The Economics of Biomass Feedstocks in the United States

A Review of the Literature

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About this document

The Biomass Research and Development Board (Board) commissioned a literature review of feedstock cost and availability to meet the priorities of the President's 20-in-10 plan. The Energy Independence and Security Act (EISA) of 2007 builds on this plan to accelerate the development of a renewable energy sector. The literature review covers economic studies available through the end of 2007 and is intended to support further economic research on expanding the production of renewable fuels.

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Table of Contents

Executive Summary

In his 2007 State of the Union address, the President announced the “20 by 10” goal to cut U.S. gasoline consumption by 20 percent in 10 years. In December 2007, the Energy Independence and Security Act set a renewable fuel standard of 36 billion gallons of biofuels for 2022, of which 21 billion gallons are to come from “advanced fuels.” These goals present several technical, economic, and research challenges, one of which is the availability of feedstock for advanced biofuel production. The high cost of producing, harvesting, and transporting some feedstocks, and of converting them to fuel, are important issues.

This report, undertaken at the direction of the Feedstock Interagency Team, is the first step toward the economic analysis of biomass and offers a comprehensive literature review of the technical and economic research on biomass feedstock available to date. Analysis of biomass feedstock is complex by virtue of its many types, differences in availability, as well as many possible end-uses. Biomass is any organic-based material that can be processed to extract sugars or thermochemically processed to produce biomaterials or biofuels or combusted to produce heat or electricity. In addition to its energy application, biomass has a variety of other uses such as food and feed, forestry products (pulpwood), and other industrial applications that are important to the U.S. economy. This complicates the economic analyses of biomass feedstocks and requires that we differentiate what is technically possible from what is economically feasible, taking into account relative prices and intermarket competition.

The report examines a large number of peer-reviewed articles and studies related to biomass and summarizes the current understanding of feedstock types, current and potential availability, geographical distribution, costs, feedstock-related R&D, and economic and market constraints likely to favor or impede using biomass for bioenergy and bioproducts. While the report also delves into the technical aspects of biomass, its central focus is on evaluating the economic information covering:

(i) main uses of feedstock both for bioenergy and non-bioenergy markets;
(ii) existing estimates of availability, information on geographical distribution;
(iii) feedstock shares in the cost of production for end-use products and relative competitiveness vis-a-vis non-biomass alternative uses (break-even prices);
(iv) sustainability of biomass production and recovery; and
(v) energy efficiency and carbon balances (lifecycle analyses).

First-Generation Feedstocks

For first-generation feedstocks, the type of end-use product is easily categorized (table ES-1). Corn and sugarcane are the most commonly used feedstocks for ethanol production. Soybean and other vegetable oils and animal fats are used for biodiesel production (and also bioproducts). Manure and landfill organic waste are used for methane production and the generation of electricity.

The leading feedstock currently used in U.S. biofuel production is **corn used for ethanol**. There is very little ethanol produced with other feedstocks. Under current law, total production of corn-based ethanol would more than double from the current 6.5 billion gallons to 15 billion gallons by 2015. Production of this volume would require a supply of corn equal to 42 percent of the 2007 corn crop (WASDE, March 2008). Such significant and growing requirements are likely to sustain relatively high corn prices for the foreseeable future. Since corn feedstocks make up 39 to 50 percent of total ethanol production costs (table ES-2), high corn prices are likely to reduce the competitiveness of U.S. ethanol relative to gasoline or Brazilian ethanol.

Table ES-1
Biomass feedstocks covered and possible bioenergy end-use applications

		First generation fuels			Second generation fuels		Biopower		Bio-Products
		Ethanol	*Biodiesel*	*Methane*	*Cellulosic ethanol*	*Thermoch fuels (ethanol, diesel, butanol..etc)*	*Stand -alone*	*Co-firing*	
First generation									
Starch and sugar-feedsdtock for ethanol	Corn	X							X
	Sugarcane	X							
	Molasses	X							
	Sorghum	X							
Vegetable oil and fats for biodiesel	Vegetable oils		X						X
	Recycled fats and grease		X						
	Beef tallow		X						
Second-generation (short-term)									
Agricultural residues and livestock by-products	Corn stover				X		X	X	
	wheat straw				X		X	X	X
	rice straw				X				
	Bagasse				X		X		
	Manure			X					
Forest biomass	Logging residues				X	X	X	X	X
	Fuel treatments				X	X	X	X	X
	Conventional wood				X	X	X	X	X
Urban woody waste and landfills	Primary wood products				X	X	X	X	
	Secondary mill residues				X	X	X	X	
	Municipal solid waste			X	X	X	X	X	
	Construction/demolition wood						X	X	
	Landfills			X	X				
Second-generation (long-term)									
Herbaceous Energy Crops	Switchgrass				X	X	X	X	X
	Miscanthus				X	X	X	X	
	Reed canary grass				X	X	X	X	
	Sweet sorghum								
	Alfalfa				X	X	X	X	
Short Rotation Woody Crops	Willow				X	X	X	X	X
	hybrid poplar				X	X	X	X	X
	cottonwood pines				X	X	X	X	X
	Sycamore pines				X	X	X	X	X
	Eucalyptus				X	X	X	X	X

Several factors favor a positive outlook for further near-term growth in corn-ethanol production. Continued high oil prices will provide economic support for the expansion of all alternative fuel programs, including corn ethanol. Strong policy support will also be important in reducing profit uncertainty in this volatile, commodity-dependent industry. Technology improvements that increase feedstock productivity and fuel conversion yields and positive spillovers from second-generation technologies (biomass gasification in ethanol refineries) will also help to lower production costs for corn ethanol.

Among the factors likely to limit future growth of corn-ethanol production are increased feedstock and other production costs; increased competition from unconventional liquid fossil fuels (from oil sands, coal, heavy oil, and shale); the emergence of cellulosic ethanol as a low-cost competitor; and new policies to reduce greenhouse gas emissions (GHGs) that could favor advanced biofuels over corn ethanol.

Another biofuel experiencing expansion is **biodiesel**. While its production costs are higher than ethanol, biodiesel has some environmental advantages, including biodegradability and lower sulfur and carbon dioxide emissions when burned. Biodiesel production in the United States has increased rapidly from less than 2 million gallons in 2000 to about 500 million gallons in 2007. Policy incentives in the Energy Independence and Security Act of 2007 are expected to sustain demand for 1 billion gallons per year of this fuel after 2011.

Table ES-2
First-generation feedstocks and biofuels: production costs, conversion yields, energy efficiency, and carbon balances

Fuel	*Cost of production ($/gallon)*	*Share of feedstock cost in total production (Percent)*	*Conversion yield (gallon/DM ton) Gallons/ton*	*Average yield (Tons/ha)*	*Fuel yield per ha Gallons/ha*	*Net renewable energy compared to petroleum (ratio)*	*Life cycle analysis of GHG emissions (percent)*
Ethanol							
Corn-based US	1.65	39-50	121.4	7.9	958.5	1.18	-18
Sugarcane Brazil	0.87-1.10	55-65	74.20	21	1556.7	1.7	-91
Wheat-based EU	2.24	68.00	91.4-101.7	7	675.9	1.1	-19 to -47
Biodiesel							
Soybean oil	1.9-2.35	80-85	55.9	2.5	139.8	1 to 3.2	-70
Tallow*	0.82-2.38	NA	19 (gallon/head)	NA	NA	0.81 to 17.3	NA
Yellow grease	1.27	NA	NA	NA	NA	NA	NA

* biodiesel yield is from Nelson and Shrock (2002)
Sources: Urbanchuk (2007); Schnepf (2003); Paulson and Ginder (2007); Kojima et al. (2007); Pimental (2005); IEA(2004);

A process know as trans-esterification is used to convert a variety of oil-based feedstocks to biodiesel. These include vegetable oils (mostly soy oil), recycled oils and yellow grease, and animal fats like beef tallow. It takes 3.4 kg of oil/fat to produce 1 gallon of biodiesel (Baize, 2006). Biodiesel production costs are high compared to ethanol, with feedstocks accounting for 80 percent or more of total costs (table ES-2).

The biodiesel industry consists of many small plants that are highly dispersed geographically. Decisions about plant location are primarily determined by local availability and access to the feedstock. Recent expansion in biodiesel production is affecting the soybean market. Achieving a nationwide B2 target (2 percent biodiesel blend in diesel transportation fuel), for example, would require 2.8 million metric tons (MT) of vegetable oil, or about 30 percent of current U.S soybean oil production (USDA-World Agricultural Outlook Board, 2008).

There is also concern about finding markets for a key biodiesel byproduct, glycerin. This problem may soon be resolved with new technologies. An alternative chemical process is being developed that would produce biodiesel without glycerin. Also, new processes are being tested that further transform glycerin into propylene glycol, which is used in the manufacture of antifreeze (Biodiesel Magazine, Feb. 2007).

Second-Generation Feedstocks: Short-Term Availability

Among the second-generation biomass feedstocks, **agricultural residues** offer a potentially large and readily available biomass resource, but sustainability and conservation constraints could place much of it out of reach. Given current U.S. cropland use, corn and wheat offer the most potentially recoverable residues. However, these residues play an important role in recycling nutrients in the soil and maintaining long-term fertility and land productivity. Removing too much residue could aggravate soil erosion and deplete the soil of essential nutrients and organic matter.

Methodologies have been developed to estimate the safe removal rates for biomass (based on soil erosion). Methodologies to determine removal rates while safeguarding soil fertility and meeting conservation objectives still need to be developed. Studies show that under current tillage practices the national-average safe removal rate based on soil erosion for corn stover is less than 30 percent. Actual rates vary widely depending on local conditions. In other words, much of the generated crop residues may be out of reach for biomass use if soil conservation goals are to be achieved (Graham et al, 2007).

The estimated delivery costs for agricultural residues vary widely depending on crop type, local resource density, storage and handling requirements, and distance and transportation costs. Moreover, existing estimates are largely derived from engineering models, which may not account for economic conditions.

A significant advantage of agricultural residue feedstocks (such as corn stover) is that they can be readily integrated into the expanding corn ethanol industry. However, dedicated energy crops (such as switchgrass) may have more benign environmental impacts.

Forest biomass is another significant biomass source that would be immediately available should the bioenergy market develop. Logging residues are associated with timber industry activities and constitute significant biomass resources in many States, particularly in the Northeast, North Central, Pacific Northwest, and Southeast. In the Western States, the predominance of public lands and environmental pressures reduces the supply potential for logging residues, but there is a vast potential for biomass from thinning undertaken to reduce the risk of forest fires. However, the few analyses that have examined recoverability of logging residues cite the need to account for factors such as the scale and location of biorefineries and biopower plants, as well as regional resource density (table ES-3).

While the potential for forest residues may be large, actual quantities available for biomass conversion may be low due to the economics of harvesting, handling, and transporting the residues from forest areas to locations where they could be used. It is not clear how these residues compete with fossil fuels in the biopower and co-firing industries. In addition, there are competing uses for these products in the pulp and paper industry, as well as different bioenergy end-uses. Economic studies of logging residues suggest a current lack of competitiveness with fossil fuels (coal, gas). But logging residues could become more cost competitive with further improvements in harvesting and transportation technologies and with policies that require a more full accounting of the social and environmental benefits from converting forest residues to biopower or biofuels.

Biomass from fuel treatments and thinnings is another source of forest residues that could be recovered in significant quantities (table ES-3). Fuel treatment residues are the byproduct of efforts to reduce risk of loss from fire, insects, and disease; and therefore present substantially different challenges than logging residues. According to the Office of Management and Budget (OMB), Federal agencies spent $12.1 billion fighting forest fires during FY 1998-2007. Estimates for fuel treatments in the West show about 5.9 million hectares of timberland--with a potential yield of 258.2 million dry MT over a 30-year period, or 8.6 million MT of wood per year.

The overall value of forest health benefits such as clean air and water is generally believed to exceed the cost of treatment. However, treated forests are often distant from end-use markets, resulting in high transportation costs to make use of the harvested material. Road or trail access, steep terrain, and other factors commonly limit thinning operations in Western forests.

Table ES-3

Second-generation feedstock: forest biomass availability, recoverability, location, and delivery costs

		Biomass Resource			
		Logging residues (growing stock)	Logging residues (other sources)	Logging residues (total)	Fuel treatment
Citation	Variable				
Smith et al. (2001)	Estimated Availability (Mil metric odt)	18.1	28.9	47	
	Geographic area	Nationwide			
Gan and Smith (2006)	Estimated recoverable residues (Mil metric odt)	13.9	22.3	36.2	
	Geographic area	Nationwide			
	Delivered cost ($/MWh; marginal cost			6.3	
	Delivered Cost ($MWh; full cost)			7.3	
Puttock (1995)	Delivered cost ($/Gj; marginal cost)			0.69	
	Delivered cost ($/Gj; full cost)			0.97	
USDA Forest Srevice (2005)	Estimated recoverable biomass (Mil metric bdt per yr)				10.4
	Geographic area				Western US
	Gross treatment costs $/ha)				35 - 107
Skog et al. (2006)	Estimated recoverable biomass (Mil odt per yr)				13
	Geographic area				Western US
Polagye et al. (2006)	Delivered costs ($/ha)				86-2,470
	Geographic area				Washington state

Transportation costs can be a significant factor in the cost of recovering biomass. As much as half the cost of the material delivered to a manufacturing facility may be attributed to transportation. Gross treatment costs in the Western States can range from $86 to over $2,470 per hectare, depending on type of operation, terrain, and density of trees (USDA-FS). The ability to separate and market larger diameter logs for higher value products is critical to the net revenues or costs of fuel treatments. If the opportunity to use larger logs for higher value products is lacking, then revenues would not cover costs. One tool being used by Federal land managers is “stewardship contracting,” where the value of material removed can help offset the treatment costs in a goods-for-services contract.

An alternative to high-cost transportation of forest thinnings is onsite densification of the biomass. This could entail pelletization, fast pyrolysis (to produce bio-oil), or baling.

The economics of transporting thinned woody residues versus onsite densification depend on the distance to end-use markets. Densification may be more economical if power generation facilities are far away. In addition to co-firing or co-generation facilities, improvements in thermochemical conversion efficiency and establishment of small-scale conversion facilities using gasification and/or pyrolysis may favor the use of forest residues for biofuel production (Polagye et al., 2007).

A third major category of immediately available second-generation biomass is wood residues from **secondary mill products** and **urban wood waste**. Urban wood waste provides a relatively cheap feedstock to supplement other biomass resources (Wiltsee, 1998). Urban wood waste encompasses the biomass portion of commercial, industrial, and municipal solid waste (MSW), while secondary mill residues include sawdust, shavings, wood trims, and other byproducts generated from processing lumber, engineered wood products, or wood particles. Both urban wood waste and secondary mill residues have several primary uses and disposal methods (table ES-4). Urban wood waste not used in captive markets (such as the pulpwood industry) could be used as biomass either to generate electricity or to produce cellulosic ethanol when it becomes commercially viable.

Table ES-4
Primary uses and disposal methods for urban wood wastes and secondary mill residues

	Urban wood waste (Wiltsee, 1998)	Secondary mill residues (Rooney, 1998)
	---------------- Percent	--------------------
Mulch	39.3	4.1
Landfill or incineration	33.4	17.2
Biomass fuel, sold or given away	12	17.3
Firewood, fuel used onsite	7.4	20.7
Furnish, logs, pulp chips	5.1	2.8
Animal bedding	1.2	26.2
Other	1.6	1.8

Significant urban wood wastes are produced in the United States and their use as biomass could be economically viable, particularly in large urban centers (Wiltsee, 1998). Several national availability estimates exist for various types of urban wood wastes, but estimates vary depending on methodology, product coverage, and assumptions about alternative uses (Wiltsee, 1998; McKeever, 2004). One of the challenges facing potential availability of urban woody waste is to sort out the portion that is available (not currently used) and determine alternative uses, including those used by captive markets (not likely to be diverted to bioenergy). One assessment of urban wood waste finds that 36 percent of total biomass generated is currently sold to noncaptive markets, and 50 percent of the unused residues are not available due to contamination, quality, or recoverability (Wiltsee, 1998).

Table ES-5
Second-generation feedstocks: urban wood waste and secondary mill residues (1999)

	Wood waste total generation (Mil MT/year)	**Available @ up to $11/MT** (Mil MT/year)	**Available @ up to $22/MT** (Mil MT/year)	**Available @ above $22/MT** (Mil MT/year)
Secondary mill	14.22	1.22	3.44	5.55
Construction	15.21	2.54	7.17	11.56
Demolition	24.00	1.58	4.46	7.20
Municipal solid waste	10.73	1.82	5.12	8.26
Yard trimmings	5.73	1.09	3.07	4.95
Urban tree residues	46.78	9.06	25.52	41.16
Used pallets	5.95	0.21	0.59	0.95
Railroad ties	1.53	n/a	n/a	n/a
Land clearing	n/a	n/a	n/a	n/a
Used utility poles	n/a	n/a	n/a	n/a
Total	**<124.14**	**<17.52**	**<49.37**	**<79.63**

Source: Fehrs (1999).

One source of recurring and potentially available carbon feedstock is municipal solid waste (MSW). In 2005, EPA estimated that 245.7 million tons of MSW was generated in the United States, of which 79 million tons were recycled, 33.4 millions tons were diverted to energy recovery, and 133.3 million tons were disposed of in landfills. As such, landfilled material represents a potentially significant source of renewable carbon that could be used for fuel/energy production or in support of biofuel production.

Few assessments of urban wood waste include both quantities and prices. In one assessment (Fehrs, 1999), total U.S. wood waste was estimated at about 124 million MT (table ES-5). But actual quantities available for bioenergy uses depend on delivered prices: from less than 17.52 million MT for prices below $11/MT to about 79.6 million MT when prices are above $22/MT, a price competitive with captive markets for wood residue (such as pulp and industry). These results highlight the importance of information about alternative uses that could compete for wood residues as a biomass resource.

