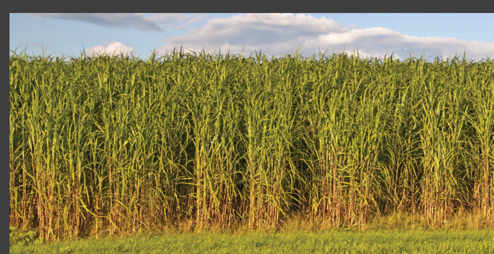
BIOMASS AND BIOFUELS

Advanced Biorefineries for Sustainable Production and Distribution



Shibu Jose • Thallada Bhaskar

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Preface

The long-held tenets of the energy sector are being rewritten in the twenty-first century. Major importers are now becoming exporters, and several countries that have been long-defined as major energy exporters are on the road to becoming leading centers of global demand growth. The right combination of policies and technologies can prove that the links among economic growth, energy demand, and energy-related CO_2 emissions can be weakened. The rise of unconventional oil and gas and of renewables is transforming our economies and improving our understanding of the distribution of the world's energy resources and their impacts. A complete knowledge of the dynamics underpinning energy markets is necessary for decision-makers who are attempting to reconcile economic, energy, and environmental objectives. Those who anticipate global energy developments successfully can derive an advantage, while those who fail to do so risk making poor policy and investment decisions. The center of gravity for energy demand is moving toward emerging economies such as those of China, India, and the Middle East, as they drive global energy use one-third higher.

Contributing around two-thirds of global greenhouse gas emissions, the energy sector will determine if climate change goals are achieved or not. There are several carbon abatement schemes that have been developed in recent times—such as the President's Climate Action Plan in the United States, the Chinese plan to limit the share of coal in the domestic energy mix, the European debate on 2030 energy and climate targets, and Japan's discussions on a new energy plan—that all have the potential to limit growth in energy-related CO_2 emissions. It has been proposed that primary energy demand will increase by 41% between 2012 and 2035, with growth averaging 1.5% per year. Among nonfossil fuels, renewables (including biofuels) are seen to gain shares rapidly from around 2% currently to 7% by 2035. The level of carbon emissions would continue to grow (1.1% per annum)—slightly slower than energy consumption but faster than that recommended by the scientific community. The biggest challenge though is in terms of sustainability of biomass–biofuel production, processing, and distribution systems.

In this scenario of increasing efforts on behalf of biomass conversion to value-added hydrocarbons and energy, the editors felt the need for a book that provides a holistic view of the entire biomass–biofuel supply chain—from feedstock to the end product. Production of biofuels from first-generation feedstocks has been documented to have a net negative impact on the environment and on climate. Research findings show that production of biofuel from food crops is unsustainable in the long run because artificial shortages in food supply and subsequent impacts will destabilize the global economy. So long as there is ethanol from food crops, the markets for corn and oil will be linked and the food versus fuel debate will continue. The question we need to ask is: How can we balance our food and fuel needs without compromising one or the other? In other words, there is no question of food versus fuel; we need both. The second-generation biofuels, specifically cellulosic biofuels, have helped balance this debate somewhat and have reduced some of the negative impacts of first-generation biofuels. For example, most second-generation feedstock can be grown on marginal lands, thereby reducing pressure on prime agricultural lands. They also have smaller greenhouse gas footprints than corn-based or first-generation feedstocks. These lignocellulosic feedstocks, which could promote large-scale energy production, include crop residues, perennial grasses, biomass sorghum, and short rotation woody crops, among others. When managed properly, the high productivity of these plants and their relatively high tolerance to soil constraints make them ideal feedstocks for biofuel production.

The advanced biorefinery concept has been garnering a lot of attention in recent years as a model of decentralized production of advanced biofuels, particularly in rural areas. Such decentralized small- to medium-scale biorefineries seem to be having the greatest potential for increasing biofuel production and accelerating economic revitalization of rural communities.

These decentralized biorefineries help in effective utilization of agricultural/forest residues or energy crops in a particular area in addition to offering a number of local and regional job opportunities. This book aims to discuss the various feedstocks that can be used as raw material in biorefineries, the methods that can be used for biomass conversion, and the effective integration of biomass to make a biorefinery more sustainable—economically, environmentally, and socially.

Acquiring new scientific information and rapidly incorporating new knowledge and experiences into planning and actions are of utmost importance in the dynamics of the renewable energy sector. It is critical to provide relevant and timely information to professionals, policy makers, and the general public so that they can make informed decisions. We recognize that one book alone cannot fill this niche. However, we hope that the current volume will serve as a reference book for students, scientists, professionals, and policy makers who are involved in the biomass and biofuel sector the world over.

We are grateful to a large number of individuals for assistance in accomplishing this task, particularly the authors for their commitment to the project and their original research or synthesis of the current knowledge. Also, the invaluable comments and suggestions made by the referees significantly improved the clarity and content of the chapters. We also wish to extend our sincere thanks to John Sulzycki and Jill Jurgensen of CRC Press for their timely efforts in publishing this book.

Editors

Dr. Shibu Jose is the Harold E. Garrett Endowed Chair Professor and director of the Center for Agroforestry at the University of Missouri, Columbia, Missouri. Prior to his current appointment, he was professor of forest ecology at the School of Forest Resources and Conservation at the University of Florida, Gainesville, Florida. He earned his BS from Kerala Agricultural University, India, and MS and PhD from Purdue University, West Lafayette, Indiana. His current research efforts focus on ecosystem services of agroforestry systems and ecological sustainability of biomass and biofuel production systems. Dr. Jose leads a regional consortium focused on commercializing integrated biomass and biofuels production systems, the Mississippi/Missouri River Advanced Biomass/Biofuel Consortium (MRABC). Dr. Jose has authored over 150 refereed publications, edited 8 books, and secured nearly $39 million in funding (~$10 million as PI). He has also served as major professor for 14 PhD students and 24 MS students during the past 17 years. He serves as editor-in-chief of *Agroforestry Systems*, academic editor of *PLOS ONE*, and editorial board member of the *International Journal of Ecology*. His awards and honors include a Fulbright Fellowship (U.S. Department of State), Aga Khan International Fellowship (Switzerland), Nehru Memorial Award for Scholastic Excellence (India), Award of Excellence in Research by the Southeastern Society of American Foresters (SAF), Stephen Spurr Award by the Florida Division SAF, the Young Forester Leadership Award by the National SAF, Barrington Moore Award by SAF, and the Scientific Achievement Award by the International Union of Forest Research Organizations (IUFRO).

Dr. Thallada Bhaskar, a senior scientist, is currently heading the Thermo-Catalytic Processes Area, Bio-Fuels Division (BFD), at CSIR–Indian Institute of Petroleum, Dehradun, India. He earned a PhD for his work at CSIR–Indian Institute of Chemical Technology (IICT), Hyderabad, India. He carried out postdoctoral research at Okayama University, Okayama, Japan, after which he joined there as faculty and has worked at the level of research assistant professor for ~7 years. Dr. Bhaskar has about 100 publications in journals of international repute with an *h-index* of 27 and around 2000 citations, contributed 16 book chapters to renowned publishers (Elsevier, ACS, John Wiley, Woodhead Publishing, CRC Press, Asiatech, etc.), and 13 patents to his name in his field of expertise, in addition to 250 national and international symposia presentations. His 20 years of research experience cover various fields of science revolving around his expertise in heterogeneous catalysis and thermochemical conversion of biomass, waste plastics, and e-waste (WEEE) plastics into value-added hydrocarbons. He has prepared several catalysts and thrown light on the structure–activity relationships of novel catalytic materials for hydrotreatment of fossil-based crudes. In view of his expertise, he is on the editorial board of three international peer-reviewed journals and editor for two books from Elsevier and CRC. Dr. Bhaskar received the Distinguished Researcher award from The National Institute of Advanced Industrial Science and Technology (AIST) (2013), Japan, and the Most Progressive Researcher award from Research Association for Feedstock Recycling of Plastics (FSRJ), Japan (2008). He is also the Fellow of the Biotech Research Society of India (FBRS) and a member of the Board of Directors (BRSI). He received the Raman Research Fellowship for the year 2013–2014. He was also a JSPS Visiting Scientist to the Tokyo Institute of Technology, Japan, during 2009. He has organized several international symposia in India and abroad in this area of expertise and has visited several countries to deliver invited/plenary lectures, for collaborative research and also as a subject expert.

