE) – part of the Brazilian Center of Research in Energy and Materials (CNPEM) – and Embrapa Agroenergy. National and state research funding agencies have been providing support for cellulosic ethanol research through programs such as the FAPESP Bioenergy Research Program (Bioen). There has also been substantial financing by BNDES (Brazilian Bank for Economic and Social Development) for technological innovation, creation of infrastructure (e.g., ethanol pipelines) and financing of new production units in the sugarcane expansion areas, as well as other initiatives such as the PAISS program to foster development, production and marketing projects of new industrial sugarcane biomass processing technologies.

The rising domestic and external demand for ethanol will lead to increased production of feedstocks in Brazil. Cellulosic ethanol production, especially from crop residues, can supply part of the increased demand, reducing the need for land use change, which can potentially increase greenhouse gas emissions. The trend towards phasing out biomass burning in Brazil, driven by municipal, state and federal legislation, as well as from sugarcane sector stakeholder arrangements will increase the availability of crop residues as feedstock for cellulosic ethanol production. In the industrial phase, improvements in boiler efficiency can make more bagasse available for 2G ethanol production. There are still challenges regarding conversion technologies, but cellulosic ethanol has the potential to be technically and economically feasible in Brazil, especially if integrated with first generation ethanol production from sugarcane.

19.3 Cellulosic Bioenergy in China

19.3.1 Feedstock Options

In China, the constraints of limited and decreasing arable land, as well as a huge population, are forcing the government to strike a balance between food security, energy security and environmental protection. Therefore, Medium- and Long-Term Development Plan for Renewable Energy in China clearly state that "Biofuel [production] must not compete with grain over land, it must not compete with food that customers demand, it must not compete with feed for livestock, [and] it must not inflict harm on the environment" [6]. To develop useful cellulosic energy crops, it is therefore important to have a basic understanding of available land and the competing needs in relation to crop production. Specifically, large scale cultivation of cellulosic energy crops is prohibited in China, unless it is done on marginal land. Therefore, because China is a large agricultural country, crop residues have been identified as the major cellulosic energy resource.

According to the survey and evaluation report on National crop straws, the theoretical annual yield of crop straws in China is 820 million tons (air-dry weight, 15% moisture) [7]. Corn, wheat and rice, which are the three most dominant grain crops, accounted for more than 75% of the total agricultural residue resources. Geographically, more than 50% of these straw resources are located in eight provinces (Sichuan, Henan, Shandong, Hebei, Jiangsu, Hunan, Hubei and Zhejiang) (Figure 19.1). The annual yield and percentage of straw contributed to the total resource is listed in Table 19.1.

The available amount of crop residue, estimated at 687 million tons, is less than the theoretical value because all harvest technologies will leave some stubble in the field. Furthermore, many of the collectable straw residues are already being used for fertilizer, feed, fuel, and industrial materials. Therefore, in addition to the 129 million tons of straw that is currently being used for fuel, it is estimated that an additional 215 million tons of straw could be utilized for biofuel production [7].

Eucalyptus, pine and poplar are three important, quick growing tree species that have been chosen for planting in China. This has given China the largest area of planted forest in the world, but the purpose of planting those lands is to provide environmental protection and fulfill industrial demand. Therefore, it is unacceptable to produce energy using these woods. However, forestry residues, including harvesting and wood processing wastes, forest management cuttings and small branches, shrub cuttings, economy forests, bamboo forests, shrubs growing under the primary trees and municipal green forest cuttings, can be used.

According to the seventh National Forestry Survey (2004–2008) [8], China processes 195 million ha of forest area with cover rate of 20.36% each year. Of this total, 64.2 million ha is for timber, 82.1 million ha is for protection forest, 20.4 million ha for economic forest, 1.8 million ha for firewood forest, 12.0 million ha for special-use forest and 14.6 million ha is for other uses. Based on these six forest categories, the total amount of available forest residues was estimated to be 368 million tons in 2008. Although it is expected that area of forest land in China will continue to increase, forestry residue resources are expected to remain stable for the next ten years due to many constraints, such as cutting regulations,

Figure 19.1 *Chinese Provinces shown to help identify where cellulosic crop residues may be available for bioenergy production.*

Table 19.1 Estimated agricultural crop straw residues available for bioenergy production.