Second-Generation Feedstocks: Long-Term Availability

In the long run, large-scale biofuels production will require other resources, including dedicated energy crops. A steady supply of low-cost, uniform and consistent-quality biomass feedstock will be critical for the economic viability of cellulosic ethanol production. During the late 1980s, the Department of Energy sponsored research on perennial **herbaceous (grassy) biomass crops,** particularly switchgrass, considered a model energy crop because of its many perceived advantages: native to North America, high biomass yield per acre, wide regional coverage, and adaptability to marginal land conditions. An extensive research program on switchgrass in the 1990s generated a wealth of information on high-yielding varieties, regional adaptability, and management practices. Preliminary field trials show that the economic viability of switchgrass cultivation depends critically on the initial establishment success. During this phase, seed dormancy and seedling sensitivity to soil and weed conditions require that recommended practices be closely followed by growers. Viable yields require fertilization rates at about half the average for corn.

Switchgrass is believed to be most suitable for cultivation in marginal lands, low-moisture lands, and lands with lower opportunity costs such as pastures, including lands under the Conservation Reserve Program (CRP) where the Federal Government pays landowners annual rent for keeping land out of production. Additionally, a large amount of highly erodible land in the Corn Belt is unsuitable for straw or stover removal but potentially viable for dedicated energy crops such as switchgrass. Factors favoring adoption of switchgrass include selection of suitable lands, environmental benefits (carbon balances, improved soil nutrients and quality), and use of existing hay production techniques to grow the crop. Where switchgrass is grown on CRP lands, payments help to offset production costs. Factors discouraging switchgrass adoption include no possibility for crop rotation; farmers' risk aversion for producing a new crop because of lack of information, skills, and know-how; potential conflict with onfarm and off-farm scheduling activities; and a lack of compatibility with long-term land tenure. Overall, production budget and delivery cost assessments suggest that switchgrass is a high-cost crop (under current technology and price conditions) and may not compete with established crops, except in areas with low opportunity costs (e.g., pasture land, marginal lands).

The economics of switchgrass production and assessments of production budgets and delivered costs show substantial variability. Factors at play include methods of storage and handling, transport distances, yields, and types of land used (cropland versus grassland). When delivered costs of switchgrass are translated into break-even prices (compared with conventional crops), it becomes apparent that cellulosic ethanol or biopower plants would have to offer relatively high prices for switchgrass to induce farmers to grow it (Rinehart, 2006). However, the economics of switchgrass could improve if growers benefited from CRP payments and other payments tied to environmental services (such as carbon credits). In the long run, the viability of an energy crop like switchgrass hinges on continued reductions in cellulosic ethanol conversion costs and sustained improvements in switchgrass yields and productivity through breeding, biotechnology, and agronomic research.

While switchgrass clearly represents a potentially important biofuels crop, it does have limitations. Switchgrass is not optimally grown everywhere. For example, in the upper Midwest under wet soils, reed canary grass is more suitable, while semi-tropical grass species are better adapted to the Gulf Coast region. State and local efforts at testing alternatives to switchgrass such as reed canary grass, *Miscanthus*, and other species are underway.

From the perspective of longrun sustainability, the ecology of perennial grassy crops favors a multiplicity of crops or even a mix of species within the same area. Both ecological and economic sustainability favor the development of a range of herbaceous species for optimal use of local soil and climatic conditions. A mix of several energy crops in the same region would help reduce risk of epidemic pests and disease outbreak and optimize the supply of biomass to an ethanol or biopower plant since different grasses mature and can be harvested at different times. Moreover, development of future energy crops must be evaluated from the standpoint of their water use efficiency, impact on soil nutrient cycling, effect on crop rotations, and environmental benefit (improved energy use efficiency and reduced greenhouse gas emissions, nutrient runoff, pesticide runoff, and land-use impacts). In the long run, developing a broad range of grassy crops for energy use is compatible with both sustainability and economic viability criteria.

Short-rotation woody crops (SRWC) represent another important category of future dedicated energy crops. Among the SRWC, hybrid poplar and willow have been extensively researched for their very high biomass yield potential. Breeding programs and management practices continue to be developed for these species. SRWC are based on a high-density plantation system and more frequent harvesting (every 3-4 years for willow and 7 years for hybrid poplar). Active breeding programs to select the most locally adapted varieties of SRWC are underway, particularly for willow (State University of New York, College of Environmental Science and Forestry), hybrid poplar (Minnesota and North-Central States) and pines and cottonwoods (Southern U.S.). The wide genetic variation among the various lines and varieties suggests great potential for increased yield and productivity through these breeding programs.

In many parts of the country, plantations of willow, poplar, pines, and cottonwood have been established and are being commercially harvested. Willow plantations are being planted in New York, particularly following the enactment of the Renewable Portfolio Standard (RPS) and other State incentives. Over 30,000 hectares of poplar are grown in Minnesota, and several thousand hectares are also grown as part of a DOE-funded project to provide biomass for a power utility company in southern Minnesota. The Pacific Northwest has large plantations of hybrid poplars, estimated at 60,000 hectares as of 2007. The South has approximately 15,000 hectares of cottonwood as well as 9.7 million hectares of pine plantations (Smith et al., 2004). SRWC--especially eucalyptus, cottonwoods, and pines--can also be grown in Florida.

Most of these plantations are currently used for pulp wood, with little volume being used for bioenergy. Since SRWC can be used either for biomass or as feedstock for pulp and other products, pulp demand will influence the cost of using it for bioenergy production.

A serious impediment to the economics of SRWC production for bioenergy remains high establishment costs and lack of efficient mechanical harvesting techniques for high-density plantations. Recent estimates of the delivered price for SRWC show that unit prices stand at $3 per gigajoule (GJ, see glossary), twice as high as for fossil fuel (coal). A big component of the SRWC delivered price is harvesting cost, which can account for 40 to 70 percent depending on the technology used. The current technique of using the feller-buncher/grapple to skid whole trees is more suitable for large-diameter than small-diameter trees (short-rotation willows), where alternative methods are required. More research in harvesting techniques is required to lower costs and make SRWC more competitive.

Another important consideration for energy crops (e.g., switchgrass, poplar, willow) is the potential for increasing yields and developing other desirable characteristics. Most energy crops are unimproved or have been bred only recently for biomass yield, whereas corn and other commercial food crops have undergone substantial improvements in yield, disease resistance, and other agronomic traits. A more complete understanding of biological systems and application of the latest biotechnological advances would accelerate the development of new biomass crops with desirable attributes. These attributes include increased yields and processability, optimal growth in specific microclimates, better pest resistance, efficient nutrient use, and greater tolerance to moisture deficits and other sources of stress. Agronomic and breeding improvements of these new crops could provide a significant boost to future energy crop production.

Cross-Cutting Issues in Second-Generation Biomass Feedstock

Overall, this report reveals the complexity of assessing the economic potential of biomass feedstocks and their future role in bioenergy systems. Key complicating factors are the great diversity of potential feedstocks and the lack of commercially viable production processes for second-generation biofuels. Still, there are many factors common to these various biomass feedstocks. Among these are considerations regarding the harvesting of the feedstock, transporting and storing large quantities of bulky material, and managing market volatility and risk. Consequently, the economics of biomass feedstocks must be approached systematically, using a supply-chain framework that takes account of the spatially dispersed nature of its supply, varying harvest times, and different sources of demand (biorefineries or biopower facilities).

Feedstock supply is inherently regional. The local availability of biomass feedstock and relative importance of one type relative to another will determine what types of bioenergy opportunities are likely to emerge in certain regions. Other determining factors include regional demand, local resources (water), and competing sources of demand for biomass. A key determinant of biomass supply is the availability and quality of infrastructure (roads, rail, and barge services) that ensures low-cost transportation from the place of production to the processing plant.

The local biorefinery and the type of conversion technology used will determine the types and quantities of feedstocks needed, as well as desirable feedstock characteristics (moisture, lignocellulosic, and mineral contents). Managing risk requires taking account of the relative abundance of the required feedstocks and local weather conditions affecting the continuity of biomass supply, transportation options, workforce availability and skill, the number of potentially competing plants in the region, and local tax advantages and other incentives.

With a multitude of feedstocks required to meet second-generation biorefinery needs, well-established local production of dedicated energy crops with long-term supply commitments may be necessary. Feedstock procurement will most likely be based on multiple sourcing of different types of biomass feedstocks as a key lever in risk management. Such multiplicity of feedstock sourcing will dictate the nature and shape of the regional infrastructure, the overall feedstock cost structure, and the economics of bioenergy production.

In addition to the economic viability of a local biomass market, sustainability is also important. Water availability is an obvious consideration; both the quantity of water use and impact on local water quality are important considerations and may prevent a biorefinery's establishment. Removing too much agricultural residue, while maximizing biomass harvest, may compromise soil conservation objectives, decreasing future productivity. Forest residue harvests for biomass also need to factor in soil nutrient management for long-term productivity. Fertilizer runoff into streams and rivers contributes to eutrophication. Converting CRP or other available lands to croplands may adversely affect species diversity, land preservation, and recreational uses. Detailed life-cycle analyses are necessary to fully assess likely carbon and other greenhouse gas emission reductions, along with the full range of environmental impacts, for various combinations of biomass-bioenergy systems.

Acronyms

B2	Diesel gas with 2 percent biodiesel share
BRDB	Biomass Research and Development Board
CAAA	Clean Air Act Amendments of 1990
CHP	Combined heat and power
CRP	Conservation Reserve Program
DDGs	Distillers dried grains
DOE	U.S. Department of Energy
E10	Transportation fuel with 10 percent ethanol and 90 percent gasoline
E85	Transportation fuel with 85 percent ethanol ad 15 percent gasoline
EPA	U.S. Environmental Protection Agency
ESA	Energy Security Act of 2005
FFV	Flexible fuel vehicle
FS	Forest Service (USDA)
GHG	Green house gases
GJ	Gigajoule (one billion joule)(1 GJ equal 0.948 million Btu)
Ha	Hectare (equal 2.471 acres)
HEL	Highly erodible land
HFRA	Healthy Forest Restoration Act
HHV	High heat value
LCA	Life cycle analysis
LHV	Low heat value
Mgpy	Million gallons per year
MJ	Megajoule (1 million joules)
MBtu	Million Btu (British Thermal Unit)
MSW	Municipal Solid Waste MT
Metric ton	Equals 1.1 U.S. tons
MW	megawatt (one million watt)
NEV	Net energy value
NRCS	Natural Resource Conservation Service
RFS	Renewable Fuel Standard
RPS	Renewable Portfolio Standard
SOC	Soil organic carbon
SRWC	Short rotation woody crops
UTR	Urban tree residue

Tables and Graphs

Figures

Tables

Chapter 1

Introduction

Biomass feedstock is very complex by virtue of its many types, sources, and degree of availability, but also because of its many possible end-uses. Biomass is any organic-based material that can be biochemically processed to extract sugars, thermochemically processed to produce biofuels or biomaterials, or combusted to produce heat or electricity. Biomass is also an input into other end-use markets, such as forestry products (pulpwood) and other industrial applications. This complicates the economics of biomass feedstock and requires that we differentiate between what is technically possible from what is economically feasible, taking into account relative prices and intermarket competition.

In order to develop action plans and to chart research and development strategies to meet specific national energy policy goals, understanding the economics of biomass feedstock costs and availability is a critical first step. And given the complexity of biomass feedstock, an important prerequisite toward such an economic analysis is to carry out a review and synthesis of the literature on biomass. Although public awareness of biofuels and biomass feedstock has developed only recently, research on biomass for energy in the U.S. goes back to the 1980s. A rich and highly specialized literature on biomass is not widely accessible, so there is a critical need for a synthesis geared toward facilitating more indepth economic and modeling analyses of emerging biomass and bioenergy issues.

This report offers a broad overview and synthesis of the literature on the major groups of biomass feedstock, beginning with the current (“first”) generation feedstocks (starch, sugar, oils), followed by second-generation feedstocks readily available in the short term (agricultural residues, animal byproducts, forest residues, and urban wood wastes), and finally the second-generation dedicated energy biomass that may become available in the longer term (switchgrass, *Miscanthus*, poplar, willow, and other short-rotation woody crops). These feedstock categories are grouped and examined in seven separate chapters.

The main objective of this synthesis is to summarize what is known on the economics of feedstocks and identify areas for future in-depth economic analyses. While the report delves into the technical aspects of biomass to some extent, the main goal of the synthesis is to evaluate the economic information addressing the themes listed below (as relevant for each feedstock):

(i) main uses of feedstock both for bioenergy and non-bioenergy markets;
(ii) existing estimates of availability, information on geographical distribution;
(iii) feedstock shares in the cost of production for end-use products and

relative competitiveness vis-a-vis non-biomass alternative uses (break-even prices);
(iv) sustainability of biomass production and recovery; and
(v) energy efficiency and carbon balances (life-cycle analyses).

For some feedstocks, the type of end-use product is straightforward. For example, current- generation feedstocks such as corn and sugarcane are used solely for ethanol production. Likewise, vegetable oils and animal fats are used for biodiesel, while manure and landfill organic waste are used to produce methane for electricity. Though most of the other feedstock types have multiple end-use products or conversion technologies, the feedstock-specific economic analyses reviewed in this report are linked to a specific bioenergy product or process.

Chapter 2

Starch and Sugar-Based Ethanol: Corn and Other Crops

2.1 Introduction

The main technologies currently in use for producing ethanol fuel involve the conversion of starchy parts of food or sugar into ethanol. Starch-based feedstocks include corn, wheat, rice, barley, grain sorghum, and root crops like potatoes and cassava. Over 97 percent of all ethanol produced in the U.S. uses corn. This production is concentrated in Iowa, Nebraska, Illinois, South Dakota, and Nebraska.

Currently, ethanol in the United States is synonymous with corn ethanol. The industry arose in the aftermath of the 1970s energy crisis, supported by tax incentives and as a way of helping to meet environmental objectives (The Clean Air Act and its Amendments). Since the early 2000s, corn ethanol use has surged again, aided by the ban on MTBE, enactment of Renewable Fuel Standards (Energy Security Act of 2005 and Energy Independence and Security Act of 2007), and the sharp rise in oil prices.

Today, corn ethanol is a maturing industry, expected to surpass the current market limit of 10-percent ethanol blend by 2010. However, the future development of corn ethanol is uncertain for various reasons. For one, interest is expanding toward a new generation of biofuels derived from cellulosic and other biomass sources.. The implications of these developments for corn ethanol are not easy to predict.

Among the factors that would favor continued growth of corn ethanol are lower corn prices, higher targets for renewable fuels, more flexible-fuel vehicles, and additional E85-capable gas stations (provided the economics of ethanol are favorable relative to gasoline). The corn ethanol industry could also benefit indirectly from improved conversion technologies, which would enhance energy efficiency and improve the economics of producing corn ethanol.

Other factors could work against corn ethanol. The economics of corn ethanol may be unfavorable vis-à-vis gasoline with high corn prices. The commercial development of cellulosic ethanol could significantly shift investment into second-generation biofuels. Also, the development of a market for carbon and other GHG credits could favor second-generation fuels with a theoretically more benign environmental impact than corn ethanol. Input costs as well as economic factors such as expiration of import tariffs or tax incentives, low prices from oversupply, and increased plant production costs could also inhibit production growth. Finally, public acceptance of corn ethanol may flag if perceptions of negative environmental and social impacts take hold.

2.2 Corn-Ethanol Process and Outputs

Corn conversion to ethanol follows one of two technologies: dry corn milling or wet corn milling. Over 80 percent of U.S. ethanol production uses a dry-mill process, and the rest comes from wet corn milling. Dry corn milling uses the starchy part of corn to produce ethanol, distilled dried grains (DDGs), and CO_2 gas, which can be collected or released (see Appendix A). The primary energy sources in both dry and wet milling are coal, natural gas, and electricity (from burning coal or from a power grid). Typically, dry milling requires 40.9-52.6 megajoules (MJ) in energy consumption per gallon of ethanol produced. Wet milling follows a more complicated process and yields a different mix of end products: ethanol, corn oil, corn gluten meal (60 percent protein), and corn gluten feed (20 percent protein). In wet milling, energy consumption in producing 1 gallon of ethanol is 30.1-69.9 MJ (Kim and Dale, 2005b).

Since the 1980s, ethanol yields from dry corn milling have increased by more than 22 percent-- from 86.5 to the current average of 108.2 gallons per metric ton (MT). The byproduct DDG is produced at a rate of 2.95 kg/gallon of ethanol (Tiffany and Eidman, 2003). The conversion rate translates into 121.4 gallons of ethanol per ton of corn, or 855 gallons per hectare (based on average U.S. corn yields) **(table 2-1**).

Table 2-1
Biomass-to-biofuels conversion for several feedstocks, 2005

		Average	Ethanol yield		
Feedstock	Residue-to-crop ratio	crop yield (dry ton/ha)	Liter/kg of dry biomass	Gallons/ dry ton	Gallons/ hectare
Corn		7.05	0.46	121.37	855.37
Corn stover	1:1	2.38	0.29	76.52	181.80
Rice straw	1.4:1	2.01	0.28	73.88	148.50
Wheat straw	1.3:1	1.35	0.29	76.52	103.13
Sugarcane		21.00	0.50	72.00	1512.00
Sugarcane bagasse	0.6:1		0.28	73.88	
Sorghum straw	1.3:1	1.42	0.27	71.24	101.37
Barley straw	1.2:1		0.31	81.79	

Source: Kim and Dale (2005a).