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PART I

Biomass Feedstock and Logistics

CHAPTER 1

Biomass Feedstocks

Types, Sources, Availability, Production, and Sustainability

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CONTENTS

1.1 PURPOSE

This chapter provides a comprehensive overview of biomass feedstocks used in production of bioenergy. Particular emphasis is given to biomass feedstocks associated with advanced biofuels derived through biological conversion technologies. A broad geographical scope is presented. The discussion is limited to feedstocks currently considered feasible, or plausibly so, in the near future, resulting from current momentum in technology, policy, and economic change. The reader will gain from this chapter an appreciation of the scope of biomass supply and related issues and will be able to apply the lens of biomass supply while reading other chapters of this book.

1.2 INTRODUCTION

As world demand for energy increases, energy providers are turning to new technologies and new sources of renewable energy. *Biomass*—recently living biological material and animal wastes—has been used since early history to cook and heat spaces where humans live and labor. Since the eighteenth century, biomass has been used to provide heat, steam, and power for work processes. Today, biomass has an expanded role in the global demand for energy. *Bioenergy*—energy produced from biomass—is a promising solution to environmental challenges and a driver of economic development from local to global levels (Coleman and Stanturf 2006; Kleinschmidt 2007).

To meet bioenergy demand, energy providers must continuously secure a sufficient and reliable supply of biomass at prices allowing them to operate profitably. As global attention increasingly focuses on sustainability of resource use, biomass producers must balance market pressures for an ever-increasing supply at low prices with demands for nonmarket benefits of sustainable production systems, such as soil conservation, water quality protection, and biodiversity enhancement. Hence, policymakers and researchers are seeking to innovate solutions that will reduce the potential trade-offs between economic development and resource conservation, and competition for land resources.

Supply and sustainability needs are driving scientific and business interests in new and improved sources of biomass feedstocks. The quest for ideal biomass feedstocks includes exploration for new biomass types, sources, and production systems, as well as improvements to existing sources and production systems. This quest generally follows in tandem with innovation in production and harvest equipment and with breakthroughs in biomass pretreatments and conversion technologies (Ragauskas et al. 2006). Universities, government agencies, and public–private partnerships provide centers of innovation and information for these discoveries (e.g., Brazilian Centers for Excellence in Bioenergy Research and Development, the European Bioenergy Research Institute, and the Great Lakes Bioenergy Research Center at the University of Wisconsin, USA).

To understand the challenges of bioenergy production, it is first necessary to know and understand the various forms of bioenergy and the types of biomass materials and sources from which bioenergy is produced. Although the primary focus of this chapter is plant sources of biomass, animal waste is also briefly considered. At the conclusion of this chapter, readers should be able to answer the following questions: What is the difference between "biomass" and "feedstock"? What are the key differences between woody and nonwoody biomass? What are the primary sources for woody biomass and nonwoody biomass? Which agricultural crops are currently feedstock sources? What are the emerging feedstock sources for the future? What are the advantages and disadvantages associated with different types of biomass? What sorts of trade-offs do decision-makers face as they attempt to optimize biomass production?

1.3 FORMS OF BIOENERGY

Bioenergy is a form of renewable energy. Forms of bioenergy include power, heat, and solid, liquid, and gas fuels. Uses of these various forms of bioenergy include industrial, residential, and commercial applications. *Biofuel* refers to liquid and gas fuels used for transportation and industrial processes. Liquid and gas biofuels are produced through fermentation, gasification, pyrolysis, and torrefaction. (For more information about conversion technologies, see Faaij 2006.) Bioethanol and biodiesel are major forms of biofuel. Biofuels produced from oils, sugars, and starches originating in food crops are known as *first-generation biofuels*. First-generation biofuels are produced through relatively simple and established technologies. Conversion technologies still under development allow the creation of *second-generation biofuels*, also known as *advanced biofuels*, which are produced from nonfood crops such as perennial grasses and woody materials and from nonfood portions of food crops. *Third-generation biofuels* are produced from algae (Goh and Lee 2010; Lee and Lavoie 2013). The form of bioenergy and conversion technology determines the quantity and quality of biomass needed.

1.4 FEEDSTOCK MATERIALS

Bioenergy *feedstocks* are biomass-derived materials that are converted to energy through the application of microbial activity, heat, chemicals, or through a combination of these processes. Feedstocks are biomass materials that have been at least minimally processed to be ready for conversion into bioenergy. That is, biomass does not usually exist in a form that can be converted directly into energy without some alteration. Combustion of fuelwood for household use is an exception. It is frequently necessary to process biomass into a form that is more economical to transport from where it is grown to where it is converted into energy. Specifically, bulk density of biomass is relatively low (McKendry 2002). Bulk density is the weight of biomass per volume of biomass. Low bulk density of biomass means it takes up space in transport vehicles that are otherwise equipped to handle heavier loads, and that means more hauling trips are necessary compared to materials with greater bulk density. A first step then is *aggregation*—the process of gathering up harvested biomass into easily handled units such as bales (Figure 1.1). Low bulk density also translates into low energy density, particularly compared to other sources of energy such as coal. Processing of biomass to reduce moisture and increase bulk density; for example, *densification*—the application of pressure and other processes to create solid fuel (Tumuluru et al. 2010)—increases energy density. Increased energy density improves conversion efficiency and therefore reduces costs associated with conversion (Stephen et al. 2010). *Pelletization*—densification into pellets—is a common method of increasing bulk density that improves storage, logistical, and transport characteristics of biomass (Figure 1.2).

As biomass moves from where it was grown to where it is converted, it passes through various stages of processing and handling. Each stage adds value to what started as a relatively low-value material. The sequence of processes is known as a supply chain, sometimes also called a value chain. Because of low bulk density and subsequent low energy density, optimal conversion facility size is frequently dependent on biomass haulage costs, and feedstock supply/value chains trend toward smaller, more distributed, and more localized facilities (Jack 2009; Searcy et al. 2007).

There are three main types of biomass materials from which bioenergy feedstocks are derived: lipids, sugars/starches, and cellulose/lignocellulose. Lipids are energy-rich water-insoluble molecules such as fats, oils, and waxes. Lipids are a feedstock source derived from nonwoody plants and algae. Soyabean (*Glycine max*), oil palm (*Elaeis guineensis* and *Elaeis oleifera*), and various seed crops such as sunflower (*Helianthus annuus*) are common agricultural sources of oils for biodiesel.

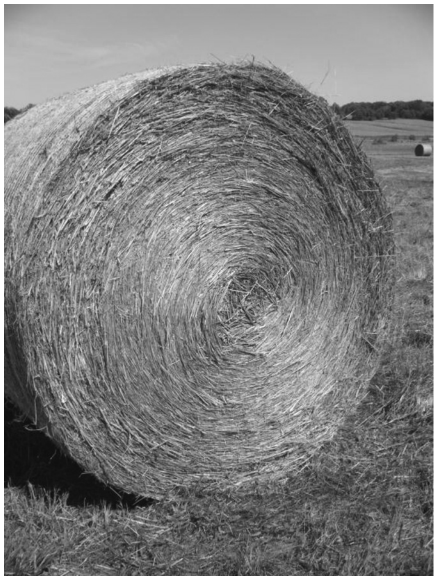

Figure 1.1 Baling of biomass is a form of aggregation that makes handling more efficient. (Courtesy of C. L. Williams, 2012.)

