University of Nebraska - Lincoln

DigitalCommons@University of Nebraska - Lincoln

Publications from USDA-ARS / UNL Faculty

U.S. Department of Agriculture: Agricultural
Research Service, Lincoln, Nebraska

2014

Selected Global Examples of Cellulosic Cropping System Trends

Douglas Karlen

USDA-ARS, doug.karlen@ars.usda.gov

Marcelo Valadares Galdos

Brazilian Center of Research in Energy and Materials (CNPEM)

Sarita Candida Rabelo

Brazilian Center of Research in Energy and Materials (CNPEM)

Henrique Continho Junqueira Franco

Brazilian Center of Research in Energy and Materials (CNPEM)

Antonio Bonomi

Brazilian Center of Research in Energy and Materials (CNPEM)

See next page for additional authors

Follow this and additional works at: <https://digitalcommons.unl.edu/usdaarsfacpub>

Karlen, Douglas; Valadares Galdos, Marcelo; Candida Rabelo, Sarita; Junqueira Franco, Henrique Continho; Bonomi, Antonio; Li, Jihong; Li, Shi-Zhong; Tumuluru, Jaya Shankar; and Ovard, Leslie, "Selected Global Examples of Cellulosic Cropping System Trends" (2014). *Publications from USDA-ARS / UNL Faculty*. 1662.

<https://digitalcommons.unl.edu/usdaarsfacpub/1662>

This Article is brought to you for free and open access by the U.S. Department of Agriculture: Agricultural Research Service, Lincoln, Nebraska at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Publications from USDA-ARS / UNL Faculty by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.

Authors

Douglas Karlen, Marcelo Valadares Galdos, Sarita Candida Rabelo, Henrique Continho Junqueira Franco, Antonio Bonomi, Jihong Li, Shi-Zhong Li, Jaya Shankar Tumuluru, and Leslie Ovard

Selected Global Examples of Cellulosic Cropping System Trends

**Douglas L. Karlen¹, Marcelo Valadares Galdos²,
Sarita Cândida Rabelo², Henrique Continho Junqueira Franco²,
Antonio Bonomi², Jihong Li³, Shi-Zhong Li³,
Jaya Shankar Tumuluru⁴, and Leslie Ovard⁴**

*¹National Laboratory for Agriculture and the Environment, USDA Agricultural
Research Service, U.S.A.*

*²Brazilian Bioethanol Science and Technology Laboratory (CTBE)/Brazilian Center of Research in
Energy and Materials (CNPEM), Brazil*

*³MOST-USDA Joint Research Center for Biofuels, Institute of New Energy Technology,
Tsinghua University, China*

⁴Biofuels and Renewable Energy Technologies, Idaho National Laboratory, U.S.A.

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.

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 baling 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 demonstration 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 corn cobs. 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].

Marjestia (*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.”

Acknowledgements

The authors would like to acknowledge Chris Wright, and J. Richard Hess of Idaho National Laboratory for their valuable contributions to this work, which was supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, under DOE Idaho Operations Office Contract DE-AC07-05ID14517.