2.3 Ethanol Industry Structure

Nationally, 147 corn-ethanol plants were operating as of May 2008, and the number is growing. Annual ethanol production reached an estimated 8.5 billion gallons as of May 2008, and another 5.1 billion gallons of capacity will be available once the 55 plants under construction and 6 plants undergoing expansion become operational in the next year (Renewable Fuels Association, 2008) (**table 2-2**). Dry mill plant size ranges from 400,000 gallons to 100 million gallons year (mgpy) of production capacity. Economies of scale are highly variable in the dry-mill industry, but wet milling plants tend to be larger, with capacity ranging from 50 to 330 mgpy.

Current plants in production average 58 million gallons per year. The average capacity for new plants and expansions is significantly larger, about 80 million gallons per year, with many plants surpassing 100 million gallons per year. Much of the new investment in the ethanol sector is by private or publicly held companies; a declining share is farmer owned. Only 12 percent of ethanol capacity currently under construction is farmer owned (Renewable Fuels Association, 2008).

Table 2-2
Corn ethanol production capacity by State

Location	Number of plants as of May 2008: Current	Under construct.	Total	Capacity: Current	Under construct	Nongrain feedstock: Type	(ethanol output)	Corn produced for ethanol	Total State corn production	Share of total corn for ethanol
				(Mil gal)	(Mil gal)		(Mil gal)	(Mil mt)	(Mil mt)	(%)
Iowa	29	14	43	2137	1435			20.1	60.2	33.4
Nebraska	19	6	25	1,144	622			10.8	37.4	28.8
Minnesota	18	4	22	782.1	290	Cheese whey	2.6	7.3	28.9	
South Dakota	14	2	16	821	118			7.7	13.8	55.8
Kansas	11	2	13	430.5	75			4.1	13.2	30.8
Illinois	7	3	10	919	254			8.6	58.0	14.9
Indiana	7	4	11	512	492			4.8	25.1	19.2
Wisconsin	7	2	9	408	90			3.8	11.2	34.1
Ohio	4	3	7	340	179	Waste beverage	3	3.2	13.8	23.3
Michigan	4	1	5	214	50			2.0	7.4	27.2
North Dakota	3	2	5	123	220			1.2	6.9	16.7
Texas	2	2	4	140	215			1.3	7.5	17.5
California	4	3	7	74	155	Cheese whey	5	0.6	0.9	66.9
Colorado	4	0	4	125	0	Waste beer	3	1.1	3.8	30.0
Missouri	5	0	5	195	0			1.8	11.7	15.6
Georgia	1	2	3	0.4	120	Brewery waste	0.4		1.5	0.0
Kentucky	2	0	2	38.4	0	Beverage waste	5.4	0.3	4.5	7.0
New York	1	1	2	50	114			0.5	1.8	26.5
Oregon	1	1	2	40	108			0.4	0.2	217.1
Tennessee	1	2	3	67	138			0.6	2.1	29.8
Arizona	1	0	1	55	0			0.5	0.1	478.7
Idaho	1	1	2	4	50			0.0	0.4	8.6
Louisiana	0	1	1	0	1.5	Sugar cane bagasse	1.5	0.0	3.1	0.0
New Mexico	1	0	1	30	0			0.3	0.2	115.4
Washington	0	1	1	0	55			0.0	0.6	0.0
Wyoming	2	0	2	6.5	0			0.1	0.2	31.1

Data for number of plants in production and under construction are as of May 2008 and are from the Renewable Fuel Association web site; corn production numbers are from NASS, USDA and are for 2007.
Source: USDA-NASS; Renewable Fuels Association (2008).
Estimated non corn grain feedstock is based on 50/50 assumption when corn and other grain feedstock are listed by the plant.

2.4 Economics of Corn Ethanol: Production Costs and Break-Even Prices

A case study by Urbanchuk (2007) illustrates the production cost of ethanol from starch based on dry-mill technology. The study derived cost data for a 50-mgpy dry-mill ethanol plant, using current data for corn, distillers' dried grains (DDG), natural gas, enzymes, yeast and chemicals, electricity, and wage rates. The plant is assumed to produce 51.5 million gallons of denatured ethanol and 154,500 tons of DDG annually from 389,150 metric tons of corn. The author also assumes that the capital cost for the 50-mgpy plant is $100 million depreciated over 15 years and financed over 10 years at 8.5 percent interest.

The study concludes that the cost of producing ethanol in a dry-mill plant is $1.65 per gallon--corn accounts for 66 percent of operating costs, while energy (electricity and natural gas) to fuel boilers and to dry DDG represents nearly 20 percent of operating costs (**table 2-3**). These data are consistent with Shapouri et al (2006). The main difference in ethanol operating costs in 2006 versus 2005 is higher corn prices.

Table 2-3
Corn ethanol operating costs, 2006

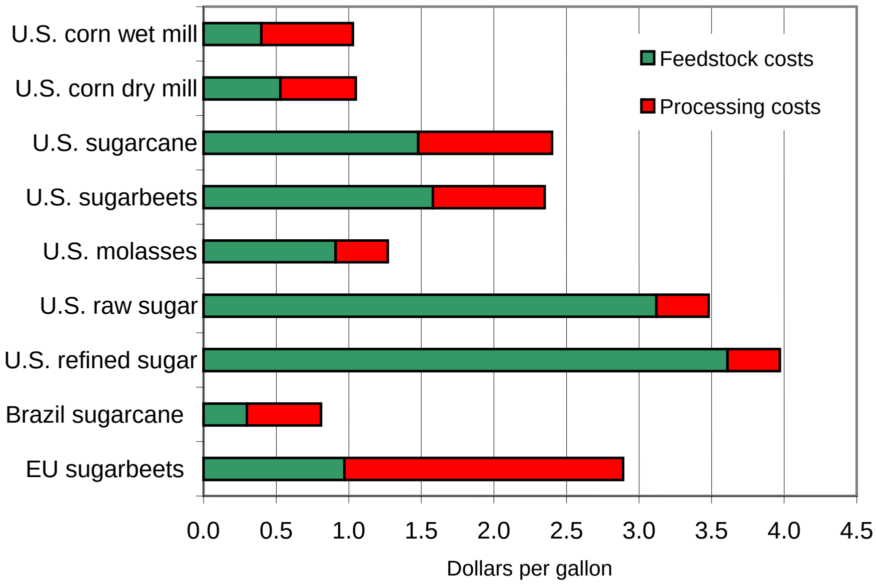
Operating costs	Units*	Units/Gal of ethanol*	Unit price*	Cost $ million/yr*	Cost $/gal*	Cost $/gal**
Raw Materials						
Corn	Bushel	0.364	$3.01	$54.73	$1.09	$0.70
Enzymes	Kg	0.016	$1.02	$1.79	$0.04	$0.04
Yeast and chemicals	Kg	0.512	$0.02	$0.84	$0.02	$0.04
Denaturant	Gallons	0.03	$1.60	$2.40	$0.05	$0.05
Electricity	$/KWh	0.8	$0.06	$2.31	$0.00	$0.05
Natural gas	$/million cubic feet	0.036	$7.78	$14.00	$0.28	$0.21
Water	Gallons/kg corn	0.465	$0.37	$0.18	$0.00	$0.00
Waste water	Gallons/kg corn	0.372	$0.50	$0.19	$0.00	$0.01
Direct labor and benefits			($.032/gal)	$1.60	$0.03	$0.05
Maintenance and repairs			($.026/gal)	$1.30	$0.03	$0.06
General services and administration			($.06/gal)	$3.00	$0.06	$0.04
Total costs				$82.35	$1.65	$1.07

Sources: Urbanchuk(2007), data (*) for 2006; Shapouri et al (2006), data (**) for 2005.

The share of feedstock cost is high for other ethanol feedstocks and technologies as well (**fig. 2-1.**) For U.S. corn dry mills, over 50 percent of the total cost of ethanol production comes from feedstock, compared to 40 percent in wet corn mills (which benefit from many coproduct credits). The share of feedstock cost is even larger for other ethanol feedstocks such as U.S. sugarcane, sugarbeets, or molasses (Shapouri et al., 2006).

Given the large share of feedstock input in the cost structure of corn ethanol, it is not surprising that rising corn prices would also push up ethanol costs. Eidman (2007) reports that ethanol prices rise from $1.30 to $1.75 per gallon when corn prices increase from $2 to $4 per bushel (fig. **2-2**). Further corn price increases, say past $5 per bushel, push the ethanol price closer to current cost estimates for cellulosic ethanol. At this price, ethanol would be even less competitive with gasoline, while making it competitive to import Brazilian ethanol even with the tariff (Appendix B).

Figure 2-1
Comparing feedstock cost shares for different feedstock-conversions



Source: Shapouri et al. (2006).

Given the upward pressure on corn prices as a result of increasing ethanol demand, a key question is the break-even price for corn, beyond which corn ethanol becomes unprofitable (even with the current subsidy). Elobeid et al. (2006) calculated the break-even price for corn that an ethanol plant would be willing to pay farmers under specific assumptions on ethanol conversion, ethanol and DDG prices, and ethanol production costs.[1] In this case, ethanol prices are assumed to be $1.89 per gallon, including the $0.51 blenders' credit. The total revenue from a bushel of corn is calculated at $6.33 ($5.67 from the 3 gallons of ethanol[2] and $0.66 from the 7.73 kg of DDGs), and the total cost of processing the bushel is $2.28--$1.56 for variable costs and $0.72 for fixed costs. Fixed costs assume a plant valued at $80 million amortized over 10 years. Subtracting revenue from cost yields a break-even price of $4.05–the maximum price the ethanol plant is willing to pay for corn, while covering its fixed and variable costs (including a return on capital, management, and labor). This calculation suggests that there is a critical corn price beyond which future investments in corn ethanol plants would not be economically viable and that the continued upward pressure on corn prices may seriously impede further growth of the corn ethanol industry, assuming constant ethanol prices.

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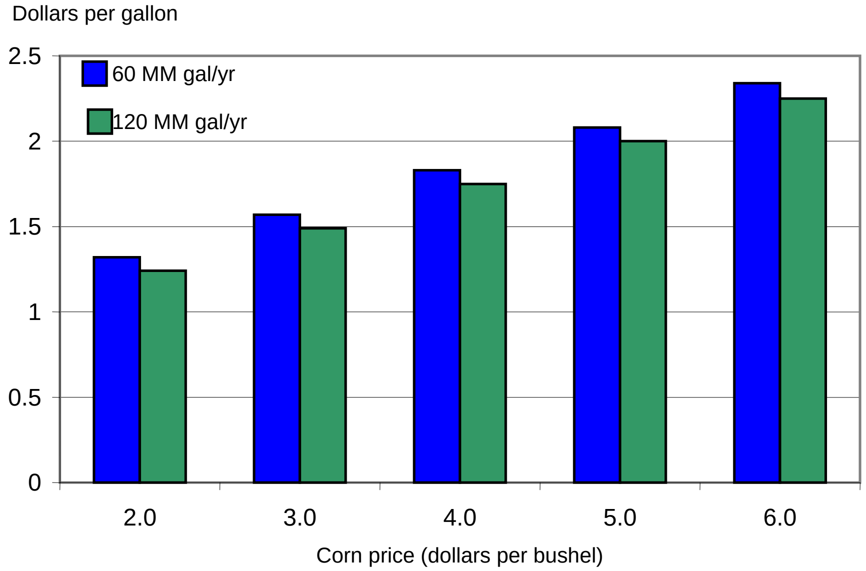
[1] These assumptions are (i) 131.9 gallons of ethanol per MT of corn and 7.73 kg of DDGS per bushel of corn; (ii) ethanol market price of $1.89 per gallon and DDG price of $70.57/MT; (iii) ethanol processing cost of $1.56 per bushel ($0.52 per gallon of ethanol) for variable costs and $0.72 per bushel ($0.24 per gallon of ethanol) for fixed costs.

[2] The 3-gallon-per-bushel conversion assumption is for an ethanol plant yet to be built and thus represents a future yield higher than current rates, which average 2.7 to 2.8 gallons per bushel.

Figure 2-2
Ethanol cost as a function of corn price



Source: Eidman (2007).

2.5 Sugar-Based Ethanol

Several crops and food byproducts can be used as feedstock for sugar-based ethanol production. The most common feedstock is sugarcane, but other common sugar-based feedstocks are beets and cane molasses (left-over concentration and precipitation of sugar from the juice.) Another feedstock is whey, an aqueous byproduct of cheese that contains lactose as its principal sugar. Sweet sorghum, which contains carbohydrates in fractions of both sugar and starch, may also be considered a sugar-based feedstock[3] (Wilkie et al., 2000).

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[3] Sugar fermentation into ethanol is a simpler process than starch-based fermentation, requiring four process steps as opposed to seven. These are milling, pressing, fermentation, and distillation (plus dehydration in the case of alcohol blends).

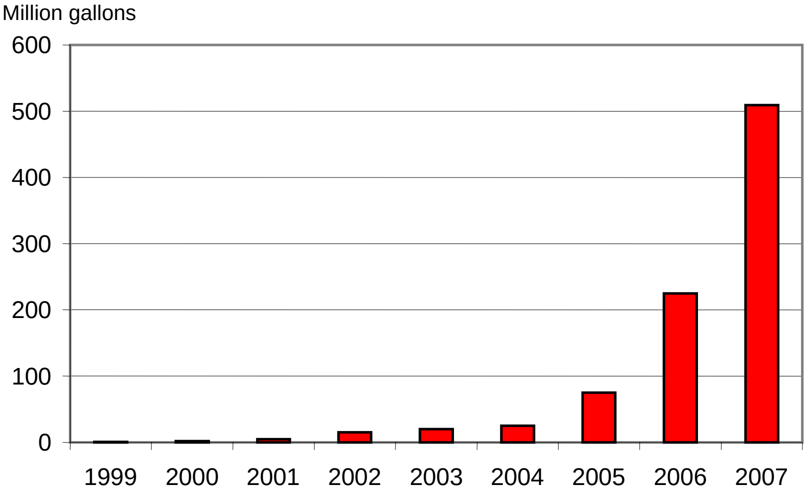
Chapter 3

Vegetable Oils and Fats for Biodiesel

3.1 Biodiesel Industry

Interest in biodiesel in the United States was given impetus by the Clean Air Act of 1990 and more recently by the Energy Act of 2005 and the Energy and Independence and Security Act of 2007. Biodiesel offers advantages over fossil-based diesel by reducing greenhouse gas emissions and various pollutants, such as particulates and sulfur. Production of biodiesel increased from less than 2 million gallons in 2000 to about 500 million gallons in 2007 (**fig. 3-1**). As of January 2008, the National Biodiesel Board reported 171 plants in operation, with potential production capacity of 2.24 billion gallons per year, far above current production levels.

Figure 3-1
U.S. biodiesel production, 1999-2007



Source: National Biodiesel Board (2007), FO Licht.

Table 3-1
Biodiesel production capacity and number of plants by State, January 2008

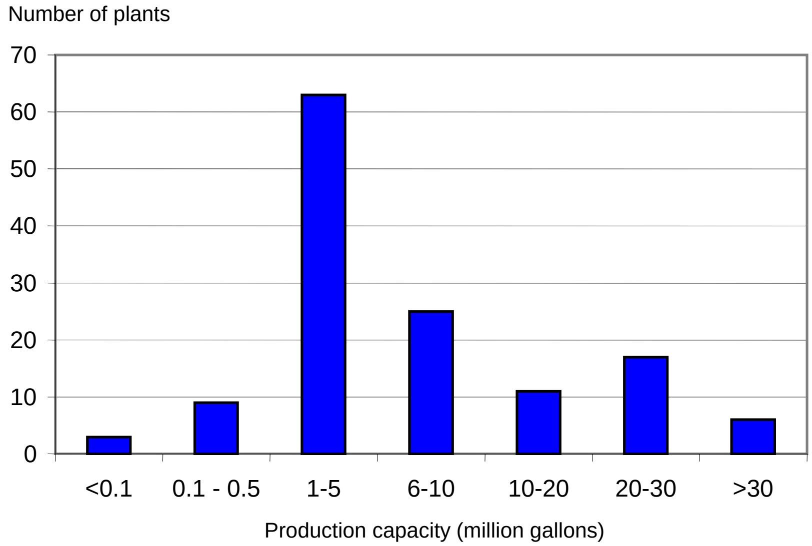
State	Number of plants	State capacity (Mil gallons)
Iowa	13	308.5
Texas	22	297.9
Washington	6	128.0
Missouri	8	122.9
Indiana	5	120.5
Mississippi	5	118.5
Tennessee	9	93.2
New Jersey	2	90.0
North Dakota	2	87.0
Illinois	4	86.0
Alabama	4	85.0
Georgia	8	78.5
Minnesota	4	63.2
Kentucky	3	56.8
Pennslyvania	7	56.5
Ohio	6	53.0
Florida	2	48.0
South Carolina	3	43.0
Michigan	3	35.0
Wisconsin	3	35.0
Arkansas	2	27.0
California	9	22.8
North Carolina	8	21.6
Virginia	4	18.6
Nebraska	3	15.5
Arizona	2	15.0
Louisiana	1	12.0
Idaho	1	10.0
Oklahoma	2	10.0
Nevada	2	9.0
South Dakota	1	7.0
Conneticut	2	5.0
Maryland	2	5.0
Utah	1	3.8
West Virginia	1	3.0
Rhode Island	2	2.8
Oregon	2	2.0
Hawaii	2	1.5
Kansas	3	1.0
Massachuesets	1	0.5
New Mexico	1	0.5
US total	171	2240.0

Source: National Biodiesel Board (www.biodiesel.org).

Note: Total annual capacity in the U.S. includes plants that did not list their capacity. Plant capacity is usually much greater than actual production.

Today, biodiesel production is predominantly oriented toward a local or regional market, with no dominant national producer. Scale varies widely from less than a million gallons to 100 million gallons per year, with most plants producing less than 30 million gallons (**fig. 3-2**).