Figure 1.2 Pelletized biomass. Cattail (*Typha* spp.) biomass has been milled and pressed into a relatively high density solid fuel. (Courtesy of C. L. Williams, 2013.)

Sugars and starches are carbohydrates typically found in the edible portions of food crops, such as corn (*Zea mays*) grain. Cellulosic/lignocellulosic biomass is composed of complex carbohydrates and noncarbohydrate molecules typically found in the leaves and stems of plants. Cellulose/lignocellulose is chemically accessible by only a narrow range of organisms and is therefore of little or no food value to humans. Advanced biofuels offer an opportunity to take these relatively low

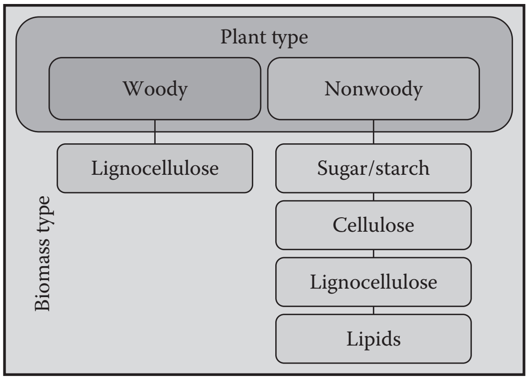

Figure 1.3 Woody and nonwoody plants are the sources of four different types of plant materials: cellulose and lignocellulose (both from plant cell walls), noncellulosic carbohydrates sugar and starch, and fatty acids (oils, fats, and waxes).

value materials and use them in the production of high value energy products (Clark et al. 2006). Thus, the remainder of this section further details the nature of cellulosic/lignocellulosic biomass.

There are two broad categories of plants from which cellulosic/lignocellulosic feedstocks are derived: woody and nonwoody (Figure 1.3). Cellulose is a fibrous glucose polymer found in plant cell walls. Cellulose provides physical strength to plant cells. Cellulose can be broken down into simple sugars, which can then be converted into ethanol and other fuels, typically through biological conversion (i.e., fermentation). In addition to cellulose, many plants also contain hemicellulose and lignin. Hemicellulose is a heteropolymer (i.e., a very large, complex carbohydrate molecule) that helps cross-link cellulose fibers in plant cell walls. Lignin is a noncarbohydrate polymer that fills the spaces between cellulose and hemicellulose. When cellulose, hemicellulose, and lignin are present together they are referred to as *lignocellulose*. Trees, for example, contain high amounts of lignocellulose; nonwoody plants, such as grasses, typically contain more cellulose than hemicellulose and lignin. Hemicellulose can be broken down into fermentable sugar and then converted into ethanol and other fuels. Lignin is difficult to convert into other usable forms and is therefore considered a by-product (i.e., waste) that is sometimes burned for heat energy (Hahn-Hagerdal et al. 2006). As technologies for transforming lignin improve, new markets for its use may emerge. In which case, lignin could become a higher-value co-product of biorefining (Hahn-Hagerdal et al. 2006).

In biological conversion of lignocellulosic feedstocks, *pretreatment* is required. Pretreatments break down cellulose and hemicellulose into sugars and separate lignin and other plant constituents from fermentable materials. The form of pretreatment will depend on the nature of the feedstock. Pretreatment technologies are physical, biological, and combinatorial. Physical pretreatment includes gamma ray exposure; chemical pretreatment methods include the use of acids, alkali, and ionic liquids; and biological methods include the use of microorganisms to degrade lignin and hemicellulose (Zheng et al. 2009). For more information on pretreatment technologies and interrelated developments in agronomic qualities of bioenergy crops, see Coulman et al. (2013) and Sticklen (2006).

1.5 BIOMASS SOURCES AND TYPES

Biomass for bioenergy comes from a variety of sources. Forests, agriculture, and wastes are currently the world's major sources of biomass (Figure 1.4). However, alternative sources such as agroforestry, conservation lands, and algae may grow in importance as demand for bioenergy grows. Forests are the primary source of woody biomass (Figure 1.4). Agriculture and

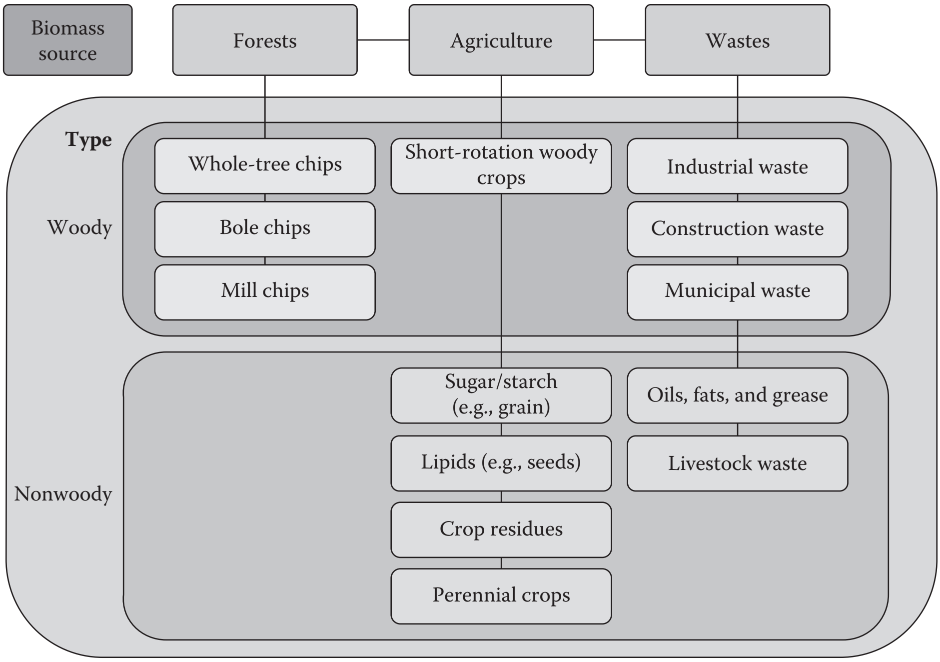

Figure 1.4 Biomass sources and types. Most biomass for biofuels comes from three sources: forests, agriculture, and wastes. Each source provides different types of woody and nonwoody biomass.

waste sources provide both woody and nonwoody biomass (Figure 1.4). Each of these sources has limitations of biomass availability and quality and has issues of accessibility. Additionally, these sources typically have competing uses for their biomass, which may affect price as well as availability (Suntana et al. 2009).

1.5.1 Forest-Based Feedstocks

Woody biomass from forests is the original source of bioenergy (Demirbas 2004). It remains the most important source of biofuel for cooking and space heating throughout the world, particularly among subsistence cultures (Cooke et al. 2008). Few extended rotation forests (i.e., growth harvest cycles of decades), whether public or private, are or will likely be managed specifically to provide biomass for bioenergy (Hedenus and Azar 2009). Instead, biomass for bioenergy is typically a coproduct of forest management activities (e.g., fuel hazard removal) or commercial activities emphasizing higher value materials such as merchantable wood. However, fast-growing tree species are sometimes purpose grown for bioenergy (White 2010). Short-rotation plantations typically receive more intensive management than timber plantations, and rotations can range from 3 to 12 years depending on management and on the species cultivated. Because of these characteristics, and the limited acreage on which they usually occur, short-rotation plantations are frequently considered as agroforestry rather than as forestry production.