Agriculture crop	Yield (tonnes)	Percentage of total supply
Rice	205 000 000	25.0
Wheat	150 000 000	18.3
Corn	265 000 000	32.3
Cotton	25 840 000	3.2
Oil crop	37 370 000	4.6
Bean	27 260 000	3.3
Tubers	22 430 000	2.7
Other	90 200 000	11.0

Data source: [7].

lack of industrial collection, processing capacity, environmental protection, and competing uses with other industrial production activities.

A national survey organized by Ministry of Land and Resources of People's Republic of China on the national land resource indicated there are about 82.5 million ha of uncultivated land of which 34 million ha, including waste land and winter-fallowed paddy land, could be made available for energy crop production. However, two critical points sought by the Chinese bioenergy market were that (1) non-food crops should be used for bioenergy production and, of even more importance, (2) neither yield nor the ability of cultivators to produce food should be threatened or reduced.

Sweet sorghum is an energy crop that can meet the requirements established for bioenergy in China. As a variant of conventional sorghum, sweet sorghum can be characterized as multiplatform crop capable of producing grain, sugar, and cellulosic straw. The production of sweet sorghum does not decrease the capability to produce grain from cultivated land since it can be rotated with conventional grain sorghum depending upon market forces. In addition, the high photosynthetic efficiency and excellent stress tolerance of sweet sorghum enables it to be grown on lower quality, drought prone or saline land. Potential grain and stalk yields for sweet sorghum in China range from 2.25 to 7.5 tonnes per ha and 40 to 120 tonnes per ha, respectively [9]. Sweet sorghum can produce one or two times more ethanol per unit land area than corn. Moreover, new sweet sorghum varieties (e.g., the Liaotian, Chuntian, or Nengsi series) with better geographic adaptability, high stalk yield, high brix, and tolerance to saline-alkali stresses have been developed by Chinese scientists. Currently, sweet sorghum is produced primarily in northern China, with the total production in 2008 being 2.5 million tonnes [10]. Therefore, as bioethanol production using advanced processing technologies improves, sweet sorghum would appear to be the most promising bioenergy crop for China.

China also has a very rich Miscanthus resource, which is being developed into a potential energy crop by Chinese research scientists and engineers. Based on average precipitation amounts, temperature ranges and other factors, areas in East, Central, South, and Southwest China are most suitable for Miscanthus production. It appears that production of Miscanthus can be an effective complement to sweet sorghum production, but due to the late start of energy crops research in China, Miscanthus studies are still in the initial stages of development.

Forestry residues could provide another cellulosic resource, but due to many existing obstacles including environmental protection policies, competing uses for industrial processing, high costs for collection, and natural conditions where forests exist, large scale use of these residues for energy production still faces many challenges. Therefore, wood energy crops will likely not be developed very fast for at least then next ten years.

19.3.2 Conversion Technologies

Several cellulosic energy crop conversion technologies exist and are being developed within China. Detailed information regarding these technologies are summarized in Table 19.2.

Energy conversion efficiency of thermochemical technologies is higher than that for biochemical technologies but currently mature thermochemical technologies cannot convert cellulosic resources into liquid fuel. Therefore, among developing technologies, only ethanol from sugar is competitive in the market. As discussed in Section 19.2.1, sweet sorghum is the most promising cellulosic energy crops to meet the requirement for China renewable energy. However, high energy costs for squeezing sweet sorghum juice and a very limited operational period have resulted in several obstacles limiting commercial operation of sweet sorghum ethanol plants using liquid fermentation technologies. To overcome