This information was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade

name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

References

1. Empresa de Pesquisa Energética (EPE) (2012) National Energy Balance 2012–2011 Base Year: Final Report.
2. U.S. Environmental Protection Agency (EPA) (2010) Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis. EPA-420-R-10-006.
3. Ratnavathi, C.V., Kalyana, Chakravarthy S., Komala, V.V., *et al.* (2011) Sweet sorghum as feedstock for biofuel production: a review. *Sugar Tech*, **13**, 399–407.
4. Shields, S. and Boopathy, R. (2011) Ethanol production from lignocellulosic biomass of energy cane. *International Biodeterioration & Biodegradation*, **65**, 142–146.
5. Dias, M.O.S., Junqueira, T.L., Cavalett, O., *et al.* (2012) Integrated versus stand-alone second generation ethanol production from sugarcane bagasse and trash. *Bioresource Technology*, **103**, 152–161.
6. China National Development and Reform Commission (NDRM) (2007) Middle and Long Term Development Plan for China's Renewable Energy.
7. Department of Science and Education, Ministry of Agriculture of China (2010) China Crop Straw Resources Investigation and Evaluation Report.
8. State of Forestry Administration (2009) China Forestry Resource Report: The Seventh Forestry Resource Survey.
9. Zhang, C., Xie, G., Li, S., *et al.* (2010) The productive potentials of sweet sorghum ethanol in China. *Applied Energy*, **87**, 2360–2368.
10. Qiu, H., Sun, L., Huang, J., and Rozelle, S. (2012) Liquid biofuels in China: current status, government policies. *Renewable and Sustainable Energy Reviews*, **16**, 3095–3104.
11. Li, S. and Chan, H. (2009) Ethanol production in (the) People's Republic of China: potential and technologies. *Applied Energy*, **86**(Suppl. 1), S162–S169.
12. China National Development and Reform Commission (NDRM) (2008) Notice from national development and reform commission for the construction of rural biogas project in 2009.
13. Ministry of Finance (MOF) (2006) Guidance on the implementation of financial support to non-cereal based biofuel development.
14. Bhalla, G.S. (1988) The Nature of Agriculture Development in India. <http://isidev.nic.in/pdf/nature.pdf> (last accessed 4 February 2013).
15. The World Bank (2012) Agriculture, value added (% of GDP). World Bank and OECD National Accounts data files, <http://data.worldbank.org/indicator/NV.AGR.TOTL.ZS/countries> (accessed 4 February 2013).
16. Eisentraut, A. (2010) Sustainable Production of 2nd Generation Biofuels: Potential and Perspectives in Major Economies and Developing Countries. Information Paper, International Energy Agency (IEA) http://www.iea.org/publications/freepublications/publication/second_generation_biofuels.pdf (accessed 4 February 2013).
17. World Resources Institute (2012) Greenhouse gas emissions by country. http://www.google.com/publicdata/explore?ds=cjsdgb406s3np_#!ctype=l&strail=false&bcs=d&nselm=h&met_y=emissions&scale_y=lin&ind_y=false&rdim=country&idim=country:77:36:185&ifdim=country&tstart=633164400000&tend=1106550000000&hl=en_US&dl=en_US&ind=false (accessed 4 February 2013).
18. Lima, M.G.B. (2012) An Institutional Analysis of Biofuel Policies and Their Social Implications: Lessons Learned From Brazil, India and Indonesia. Occasional Paper Nine, Social Dimensions of Green