Figure 3-2
U.S. biodiesel plant size, July 2007



Biodiesel facilities, which can use a wide range of plant and animal-based feedstocks, are dispersed geographically (**table 3-1**). Moreover, producers can extract the raw vegetable oil at one site and send it to a different location for processing.

Today, soybean oil is the most widely used biodiesel feedstock in the United States According to U.S. data on plant capacity and feedstock utilization as of January 2008 (National Biodiesel Board, 2008), soybean oil accounted for at least 40 percent of biodiesel feedstock. Since many plants report utilization of multiple feedstocks, the actual soybean oil share is likely much larger (**table 3-2**). Other vegetable oils made up much smaller shares. Canola accounted for about 5 percent and recycled and waste vegetable oil for less than 1 percent of feedstock that was explicitly reported.

To meet the demand generated by a nationwide B2 requirement (2-percent biodiesel blend with diesel fuel), approximately 2.8 million MT of soy oil would be needed—or about 30 percent of total U.S. production in 2007 (USDA-World Agricultural Outlook Board, 2008).[4] While soybean oil is the predominant biodiesel feedstock now, there are other options, including other vegetable oils and recycled cooking oil. Of the animal fats and greases used to produce biodiesel, yellow grease and trap grease are the most common. Yellow grease is recovered from used cooking oil from large-scale foodservice

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[4] One metric ton of soybeans yields 183 kg of crude soy oil and 798.5 kg of soybean meal.

operations. Renderers collect yellow and trap grease and remove the solids and water to meet industry standards. Yellow and trap grease are limited in supply, and they have other uses (**table 3-3**). For example, yellow grease is used in animal feed and to produce soaps and detergents.

Table 3-2
Biodiesel feedstock: number of plants, total capacity, and locations as of January 2008

Primary feedstock(s)	**Number of plants**	**Total capacity (million gallons)**	**States (number of plants)**
Multi-feedstock[1]	**83**	1132.75	AL (1), AZ (1), AR (2), CA (6), CN (1), FL (1), GA (3), HI (2), Il (1), IN (2), IA (4), KS (1), KY (1), MD (1), MI (3), MN (1), MS (4), MO (4), NV (2), NJ (2), NM (1), NC (6), OH (3), OK (1), OR (1), PA (2), SC (1), TN (4), TX (12), UT (1), VA (2), WA (6)
Soybean oil	**59**	896.05	AL (3), CN (1),GA (3), ID (1), IL (3), IN (3), IA (8), KY (2), LA (1), MD (1), MN (2), MO (4), NE (2), ND (1), OH (3), PA (5), RI (1), SC (2), SD (1), TN (5), TX(3), VA(1), WA (1), WV (1), WI(1)
Canola	**5**	91	KS (1), ND (1), OR (1), TX (2)
Yellow grease	**1**	18	FL (1)
Palm	**1**	15	TX (1)
Cottonseed	**1**	12	TX (1)
Recycled cooking/waste veg oil	**8**	10.85	CA(1), KS (1), MA (1), MN (1), RI (1), TX (2), WA (1)
Animal fat/tallow	**3**	7	NE (1), TX (1), GA (1)
Corn	**1**	2	IA

Source: Adapted from National Biodiesel Board.

[1] Multi-feedstock refers to the plant's capacity to process vegetable oils, animal fats, recycled cooking oil, or yellow grease.

Table 3-3
Rendered grease and fats

	2003	2004	2005
Production		1,000 metric tons	
Inedible tallow and grease	2,833.0	2,889.5	2,814.1
Inedible tallow	1,678.0	1,679.9	1,649.5
Yellow grease	586.7	690.9	605.7
Other grease	568.3	518.7	558.9
Edible tallow	892.2	824.6	789.6
Lard	113.6	118.8	119.6
Poultry fat	404.6	470.1	462.2
Total fat and grease	4,243.4	4,302.9	4,185.5
Consumption		1,000 metric tons	
Inedible tallow and grease	1,473.9	1,485.7	1,515.0
Edible tallow	201.1	182.0	198.1
Lard	122.2	121.4	105.7
Total consumption	1,797.2	1,789.0	1,818.8
Exports		1,000 metric tons	
Inedible tallow	705.4	733.5	649.7
Yellow grease	279.1	319.7	289.2
Other	122.6	70.9	53.0
Edible tallow	190.6	116.2	138.8
Lard	53.5	132.8	42.8
Total exports	1,351.3	1,373.0	1,173.6

Note: Data do not include imports.

Source: National Renderers Association.

Tallow is a byproduct of the meat production and processing sector. Most tallow (edible and inedible) in the United States is currently generated by the meatpacking, poultry, and edible/inedible rendering industries. Inedible tallow is most often used as a supplement for animal feed (majority of market share), followed by use in fatty acids, soap, and lubricants. National statistics show average production of 0.82–1.6 million MT of edible and inedible tallow, respectively, during 2000-03 (Nelson and Schrock, 2006). The average quantity of tallow (inedible plus edible) generated per head of cattle slaughtered has been estimated at 63 kg. Four-fifths of the Nation's tallow is produced in Kansas, Nebraska, Texas, Iowa, Colorado, Illinois, Wisconsin, California, and Minnesota.

3.2 Biodiesel Production Costs

Haas et al. (2006) estimate the capital and operating costs of a 10-million-gallon biodiesel facility that produces ester and glycerin. The glycerin is sold to industrial refiners. Estimated investment costs are $11.5 million, or $1.15 per gallon of annual capacity. Operating costs are estimated to be 27.1 cents per gallon and the capital costs, assuming a 10-year life and 15 percent rate of return on capital, are 22.9 cents per gallon. Sale of the coproduct, glycerin, at 33.0 cents per kg, provides a credit of 12.8 cents per gallon. With the plant operating at capacity, the estimated cost per gallon ranges from $1.48 if degummed soybean oil costs 33 cents per kg to $2.96 per gallon if it costs 77 cents per kg (current prices as of April 2008 are more than $1.20 per kg). The oil feedstock accounts for 88 percent of total estimated biodiesel production costs (Haas et al.). According to a recent report (IMF, 2007), total cost of production for U.S. biodiesel from soy oil is about $2.50 per gallon, about a dollar more than U.S. corn-based ethanol ($1.50 per gallon) but less than biodiesel from European rapeseed ($3.29 per gallon).

These estimates show that the costs of biodiesel production are relatively high, and that the feedstock share of the total cost of production is much higher than in the case of ethanol (**table 3-4**). Yet, despite these high relative costs, production has been expanding rapidly under the stimulus of several tax incentives. These include the volumetric "blender" tax credit, which provides $1.00 per gallon for biodiesel made from virgin oils and $0.50 per gallon for biodiesel made from non-virgin oil, such as yellow grease. The Small Agri-Biodiesel Producer Tax Credit is a volumetric-based income tax credit for the production of agri-biodiesel (biodiesel made from first-use vegetable oils and first-use animal fats). The Alternative Fuel Refueling Infrastructure Tax Credit applies to the installation of qualifying infrastructure that dispenses higher biodiesel content fuels, like B20 and higher (NBB, 2007). Another significant motivating factor for biodiesel expansion is the implementation of a rule requiring sulfur levels in diesel fuel to be reduced from 500 parts per million (ppm) to 15 ppm.

3.3 Demand for Biodiesel and Market Implications

The choice of feedstock for biodiesel production depends largely on the available supply and its price. Greater demand for vegetable oils has driven soybean oil prices higher and increased crushers' relative returns from oil versus meal. Demand for livestock feeds has also been strong, but profit margins across many livestock products are declining, and eventually will reduce the derived demand for feed. Distillers' dried grain with solubles (DDGS), a byproduct of corn ethanol production, competes with soybean meal as a protein-rich feed additive in dairy and beef rations and, in more limited amounts, in hog and poultry rations. Soybean crushing margins have risen sharply since mid-2006.

Table 3-4
Cost of production for biofuels from selected feedstocks

Biofuel/Country	Feedstock	Feedstock (percent of total)	Total production costs
		Percent	$ per gallon
Biodiesel			
United States	Soybean oil	80-85	2.50
Malaysia	Palm oil	80-85	2.04
EU	Rapeseed	80-85	3.29
India	*Jatropha*	80-85	1.99
Diesel			
United Staes	Diesel	75	1.50
Ethanol			
United States	Corn	39-50	1.50
United States	Cellulosic sources	90	2.69
Brazil	Sugarcane	37	0.98
EU	Wheat	68	2.23
EU	Sugar beets	34	2.88
Gasoline			
United States	Gasoline	73	1.29

Source: IMF (2007)

There is also concern about finding markets for a key biodiesel byproduct, glycerin. This problem may soon be resolved with new technologies. An alternative chemical process is being developed that would produce biodiesel without glycerin. Also, new processes are being tested that further transform glycerin into propylene glycol, which is used in the manufacture of antifreeze (Biodiesel Magazine, Feb. 2007).

Recycled fats and oils are less expensive feedstock than virgin oils (Schnepf, 2003), but the amount required to produce a gallon of biodiesel is slightly higher (3.5 kg versus with 3.4 kg). (Eidman, 2007a). Historic prices of yellow grease are about half of soybean oil prices (EIA, 2004), but yellow grease and grease have alternative uses in livestock feed and the production of soaps. There are also high costs associated with collecting and transporting yellow grease from dispersed sources (restaurants and other eating establishments) to a local biodiesel plant.

Although beef tallow may be available in significant quantities at relatively low cost, it has not historically been produced as a feedstock for biodiesel, but is available as a potential source (**table 3-3**). However, animal fats such as beef tallow are less uniform than processed vegetable oils and require more processing to produce a uniform biodiesel product. Considering price, uniformity of product, and supply, yellow grease and soybean oil are preferable for biodiesel production.

Nelson and Schrock (2006) investigated the resource availability, energetic efficiency, and economic feasibility of converting edible and inedible beef tallow into biodiesel. A resource assessment showed that an average of more than 1.8 million MT of edible and inedible tallow was generated each year over 1997-2001 in the 11 largest commercial cattle slaughtering States. If all such feedstock were used, this would generate more than 551 million gallons of biodiesel. The authors also estimated the biodiesel production cost of using beef tallow as a feedstock[5] and reported a range between $0.83 and $2.38 per gallon, depending on plant size, feedstock costs, and the size of the byproduct (glycerin) credit.

After a slow start, biodiesel production has taken off in the last couple of years under the twin stimuli of policy incentives and renewable fuels mandates, both at the Federal and State levels. While biodiesel production is relatively high cost compared with diesel, under a B2 national target the price relative to diesel would not be a significant factor, not having a significant impact on the product’s retail price. This would change, however, if the target were expanded to B5 or B10.

Even though biodiesel production can draw from several feedstocks, the prime feedstock used to date has been soybean oil. Meeting a B2 target with soy oil would require a substantial shift of current soybean production toward biodiesel, with significant implications for the soybean industry. Relative prices, technical constraints, and local availability are all factors likely to determine the composition of feedstocks used for biodiesel production.

While biodiesel offers environmental benefits, like biodegradability, improved air quality, and lower sulfur emissions, the impact on fossil energy displacement is likely to remain limited. Under a B2 regime, biodiesel would make up just 2 percent of total diesel consumed. While net CO_2 emissions may be lower with biodiesel, the process itself relies on natural gas and coal. However, second-generation biodiesel using gasification technology could open up new production possibilities for this fuel.

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[5] Minimum, average, and maximum tallow feedstock costs were obtained from a national source for 1997–2001 [*Chemical Marketing Reporter*, 2004]. These values ranged from 20.6 to 55.25 cents/kg over this time period.

Chapter 4

Agricultural Residues

4.1 Introduction

Agricultural crop residues are the biomass that remains in the field after the harvest of agricultural crops. The most common residues are corn stover (the stalks, ears, leaves, and/or cobs) and straw associated with wheat, rice, barley, or oats production. Because of their immediate availability, agricultural residues (along with forestry residues and urban waste) are expected to play an early role in the development of the cellulosic ethanol industry. Moreover, agricultural residues could also be used for power generation either through direct combustion, gasification, or co-firing with fossil fuels. **Table 4-1** gives examples of demonstration cellulosic ethanol plants under construction that plan to use agricultural residues as feedstock.

Table 4-1
Demonstration cellulosic plants using agricultural residues as feedstock

Company	Location	Feedstock	Capacity (gallons/day)	Year of operation
Pilot plants				
Iogen	Ottawa, Canada	Wheat straw	301.0	1993
NREL/DOE	Golden, CO	Corn stover, others	301.0	2001
Pearson Technologies	Aberdeen, MS	Wood residues, rice straw	9,030.1	2001
PureVision	Ft. Lupton, CO	Corn stover, bagasse	30.1	2004
Sicco A/S	Odense, Denmark	Wheat straw	802.7	2005
Abengoa Bioenergy	York, NE	Corn stover*	1,524.9	2006
Demonstration plants				
Iogen	Ottawa, Canada	Wheat, oat, and barley straw	2,261.6	2004
Celunol	Jennings, LA	Bagasse, rice hulls*	3,769.3	2007
Near-term commercial plants				
Abengoa Bioenergy & SunOpta	Babilafuente, Spain	Wheat straw*	3,769.3	2007
Iogen	Shelley, ID	Wheat, barley and rice straw	82,924.3	2008
Colusa Biomass Energy	Colusa, CA	Rice straw and hulls, corn stover	28,646.6	2007

Source: Ethanol Producer Magazine, various issues.
* Co-located with grain ethanol plant and assuming 350 days plant operation.

The eight leading U.S. crops produce more than 500 million tons of residues each year, half of which is corn stover. Only a fraction of those residues will be available for use in fuel or energy production because of equipment constraints and soil erosion concerns (i.e. some residue must be left on the field to sustain fertility and limit erosion). In addition to major residue producing crops like corn and wheat, crops such as rice and sugarcane, which face residue disposal issues, might also contribute significant quantities of biomass in some areas (DiPardo, 2000; Wilhelm et al., 2004).

While the collection of residues, particularly corn stover, is feasible once a market exists, new infrastructure for the collection and processing of biomass crops will need to be built. An important consideration in using agricultural residues as biomass is the sustainability of their removal and its compatibility with long run preservation of soil quality and conservation imperatives.

4.2 Potential Availability Versus Sustainable Recovery

Agricultural residues are important in maintaining and improving soil tilth, protecting the soil surface from water and wind erosion, and helping to maintain nutrient levels. Soil erosion is an extremely important national issue. Most, if not all, agricultural cropland in the United States experiences some degree of soil erosion each year due to rainfall and/or wind. The amount of soil erosion is a function of many factors, including field operations (field preparation, tillage, etc.) and climate (rainfall, wind, temperature, etc.). USDA's Natural Resources Conservation Service (NRCS) has established tolerable soil loss limits (T values) for all soil types in all U.S. counties.[6]

Collection and removal of agricultural residues must take into account concerns about the potential for increased erosion, reduced crop productivity, and depletion of soil carbon and nutrients. However, in certain areas of the United States and depending on tillage practices (particularly under various mulch (reduced) tillage and no-till), it is possible to remove a portion of the residues so long as soil erosion does not exceed tolerable soil loss limits (the T value, as defined in footnote 6). The NRCS has advised that any corn and/or wheat residue removal be confined to soils with a land capability classification between I-IV and all subclasses.

Larson et al. (2005) investigated crop residue removal and its effect on soil erosion in the Corn Belt, the Great Plains, and the Southeast. Crops included corn, grain sorghum, wheat, soybeans, and cotton. The study investigated the effect of tillage practices (conventional, conservation, and no-till) and residue management with respect to rainfall and wind erosion, runoff, and potential nutrient removal. The study concluded that limitations exist with respect to crop residue removal and that the potential for safe residue removal is highly dependent on cropping practices and management. Mann et al. (2002) concluded that before specific recommendations could be made, more information was needed on the long-term effects of residue harvest on water quality, soil biota, transformations of different forms of soil organic carbon (SOC), and subsoil SOC dynamics.

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[6] The tolerable soil loss value denotes the maximum rate of soil erosion that can occur for a particular soil type without leading to prolonged soil deterioration and/or loss of productivity. The NRCS also implemented a land capability classification (LCC) applied to all soils within a county and ranging from I (one) to VIII (eight). Class I soils have no significant limitations that restrict their use for raising crops, and are generally flat and unlikely to erode. Classes II and III are suited for crop production but have some limitations such as poor drainage, climatic restrictions, or the potential to erode. Soils with a class IV designation have moderate limitations and have restrictions placed on the type of cropping practices that may be applied to them. Classes V– VII soils are generally best suited to pasture and range, while class VIII soils are best confined to wildlife, recreation, and other nonagricultural uses.

Current USDA/NRCS standards for residue management recommend following the guidelines in a decision model for agricultural residue removal rates known as RUSLE2 (USDA-NRCS, 2006). The factors that influence the amount of stover (and likely other residues) that can be removed include climatic (precipitation, temperature), soil, management (tillage practices), and type of crop rotation used. RUSLE2 can also be combined with other decision tools such as WEQ and the Soil Conditioning Index (SCI) to provide more complete and practical ways to predict removal rates that keep soil loss below the T value.

4.3 Estimating Sustainable Removal Rates for Agricultural Residues

Estimating the potential quantity of available crop residues for use as biomass requires that soil conservation constraints be factored in. Nelson (2002) estimated the amount of corn and wheat straw residue available for harvest from all category I-IV soils in 37 States in the East and Midwest. To accomplish this, the author estimated the crop yield required at the time of harvest to ensure that the tolerable soil loss limit (T) not be exceeded for each county using NRCS databases and applying either RUSLE (wind erosion) or WEQ (water erosion) decision models, depending on whether wind or water erosion posed the greatest risk of soil loss.