Table 19.2 *Summary of conversion technologies for cellulosic energy crops.*

Conversion technology	Cellulosic feedstock/optimum characteristics	Bioenergy form	Application status
Direct combustion biomass power generation	Agricultural and forestry residues/low alkaline metal content	Electric and heat	Commercialization
Co-firing of coal and biomass power generation	Agricultural and forestry residues/Portion of biomass less than 20%	Electric and heat	Pilot and Demonstration
Power generation from biomass gasification	Agricultural and forestry residues/No specific criteria established for use in China	Electric and heat	Commercialization
Biomass pellet fuel	Agricultural and forestry residues/Low moisture and ash	Solid biofuel	Commercialization
Biomass carbonization	Agricultural and forestry residues/No specific criteria established for use in China	Fuel gas, Tar, Wood vinegar, Biochar	Commercialization
Anaerobic digestion	Agricultural residues/No specific criteria established for use in China	Biogas	Commercialization
Sugar ethanol	Sugar crops/Sweet sorghum	Ethanol	Demonstration
Cellulosic ethanol	Agricultural and forestry residues/No specific criteria established for use in China	Ethanol	Pilot and Demonstration
Pyrolysis	Agricultural and forestry residues/No specific criteria established for use in China	Bio-oil	Pilot
Gasification syngas	Agricultural and forestry residues/No specific criteria established for use in China	Methanol, DME, FT diesel	Pilot and Demonstration

drawbacks associated with liquid fermentation and reduce the fermentation period to just 30 hours [11], advanced solid state fermentation (ASSF) technology for crushed sweet sorghum stalks has been developed by Chinese scientists.

19.3.3 Progress Towards Commercialization

The biomass energy industry has developed rapidly since the renewable energy law was promulgated in 2006. So far, commercial operations of biomass energy plants in China are focused primarily on agricultural and forestry residues that are being used for power generation by direct combustion, co-firing, gasification, pellet fuel, and biomass carbonization technologies. At the end of 2010, the total installed biomass power capacity was 5500 MW. Compared to coal power generation, biomass power currently depends on national government subsidies due to its high capital cost and low energy conversion efficiency. In addition, without the development of efficient solutions for questions regarding collection, transportation and storage of cellulosic feedstock, commercialization of biomass power generation will be difficult to implement.

Biogas is a mature technology that has been implemented in China but anaerobic digestion of cellulosic feedstock is still at the initial stages of development. Some challenges, such as recalcitrance of straws and difficulty in feedstock material transfers, have yet to be faced. So far, more than 10 large scale biogas projects using crop straws have been developed to an operational scale in China. More large scale power grid-compatible, biogas power generation technologies should be encouraged and prioritized for future development.

Finally, although the technology for cellulosic ethanol is not mature, the Longli Group Co. Ltd. has implemented a commercial scale ethanol production facility using corncobs. More efforts need to be made to reduce production costs for second generation biofuel. The market benefit for sweet sorghum ethanol is being improved with the perfection of ASSF technology. Therefore, sweet sorghum ethanol production and planting of sweet sorghum will likely be encouraged and promoted by the government.

19.3.4 Enabling Government Policies

Promulgation of the twelfth, "Five-year Plan for the Biomass Power Industry" in 2012 clearly stated that the installed power capacity for biomass power generation was targeted at 13 000 MW by 2015 and 30 000 MW by 2020. Furthermore, annual production of biomass pellets was targeted on 10 million tonnes and annual production of bioethanol was targeted on 3.5 million tonnes. To achieve these targets, a series of substantial supporting policies that include direct financial subsidies, tax exemptions, and low-interest loans for capital investment for feedstock development through bioenergy production and consumption, have been taken by the Chinese government. The policies for promotion of cellulosic energy can be divided into two categories: one for conversion technologies and the other for feedstock development.

For biomass power generation, China has applied a "feed-in" tariff system for biomass power projects of 0.25 Yuan/kWh since 2006. An additional subsidy of 0.10 Yuan/kWh for biomass direct combustion power generation projects is also available. To promote biogas development, a policy issued by the China National Development and Reform Commission (NDRC) in 2009 announced that the government would supply partial project investment incentives according to the scale of biogas production [12].