In general, only wood that is not merchantable as lumber or pulp is used in bioenergy production (Figure 1.4). There are two main ways low grade wood is removed from forests for bioenergy use: as bark and as wood chips. Bark is typically burned to fire wood kilns at mills, or it is sold in higher value markets such as for landscaping materials. Although bark has a high energy density (more than wood chips), it has high silica and potassium content that affect its quality as a feedstock (Lehtikangas 2001). Woodchips, however, can be used directly as a solid fuel (for combustion) or they can be refined and densified into pellets. There are three main types of woodchips: mill chips, whole-tree chips, and bole chips (Figure 1.4). Mill chips are produced from waste wood (offcuts and slabs from sawing logs into lumber). Because logs are debarked before sawing, mill chips are usually very clean. Whole-tree chips originate from managed forests with little commercial value for lumber and where removal of trees could improve future commercial timber value. Whole-tree chips are produced by either chipping the entire low-grade tree or from only the tops and limbs severed from logs. Although a majority of whole-tree chips are generated from forest management activity, they are also produced from land clearing and land-use conversion projects making way for roads, parking lots, buildings, and open spaces, for example. The felled trees are typically chipped on site. Bole chips are produced from low-grade or pulp logs usually from managed forests. The difference between whole-tree chips and bole chips is that bole chips do not include branches or foliage.

1.5.2 Agriculture-Based Feedstocks

Agriculture is a source of sugars, starches, lipids, nonwoody cellulosic materials, and woody materials (i.e., lignocellulosic biomass; Figure 1.4). Agriculture-based biomass comes from crops grown specifically for bioenergy production, or *dedicated bioenergy crops*, as well as agricultural *residues*. Agricultural residues are nonedible cellulosic materials that remain after harvest of edible portions of crops. Dedicated bioenergy crops include annual crops grown for their sugars, starches, or oils, and perennial herbaceous nonfood plants grown for their cellulose. Agricultural residues include plant leaves and stems. Some annual crops, such as corn, can be dedicated bioenergy crops for both their grain and their cellulosic residues.

Most of the world's first-generation bioethanol is made from feedstocks derived from annual food crops. Annual row crops are grown and harvested in a single year and must be planted every year. Sugarcane (*Saccharum officinarum*) and corn are the primary feedstock sources for first-generation bioethanol. However, bioethanol is also produced from cereal crops, sugar beets (*Beta vulgaris*), potatoes (*Solanum tuberosum*), sorghum (*Sorghum bicolor*), and cassava (*Manihot esculenta*) as well. Sugarcane is the primary feedstock in Brazil, and corn grain is the primary feedstock in the United States. These two feedstock sources are converted into approximately 62% of the world's bioethanol (Kim and Dale 2004).

The primary agricultural sources of lipids for first-generation biodiesel are annual row crops—soybean, palm, and oilseed rape (or rapeseed, *Brassica napus*). Soybean is the primary feedstock source for biodiesel produced in the United States, Europe, Brazil, and Argentina—the world leaders in biodiesel production (Bergmann et al. 2013). Palm, a tropical plant, is the primary feedstock source in Southeast Asia (e.g., Malaysia and Indonesia), while oilseed rape is grown in Europe, Canada, the United States, Australia, China, and India (Rosillo-Calle et al. 2009). Inedible oil crops are being examined for commercial potential in second-generation biodiesel production, including castor (*Ricinus communis*) and Camelina (*Camelina sativa*; Atabani et al. 2012). For more information on biodiesel feedstocks and production technologies, see Salvi and Panwar (2012).

Perennial crops are the primary sources of lignocellulosic biomass for second-generation biofuels. They have received considerable attention because they are not food crops, and they provide long-term yield potential and environmental benefits not usually achieved in annual row crop agriculture (Sanderson and Adler 2008, and references therein). These potential environmental benefits include wildlife habitat, soil erosion prevention, and water quality improvement. Perennial crops live for more than one growing season and do not have to be planted every year. Perennial crops include *herbaceous plants* (plants lacking permanent woody stems) and woody plants. Perennial grasses in particular are of considerable value in advanced biofuels as are fast-growing trees such as hybrid poplars (*Populus* spp.) and willows (*Salix* spp.). Whether they are herbaceous or woody, perennial dedicated bioenergy crops are typically grown with some amount of agronomic intensity (e.g., inputs of fertilizer and pesticides), which is why they are considered as crops.

Agricultural residues also are an important source of cellulosic feedstocks (Figure 1.4). Their use potentially limits the impacts of biofuels on food security (Kim and Dale 2004). Global residue biomass is estimated as 3.8 billion Mg yr^{-1} (Lal 2005). Availability of residues differs by region, country, and within countries according to climate and soil variations affecting the growth suitability of particular crops. For example, rice straw is readily available in Asia, and stover (corn residue) is available in the United States, Mexico, and Europe (Kim and Dale 2004). The amount of residue available differs widely among crops (Lal 2005; see further discussion in Section 1.6). Use of agricultural residues must be carefully planned and managed due to their important role in soil erosion control and maintenance of soil quality, and their use as forage, fodder, and bedding for livestock (Lal 2005).

1.5.3 Waste-Based Feedstocks

Waste-based biomass includes organic materials left over from industrial processes, agricultural liquid and solid wastes (e.g., manure), municipal solid wastes, and construction wastes (Figure 1.4). Many industrial processes and manufacturing operations produce residues, wastes, or coproducts that can be potentially used for bioenergy. Major sources of nonwoody wastes include waste paper, liquid left over from paper production (called black liquor), and textile manufacturing. Major sources of woody waste materials include used pallets, sawmill by-products such as sawdust and shavings, cut-offs from furniture manufacturing, and composite wood products containing nonwood resins, adhesives, and/or fillers. Conversion technologies for these wastes are potentially the same as for virgin wood (Antizar-Ladislao and Turrion-Gomez 2008).

Agricultural wastes include by-products of agro-industrial processes and manure from livestock. Agro-industrial processes such as animal processing, grain milling, starch production, and sugar production result in by-products that may be used as bioenergy feedstocks. Bagasse, the fibrous material left over from sugarcane and sorghum crushing in sugar production, for example, is sometimes used as a fuel source for heat in sugar mills but it can also be converted to bioethanol (Botha and Blottnitz 2006). Animal processing generates large quantities of feathers, bones, and other materials. These animal by-products are a potential source of diseases that have public and/or animal health risks (e.g., bovine spongiform encephalopathy), and rigorous protocols must be followed to eliminate the possibility of spread of disease. Accordingly, animal by-products are used as feedstocks in anaerobic digesters that kill potential pathogens and that produce biogas (i.e., methane). Biogas is a substitute for propane, kerosene, and firewood, and it is used to produce heat and electric power. It can also be compressed and liquefied for use as a transportation fuel.

Manure can be used as a fertilizer on agricultural fields, and land application is often an important component of on-farm nutrient management (Binford 2005). However, manure application can be a highly regulated agricultural activity (e.g., Concentrated Animal Feeding Operations), and its disposal can present challenges to farm profitability (Centner and Newton 2008; Keplinger and Hauck 2006). In some circumstances, manure cannot be applied directly to fields because the ground is frozen, or the amount of manure available exceeds the amount that can be put onto fields without endangering nearby water resources with contamination (Funk et al. 2014). Use of manure as a bioenergy feedstock, then, is an opportunity for turning a potentially expensive liability into a benefit. Livestock manure is converted into biogas via anaerobic digestion.

Municipal solid waste is a major source of biomass. Also called trash and urban solid waste, municipal solid waste is predominantly household or domestic waste. Municipal solid waste includes biodegradable waste such as kitchen food waste and food packaging; clothing and toys; recyclable materials such as paper, plastics, and metals; appliances and furniture; and debris. Most municipal solid waste is diverted to landfills, but in some locations, it is incinerated to make electricity. Portions that are not incinerated can be converted to syngas through gasification. Syngas can be cofired in boilers with coal, for example, to produce electricity.