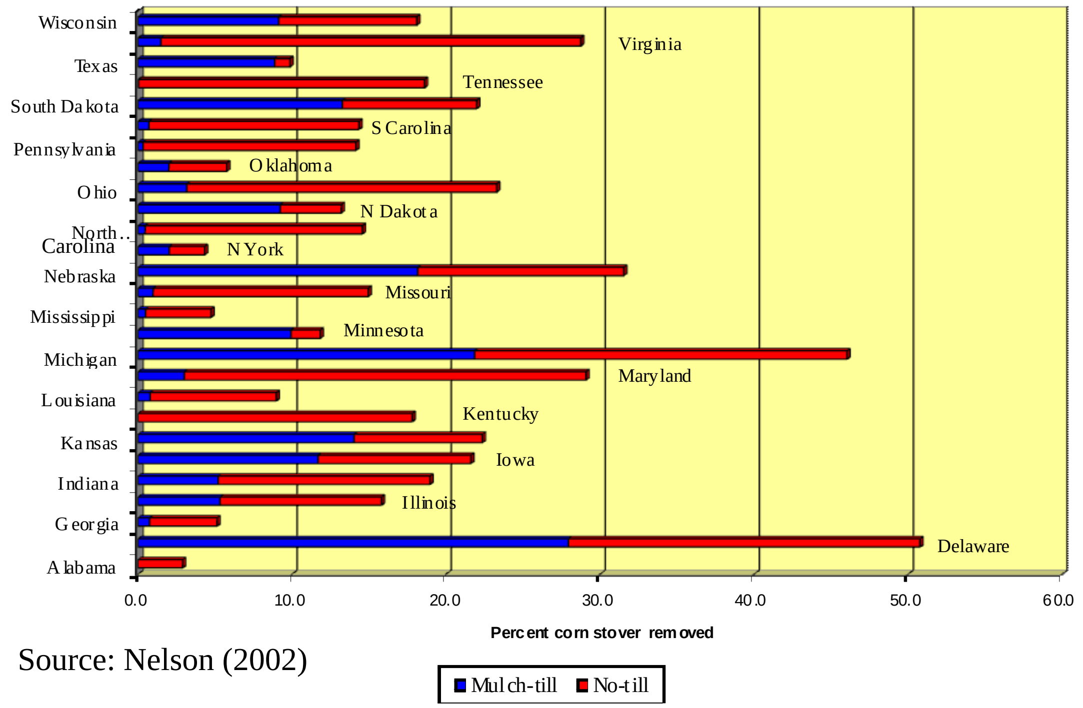
Nelson concluded that 42 million metric tons of corn stover (primarily in NE, IA, IL, IN, and KS) could be safely harvested (with soil loss below the T value). Also, the removable rate (share of removal to total crop residue) varied significantly among States, reflecting the local soil and erosion conditions as well as tillage practices (f**ig. 4-1**). There was also tremendous variability in the amounts of removable residue during the 3-year period. Kansas experienced an increase of almost 80 percent in removable corn stover between 1995 and 1996, and over 116 percent between 1995 and 1997. This and other increases (decreases) in removable residue in other States can be attributed to an increase (decrease) in the number of mulch-till and/or no-till hectares and crop yields between 1995 and 1997, as well as weather conditions.

For wheat straw, following the same methodology as for corn stover, the analysis showed that more than 8 million MT of residues (in KS, TX, OH, IL, and MO) were available for removal each year, from 1995 to 1997 without exceeding the T value. Results indicate significant winter wheat straw residue in Kansas, Texas, Ohio, Illinois, and Missouri. Nearly one-half of the removable spring wheat straw was in North Dakota.

This study represented an important first step toward recommending residue removal rates. Further work could extend the analysis to include the removal effect on soil carbon and nutrients. Graham et al. (2007) estimated the amount and location of removable corn stover available for cellulosic ethanol in the U.S. using existing commercial equipment. While erosion constraints were factored in explicitly (i.e. not exceeding the T value), other factors such as crop productivity and soil nutrient constraints were treated indirectly (for example, by including the cost of fertilizer required to replace the removed nutrients). In this study, with an annual production of 196 million dry MT of corn grain (9.2 billion bushels) and an equivalent amount in total stover production (using 1:1 stover-to-grain ratio), less than 30 percent of this stover (58 million MT) could be harvested under current rotation and tillage practices at a farmgate price for corn stover under $33/MT.

Moreover, this 28-percent national average is subject to considerable uncertainty because of variation in the stover harvest index and the need to keep more corn stover in the soil to maintain or enhance soil organic matter and tilth. The estimated removable portion of corn stover production could be considerably lower if more stringent soil loss constraints are applied. On the other hand, if farmers chose to convert universally to no-till corn management and total stover production did not change, the removable portion of corn stover would increase substantially.[7] (Under no-till, more stover can be removed and still remain below the T value.) However, even if all acreage were under no-till (an unlikely scenario), nearly 50 percent of stover would remain uncollectible because of constraints imposed by erosion requirements, moisture constraints, and equipment collection efficiency. Since sustainably collectible stover does not necessarily overlap with the millions of hectares NRCS classified as highly erodible land (HEL)[8] (Heimlich, 2003), much of this HEL would be excluded from corn stover removal, even with no-till management.

Figure 4-1
Estimated share of corn stover safely removable by State, 1995-1997



Source: Nelson (2002)

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[7] Conventional tilling involves aggressive mechanical turnover of the soil that leads to high rates of soil organic matter loss and erosion by wind and rain. No-till leaves the soil undisturbed, providing protection from erosion and loss of soil organic carbon to the atmosphere.

[8] HEL is defined as land where the erosion potential is at least eight times its T value.

Nonetheless, Graham et al. show that sufficient corn stover could be sustainably collected (based on meeting T values) in many parts of the Midwest to support the development of stover-based biorefineries. High corn stover concentrations exist in central Illinois, northern Iowa/southern Minnesota, and along the Platte River in Nebraska. Each of these regions would generate enough corn stover to support biorefineries handling up to 1 million metric tons per year of biomass feedstock.

4.4 Production and Procurement Costs

Few studies have estimated the costs of procurement and delivery of agricultural residues to biorefineries. Perlack and Turhollow (2003) used an engineering approach to estimate the costs for collecting, handling, and hauling corn stover to ethanol conversion facility (ranging from 454.5 to 3,636.4 dry MT/day) using conventional baling equipment. Estimated costs range from $42.74 to $47.10/dry MT, with the cost difference between facility sizes due to transportation distance (**table 4-2)**. Transportation, collection/baling, and farmer payments account for over 90 percent of total delivered costs**.** These estimates are based on average per-acre corn stover availability assumptions (grain yield and resulting total stover yield, fraction of total stover harvestable, fraction of corn stover acreage contracted to harvest and fraction inaccessible or uncollected due to factors such as weather, and the effect of corn production density on transport and costs). If stover is more widely available, costs can be lowered by $6.6–$11/dry MT.

Table 4-2
Delivered cost for baled and unprocessed corn stover

	Facility size - dry ton/day			
	500	1,000	2,000	4,000
	$/dry ton			
Large round bales				
Delivered cost in storage	$23.68	$23.94	$24.29	$24.80
Transport costs	$7.02	$7.71	$8.68	$10.06
Farmer payments	$10.00	$10.00	$10.00	$10.00
Operation expenses (5%)	$2.04	$2.08	$2.15	$2.24
Total delivered at conversion facility	$42.74	$43.73	$45.12	$47.10
Unprocessed pickup - average				
Delivered cost in storage	$17.92	$20.53	$22.12	$24.24
Transport costs[1]	$4.23	$4.93	$5.92	$7.32
Farmer payments[2]	$10.00	$10.00	$10.00	$10.00
Operation expenses (5%)	$1.61	$1.77	$1.91	$2.08
Total delivered at conversion facility	$33.75	$37.22	$39.94	$43.46

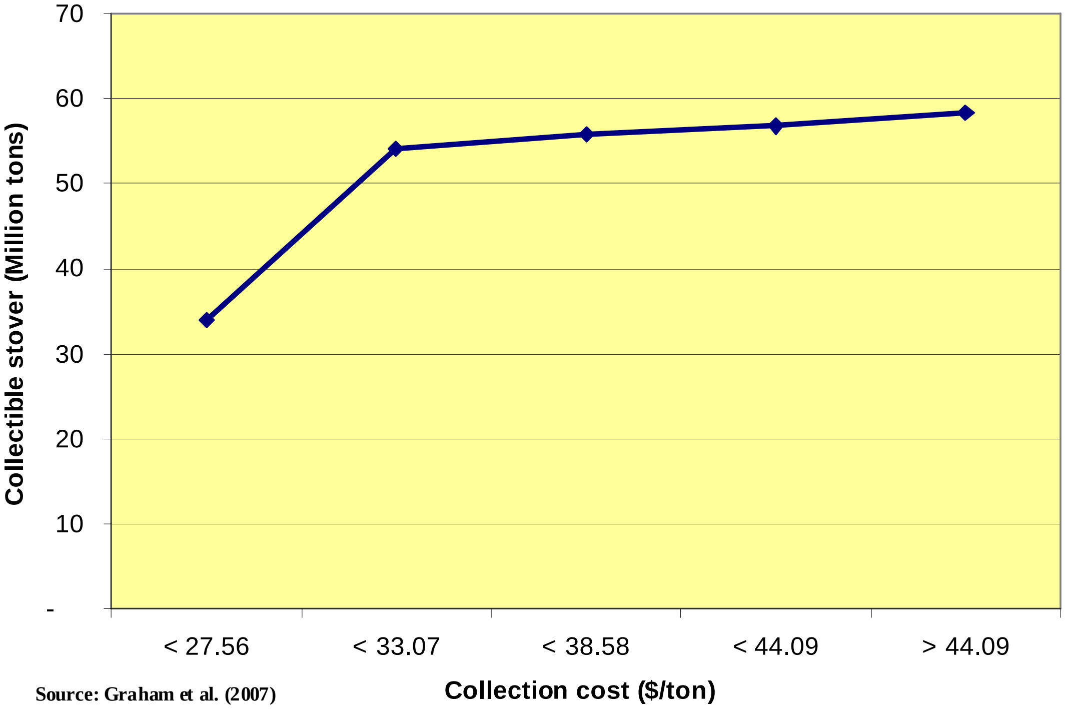
Source: Perlack and Turhollow (2003).

1 Trucks and flatbed trailers to move stover from storage to conversion facility.

2 Farm payments to cover nutrients removed from the field plus soil compaction, and diminished soil organic matter.

Graham et al. (2007) also used an engineering approach to estimate the production and delivery cost of corn stover to the field edge (farmgate price), in 2002 dollars. These costs include the value of the stover and the equipment and labor costs for collecting it in mesh-wrapped large round bales and transporting them to the field's edge. Collection costs were estimated for a range of stover collection quantities and a regression equation related collection costs with amount of stover collected (f**ig. 4-2**). Nearly all the collectible stover (93 percent) came from land where at least 2 metric tons of stover could be collected per hectare and collection costs were less than $33/MT. More than half the supply of harvestable stover was from fields where 4 metric tons or more per hectare could be collected at a cost of less than $27.56/MT.

Figure 4-2
Collectible corn stover by collection cost, 2002



Source: Graham et al. (2007)

A 2001 analysis on wheat straw showed that the average price for delivering straw to a hypothetical 20-million-gallon-per-year cellulosic ethanol plant increases from $35.2/MT (with 3 MT per hectare of wheat straw required to remain in the field) to $59.4/MT (with 5 MT per hectare to remain in the field) as the straw availability decreases (Kerstetter and Lyons, 2001).

The potential use of rice straw as feedstock was examined in a California study focusing on the region around Colusa, where approximately 200,000 hectares of rice are grown annually. This production yields approximately 6.7 dry tons/ha of straw, for a total of nearly 1.4 million dry tons of rice straw annually (Kadam et al., 2000).

In California, open-field burning of rice straw is being phased out because of resulting air pollution, and rice growers and government agencies are looking for new rice straw uses. Gainfully using this residue can ease the disposal problem facing agricultural operations in the State. The amount of rice straw that may be available as a feedstock ranges from 1.0 to 1.4 million tons per year. The only method commonly used to harvest and handle rice straw is baling, and even this has been on a limited basis because of lack of demand for the straw.

Kadam et al. (2000) sought to ascertain whether enough rice straw could be supplied to an ethanol plant using 550 dry tons per day (producing over 14 mgpy of ethanol). The analysis found that 550 tons/day of straw can be accessed in the Sacramento Valley area at an estimated net delivered cost of less than $20/dry MT (**table 4-3**). This includes in-field costs of $22/dry MT, a transport cost to the ethanol facility of $7/dry MT, and a disposal credit of $11/dry MT. In this case, the $11/ MT payment made by farmers for rice straw removal is applied as a credit in the cost calculation (whereas farmers are paid a "stumpage" fee to allow a portion of crop residue to be removed).

Table 4-3
Cost estimates for delivering rice straw to a user facility, California

Operation	$/ton (dry)
Swathing, raking, baling, roadsiding, and loading from fields	21.54
Hauling to facility	7.13
Total FOB facility, as-is basis	28.73
Total FOB facility, net basis[1]	17.73

Source: Kadam et al. (2000)

[1] Cost includes $11.00/dry ton credit from farmers for off-field use.

4.5 Energy and Carbon Balances: Life-Cycle Analyses

Cellulosic ethanol has the potential to displace gasoline and to help lower greenhouse gas emissions and air pollution, both reasons given for promoting its production. The only life-cycle analyses (LCA) on U.S. biofuels from agricultural residues are on corn stover. Sheehan et al. (2004) carried out a LCA for corn stover ethanol (for E85 fuel) in Iowa (including onfarm production, transport of the stover to the biofuel plant, conversion to ethanol, distribution of the final product, and use in a flexible fuel vehicle). They found that, per km, ethanol (as E85) from corn stover saves 80 percent of nonrenewable energy consumption compared with gasoline use while ethanol (as E85) from corn grain saved only 32 percent of nonrenewable energy consumption. Use of corn stover ethanol also reduces greenhouse gas emissions (fossil CO_2 and soil carbon impacts, N_2O, CH_4) by 106 percent. However, impacts on air quality are mixed, with emissions of CO, NO*x*, and SO*x* increasing and hydrocarbon (HC) decreasing.[9]

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[9] NOx and HC are ozone precursors.

Kim et al. (2005) constructed a LCA comparing ethanol from corn grain (wet milling), corn stover, and switchgrass in Fulton County, Illinois. The authors calculated the net energy value (NEV) for each system, defined as the energy content of ethanol minus nonrenewable energy consumed in the overall production system. They also added an energy credit from nonrenewable energy saved from alternative product systems that are displaced by the coproducts (mostly electricity) under the cellulosic ethanol process. The authors found the NEV for corn grain ethanol to be much lower (15.1 million joules (MJ)/gallon of ethanol) than for corn stover (138.9 MJ/gallon) and switchgrass (194.0 MJ/gallon), largely due to the energy credits from coproducing electricity with cellulosic ethanol. The study also found that crude oil displacement amounted to 0.619 gallon per gallon of ethanol for corn grain, 0.622 gallon for corn stover, and 0.729 gallon for switchgrass. Based on the 100-year global warming potential, using corn stover-derived ethanol as E10 fuel would reduce greenhouse gas emissions by 13.4 percent, while using corn grain-derived ethanol results in no change in greenhouse gas emissions compared to gasoline.

In summary, the literature review suggests that corn stover could be one major feedstock source for biorefineries. Overall, soil conservation constraints require that 30 percent or less of corn stover produced can be safely removed given current practices. This rate could be lower if constraints other than soil erosion are taken into account.

Estimated production and delivery costs of corn stover may not seem prohibitive. However, inclusion of delivery over long distances could make the total cost too high. And there is still a need to build the infrastructure and logistics required to transport large quantities of crop residues to cellulosic ethanol and biopower plants. Finally, while life cycle analyses show that net energy value, displacement of fossil energy, and reductions in greenhouse gas emissions are positive and much improved for agricultural residues compared with corn grain ethanol, increased emissions of some gases (like nitrous oxide) remain a concern.

Chapter 5

Forest Biomass

5.1 Introduction

The United States is endowed with vast amounts of forest resources that are increasing faster than forest removal rates. Moreover, large quantities of renewable woody biomass are available for bioenergy applications. Today, the largest source of biomass used for heat and power generation comes from forest sources used in the pulp and paper industry. Future cellulosic ethanol or thermochemical biofuels industries could also tap into woody biomass (Perlack et al., 2005). Research efforts are underway to develop biomaterials and biofuels from woody biomass. An economically viable and sustainable use of forest biomass feedstock for biofuels, biopower, and biomaterials faces technical and economic challenges (U.S. DOE, 2008; Zerbe, 2006). Still, using forest biomass for bioenergy has many environmental benefits.

One of the major sources of woody biomass is *logging residues*. The U.S. timber industry harvests over 272.5 million metric tons (mt) (roundwood equivalent) a year and leaves behind substantial amounts of nonmarketable woods and residues that could be used as biomass (Perlack et al., 2005). However, not all logging residues are recoverable because of their low bulk density and energy content. The economics of hauling logging residues over a long distance to an electricity generation facility or cellulosic ethanol plant may be prohibitive. Moreover, recovery of logging residues may be limited by constraints such as the need to maintain long-term soil/site productivity or competing uses for other wood products.

Another potential source of forest biomass could be from forest fuel treatments or thinning to prevent wildfires. This is particularly true in the Western U.S. where logging residues are restricted because of the prevalence of public lands. However, here too there are major economic and technical hurtles owing to the high and variable costs of wood recovery, long distances to end-use markets, site accessibility, lack of a qualified labor force, low value added from removed materials, and non-adapted harvest and collection machinery.