To encourage the development of non-cereal based bioethanol, the Ministry of Finance (MOF) announced that it will provide financial support to non-cereal bioethanol plants in the form of low interest loans and direct subsidies [13]. So far, there is no subsidy for cultivation of energy crops, whereas in order to promote the production of feedstocks on marginal lands, the MOF in 2007 stated that firms reclaiming new marginal lands for non-cereal feedstock production would get a one-time subsidy of RMB 2700 or 3000 yuan per hectare.

19.4 Bioenergy in India

19.4.1 Biofuel Challenges and Opportunities

Planning for the future needs of India's large and growing population has driven much discussion regarding the importance of agriculture. Agriculture occupies center stage for India's social security and overall economic welfare, as 70% of the population depends on it as a means of livelihood. Since Independence, India has experienced significant production increases in food grains (green revolution), oilseeds (yellow revolution), milk (white revolution), fish (blue revolution), and fruits/vegetables (golden revolution). All of these revolutions became possible by applying cutting-edge science, coupled with positive policy support and the hard work of Indian farmers. The post-independence period marks a turning point in the history of Indian agriculture, as the rate of growth grew from less than 0.5% annually between 1904 and 1945 to 2.7% between 1950 and 1984 [14].

This growth has been achieved as a result of the high priority accorded to agriculture. Policy makers adopted a twofold strategy for regenerating agriculture immediately after independence. The first element was to implement land reforms to remove institutional bottlenecks and the second was to undertake massive investment in irrigation and other infrastructure in order to update existing agricultural technology [14]. According to World Bank data, the agricultural sector value added (% GDP) in India during 2008–2012 was about 18% [15].

India's continued growth depends on energy availability, and the country is struggling to meet its growing energy demands. With 0.5% of the world's oil and gas resources but 16% of the world's population, the country is heavily dependent on expensive oil imports [16]. Energy self-sufficiency has outpaced food self-sufficiency as a national priority and India is aggressively pursuing alternative energy resources. India is also the world's third largest producer of greenhouse gas (GHG) emissions [17], adding to its motivation to develop more green energy resources.

Biofuel production is considered one of the most promising options to promote energy security and reduce emissions in India and, in 2009, the Government of India approved the National Policy on Biofuels and launched the National Biodiesel Mission. Presently, biofuel production in India is limited for a number of reasons [18]. For example, India is the world's second largest producer of sugarcane (after Brazil), but its sugar supplies are matched by an equally large demand, and therefore the country cannot afford to divert any sugarcane for other purposes. This means that India's ethanol production comes only from molasses, a by-product of sugar [19]. Secondly, India is a net importer of edible oils; therefore, to avoid any biofuel policies that could aggravate the country's already dire situation of food insecurity for more than 220 million Indians [20], the country cannot afford to divert any of its edible oil supplies into biodiesel manufacturing. Finally, the arable land availability for growing biomass feedstock for biofuels applications is a significant constraint. Given these conditions, India's bioenergy program has focused primarily on sugar by-products (sugarcane molasses) and on cultivating non-food crops on what the government perceives as "marginal lands" – that is, lands with suboptimal soil and water conditions, which are not already being used by intensive agriculture [21].

Agricultural residues seemed to be the most promising near-term feedstock for cellulosic biofuel production. A nationwide assessment of available agricultural residues estimated that there were 134.4 million metric tonnes (MMT) of rice residues, 109.9 MMT of wheat straw, and 199.1 MMT of sugarcane residues (Table 19.3) [22]. These estimates account for almost 80% of the residue generated by the crops that were studied. However, a significant portion of the residues generated is already consumed for fodder and other uses, thus limiting their availability for biofuel production (Table 19.3) [22]. Other plant residues that could be used for bioenergy production include 18.9 MMT from cotton cultivation, processing wastes from forest products such as bamboo and reed, or even pine needles, which have an estimated annual availability of 1.6 MMT. However, many of these resources present problems with respect to collection and logistics [22]. Physical properties as well as the cellulose and fermentable pentosans content in each of these materials are different and, therefore, processing technologies will likely differ if they are to be used as raw material for ethanol production [22].