- Economy and Sustainable Development, United Nations Research Institute for Social Development, <http://www.fes-globalization.org/geneva/documents/9%20%20UNRISD%20Bastos%20Lima.pdf> (accessed 4 February 2013).
19. Ravindranath, N.H., Lakshmi, C.S., Manuvie, R., and Balachandra, P. (2011) Biofuel production and implications for land use, food production, and environment in India. *Energy Policy*, **39**, 5737–5745.
 20. Food and Agriculture Organization of the United Nations (FAO) (2011) The State of Food Insecurity in the World 2011: How Does International Price Volatility Affect Domestic Economies and Food Security? FAO, Rome, Italy.
 21. Kumar, B., Hiremath, R.B., Balachandra, P., and Ravindranath, N.H. (2009) Bioenergy and food security: Indian context. *Energy for Sustainable Development*, **13**, 265–270.
 22. Sukumaran, R.K., Surender, V.J., Sidhu, R., *et al.* (2010) Lignocellulosic ethanol in India: prospects, challenges and feedstock availability. *Bioresource Technology*, **101**, 4826–4833.
 23. Energy Alternatives India (EAI) Shweta's Blog (2012) Energy crops for biomass power generation (4 August 2012). <http://www.eai.in/club/users/Shweta/blogs/15586> (accessed 25 October 2013).
 24. BioZio (2011) Comprehensive Jatropha Report. http://www.biozio.com/ref/report/jat/Comprehensive_Jatropha_Report_Preview.pdf (accessed 4 February 2013).
 25. Bhattacharya, A. and Kumar, P. (2010) Water hyacinth as a potential biofuel crop. *Electronic Journal of Environmental, Agricultural, and Food Chemistry*, **9**(1), 112–122.
 26. Gupta, N.S. (2012) Popularity of diesel driving growth in petro product consumption: CMIE, *The Times of India* (18 July). <http://timesofindia.indiatimes.com/business/india-business/Popularity-of-diesel-driving-growth-in-petro-product-consumption-CMIE/articleshow/15032452.cms> (accessed 4 February 2013).
 27. Fan, X. and Burton, R. (2009) Recent development of biodiesel feedstock and application of glycerol: a review. *The Open Fuels and Energy Science Journal*, **2**, 100–110.
 28. Simms, B. (2012) JOil achieves first-year yields in India jatropha field trials, *Biodiesel Magazine* (13 March). <http://www.biodieselmagazine.com/articles/8389/joil-achieves-first-year-yields-in-india-jatropha-field-trials> (accessed 4 February 2013).
 29. Clenergen Corporation (2009) Clenergen's Clean Energy Power Projects in India. <http://www.businesswireindia.com/pressrelease.asp?b2mid=20375> (accessed 4 February 2013).
 30. Clenergen Corporation (2011) Energy crop plantations. (Website) <http://www.clenergen.com/clenergen-india/energy-crop-plantations> (accessed 4 February 2013).
 31. IndianOil Corporation Ltd. Research and Development Centre http://www.iocl.com/aboutus/Research_Development.aspx (accessed 4 February 2013).
 32. Gonsalves, J.B. (2006) An Assessment of the Biofuels Industry in India. UNCTAD/DITC/TED/2006/6, United Nations Conference on Trade and Development, Geneva, Switzerland.
 33. Srinivas, K. (2008) Naturol begins biodiesel exports from Kakinada. *Business Standard* (24 June); http://www.business-standard.com/article/companies/naturol-begins-biodiesel-exports-from-kakinada-108062401018_1.html (last accessed 25 October 2013).
 34. Kavitha (2011) Southern Online Bio Technologies. Agriculture and Industry Survey. (BLOG, 22 January) <http://www.agricultureinformation.com/mag/2011/01/southern-online-bio-technologies/> (last accessed 25 October 2013).
 35. Cohen, T. (2012) U.S.-Israeli firm to launch algae biodiesel in India. Reuters (4 April). <http://in.reuters.com/article/2012/04/04/worldhealthenergy-algae-idINL6E8F42F220120404> (last accessed 3 November 2013).
 36. Kenney, K.L., Smith, W.A., Gresham, G.L., and Westover, T.L. (2013) Understanding biomass feedstock variability. *Biofuels*, **4**(1) 111–127.
 37. Government of India, Planning Commission (2003) Report of the Committee on Development of Bio-Fuel. http://planningcommission.nic.in/reports/genrep/cmtt_bio.pdf (accessed 4 February 2013).

38. Government of India, Ministry of New and Renewable Energy (MNRE) (2009) National Policy on Biofuels. http://mnre.gov.in/file-manager/UserFiles/biofuel_policy.pdf (accessed 4 February 2013).
39. Bloomberg New Energy Finance (BNFE) (2012) India saw record \$10.3bn clean energy investment in 2011. (Press release) <http://bnf.com/PressReleases/view/186> (accessed 4 February 2013).
40. Government of India (2012) The Bioenergy Road Map: Vision 2020. Ministry of Science and Technology, Department of Biotechnology (DBT).
41. Perlack, R.D., Wright, L.L., Turhollow, A.F., *et al.* (2005) Biomass as feedstock for a bioenergy and bioproducts industry: The technical feasibility of a billion-ton annual supply. DOE/GO-102005-2135 and ORNL/TM-2005/66.
42. U.S. Department of Energy, Perlack, R.D. and Stokes, B.J. (Leads) (2011) U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry. U.S. Department of Energy, ORNL/TM-2011/224, Oak Ridge National Laboratory, Oak Ridge, TN.
43. European Commission – Agriculture and Rural Development (2012) Agriculture and bioenergy. http://ec.europa.eu/agriculture/bioenergy/index_en.htm (last accessed 17 October 2013).