5.2 Logging Residues: Estimates of Recoverability

There are two sources of logging residues: growing stock, which is the main stem of marketable trees; and other sources, which include nonmarketable trees and tops/branches of marketable trees (USDA-FS, 2004). In addition, there is wood material from “other removals” from cultural operations or timberland clearing – not commercial timber harvesting. Reliable information on logging residues and primary wood products industry residues (pulp mills and sawmills) is either directly available from USDA Forest Service statistics or can be readily derived from them. According to the Forest Service's Forest Inventory and Analysis (FIA) data, logging residues left at harvest sites in 1997 totaled 19.9 million MT from growing stock and 51.7 million MT from both growing stock and other sources (Smith et al., 2001b).

Despite the potential significance of logging residues, literature dealing with the amount of recoverable logging residues is limited. Gan and Smith (2006) conducted a technical and economic feasibility assessment of wood energy production from forest residues based on 1997 Forest Inventory Analysis (FIA) data and the recovery restriction imposed by distribution density of residue. If logging residues are low density, a large forest area is required to meet the fuel needs of a given power plant and thus high delivery costs may prohibit the recovery of logging residues. Even if the minimum spatial density requirement is met, some logging residues cannot be recovered due to accessibility constraints and loss during procurement. To account for these constraints, the authors imposed a minimum spatial density and assumed that only 70 percent of the residues that meet the requirement can be recovered.

The estimates were made at the State level and were limited to logging residues (i.e., no biomass from forest fuel treatments, commercial and noncommercial thinning, or urban forests/mill residues). The analysis further assumed the energy content of logging residues to be 21.1 gigajoule (GJ)/dry MT and the energy efficiency of the power plant to be 35 percent (according to major timber-producing regions, including the Southeast, South Central, and Northeast).[10]

Assuming a 70-percent residue recovery rate and a minimum viable plant size of 10 megawatt (MW), the authors estimate that recoverable logging residues from U.S. growing stock is 13.9 million MT annually. When residues from both growing stock and other sources are added together, recoverable logging residues would reach 36.2 million MT.

Another concern in bioenergy development is ensuring a sustainable supply of logging residues in the long run. Gan and Smith also projected future availability of logging residues as a function of timber harvests and the ratio of logging residues to timber harvested. Timber harvests are influenced by forest inventory, market conditions, and environmental regulations. With increased demand (and higher prices) for wood products and improved timber harvesting and wood product-processing technologies, the ratio of logging residues to timber harvests is expected to decline as more of the tree is used for manufacturing traditional forest products.

The recoverable residues from both growing stock and other sources could generate 67.5 tetrawatt hours (thousand billion watt hours) of electricity annually. This would displace 16 million MT of carbon emitted from coal-fueled power plants (about 3 percent of total

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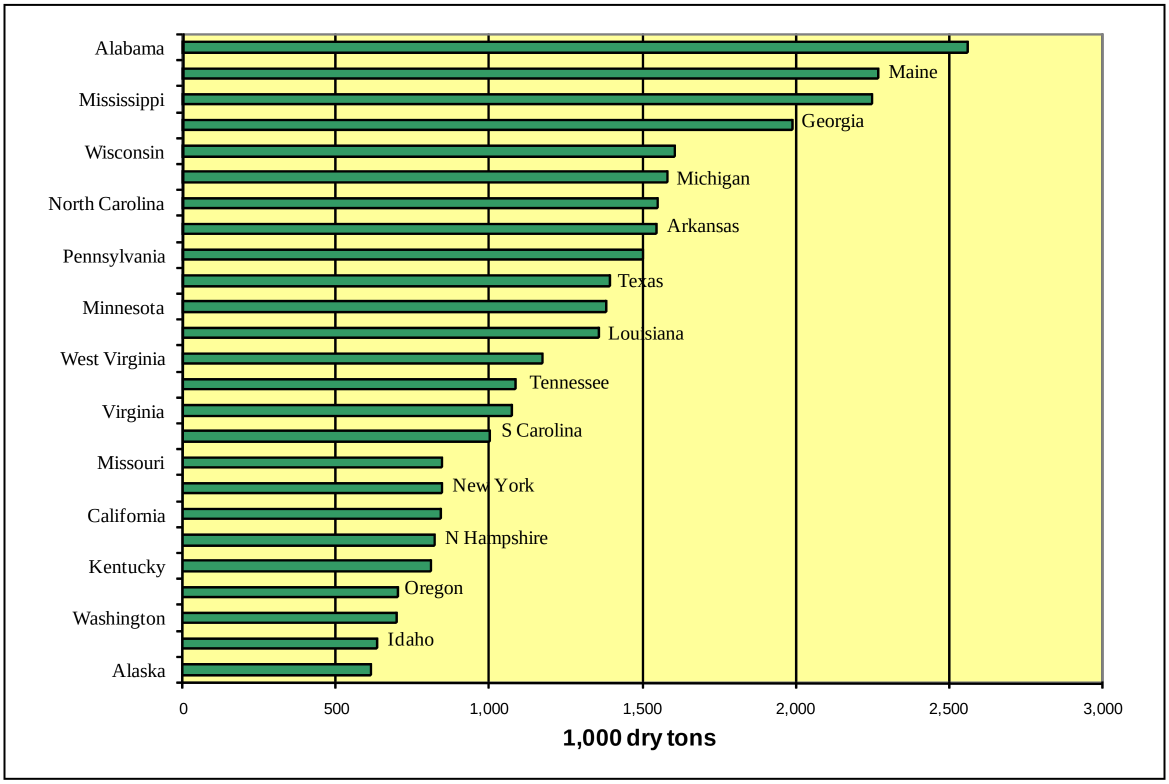
[10] The amount of utilizable energy in the form of electricity amounts to 35 percent of the energy embedded in the biomass input (as typically measured by low heat value (LHV) or high heat value (HHV) measures). When woody biomass is used in combined heat and power (CHP) facilities, the generated energy efficiency is typically higher than power-alone facilities.

carbon emissions from the U.S. electricity sector in 1997) at a cost of $66-$88/MT of carbon (Gan and Smith, 2006).

5.3 Logging Residues: Regional Distribution

There is even less literature dealing with the geographic distribution of recoverable logging residues, and studies of their potential for bioenergy, biopower production, and carbon displacement are rare. Using the assumptions of a 70% recovery rate and a minimum viable plant size of 10MW, Gan and Smith (2006) find that most residues are in the eastern U.S., with the Southeast and South Central accounting for approximately two-thirds of the national total from growing stock and about half from both growing stock and other sources. Their analysis shows that Georgia, Alabama, and Mississippi are the top three States for logging residues from growing stock. As these States have become increasingly important in U.S. timber production (partially as a result of harvest restrictions on public lands), the availability of logging residues in the Southeast and South Central could increase in the foreseeable future.

Figure 5-1
Estimated recoverable logging residues by State, 1997



Source: Gan and Smith (2006)

The distribution density of logging residues from other sources in the Northeast and North Central is relatively high. When residues from both growing stock and other sources are combined, the share of logging residues by the Northeast and North Central increased considerably. Alabama, Mississippi, Maine, and Georgia led the Nation in terms of logging residues from growing stock and other sources (fig. 5.1).

In the Western U.S., the top States for forest biomass are California, Oregon, Washington, Idaho, and Alaska. However, the availability of residue supply in these States is uncertain as timber harvests on public lands have been substantially reduced over the last decade (Smith et al., 2004).

5.4 Logging Residues: Delivery Costs and Supply Economics

The economic viability of biomass from logging residues hinges on the costs of harvest, transport and overall procurement, yet few estimates of such costs exist. Puttock (1995) estimated the procurement cost of logging residues based on an *integrated harvesting system*, which simultaneously procures both conventional timber products and logging residues. According to Puttock, the common elements of an integrated harvesting system are felling and primary extraction of the whole trees. The equipment system in Puttock's analysis consists of a feller-buncher/grapple to skid whole trees to a landing, a flail processor at the landing, and a tub-grinder for residue collection.[11]

Puttock estimated both the marginal and full costs of procuring logging residues. The full cost reflected total production/harvesting costs of logging residues, including their share of conventional logging costs and new costs incurred in their procurement. The marginal cost included only the additional costs from logging residue procurement. No stumpage value was included. According to this analysis, the marginal cost of procuring fuel wood from logging residues is $0.26/GJ, and the full cost is about $0.54/GJ. Adding the delivery cost, the total cost of delivered biomass produced from logging residues reached $0.69/GJ (marginal cost) and $0.97/GJ (full cost).

Gan and Smith (2006) used Puttock's estimates for marginal and full procurement costs, and added a delivery/transportation cost of 8.5 cents/ton/km[12] and handling/loading/ unloading costs of $20/ton. Assuming a 45-percent moisture content for green logging residues, they estimated the total cost for an average transport distance of 100 km to be $6.30 per million watt-hour (MWh) (marginal cost) and $7.30/MWh (full cost).

Based on these estimates, Gan and Smith derived a supply curve for logging residues. For a power plant capacity of 25 million watts (MW), the fuel cost (the cost of logging residue procurement, processing, and delivery) would increase gradually with the amount of logging residues as more is procured from greater distances. Almost all the recoverable logging residues (about 98 percent) could be supplied at a cost of less than $7/MWh. The analysis also showed that biomass from logging residues was more cost effective than

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[11] Descriptions of a variety of equipment and systems can be found at http://www.srs.fs.usda.gov/pubs/biomass_cd/

[12] The authors applied a formula developed at the University of Tennessee, Knoxville, showing that the transportation cost for wood residues is $35/truckload + ($1.25/km).

energy from short-rotation woody crops (Sedjo, 1997; Tharakan et al., 2005; Elliott, 2005). However, using the cost assumptions in the analysis, biomass from logging residues could compete only with coal under the provision of a carbon credit (or imposition of an emission tax at around \$25/Mg CO_2).

5.5 Fuel Treatment Residues: Potential Availability

Biomass from fuel treatments and thinning is another major source of forest residues that could be recovered in significant quantities. While logging residues in Western States may be constrained by a downward trend in harvesting on public lands, forest fuel treatments or thinnings could become a major source of biomass in this part of the country.

Fuel treatment residues are the byproduct of efforts to reduce the risk of wildfires and associated losses, and therefore present substantially different challenges than logging residues, which are closely tied to timber production. Over 1998-2007, Federal agencies have spent more than \$12.1 billion fighting forest fires, which have consumed over 22.3 million hectares. The Healthy Forest Restoration Act (HFRA) of 2003 was enacted to encourage the removal of hazardous fuels and promote use of the resulting material.

USDA’s Forest Service has identified timberland and forestland near people and infrastructure where tree volumes exceed prescribed or recommended stocking densities and require treatment or thinning to reduce fire risks. Using a modeling tool called the Fuel Treatment Evaluator, the Forest Service estimated that there are about 6.3 billion dry MT of treatable biomass on U.S. timberland and another 524 million dry MT of treatable biomass on other forestland (USDA Forest Service, 2005).

Large areas of forest in the West are severely overstocked with small-diameter trees, and as such pose extreme risk for catastrophic wildfires. For the 15 Western States, treatment opportunities exist on three-quarters of the timberland base (59.1 million hectares), providing a potential yield of 2.1 billion dry MT biomass from a standing inventory of almost 5.8 billion dry MT under the default silvicultural prescription (Miles, 2004).

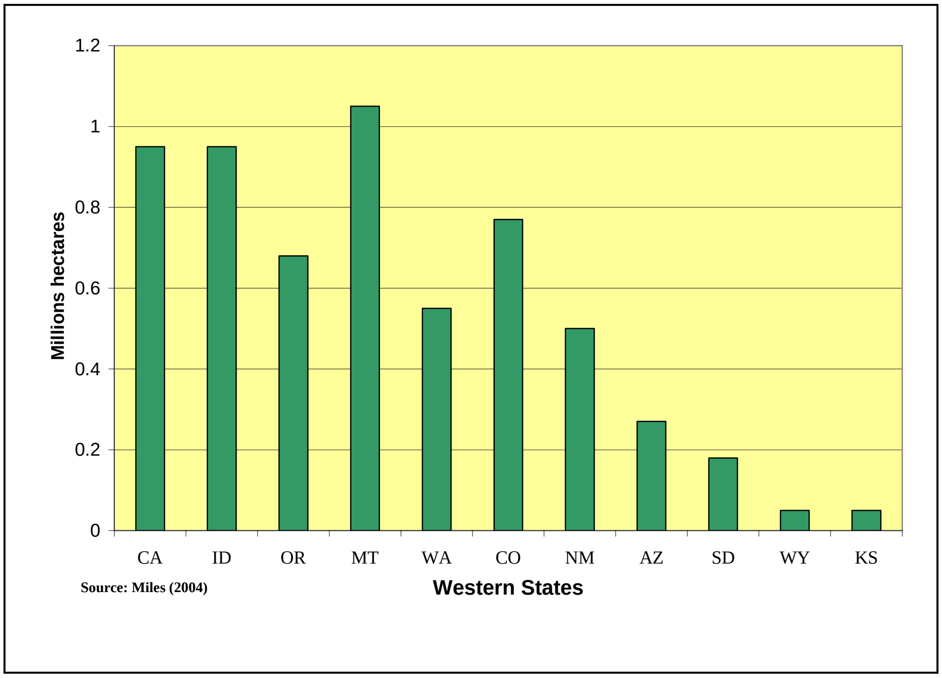
Removal of these trees, or forest ‘‘thinning,’’ can help mitigate wildfire risk, and represents a potential source of biofuels. For example, California has 72.1 million dry MT of fuel treatment residue spread over 950,000 hectares (fig. 5-2). Montana, by comparison, has 37.6 million MT available, but spread over a larger base of 1.04 million hectares. Accessibility—in terms of topography and distance from processing facilities—is another consideration.

5.6 Estimating Recoverable Fuel Treatment Residues

The Forest Service (2005) found at least 27.1 million hectares of forest in the 15 Western States that could benefit from treatment to reduce hazardous fuel loading. About 60 percent of this area could be operationally accessible for treatment, with recoverable biomass of 313 million bone-dry metric tons (MT). Two-thirds of this forest area is on public lands.

Most of the volume is in trees 6 inches or more in diameter that can be used conventionally.

Figure 5-2
Prime target States for fuel reduction treatment, 2004



Source: Miles (2004)

Treatable areas were further classified by Fire Regime Condition Class (FRCC)—a measure of how much a forest has departed from natural wildland fire conditions (Schmidt et al., 2002). Overlaying the FRCC map and focusing only on areas that would require mechanical fuel reduction before fire can be used as a management tool (Condition Class 3) demarcates those areas in greatest need of fuel reduction treatment with potential for the greatest biomass yields (Schmidt et al., 2002). These hot spots encompass 11.5 million hectares of timberland with a potential yield of 524 million dry MT. Of these, 6.9 million hectares of timberland are considered to be the highest-priority hot spots, with a potential yield of about 312 million dry MT over 30 years, or 10.4 million dry MT annually. About 60 percent of the highest-priority hot spots are on National Forest lands.

Ecological objectives are important factors in justifying or estimating biomass from fire hazard reduction thinnings. Skog et al. (2006) applied ecological and sustainability criteria in estimating potential biomass from reduction thinnings by first screening forest area to identify high-hazard acres and then applying alternate treatments to meet fire hazard reduction targets. The authors estimated between 153.6 and 581.8 million oven-dry MT (odt) of biomass which, if removed by treating 230,000 hectares per year, would yield up to 13 million MT per year.

5.7 Fuel Treatment Residues: Economic and Technical Constraints

The most direct approach to forest thinning is mechanical, wherein brush and small-diameter trees are physically removed. This treatment results in a forest with fuel loadings more consistent with periodic, low-intensity burns and stand-replacing wildfires.

The economic feasibility of producing biofuels and bioenergy with thinnings from overstocked forests has not been fully examined. Bioenergy options are economically preferable to landfill or open burning of thinned biomass; however, revenue from biofuels will not cover the cost of thinning. While the overall value of forest thinning benefits is generally believed to exceed the cost of thinning, reduced fire hazard may not be directly monetized to pay for thinning treatments. Also, forests thinned are often distant from end-use markets, resulting in high transportation costs to make use of the harvested material. One tool being used by Federal land managers is “stewardship contracting” where the value of material removed can help offset treatment costs in a goods-for-services contract. The revenues do not necessarily cover the costs, but total costs can be reduced when the contracts are longer term (up to 10 years) and the continuity of supply attracts business investment that uses (and finds value) in the small-diameter materials and residues.[13]

Road or trail access, steep terrain and sensitive sites commonly limit thinning operations in Western forests. While access and slope do not preclude fuel reduction treatments (treating biomass on site may still be feasible with limited road access), they significantly reduce economically viable opportunities for product recovery.

Transportation costs are also a significant factor in the cost of recovering biomass for ethanol and bioenergy production. As much as half the cost of the material delivered to a manufacturing facility may be attributed to transportation. Recent studies have cited haul rates from 22 to 66 cents per bone-dry MT (bdt) per mile, depending on truck configuration, travel speeds, and payload. Hauling costs determine the economically viable distance between the forest treatment site and a processing facility (Rummer et al., 2005). Assuming chip values of $33/MT delivered to the mill and chip transport costs of $0.38/MT per mile, the maximum distance that chips can be transported without additional subsidies is 86 miles. At this distance, the chip value just covers the transport cost, and no fuel treatment costs are recovered. Operations to recover products are not efficient when using equipment designed for handling conventionally merchantable wood. This makes small-diameter treatments less cost-effective and highlights the need for development of better systems. Equipment designed for treating small material (mulching machines, purpose-built small-diameter harvesters, and other technologies) needs additional evaluation on costs, performance, and compatibility with fuel reduction objectives.
Gross operational costs to cut and move fuel-reduction biomass to the roadside can range from $30 to over $117 per dry ton, depending on type of operation, terrain, and number of trees to be treated (USDA Forest Service, 2005; Skog et al., 2006). Some areas will likely be prohibitively expensive to treat, although cost estimates presented here may be high because they are based on the use of conventional timber harvesting systems applied to

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[13] From Marcia Patton-Mallory, USDA-FS (personal communication)

small-diameter treatments. Significant fuel reduction effort will generate large volumes of biomass and require additional workforce and operations capacity in Western forests.