19.4.2 Feedstocks

The concept of growing dedicated energy crops is relatively new to India compared to North America, where there is available land suitable for growing crops but not currently being

Table 19.3 *Major agricultural and forest residue resources and promising oil seed and cellulosic energy crops being explored for bioenergy applications in India [22–25].*

Type	Annual agriculture and forestry residue generation (MMT)	Annual available agriculture and forestry residue for bioenergy production (MMT)	Energy Crop Yield Potential (MT/Acre)
Rice (straw and husk)	134.4	8.9	
Wheat (straw)	109.9	9.1	
Sugarcane (tops and bagasse)	199.1	85.9	
Corn/maize (stover, cobs, husk)	29.6	3.9	
Cotton (stalk)	18.9	11.4	
Pulses waste	18.9	5.7	
Sorghum (stover)	15.6	1.6	
Millets	14.9	1.2	
Bamboo (top, root, leaves)	5.4	3.3	
Oil seed wastes	57.7	17.3	
Pine needles	1.6	1.2	
Water hyacinth (whole)	15	14	7/day
Jatropha seed	—	—	2.6/yr
Beema bamboo	—	—	50/yr
Majestica (Paulownia)	—	—	40/yr
Melia dubia	—	—	40/yr

used for food, feed or fiber production. In India, energy plantations are being promoted in designated non-farmland areas, where poor soils and lack of water are often limiting factors. Crops suitable for biodiesel production have been given a greater priority in India because high gasoline prices are quickly driving the transportation infrastructure to favor diesel [26], with diesel demand now four times that of gasoline. Diesel has been the standard for agriculture but its use is increasing to fuel urban generators that provide backup to unreliable power utilities and irrigation pumps during seasons of drought [26].

Investment in biodiesel development in India has largely focused on the cultivation and processing of Jatropha seeds, which are very rich (50%) in oil [27] and were reported to grow well on marginal lands. Questions regarding performance of Jatropha plantations have prompted the Indian Union Rural Development Ministry to put a hold on the Jatropha plantations, pending further development [27], and to explore other energy crops. Estimated current hectares under Jatropha cultivation are just less than 500 000, which, at mature annual yields of at least 5 MT seeds per hectare, would produce 62.5 million liters biodiesel [28].

In terms of cellulosic energy crops, a few India-native species have been identified as promising but these are in early stages of development. Beema bamboo is a newly developed variety that grows quickly, produces high yields, and has high energy value and low ash content. Beema is suitable for high-density planting, is disease resistant, has good water-use efficiency, and responds well to agricultural practices. Under optimum growing conditions, a mature Beema plantation yields over 50 tonnes per acre. Plantation establishment time ranges from 2–4 years before the first harvest but then has a life span of over 50 years [23].

Marjestica (Paulownia) is a species of tree that will grow up to 28 feet in the first year and can be coppiced annually at least eight times. It has a low water requirement and can yield up to 40 tonnes per acre annually over an eight-year period before replanting [23]. *Melia dubia* also has promising qualities for plantation production. Traditionally grown as a source of firewood and for the plywood industry, *melia dubia* can be cultivated in all types of soil and requires a low supply of water on a daily basis. It is fast growing, has high energy value, and can reach a height of 40 feet within two years after planting [23]. It can then be pruned and harvested, often yielding more than 40 tonnes of biomass per acre every 18 months for up to 10 years before needing to be replanted.

Water hyacinth, an invasive floating plant that often jams rivers and lakes with uncounted thousands of tonnes of floating plant matter, is also under consideration as a promising biofuel crop [25]. A healthy acre of water hyacinths can weigh up to 200 tonnes. Water hyacinth in most places is under “maintenance control” and field crews are continuously working to keep the plant numbers at their lowest possible levels in order to keep rivers and lakes usable. Research institutes in India are working on identification of microorganisms that will produce enzymes to degrade the plant’s complex sugars or polysaccharides [25].