Construction waste consists of wood, plastic, and metal debris. Although plastic and metal may be used in combustion for production of power, for example, only woody construction wastes are feedstocks for *bio*energy. Construction waste varies greatly in composition and by location. Currently, the primary conversion technology for construction waste is combustion for heat, steam, and biopower; although as lignocellulosic material, it can potentially be used in biological and other conversion technologies for biofuels (Antizar-Ladislao and Turrion-Gomez 2008).

1.5.4 Agroforestry Feedstocks

Agroforestry is the intentional integration of perennial nonfood crops with annual food crops on a farm. This may occur as *alley cropping*—the planting of trees or shrubs in rows of wide spacing that allow for the planting of crops in between rows of woody crops (Holzmueller and Jose 2012). Alternatively, fast-growing, intensively managed woody crops may be grown in monoculture as part of a diverse farm enterprise (Dickmann 2006). Regardless of the production system, agroforestry is an emerging source of lignocellulosic feedstocks for second-generation biofuels. Short-rotation woody crops (SRWC) typically grow to harvestable size in less than 15 years; depending on species and management this could be as soon as three years (Volk et al. 2004). Globally, *Eucalyptus* is the most extensively planted species, although other hardwoods predominate in temperate regions—such as Europe (Rockwood et al. 2008). In temperate regions, SRWC include hybrid poplars (*Populus* spp.), willows (*Salix* spp.), and maples (*Acer* spp.). Most SRWC are shade-intolerant, which makes them suitable to the openness of farm fields. Many temperate SRWC have the ability to coppice (sprout new growth from stumps) when harvested. Hence, coppicing will produce harvestable biomass on shorter rotations.

A potentially important source of whole plant biomass for biorefineries is jatropha (*Jatropha curcas*), an oil-bearing tree that can be grown in agroforestry systems (Achten et al. 2007). Jatropha is native to Mexico, Central America, and parts of South America. It is drought-resistant, easily propagated, and performs well in a wide variety of soils, including degraded lands. Jatropha contains inedible oil and is toxic to humans and animals. The biodiesel production with Jatropha results in valuable by-products such as seed cake and husks. These characteristics make it an attractive biorefinery feedstock candidate. India, in particular, has set ambitious goals for establishing Jatropha on degraded lands in rural areas to replace diesel used in transportation (Achten et al. 2010). Challenges remain in the commercial-scale use of Jatropha, however. Among them are the issue of relatively low yields on wastelands and agriculturally marginal lands (i.e., lower revenues), relatively high costs of establishment, efficiency of harvesting, and logistics (Achten et al. 2010; Francis et al. 2005).

1.5.5 Biomass from Conservation Lands

To avoid potential competition with production of food and forage on prime agricultural lands, government authorities and researchers are considering the potential benefits and risks associated with periodic harvest of biomass from conservation lands, such as those set aside in agriculturally dominated landscapes for purposes of soil conservation, water quality improvement, wildlife habitat, hunting access, or other nonagricultural purposes (Adler et al. 2009; Fargione et al. 2009; Rosch et al. 2009). Conservation lands, whether privately or publically owned, typically require management for maintaining cover types and various conservation goals. Harvest may be a viable form of management (Figure 1.5). Biomass resulting from habitat management actions has the potential to be used in a variety of conversion technologies. Land managers, therefore, may be able to offset management costs with the sale of biomass resulting from periodic management actions. However, the long-term impacts of removal of biomass from conservation lands, such as nutrient loss and soil compaction, are currently unknown. Hence, greater scrutiny is necessary

Figure 1.5 **(See color insert.)** Harvest of grassland biomass for habitat management on public conservation land in Wisconsin. (Courtesy of C. L. Williams, 2012.)

to understand the impacts of biomass harvest on lands set aside for wildlife and other resource management goals, and ultimately on their contribution to world energy needs.

1.5.6 Algae

Challenges in meeting the demands for bioenergy include competition for land, water, and other resources needed to produce plant-based feedstocks (Dale et al. 2011). Algae are promising sources of feedstocks for advanced biofuels because they do not compete for additional land use, and they have minimal water requirements compared to land crops (Dismukes et al. 2008). Micro- and macroalgae are thus being explored as commercially viable feedstocks for *third-generation biofuels*. Microalgae are unicellular and simple multi-cellular organisms, including prokaryotic microalgae and eukaryotic microalgae. Macroalgae are macroscopic, multicellular marine algae. Algae are sources of lipids and carbohydrates for biofuels. However, they are most frequently used as lipid sources for second-generation biodiesel. Carbohydrates can be recovered after oil extraction and fermented into bioethanol. Algae are capable of year-round production; therefore, their yield can exceed that of oilseed crops (Brennan and Owende 2010). For a comprehensive review of microalgae cultivation for biofuels, see Brennan and Owende (2010), John et al. (2011), and Mata et al. (2010).

1.6 BIOMASS SUPPLY AND AVAILABILITY

A chief question regarding the potential for bioenergy to provision a growing world population is the size of the global biomass supply and the amount of energy available within biomass. Many studies have been conducted to answer this question at the global level—with widely varying results (Beringer et al. 2011; Berndes et al. 2003; Hoogwijk et al. 2003; Tilman et al. 2006). At issue are the various assumptions necessary to model and compare potential yields of different plants in different natural and human systems of biomass production and the various factors influencing them including climate, soils, and topography. This task is made all the more challenging by rapid climate change and by the different approaches to modeling impacts on agriculture (see, e.g., Lobell and Fields 2007).

There is additional uncertainty about availability of land for biomass production (i.e., competition for other land uses such as food production), improvements in plant yields due to human innovation over time, differing capabilities among countries to address the gap between potential yields and actual yields, and differences in energy yields among feedstock types and conversion technologies (Johnson et al. 2009). The issue of land availability is particularly acute as the world population grows and diets drift toward more calories and the increased proportion of calories provided by meat (McMichael et al. 2007). Many studies of potential biomass supply consider biodiversity protection and other conservation measures, at least to some minimal extent (e.g., Beringer et al. 2011). So in effect, the question of potential biomass supply must be answered by (1) considering intrinsic productivity of lands, (2) deciding which plant species to include in the analysis, (3) estimating potential biomass yield of plant species, varieties, and cultivars, (4) identifying the differences between potential yields and actual yields, (5) identifying how much land will be allotted to biomass production over time, and (6) determining the degree to which environmental impacts of biomass production will curb future biomass supply.

Biomass supply is likely to be sufficient to play a significant role in global energy consumption, estimated as 285 EJ in 2005 (IEA 2008). Use of residues only could produce about 100 EJ yr^{-1}, although use of all biomass sources could potentially be converted into 1500 EJ yr^{-1} (Dornburg et al. 2008). A cautious range of 200–500 EJ yr^{-1} from all biomass sources has been found in a survey of global studies (Dornburg et al. 2008). Potential biomass supply has also been modeled at regional and national levels under a variety of assumptions, including economic drivers. For example, the U.S. Department of Energy (2011) estimated U.S. bioenergy production in 2012 at about 450 Mg DM yr^{-1}, or about enough to displace approximately 30% of current petroleum consumption. The European supply is estimated at up to 11.7 EJ yr^{-1} (Ericsson and Nilsson 2005). Studies also show that potential biomass supply is unevenly distributed such that it is/will be abundant at some locations and less available in others (e.g., Milbrandt 2005). These differences will have profound effects on economies and on trade (Milbrandt 2005) and are likely to impact poorer rural areas in particular (Phalan 2009). Therefore, it is recommended that the entire value/supply chain of advanced biofuels be carefully planned and managed to limit negative effects on human livelihoods (Bailey et al. 2011).