The vast majority of trees targeted for thinning are less than 25 centimeter (cm) in diameter, and over 2 billion trees are in the 5-cm diameter class (USDA Forest Service 2005). While 86 percent of the trees that would be cut are less than 25 cm, most of the volume that would be treated comes from the 14 percent of trees that are larger. The ability to separate and market larger diameter logs for higher value products is critical to determining the net revenues or costs of fuel treatment operations. If the opportunity is lacking, revenues from thinning would not cover costs.

Polagye et al. (2007) examined the economics of forest thinning in Washington State. In the study area, the average yield of nonmarketable biomass is an estimated 30.1 wet MT/ha. This is based on thinning an at-risk forested area of 10.1 million hectares, yielding 67,000 MT of biomass (30 percent, by weight, nonmarketable). The cost to cut and skid this material back to the logging deck is forecast at $0.99-$12.1/MT. Thinning costs have a significantly higher range ($86-$2,470/ha) due to terrain features and stand density.

5.8 Forest Residue Thinning: Densification Option

Technical constraints facing a meaningful recovery of thinnings from overstocked forests may be overcome by biomass densification. Options for using unmerchantable forest thinnings as a feedstock include production of wood pellets[14] or bio-oil (via pyrolysis).[15]

Polagye at al. (2007) examined densification in the context of accomplishing both forest wildfire reduction and the generation of energy using a single integrated pathway. The authors considered a number of energy uses for thinnings, including co-fire of wood chips with coal, steam-cycle cogeneration, and production of wood pellets or bio-oil. Sale of chips for pulp and disposal of thinnings were modeled as non-energy options. The effects of both thinning operation scale and duration were considered, as well as transportation distance to end-use markets. For example, conversion of thinnings to a high-density biofuel incurs a significant production cost, but decreases downstream transportation costs.

The study quantified the economic effects of thinning scale, thinning duration, and distance to end-use markets. Transportation costs help determine where a high-density biofuel should be produced. If biofuel is produced at the logging deck, transportation costs will be minimized. However, production facilities at logging decks would have low throughputs and high unit production costs compared with a large, centralized facility. For transportation distances from the logging deck to an end-user of less than about 250 miles, co-fire is the preferred option for moderate to large-scale thinning operations. Beyond 250 miles, pelletization or fast pyrolysis become increasingly cost competitive.

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[14] Wood pellets are produced by extruding ground wood through a mechanical die at high pressure.

[15] The U.S. Forest Service as reported by Rummer, is researching balers as a lower cost process for densifying logging residues.

Polagye et al. (2007) also found that pelletization is cost competitive with co-fire for low to moderate yield and duration. This is unsurprising since pelletization is less capital intensive than other biofuel production options, and therefore less dependent on achieving economies of scale. Pelletization also is the most technically mature biofuel production option and could be readily deployed in the immediate term.

Bio-oil is produced via fast pyrolysis, which uses debarked wood chips as an input[16] Fast pyrolysis can compete with co-fire for moderate to large yields. Fast pyrolysis becomes significantly more competitive with larger feedstock sizes, highlighting the benefit of developing densification processes that do not require energy-intensive pretreatment of feedstock.

Overall, densification has clear benefits over long transportation distances, and is most viable when the feedstock requires only limited pretreatment. Given the low energy density of raw biomass, long-distance transport to end-use markets is economically inefficient, resulting in “stranded” biomass resources that stay potentially available but unused.

In summary, this review suggests that there are substantial amounts of forest residues available for biomass in several U.S. regions, especially the South and South Central. However, except for the pulp and paper industry’s long history of using wood fuel for internal energy generation, the economics of forest residue recovery are still not competitive for biomass under current market conditions and available collection/transportation technologies.

As biomass markets develop, the use of forest residues in biopower or biofuel plants will likely depend on local conditions and will likely be influenced by the availability of other biomass resources in the region. Viable sourcing of forest residues for biopower hinges on favorable price competitiveness with coal fuel. Other factors, such as accounting for social and environmental benefits (carbon credits), could improve forestry biomass competitiveness. Also, advances in thermochemical conversion efficiency and successful development of small-scale conversion facilities using gasification and/or pyrolysis may promote the use of forest residues for biofuel production, including onsite densification.

Forest biomass resources from fuel treatments or forest thinnings to protect against wildfire in the West, still face considerable economic, technical, and resource constraints. These make it difficult to predict how much forest biomass is actually recoverable. Further advances in harvesting, hauling, and processing machinery and more creative approaches to marketing the harvested woody materials are key to making this biomass resource viable in the future.

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[16] Fast pyrolysis is the rapid heating of biomass in the absence of oxygen, which decomposes the biomass to char, light gases, and vapor phase-oxygenated hydrocarbons and water. Char and light gas are separated and usually burned for process heat. The condensed mixture of oxygenated hydrocarbons and water is termed bio-oil.

Chapter 6

Urban Woody Waste and Secondary Mill Residues

6.1 Introduction

U.S. urban wood waste and secondary mill residues represent a possible substitute for fossil fuels, whether in generation of electricity, co-fired fuel in coal- or natural gas-fired power plants, or in future cellulosic ethanol plants. Other urban waste resources like organic materials in landfills can also serve as biomass feedstock for cellulosic ethanol or as sources of methane gas that can be used to produce renewable electricity. Secondary mill residues are made up of sawdust, shavings, turnings, and trims that are byproducts of the manufacture of wood products. They are covered in this chapter together with urban wood waste because many assessments of these urban-based resources include both categories.

In developing biomass and bioenergy markets, urban wood wastes and secondary mill residues could provide significant supplementary low-cost biomass resources procured locally. In some cases (e.g., organic matter in landfills), these sources could even be free. However, despite many assessments of urban woody resources, there is still a lack of reliable data on delivered prices for many urban wood resources; issues of quality and usability as an input for bioenergy; and little understanding of potential competition with captive markets that currently use these urban woody products.

6.2 Urban Wood Waste

Urban wood wastes are used in a variety of ways, with much variation among cities (Wiltsee, 1998). Most commonly, these wastes are ground into mulch for land application, dumped into landfills, or incinerated along with municipal solid waste (MSW) or construction and demolition (C/D) debris (table 6-1). The diversion of urban wood waste from these uses into bioenergy uses could generate significant amounts of biopower and biofuels.

Urban wood waste encompasses a variety of wood resources such as wood-based municipal solid waste (MSW), wooden pallets, and wood debris from construction and demolition. Urban waste also includes right-of-way clearings, tree trimmings, and other land clearing. In some areas, these can be huge amounts and are often banned from landfills, or charged a substantial fee for disposal. Unlike feedstock from forest logging and the primary wood products industry, for which data are regularly collected by USDA's Forest Service, no data are collected at a national or Federal level for urban wood waste. Information comes from surveys and assessments that often cover only a portion of the total urban waste stream.

Table 6-1
Primary uses and disposal methods for urban wood wastes

	Urban wood waste (Wiltsee, 1998)	**Secondary mill residues (Rooney, 1998)**
	------------ Percent	**--------------------**
Mulch	39	4
Landfill or incineration	33	17
Biomass fuel, sold or given away	12	17
Firewood, fuel used onsite	7	21
Furnish, logs, pulp chips	5	2.8
Animal bedding	1	26.2
Other	2	2

6.3 Secondary Mill Residues

Rooney (1998) estimated state-level quantities of secondary mill residues using 1992 U.S. Bureau of Census data on secondary mills and relying on a Minnesota wood waste study for mill generation factors.[17] In his analysis, Rooney distinguished between hardwood and softwood residues and separated "unused" residues from those used by noncaptive markets. The author estimated that about 48 percent of generated secondary mill residues are used onsite or sold as fuel, 26.2 percent are used as animal bedding, and 17.2 percent are disposed of in landfills or as solid waste. Less than 7 percent is used for mulching, pulp and paper, or for engineered wood products (**table 6-1**).

Haase et al. (1995) estimated wood waste residues for Indiana, and distinguished between the usable and unusable components of residues. The authors argued that among primary and secondary residues, recycled materials and wood pallets are most usable since they are generated by processes that preserve uniform physical and chemical characteristics for fuel use. With a moisture content of 35 percent, fuel from these residues is ideal for co-firing. However, competing uses for these residues include mulch, animal bedding, and compost.

Milbrandt (2005) estimated secondary mill residues using county-level data by correlating residues with the number of wood-generating businesses and number of employees and using assumptions on the wood waste generated by one company as derived from Wiltsee's (1998) study. Seven States generate more than 100,000 tons of wood waste per year, led by California, Texas, and Pennsylvania (table 6-2).

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[17] *Minnesota Wood Waste Study*: *One Man's Waste is Another Man's Gold,* published by the Minnesota Department of Natural Resources in 1994.

Table 6-2
Estimated mill residue and wood waste resources, by State, 2002

State	Secondary mill residues	Urban wood waste
	--------------- (1,000 tons/year)	------------------
Alabama	57	483
Alaska	2	65
Arizona	41	526
Arkansas	32	314
California	247	3,901
Colorado	41	451
Connecticut	24	376
Delaware	8	85
District of Columbia	0	56
Florida	130	1,678
Georgia	97	924
Hawaii	10	133
Idaho	20	129
Illinois	96	1,337
Indiana	71	715
Iowa	29	320
Kansas	19	332
Kentucky	52	454
Louisiana	33	474
Maine	15	133
Maryland	33	624
Massachusetts	52	687
Michigan	86	1,196
Minnesota	59	496
Mississippi	33	307
Missouri	69	613
Montana	13	106
Nebraska	13	189
Nevada	17	232
New Hampshire	18	126
New Jersey	58	894
New Mexico	9	191
New York	119	2,041
North Carolina	115	833
North Dakota	7	67
Ohio	124	1,272
Oklahoma	23	377
Oregon	86	382
Pennsylvania	127	1,238
Rhode Island	6	109
South Carolina	38	467
South Dakota	7	75
Tennessee	75	614
Texas	148	2,307
Utah	18	228
Vermont	9	65
Virginia	62	813
Washington	85	675
West Virginia	15	184
Wisconsin	69	548
Wyoming	4	59
U.S.total	**2,615**	**30,902**

Source: Milbrandt (2005).

So far, all these studies estimate quantities generated, shares used by various market outlets, and some qualitative assessment of how much of available quantities is usable for bioenergy. What is missing in these assessments are full-cost analyses and delivery price estimates for bioenergy markets to determine if they could compete with noncaptive markets.

6.4 Municipal Solid Waste

Municipal solid waste (MSW) is generally divided into wood waste and yard waste. Yard waste is recognized as the larger component of MSW. The first national assessment of yard waste was carried out by NEOS Corporation (1994) in a study to quantify "urban tree and landscape residue" (UTR) generated in the contiguous 48 States. The components of UTR estimated include wood (chips, logs, tops and brush, mixed wood, whole stumps), leaves collected during seasonal leaf collection, and grass clippings. Data from telephone and mail surveys of UTR generators throughout the U.S. were extrapolated to estimate national UTR quantities. The assessment concludes that just over 200 million cubic yards of UTRs were generated in the U.S. in 1994, with 88 percent potentially available for fuel use (t**able 6-3**).

Franklin Associates, cited in Fehrs (1999), use manufacturing data for durable and non-durable goods and attempt to quantify only the MSW portion of the total solid waste stream (leaving out industrial process wastes, hazardous wastes, etc.). MSW is characterized as durable goods, nondurable goods, containers and packaging, food wastes, and yard trimmings, as generated by residential, commercial, institutional, and industrial (packaging and administrative, but not process waste) sources. This analysis concludes that in 1997, total MSW generated in the U.S. was just under 190.9 million MT, of which wood waste accounted for 5.2 percent (just under 10 million MT) and yard waste 13.4 percent (25.4 million MT). Of the wood waste, only 4.5 percent (or 445,454.5 MT) was recovered or recycled in some way, while the remaining 9.5 million MT was disposed of. Of the estimated yard waste generated, the portion recovered or recycled was 38.6 percent (just under 10 million MT).

Table 6-3
Estimated urban tree residue wood waste generation, 1994

	Amount	
Urban tree residue type	**Amount all UTRs** (Million MT)	**UTR wood waste** (Million MT)
Chips	53.38	53.38
Unchipped logs	11.95	11.95
Unchipped tops and brush	6.37	6.37
Unchipped mixed wood	4.78	4.78
Fall leaves	1.59	0.00
Grass clippings	1.59	0.00
Whole stumps	0.80	0.80
Total	80.46	77.28

Source: NEOS Corporation (1994).

According to U.S. EPA (2006), 223.4 million MT of MSW were generated in the U.S. in 2005. Of 12.6 million MT of wood waste generated, only 9.4 percent or 1.19 million MT was recovered. Of 29.2 million MT yard waste generated, about 61.9 percent (18.1 million MT) was recovered. A quick comparison with the Franklin Associates assessment shows that EPA numbers are slightly higher and that share of recovered material has increased for both wood waste and yard waste. The increase in recovered material is likely due to emerging markets, new uses, and technology developments.

6.5 Construction and Demolition Woody Resources

Few wood waste assessments include construction and demolition wood residue. McKeever (1998, 2004) estimated wood waste generation and availability for use as fuel in the U.S. The assessment focused on three sources of wood waste: (i) municipal solid waste (MSW), including the wood waste components of MSW as well as woody yard trimmings; (ii) construction and demolition (C&D) activities; and (iii) the primary wood products industry, including bark and wood residues. The author uses MSW data published by Franklin Associates, but excludes pallets that were repaired, refurbished, or recycled (citing an estimated 4.8 million MT of used pallets that were repaired or recycled in 1998). Also, McKeever excludes land clearing debris since this material is typically not managed as MSW, is not included as a type of construction wood waste, and is clearly not a demolition wood waste or primary mill residue. Also excluded are secondary wood products industry (“secondary mill”) residues.

McKeever’s estimates show yard waste to be the largest woody component of MSW, comprising about 12 percent of total MSW generation. Estimates of wood waste generated by construction, repair, or remodeling of residential and nonresidential buildings are based on construction activities as well as the wood products used in the construction. Overall MSW wood waste for 1998 was an estimated 4.9 million MT, or 45.8 percent of total wood waste; woody yard trimmings totaled 6.2 million MT, or 27 percent; and building-related construction wood waste was 7.9 million MT, of which 6.1 million MT was available for recovery.

Milbrandt (2005) also reported county and State estimates of urban wood residues. The urban wood waste covered includes MSW (wood chips, pallets, and yard waste), utility tree trimming, and/or private tree companies, and construction/demolition wood. MSW wood and yard waste was determined based on per capita MSW data from *BioCycle Journal*, county population data, and assumptions from Wiltsee to estimate total MSW generated by county. Estimates for utility tree trimming and/or private tree companies were derived from data on forestry support activities and electric power distribution by county, while construction and demolition wood was estimated based on population. Close to 31 million MT of urban wood waste was produced in 2002 according to this study (table 6-2).

In addition to urban wood waste found in MSW, MSW also contains a significant fraction of biogenic and nonbiogenic carbon resources that have the potential to be made into energy products. In 2006, EPA estimated that 12.5 percent of MSW disposed in the U.S.

was recovered for the production of energy using incineration.[18] Today, the energy content of most waste materials is not used for energy production. The production and disposal of waste is expected to increase over time[19], making MSW one of the largest recurring biomass energy resources available in the U.S., one that is already captured and managed in discrete locations across the Nation.

Franklin Associates applied the same methodology used for the MSW study to estimate construction and demolition (C/D) wood waste at 123.6 million MT in 1996. The study did not include land clearing debris, and separate estimates have shown this to represent 7-20 percent of total C/D residues.

Haase et al. (1995) reported that urban tree residues, construction, and demolition waste accounted for 55 percent of total wood residue resources in Indiana in 1992. However, these materials are not recommended for combustion in biopower plants because of the irregular particle sizes and dimensions, a high moisture content (50 percent or higher), and foreign materials mixed in with the wood. The supply of these fuels is also affected by season, housing starts, and demolition activity.

6.6 Urban Wood Residues: Quantities and Prices (Supply Curves)

No single assessment covers all types of secondary mill residues and urban wood waste. With few exceptions (Rooney, 1998; Antares, 1999), none of the assessments estimate the prices at which wood waste will be available for energy use.

Wiltsee (1998) included prices in his analysis and generated “supply curves”[20] for 3 urban wood waste categories in 30 randomly selected U.S. metropolitan areas (as defined by the U.S. Office of Management and Budget). The three categories are wood waste in municipal solid waste, industrial wood waste, and construction/demolition wood waste. Estimated quantities combined with price/cost information were used to create supply curves for each metropolitan area as well as total area. A predictive equation estimated urban wood resources in 281 metropolitan areas and projected the total urban wood waste resources to be slightly over 58.2 million MT per year, of which 95 percent, or 55.3 million tons, is available for free or at negative cost. The remaining 5 percent is available at a price ranging from $3.30 to $26.40/MT.

Antares Group (1999) developed supply curves for seven types of wood waste that are considered to be available or “not currently destined for other productive uses.” These were forest wood residues, bark residues from primary mills, wood residues from primary mills, construction wood waste, demolition wood waste, woody yard trimmings, and other wood waste (pallets, shipping containers, secondary wood products industry wood residues, industrial wood waste, and wood in MSW). The supply curves were constructed by State based on available wood waste quantities and projections of the “delivered residue cost”

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[18] http://www.epa.gov/epaoswer/non-hw/muncpl/pubs/msw06.pdf

[19] http://www.epa.gov/reg3wcmd/solidwastesummary.htm#trends

[20] These “supply curves” do not represent urban wood waste availability (for fuel or other uses) because they lack processing and transportation costs.