19.4.3 Progress Towards Commercialization

CLENERGEN, in collaboration with partners, has carried out trials on short-rotation cellulosic crops on 150 acres in Valliyur, Tamilnadu, to determine the optimum yield. Preliminary results have been very positive and the company has sublease agreements for 5000 acres in Valliyur, Tamilnadu, and 4000 acres near Tutitcorin, Tamilnadu, to demonstrate commercial plantations to support a 32 MW/h biomass power plant [29]. The same company has entered into agreement with Yuken India Limited (YIL), located in Bangalore, Karnataka State, to install a 4 MW/h gasification biomass power plant [30].

IndianOil has been in the forefront of technology development for biodiesel production from various edible and non-edible oils and its application in vehicles. Pioneering studies by IndiaOil's R&D Centre established that biodiesel produced from Jatropha seed was at par with that produced from vegetable oils [31]. In the past few years, the R&D Centre has collaborated with several vehicle manufacturers, railways, and state transport institutions to study the entire value chain of biodiesel. The breadth of these studies has spanned Jatropha plantation field studies to field trials on passenger cars, light commercial vehicles, and railway locomotives.

IndianOil, along with its subsidiary IndianOil Technologies Ltd., has been engaged in successful marketing of in-house developed technologies, technical services and training, not only in India but abroad as well [31]. IndianOil has invested close to $250 million in setting up world-class facilities at its R&D Centre for building capabilities in analytical services, engines, test rigs and pilot plants for all major refinery processes, catalyst characterization, development, and so on. It planned investments of about $125 million during the period 2007–2012 to maintain its leadership in downstream R&D activities in the hydrocarbon sector. While continuing with cutting edge R&D in the core areas of lubricants formulations, refinery process technologies and pipeline transportation, research emphasis is now expanding to commercialize the developed technologies and initiate research in new frontier areas, such as petrochemicals, residue gasification, coal-to-liquid, gas-to-liquid, alternative fuels, synthetic lubricants, and nanotechnology. Through these R&D initiatives, IndianOil will continuously enhance value for all its stakeholders [32].

Although progress has been more challenging than hoped, a few companies have constructed commercial transesterification plants to produce biodiesel. Naturol Bioenergy Limited (NBL), a joint venture with Energea Gmbh (Austria) and Fe Clean Energy (United States), built a 100 000 MT/year plant in Kakinada, Andhra Pradesh, and began biodiesel exports to Europe in 2008 [33]. Southern Online Bio Technologies installed its first biodiesel production plant (12 000 MT/year) in Andhra Pradesh from mixed non-food oils. The company's second biodiesel plant (250 MT/day) was installed in Vizag and became operational in 2011 [34].

World Health Energy Holdings (WHEN), a US–Israeli company commercializing algae-based biodiesel, announced plans for two projects to commence in India in 2012 [35]. One project targeted $100 million in sales of biodiesel and food for commercial fish farms from algae grown on 250 acres [35]. India-based Prime, which provides transportation services to the oil industry, financed the project in exchange for a 70% equity stake. The second project with SHK Energy Projects of India, targeted $25 million in revenue from a 45-acre algae farm [35]. Recently WEHEN acquired GNE-India an algae technology company with distribution and licensing rights to the GB3000 system, which is a unique system for commercial production of algae for energy and food.

India's feedstock development challenges may be addressed in part by engineering feedstock properties to produce customized plant materials to meet specific end-use applications, which can play an important role in economically and efficiently converting biomass into bioenergy products. Preprocessing treatments can transform biomass from its diverse, raw forms into high-value, high-density, on-spec feedstocks that are optimized for bioenergy conversion performance, which offers the advantages of improved digestibility in biochemical conversion, reduced slagging and fouling in gasifiers and boilers, and more efficient handling [36]:

- Mechanical preprocessing treatments tackle the challenge of reducing size, fractionating, and separating feedstocks for downstream processing. Size reduction is achieved through mechanical grinding and milling, which increase surface area and make the biomass more reactive in subsequent processing steps. Fractionation breaks biomass into separate components that can be separated, concentrated, and later blended to form highly optimized, advanced feedstocks.
- Thermal and chemical preprocessing treatments reduce moisture content, remove contaminants, and improve feedstock condition, processing, and stability. These treatments also produce molecular and structural changes that enhance biomass reactivity during conversion processes.
- Formulation is the blending and mixing of biomass ingredients to develop customized feedstock recipes. Blended ingredients include treated or untreated biomass products, as well as chemical or biological additives that improve catalytic reactions and preserve a feedstock's best conversion attributes.