1.7 AGRICULTURAL CELLULOSIC BIOMASS PRODUCTION

Forests and waste sources of biomass alone do not meet current demand for advanced biofuels and are unlikely to expand to the degree necessary to meet anticipated future needs (Simmons et al. 2008). Agriculture, therefore, has a vital role in bioenergy and is the focus of much innovation particularly in crop improvements, cropping systems, and related technologies. This section highlights some important crops, production systems, and related issues in agricultural production of cellulosic biomass.

1.7.1 Perennial Grass Crops

Perennial grasses are an important feedstock source for second-generation biofuels. Traditionally used as forages, perennial grasses have recently been the focus of breeding research to improve yields and other traits important in conversion (e.g., lignin content; Coulman et al. 2013). Cool season (C3 photosynthetic pathway) grass species are not generally recommended for bioenergy use because of their poor feedstock quality (Lewandowski et al. 2003). Warm season grasses (C4 photosynthetic pathway), however, demonstrate great promise for yield and feedstock quality, as well as water use efficiency (McLaughlin et al. 2006, Boehmel et al. 2008, and Carroll and Somerville 2009). Warm season grasses, however, are slow to establish. Depending on species, peak yields are not usually achieved until three to five years after planting. Even with slow establishment though, overall operating costs of perennial grass crops may be lower than conventionally managed annual row crops (Sanderson and Adler 2008). When agronomically managed, perennial grasslands can be maintained in long-term rotations (10-plus years; McLaughlin and Kszos 2005).

Governments and academic researchers have embarked on rigorous evaluations of a variety of perennial herbaceous plants as candidates for advanced biofuels (Lewandowski et al. 2003). Switchgrass has been extensively studied for second-generation biofuels particularly in North America (Lewandowski et al. 2003; McLaughlin and Kszos 2005; Wright and Turhollow 2010); and miscanthus has been widely evaluated in Europe (e.g., Christian et al. 2008). Hence, these two bioenergy crops are further detailed here.

Switchgrass is a C4 grass that has evolved as a component of diverse tallgrass prairie ecosystems in the eastern two-thirds of the United States (Parrish and Fike 2005). It has been used there since the arrival of Europeans to graze ruminant livestock; over time, it has been intentionally managed and improved for forage. In the last 20 years, switchgrass has been scrutinized for bioenergy purposes (Wright and Turhollow 2010). Switchgrass as managed forage and in bioenergy research is typically grown as a pure grass sward (i.e., monoculture), although interest is high in its use in *polycultures*—diverse plant mixtures that may include different plant functional groups (e.g., grasses, forbs, and legumes; Tilman et al. 2006). Polycultures are receiving research and development attention for their biomass yields as well as wildlife habitat and environmental benefits compared to monocultures (Sanderson and Adler 2008; Tilman et al. 2006, 2009). However, there is conflicting evidence regarding the effects of plant diversity on biomass yields. Tilman et al. (2006) reported increases in biomass yields with increases in the number of species in a polyculture. Others report lower yields in polycultures containing switchgrass compared to switchgrass monocultures (Wang et al. 2010). Therefore, further study is required to more fully understand the effect of species richness and plant functional types on biomass yields.

There are numerous switchgrass varieties and cultivars, each having different responses to characteristics of location (e.g., soil, day length) and fertilization (Casler et al. 2007; Fike et al. 2006; Virgilio et al. 2007). Choice of variety or cultivar will depend on characteristics of the location where it will be grown (e.g., growing season) and on the management that will be used. Management of switchgrass in monocultures can be quite different than polycultures in which it is a component. Whether in monoculture or polyculture, switchgrass is grown from seed. Seedbed preparation ranges from "conventional" well-tilled soil to no-till seed drilling and "frost-seeding" during soil freezing and thawing activity (Lewandowski et al. 2003; Teel and Barnhart 2003). Weed control during establishment is critical. Weed control strategy will be affected by weed species present; however, chemical control is common (Parrish and Fike 2005). Pest control may be necessary during sward maturity depending on the cultivar (Coulman et al. 2013).

Reports of yield responses of switchgrass to fertilizer, particularly nitrogen, vary greatly (Heggenstaller et al. 2009; Vogel et al. 2002), and consensus for any nutrient has not emerged (Parrish and Fike 2005). However, yield declines are reported over time without nitrogen fertilization (Mitchell et al. 2008). Harvesting of switchgrass involves cutting, swathing, and aggregating (e.g., baling). It is usually not harvested in its first growing season (Lewandowski et al. 2003). Depending on location and cultivar, switchgrass may be harvested once or twice annually (Parrish and Fike 2005). However, one annual harvest after senescence is recommended for plant nutrient management and wildlife considerations (Hull et al. 2011). Reported yields for switchgrass vary according to cultivar, location, fertilizer use, and other factors, and generally range from 5.3 to 21.3 Mg DM ha^{-1} yr^{-1} (Fike et al. 2006; Lemus et al. 2002; Lewandowski et al. 2003).

Perennial C4 grasses of the genus *Miscanthus* originate in the tropics and subtropics of East Asia. Due to their high yields and wide climatic adaptability, they have received much attention as potential bioenergy crops (Lewandowski et al. 2000). *Miscanthus* × *giganteus* (hereafter, miscanthus) is a hybrid of *M. sinensis* and *M. sacchariflorus* and is the frontrunner in bioenergy crop research, development, and production in Europe (Lewandowski et al. 2003), although it has recently begun receiving attention in the United States (e.g., Heaton et al. 2004, 2008).

Miscanthus is a sterile hybrid that does not produce seeds and instead reproduces vegetatively from rhizomes. It is grown in monocultures that are established through manual or mechanical planting of rhizomes or rhizome pieces (Lewandowski et al. 2000). Miscanthus plantations, therefore, are monocultures of clones (i.e., genetically identical plants). The rhizomes are grown in nursery fields where they are mechanically collected and divided just before planting in fields for biomass production (Lewandowski et al. 2000). Mechanization of miscanthus culture and management has been a source of rapid innovation (Anderson et al. 2011). Nonetheless, relatively high costs of propagation and planting are barriers to adoption of miscanthus as a bioenergy crop (Atkinson 2009; Coulman et al. 2013).

Plowing is the recommended soil preparation method for miscanthus planting (Lewandowski et al. 2000). Winter kill can be a problem in miscanthus cultivation (Heaton et al. 2010; Lewandowski et al. 2000). Miscanthus has low fertilizer demand (Lewandowski et al. 2000). In soils with sufficient nitrogen mineralization from soil organic matter, there is no effect of nitrogen fertilization on miscanthus yield (Lewandowski et al. 2000). Weed control is necessary during establishment of miscanthus (Anderson et al. 2011). Mechanical and chemical controls are used in Europe, but in the United States no herbicides are registered for biofuel plantings of miscanthus (Anderson et al. 2011). There is currently no evidence of pest or pathogen issues affecting yields of miscanthus; hence, pesticide and other interventions are not yet developed (Anderson et al. 2011).

Miscanthus is harvested only once per year, usually after senescence (Lewandowski et al. 2000). In Europe, miscanthus is typically harvested in early spring because stems dry during winter and chemical constituents are leached consequently improving feedstock quality, although yield losses may be as much as 25% (Lewandowski et al. 2000, 2003). Harvest consists of mowing, swathing, and aggregating (e.g., baling). Standard mowing machines for grain and grass do not work well with miscanthus because it is taller and stiffer than the crops for which these machines are designed. Equipment modifications have therefore been necessary (Lewandowski et al. 2000). Biomass yields of miscanthus vary widely depending on location, use of irrigation, and harvest timing. Yield reports range from 7 to 40 Mg DM ha^{-1} yr^{-1} (Lewandowski et al. 2000, 2003; Price et al. 2004). For a comprehensive overview of miscanthus improvements, agronomy, and biomass characteristics, see Lewandowski et al. (2000) and Jones and Walsh (2001).