19.4.4 Enabling Government Policies

India has a history of commitment to the use of renewable sources to supplement its energy requirements. In 2003, the Planning Commission of the Government of India brought out an extensive report on the development of biofuels [37] and bioethanol and biodiesel were identified as the principal biofuels to be developed for the nation. The National Biofuel Mission was launched with the Ethanol Blended Petrol Programme and Biodiesel Blending Programme as integral components.

The National Policy on Biofuels was approved in December of 2009 and proposed a target of 20% biofuel blending by 2017 [38]. The National Biodiesel Mission was launched and identified Jatropha as the focus for cultivation and commercialization. The mission targeted 11.2–13.4 million hectares of land under Jatropha cultivation by the end of 2012 [38], and provides a package of economic and regulatory incentives (for example, tax reductions, credit provision through national banks, facilitated access to land) to private companies willing to develop industrial plantations or to engage in contract farming schemes with smallholders [38]. The government also made such feedstock cultivation eligible for its National Rural Employment Guarantee scheme (NREGA), which provided up to 100 government-paid days of manual rural labor per year [38].

The working group developing India's 12th Five-Year Plan (2012–2017) says the government intends to spend $44.6 billion on its various missions, such as its National Solar Mission [34]. In the year 2011, renewable energy investments reached $10.3 billion, 52% higher than the $6.8 billion invested in 2010, the highest growth of any significant economy in the world [38]. Presently India accounts for 4% of global investment in clean energy [39].

In November 2012, the Department of Biotechnology in the Indian government's Ministry of Science and Technology, released its Bioenergy Roadmap: Vision 2020, outlining a research and development framework for achieving commercial production of biofuel from different feedstock for 20% blending by the year 2020 [40].

19.5 Summary

These three perspectives on the development of cellulosic biofuels in Brazil, China, and India provide just a glimpse of the global effort that is occurring during the early decades of the twenty-first century. An example of the activity in the United States is the advances that were made between the initial Department of Energy (DOE) and USDA Billion Ton Study (BTS) [41] and the Billion Ton Update [42].

The European Union (EU) is similarly committed to combat climate change and to increase security of its energy supply [43] through bioenergy development. Forestry and agriculture have been identified as being crucial for solving both challenges. To foster those developments, the EU has developed a "Common Agricultural Policy" to produce biomass for energy and to encourage the use of bioenergy in rural areas. Their basic policy assumptions are that:

- Bioenergy is one form of renewable energy among many from other sources (wind, solar, hydraulic, geothermal, etc.).
- Bioenergy, if produced sustainably, saves greenhouse gas emissions.
- Bioenergy accounts for more than two thirds of total renewable energy in the EU.
- Biomass for energy is mainly provided by forestry (which provides half of the EU's renewable energy), agriculture and organic waste. The share of agriculture – although still modest – is growing fast.
- Feedstocks for bioenergy are storable; bioenergy can thus be produced constantly and is a reliable source of energy.
- Biomass is amply available in most parts of Europe.
- Biomass can be either in solid, liquid or gaseous form and can be used to produce electricity, direct heating, or transport fuels.

Some may scoff that current bioenergy developments will soon fade as they did in the United States following the 1970s oil crisis. We disagree because now there is a much better public awareness of sustainability and the fact that fossil fuel resources are finite. Private sector and government investments have been and are continuing to be made in these new technologies. Hopefully these examples and this book as a whole help sustain those efforts which are essential as humankind recognizes that we are just stewards of this planet and that truly "from dust we have come and to dust we shall return."

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