1.7.2 Short-Rotation Woody Crops and Agroforestry

The oil embargo of the Organization of Petroleum Exporting Countries (OPEC) in 1973 was a boon to research and development of SRWC (Dickmann 2006). The embargo forced governments and international agencies to investigate alternative sources of energy, and as a result of the upheaval, SRWC gained a new status as candidate domestic bioenergy crops (Wright 2006). Generous government funding facilitated creation of new hybrids and genetic transformations of practical advantage, improvement of propagation methods, invention of high-density cropping systems, and innovations in stand management were enabled (Dickmann 2006).

SRWC are genetically improved tree species purpose-grown in short cycles, usually 1–15 years, and using intensive cultural techniques of fertilization, irrigation, and weed control—often relying on coppice regeneration (Dickmann 2006; Drew et al. 1987; Hinchee et al. 2009). Essentially, SRWC are grown more like annual commodity crops than traditional pine, oak, or spruce forests. In temperate regions, SRWC tend to be grown in plantations (i.e., extensive monocultures), although in the tropics, very fast growing trees tend to be alley-cropped (Dickmann 2006; Holzmueller and Jose 2012).

Site preparation typically involves soil tillage and removal of plant debris (Tubby and Armstrong 2002). Unrooted cuttings (clones) are planted using mechanical equipment, and weed control is required. Cover crops can be established on erosion-prone sites (Volk et al. 2004). When planted with other crops in agroforestry systems, SRWC species produce multiple benefits such as increased yields and improved water quality (Holzmueller and Jose 2012). Some SRWC species tolerate alley cropping, a form of intercropping where trees are placed in rows of wide spacing creating alleys for growing of agricultural or horticultural crops, including grains and forages (Headlee et al. 2013). Other agroforestry practices include placement of trees and shrubs in shelterbelts and along riparian areas (Holzmueller and Jose 2012).

There are several important pests of SRWC including grazing mammals, boring and defoliating insects, and disease (Mitchell et al. 1999). Tending of SRWC will therefore require interventions as necessary to avert biomass loss. Harvest is conducted with agricultural equipment that cuts and chips the biomass in a single operation (Berhongaray et al. 2013; Mitchell et al. 1999). Yields of SRWC vary widely depending on location, species (or hybrid), water availability, pests, management, and harvest timing (Dickmann 2006). Holzmueller and Jose (2012) summarize woody biomass crop yields in annual and short-rotation systems of the U.S. Upper Midwest and report a range of 5.4–30.0 Mg DM ha^{-1} yr^{-1}. Labrecque and Teodorescu (2005) report on 12 willow and poplar clones in southeastern Canada, finding a biomass yield range of 5.6–16.4 Mg DM ha^{-1} yr^{-1}. Yield ranges of 6 to more than 20 Mg ha^{-1} yr^{-1} are reported for poplars and willows in Europe (Hoffmann and Weih 2005).

1.7.3 Annual Row Crop Residues

Around the world, human populations depend on the production of commercial crops to satisfy daily calorie needs. As a result, annual food crop agriculture occupies almost half of the Earth's land surface (Ramankutty et al. 2008). There exists, therefore, great potential for biofuel use of the cellulosic residues remaining after harvest of the food portions of these crops. Corn stover, rice, wheat straw, and bagasse have been considered for bioenergy production. Conventionally managed, these annual crops require external inputs including mineral fertilizer, pesticides, and herbicides, and in some places, irrigation. The energy value of global crop residues is estimated at 69.9 EJ yr^{-1} (Lal 2005). Graham et al. (2007) conclude that 30% of corn stover produced in the United States could be harvested with existing equipment—enough to produce more than the current volume of corn grain ethanol.

Harvesting crop residues has been associated with declining soil quality and productivity (Lal 2005; Moebius-Clune et al. 2008). Trade-offs exist among beneficial effects of residue harvest—such as faster warming of soils in spring, better seed germination, and less favorable habitat for plant pathogens, and the potential adverse effects—such as organic matter declines, greater soil temperature fluctuations, and faster losses of stored soil moisture (Mann et al. 2002; Wilhelm et al. 2004). Crop residues are typically important reservoirs of elements necessary for crop growth (e.g., C, K, Ca, N, and P), thus their return to the soil after harvest is essential for sustaining grain and biomass yields (Blanco-Canqui and Lal 2004). The economic benefit of harvesting crop residues must therefore be weighed against the potentially negative effects that such management may have on soil quality (Moebius-Clune et al. 2008). Trade-offs also exist with livestock agriculture. As previously mentioned, some residues are used as fodder and bedding for animals.

1.8 SUSTAINABILITY ISSUES

It is beyond the scope of this chapter to discuss the complexity of specific challenges to sustainability of biofuels. Hence, a broad, integrated definition of sustainability as well as a statement about its importance is offered here. A brief survey of major sustainability issues of biomass supply is then given. These issues include: food insecurity, climate change, invasive and transgenic plants, marginal lands, water supply and quality, and rural development and social justice.

1.8.1 Sustainability Defined

There are many definitions of sustainability, each supporting various principles and concepts. Essentially, however, sustainability can be described as a set of goals and the practices and behavior that support such goals. As a set of goals, sustainability describes desired conditions of the environment and human well-being as a result of interaction with the environment, now and in the future. As practices and behaviors, sustainability describes human actions that support and enhance the environment and human benefits. Sustainability is important because the choices and actions of today affect everything in the future. Sound decisions at present may prevent undesirable outcomes in the future.

Bioenergy is frequently evoked as an important tool in improving environmental conditions, as well human lives and livelihoods (Domac et al. 2005; Faaij and Domac 2006; Tilman et al. 2009). However, much remains to be understood about the impacts of bioenergy on the environment and human society. Ultimately, however, sustainability of bioenergy will depend on the goals defined, and when, where, and by whom those goals are defined; what actions and behaviors people are willing and able to adopt to support those goals; and the ability of science to assist human knowledge of connections among the many aspects of bioenergy and sustainability goals. In the meantime, governments, international agencies, and nongovernment organizations at different levels have produced white papers and various guidelines in an effort to encourage sustainable practices in biomass production (Hull et al. 2012; RSB 2011; UNEP 2009).

1.8.2 Food Insecurity

Chief among the concerns over the impacts of biomass production is food insecurity. This concern is related to abrupt rises in short-term food commodity prices (e.g., corn and grain) that lead to hunger or starvation in some areas (Economic Research Service 2013). The food insecurity impact of biofuels stems largely from a mid-2008 crisis when an unexpected rise in grain prices created supply shortages in some countries (Nonhebel 2012). Critics were quick to label biofuels as the leading cause of the crisis, but years later the cause is still being debated. Many analysts have concluded that tight interlinkages of global commodity supply and trade, price speculation, and other factors were as much if not more to blame as biomass production (Godfray et al. 2010; Mittal 2009; Mueller et al. 2011). This is not to say, however, that in a globalized world economy biomass and biofuels are not at all connected to price and supply fluctuations and the effects thereof. Indeed, sustainability analyses appear to converge on a multitactic approach for resolving the multiple challenges of providing food, energy, and environmental protection for the world population (Groom et al. 2008; Reijnders 2006; Tilman et al. 2009). These concerns have motivated a focus on inedible feedstocks for bioenergy and on the use of nonagricultural lands for biomass production. For more consideration of food insecurity challenges and connections to biomass production, see Bryngelsson and Lindgren (2013), Foley et al. (2011), and Tilman et al. (2009).

1.8.3 Climate Change

Climate change and climate change mitigation are major concerns in the production of biofuels. The concerns center on emissions of greenhouse gases associated with land use and land-use change in production of biomass for biofuel (e.g., carbon capture in, or release from, soil due to agricultural practices; Delucchi 2011). There is contradictory evidence as to whether advanced biofuels and cellulosic biomass production are solutions or problems (Georgescu et al. 2009; Searchinger et al. 2008). This suggests more study is needed and that much depends on the ability of science—in coordination with policy, to deliver solutions. For more on climate change and sustainability of biomass/biofuels, see Fargione et al. (2008), Robertson et al. (2008), and Menten et al. (2013).

1.8.4 Invasive and Transgenic Plants

There is growing concern about the invasiveness of plants used for biomass production because the traits of ideal biomass crops are also commonly found among invasive plant species (Raghu et al. 2006). Invasive species are of concern due to adverse environmental and ecological impacts and the economic costs associated with lost productivity of natural ecosystems and the services they provide, as well as costs associated with invasive species control (Pimentel et al. 2005). The invasiveness issue is particularly acute for wildlife and biodiversity managers in public agencies and in nongovernment organizations (Smith et al. 2013). Warm season grass monocultures, for example, are seen as providing very little value as wildlife habitat (Fargione et al. 2009; Hartman et al. 2011). Switchgrass is another example of concern. Although it is native to North America, many switchgrass ecotypes and improved germplasm are being introduced to new locations and subsequent outcross with local ecotypes could erode native biodiversity at local and regional levels (Kwit and Stewart 2012). Use of transgenic plants, particularly SRWC in agroforestry, is also of grave concern to managers of ecological systems and wildlife species (Hinchee et al. 2009). There are no easy solutions for these challenges, and many decision-makers must seek to balance the benefits of biofuels and biomass production with known and potential risks. For a further overview of invasive plants and biofuels, see Gordon et al. (2011) and Smith et al. (2013).

1.8.5 Marginal Lands

Definitions of marginality with regard to productivity of arable lands vary greatly but, in general, marginal lands are those that have one or more characteristics not conducive to annual crop production. Characteristics such as steep slopes, shallow soils, excessive wetness, or drought-proneness generally have negative effects on profitability of agricultural use; hence, marginal lands usually are of fairly low value (i.e., comparatively low price per acre for rent or taxation purposes). Row crop production on marginal lands is associated with land degradation and decreased productivity over time as a result (Pimentel 1991). Hence, production of perennial crops is seen as a potential source of resource protection and income for farmers.

It has been suggested that marginal lands be targeted for production of biomass for bioenergy not only for meeting renewable energy goals but also as a potential means for avoiding land-use conflicts contributing to food insecurity (Achten et al. 2013; Campbell et al. 2008). The 2007 U.S. Census of Agriculture, for example, identifies approximately 12 million ha of idle lands, land in cover crops for soil improvement, and fallow rotations as potentially available for biomass production (COA 2009). Conversion of steep or wet land currently in food crop production (i.e., row crop) to less intensive bioenergy crops such as high diversity, low-input perennial mixes is thought to have the potential to generate more ecosystem services (Tilman et al. 2009). However, some researchers caution that conversion of marginal lands, particularly those in set-aside programs (i.e., currently idle or planted in perennial cover), to more intensively managed bioenergy cropping systems could lead to permanent land degradation and a net increase in greenhouse gases as well as food insecurity (Bryngelsson et al. 2013; Zenone et al. 2013). Government, academic, and private sector research is needed to assess whether and to what degree marginal lands can be relied upon for meeting future bioenergy demands, while policymakers and other decision-makers address questions of whether and to what degree marginal lands should be relied upon for bioenergy needs.

1.8.6 Water Supply and Quality

Cultivation of crops for biomass, food, feed, and fiber requires vast amounts of water. In many temperate areas, there is sufficient water from precipitation to meet crop needs during the growing season. In other areas, crop production requires irrigation. There is growing concern, therefore, over expansion of bioenergy crop production into drier areas, and hence requiring more irrigation, and the associated impacts on food crops and therefore food insecurity (De Fraiture and Berndes 2009). Floodplains represent a potential opportunity for growing biomass crops without threats to water supply and without displacing food crops. Food crops planted in floodplains are prone to failure because of flooding and soil erosion, but perennial biomass crops such as SRWC and perennial grasses are less vulnerable (Bardhan and Jose 2012). Such biomass crops could help reduce floodplain soil erosion while providing a source of income for farmers and a source of renewable energy (Bardhan and Jose 2012).

Also of concern is the use of agrochemicals in agricultural production of biomass. Water quality and aquatic habitats can be affected by agricultural drainage of fertilizers, pesticides, and sediments. Thus, expansion of bioenergy crop production must be carefully managed to avoid water pollution (Gopalakrishnan et al. 2009). For more information on the opportunities to limit and mitigate the *water footprint* of biofuels, see Dominguez-Faus et al. (2009).

1.8.7 Rural Development and Social Justice

In rural areas, community leaders are reconsidering traditional drivers of economic activity in search of sustainable, diversified, and environmentally friendly options. Bioenergy may be a viable economic development option for communities that can grow dedicated energy crops and that can develop energy industries to process those crops into power or fuel. The development of a bioenergy industry may be particularly well suited for local economies—given adequate investors—in that the costs of transporting bioenergy crops makes local processing necessary. Thus, economic activity and economic benefit may stay local; although local net benefits are not always guaranteed when balanced against negative impacts to community life and well-being, such as food insecurity, increased truck and/or train traffic (i.e., noise, air quality, traffic safety), and odors and noise from the biomass conversion facility (Selfa et al. 2011). Economic benefits must also be weighed against impacts to water supply. Each community and situation is different, and local decisions around the choice of energy crops, processing systems, and markets will define the economic benefits, while state and federal policy can provide incentives and influence outcomes. An additional issue, however, is rural self-determination and empowerment. Government policies tend to overlook social considerations in biofuel development strategies (Mol 2007; Rossi and Hinrichs 2011), leading to macrolevel goals that adversely affect local-level realities. For a comprehensive review of rural development and social justice issues of biofuels, see Dale et al. (2013) and van der Horst and Vermeylen (2011).

1.9 SUMMARY

Biomass feedstocks for bioenergy, particularly advanced biofuels, have an important role in global, regional, and local energy consumption and economic development. Expansion of biomass production, processing into feedstocks, handling, transportation, and storage, if done sustainably, may provide supply/value chains that support renewable energy goals while enhancing rural livelihoods. Although second-generation lipid feedstocks are important in the production of biodiesel, it is cellulosic/lignocellulosic feedstocks that hold the greatest potential for transforming fuel energy portfolios while simultaneously transforming agriculture and resource management. Crop residues have the potential to contribute substantially to second-generation biofuels, but their collection and use must be carefully planned and managed so as not to degrade soils and water, nor to generate shortages in fodder and bedding for livestock. Perennial grasses are chief among cellulosic/lignocellulosic feedstock sources at the center of research and development efforts—in part because of their yield potentials and environmental benefits, but due in greater part to their lack of food value. Innovations in biomass crops and cropping systems must occur to increase their overall contribution to global renewable energy consumption. These innovations must run apace with improvements in agricultural equipment and conversion technology. Sustainability of biomass production and the feedstocks derived therefrom will depend on the ability of science and public policy to limit competition for land use that leads to food insecurity; to curtail land-use practices that contribute to climate change, environmental degradation, and reduction in water supply and quality; to enhance rural self-determination and empowerment; and to prevent creation of energy poverty. Ultimately, decision-makers at all levels must consider advantages and disadvantages among specific biomass types and production systems and make informed decisions with regard to desired goals for the present and the future.

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