(DRC), calculated as the sum of disposal (in landfills), collection/processing, and transportation costs. The authors obtained collection/processing costs for the seven types of wood waste from several published sources and used the average value to calculate DRC. For each State, a total of 28 data points (7 wood waste types and 4 transportation distances of 25, 50, 75 and 100 miles) were calculated and used to plot the supply curve. The data used to create the state supply curves were aggregated to create a national and several regional supply curves.[21]

Antares concluded that just over 100.9 million green MT of all types of wood residues and wastes are available annually in the U.S. (i.e., "not currently destined for other productive uses"). Of this total quantity:

1) 34 percent, or about 34.5 million MT/year, are low-cost residues (< $1/million Btu) consisting of construction wood waste, demolition wood waste, yard waste, and other waste wood;
2) 6 percent, or about 6.4 million MT/year, are medium-cost residues ($1-$2.50/million Btu) consisting of primary mill residues and bark;
3) 60 percent, or about 60.9 million MT/year, are high-cost residues ($2.50- $5/million Btu) consisting of forestry residuals.

Fehrs (1999) estimated national wood waste generation as a sum of individual types of secondary mill residues and national urban wood waste estimates. The author distinguished between total generated waste and that which was potentially available for fuel or other uses, assuming that for each unit of wood waste, a portion is contaminated and commingled with other products (and hence not available). For example, secondary mill residues or urban tree wastes were not commingled, and hence potentially available. By contrast, construction and demolition waste, as well as MSW, were in part commingled and hence partially unavailable. The author also assumed that wood residues or wastes currently used by "high-value" markets such as pulp, saw timber, or engineered wood products, are all considered *not available* for use as fuel. Hence, the amount potentially available for fuel is the total amount of a wood residue or waste generated less the amounts commingled, contaminated, or used in high-value markets.

The amount of wood waste generated is estimated to be over 124.1 million MT/year, of which 64 percent is potentially available for fuel or other lower value uses (table 6-2). At a price of up to $11/MT, it is estimated that just under 17.52 million MT are available. At a price of up to $22, an estimated 49.37 million MT are available. At a delivered price of $0 - $11/MT, woodfuel is considered to be competitive with fossil fuels, in particular with coal. At about 46.78 million MT/year, urban tree residues are the largest source of available wood waste (**table 6-4**).

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[21] Fehrs (1999) concluded that supply curve derivations in this study suffered from two limitations. First, the Antares study omitted secondary mill residues; second, the assessment implicitly assumed that "energy production uses will not compete for materials already used productively." The latter assumption means that a great amount of potentially low-cost woodfuel is not addressed. If and when woodfuel markets expand, wood waste could be diverted from low-value markets (such as landfill cover, compost amendment, and mulch) to fuel markets.

In summary, these assessments indicate the potential quantities available for use as fuel, though they often cover only a subset of urban wood waste streams. Within a developing biomass market, urban wood wastes and secondary mill residues could provide significant supplementary low-cost biomass to local bioenergy facilities. In some cases (e.g., organic matter in landfills), these feedstock resources could even be free. At the same time, the widespread distribution of wood wastes makes collection expensive and limits it practically to areas with high wood waste concentration.

A common weakness of the reviewed analyses is their lack (with few exceptions) of estimates on delivered prices for many urban wood resources; issues of quality and usability of urban wood waste as inputs for bioenergy; and little understanding of potential competition with alternative or captive markets that currently use these urban woody products. Another consideration in the economics of urban wood waste is residual management, particularly ash that is subject to solid waste regulation. Such additional information will be critical in better assessing the extent to which these urban wood waste streams could supply biomass feedstock markets.

Table 6-4
National wood residue and waste quantities, 1999

	Wood waste total generation	Available @ up to $11/MT	Available @ up to $22/MT	Available @ above $22/MT
			Million MT/year	
Secondary mill	14.22	1.22	3.44	5.55
Construction	15.21	2.54	7.17	11.56
Demolition	24.00	1.58	4.46	7.20
Municipal solid waste	10.73	1.82	5.12	8.26
Yard trimmings	5.73	1.09	3.07	4.95
Urban tree residues	46.78	9.06	25.52	41.16
Used pallets	5.95	0.21	0.59	0.95
Railroad ties	1.53	n/a	n/a	n/a
Land clearing	n/a	n/a	n/a	n/a
Used utility poles	n/a	n/a	n/a	n/a
Total	**<124.14**	**<17.52**	**<49.37**	**<79.63**

Source: Fehrs (1999).
n/a = not available

Chapter 7

Energy Crops: Herbaceous (Grassy) Feedstocks

7.1 Advantages of Herbaceous (Grassy) Crops for Energy

In the long run, a viable option for large-scale biofuels production is the cultivation of dedicated energy crops. A steady supply of uniform and consistent-quality feedstock is critical for the economic viability of cellulosic ethanol production. The development of herbaceous (grassy) energy crops such as switchgrass and other grassy species, like *Miscanthus*, reed canary grass, alfalfa and other forages, may require large-scale changes in the agricultural system, principally because these perennial crops are likely to affect rotation patterns and the makeup of U.S. crop production.

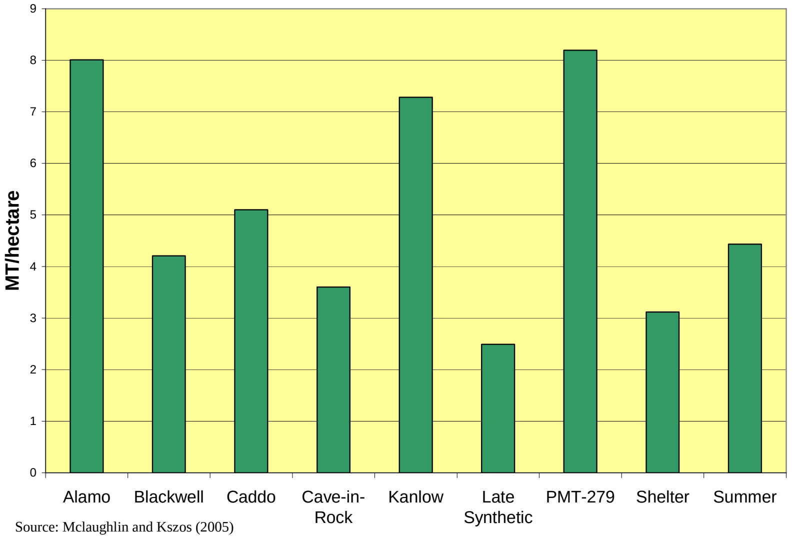
In the early 1990s, the U.S. Department of Energy (DOE) identified switchgrass (*Panicum virgatum*) as the model herbaceous energy crop for North America, with the Agricultural Research Service, USDA, assuming a central research role in 2002. Switchgrass was selected for a variety of reason, including “high productivity across many environments…[and] suitability for marginal lands” (Sanderson et al., 2006). Switchgrass is native to North America and occurs widely in grasslands and nonforested areas. Switchgrass has been seeded in pasture and range grass mixtures in the Great Plains over the past 50 years, and has become increasingly important as pasture grass in the central and eastern U.S. because of its ability to be productive during the hot summer months, when cool-season grasses are less productive (McLaughlin and Kszos, 2005). Also, switchgrass does well on a wide variety of soil types, and the plant can reach 3 meters in height and 3.5 meters in root depth. Once established, it is drought tolerant and grows well on shallow rocky soils.

7.2 Switchgrass Biomass Breeding Programs

Breeding work on switchgrass first began in the Great Plains in 1930 (McLaughlin and Kszos, 2005). From 1992 through 2002, the DOE through the Biomass Feedstock Development Program (BFDP), funded a series of field test trials for switchgrass across a network of research stations covering the mid-Atlantic (VA, WV), Southeast (TN, KY, NC, GR, AL), South Central (TX, AR, LA), North Central (ND, SD), and Central (IO) regions. Yields of nine switchgrass cultivars were evaluated, and several high yielding varieties were identified (**fig. 7-1 and table 7-1)**. The lowland varieties “Alamo” and “Kanlow” stood out at Southern and Mid-Atlantic sites, while the “Cave-in-Rock” upland variety performed best in Northern central plains (McLaughlin and Kszos, 2005). All these varieties are late maturing, thus ensuring production into early fall and promising higher biomass yields. In 2002, plant science research related to switchgrass production shifted from the DOE to the Agricultural Research Service, USDA. USDA’s goals were to develop economically viable switchgrass production systems by raising crop yields, lowering production costs, and improving ethanol conversion efficiency (Sanderson et al., 2006)

Potential upper limits of switchgrass yields may be much higher than yields achieved to date. In small plot yield trials, the best two varieties yielded on average 15.3 MT/ha/yr, while the best yielding variety reached 21 MT/ha/yr over 5 years (McLaughlin and Kszos, 2005). Switchgrass exhibits significant genetic variation, pointing to high expectations for future yield improvement through breeding programs. Switchgrass yield trials in Iowa's Chariton River watershed for 1999 and 2000 achieved yields ranging from 1.9 to 12.1 MT/hectare, with an overall mean of 5.5 MT/hectare (Brummer et al., 2002).

Figure 7-1
Switchgrass variety trials: 10-year average yields



Source: Mclaughlin and Kszos (2005)

7.3 Switchgrass Management Practices

The decade-long DOE-funded research program on switchgrass provided a basis for developing best-management practices. Recommendations for breaking seed dormancy, planting depth by no-till techniques, planting dates, and herbicide types/levels have been established. Switchgrass stands are typically not harvested during the first growing season, reach two-thirds of their yield capacity in the second season, and attain full yield in the third. Harvest can be done either once or twice a year. Harvesting twice a year can bring higher yields, but also higher costs and higher nitrogen withdrawal from the soil. The most important management issues affecting switchgrass as a bioenergy crop are establishment, the timing of harvests, and nitrogen/fertilization strategies.

Actual gains in switchgrass yields achieved by breeding have varied, by region and by ecotype, from 1 to 5 percent per year (a value that compares favorably with corn breeding, which has averaged 0.7 to 1.2 percent per year over the past 70 years) (McLaughlin and

Kszos, 2005). However, substantial environmental influences on biomass yield estimates suggest that gains need to be substantiated with field trials (Schmer et al., 2006). Large-scale field testing (as opposed to small-plot experimental station trials) is critical for the development of switchgrass as a viable crop for bioenergy.

Table 7-1
Switchgrass field trials: locations, years and yields

State (number of sites)	Years evaluated	Best two yielding varieties	Average yield (metric ton/ha)	Range in average yield for best varieties (metric ton/ha)
Virginia (3)	1992-2001	Kanlow	13.9	10.9-17.5
Tennessee (2)		Alamo	13.8	9.8-16.6
West Virginia (1)				
Kentucky (1)				
North Carolina (1)		NC1	15.6	11.3-19.7
		Alamo	15.6	13.4-21.6
Texas (3)	1995-2000	Alamo	13.5	8.1-16.5
Dallas		PMT-785	10.7	5.5-13.3
College Station				
Stephenville				
Texas	1995-2000	Alamo	16.1	
Stephenville				
Texas (2)	1998-2001	Alamo	19.1	10.7-19.5
Arkansas (1)				
Louisiana (1)				
Iowa (1)	1998-2001	Kanlow	13.1	
		Alamo	12.1	
Alabama (1)	1989-2001	Alamo	23	
		Kanlow	18.2	
Alabama (5)	1994-2001	Alamo	14.55	10.4-20.5
		Kanlow	13.55	8.3-19.1
Georgia (2)	1996-2001	Alamo	16.2	16.1-16.3
		Kanlow	15.7	15.5-15.9
Nebraska (1)	1999-2001	Kanlow	20.6	
		Cave In Rock	16.3	
Kansas (1)	2000-2001	Blackwell	9.50	
		Shelter	9.47	
North Dakota (2)	2000-2001	Sunburst	11	9.8-12.2
		Trailblazer	9.9	9.1-10.8

Source: McLaughlin and Kszos (2005).

Critical to the production of switchgrass is the first-year establishment of the crop. Stand failure resulting from poor seed quality or weed competition will hamper the economic viability of the switchgrass crop for successive years. Switchgrass is a small-seed grass that is vulnerable to weed competition and suboptimal soil acidity and temperature immediately following emergence, even though the established switchgrass plant is very tolerant to these soil conditions (Schmer et al., 2005). Also, since switchgrass is not a fully domesticated crop, it has a high rate of seed dormancy at harvest. To ensure adequate emergence at planting, the seeds need to be stored for 2-4 years in a warm place prior to planting.

A firm seedbed, proper planting depth, and good weed control during the first year are essential to switchgrass establishment, and hence future yields and economic viability. Optimum establishment protocol will vary from region to region, but the most critical guidelines for switchgrass establishment include (1) using seed of known viability, (2) planting into firm seedbed, (3) reduced nitrogen application during initial year, and (4) achieving good weed control in the initial year. Under conventional tillage operations, switchgrass field operations are similar to small seed forages (such as alfalfa). Also under no-till planting, where soil moisture is of less concern than conventional tillage seeding, less seed is required (9 kg/ha vs. 11 kg/ha for conventional planting). Viable yields require fertilization rates between 50 to 100 kg nitrogen /hectare/year (about half the average U.S. rates for corn). The effect of nitrogen can be quite specific; nitrogen fertilizer is effective only on poor soils. On more fertile soils, the effect of nitrogen fertilizer is either negligible or negative.

7.4 Switchgrass: Land Suitability and Adoption Factors

Switchgrass is best adapted to drier areas. Planting and growing conditions of switchgrass are more flexible than for high-value perennials such as alfalfa, which grow best on deep, well-drained soils (Raneses et al., 1998). Paine et al. (1996) recommend growing switchgrass on marginal lands such as highly erodible land (HEL), poorly drained soils, or areas used for wastewater reclamation, thus avoiding competition with food crops. A large amount of land in the Corn Belt is classified as HEL, making it unsuitable for straw or stover removal but potentially viable for dedicated energy crops such as switchgrass (Wilhelm et al., 2004).

Several factors are likely to affect the adoption and expansion of a new perennial crop like switchgrass, assuming a supportive market environment. Perennial biomass crop systems cannot use crop rotation, which is a key strategy in many areas for controlling pests and diseases in annual crops. On the other hand, a market valuation of the benefits (reduced erosion and carbon sequestration in the soil, and recycling of nutrients by their rhizome systems) from perennial crops could encourage switchgrass adoption. Another factor favoring the adoption of switchgrass is that producers can employ the same production tools and techniques commonly used for hay.

Some switchgrass is currently grown on CRP land (as grass cover) and could be used for biomass if allowed under the CRP program (through the grazing and haying policy clause) (**table 7-2**). One illustration is the unique experience of the lower Chariton River watershed in southern Iowa, where switchgrass has become an important crop in the past 15 years. In this region, farmers have grown switchgrass in 10-15 percent of the 50,000 hectares under the CRP program to serve as soil conservation cover (Cooper, 2001). Beginning about 1996, farmers in the Chariton River Valley began to raise switchgrass on CRP land as a potential biofuel to be mixed with coal and burned to generate electricity in the Ottumwa generating station. The farmers received Federal approval whereby they would continue to receive 90 percent of their CRP payment and still harvest and sell the switchgrass for biomass (Brummer et al., 2002).

To date, few farm surveys have been conducted to ascertain growers' interest in energy crops, switchgrass in particular. In southern Iowa, a farm survey of growers' practices and intentions provided a test case for what to expect more broadly (Hipple and Duffy, 2001). According to this survey, farmers tend to be motivated by a range of factors and considerations. Farmers were primarily concerned about the profitability of switchgrass and potential returns on investment. They were also interested in whether profitable switchgrass can be sustained over time, whether switchgrass production fit with current farming operations, and whether they have the required skill to manage it. Other concerns included additional capital outlays, switchgrass compatibility with land tenure and acreage control, and the risk inherent in switchgrass production.

Table 7-2 ***CRP enrollment by State, and share of grass and tree plantings, 2006***

State	Total enrollment (hectares)	Grass plantings (hectares)	Percent grass acres in total CRP	Tree plantings (hectares)	Percent tree acres in total CRP	Annual rental payments ($/hectare)
Alabama	207,551	61,597	29.7	145,954	**70.3**	99.286
Delaware	2,445	991	40.5	1,454	**59.5**	223.916
Florida	38,270	2,722	7.1	35,548	**92.9**	82.72
Georgia	137,285	7,394	5.4	129,891	**94.6**	87.78
Illinois	310,470	278,800	89.8	31,670	10.2	225.148
Indiana	91,840	78,294	85.2	13,547	14.8	200.794
Iowa	616,869	604,968	98.1	11,901	1.9	231.704
Kansas	1,188,199	1,187,273	99.9	926	0.1	85.932
Kentucky	128,205	124,220	96.9	3,985	3.1	165.308
Louisiana	104,035	19,795	19.0	84,240	**81.0**	111.122
Maryland	10,948	10,085	92.1	863	7.9	268.158
Michigan	90,998	83,721	92.0	7,277	8.0	163.592
Minnesota	492,151	465,627	94.6	26,524	5.4	131.054
Mississippi	354,980	66,520	18.7	288,460	**81.3**	92.642
Missouri	639,352	626,196	97.9	13,156	2.1	146.278
Nebraska	500,542	498,179	99.5	2,363	0.5	125.554
New Jersey	969	904	93.3	65	6.7	124.608
New York	22,772	21,545	94.6	1,228	5.4	115.83
North Carolina	38,733	11,219	29.0	27,514	**71.0**	136.598
North Dakota	1,110,115	1,109,226	99.9	889	0.1	72.908
Ohio	106,435	99,707	93.7	6,728	6.3	212.08
Oklahoma	464,601	464,033	99.9	568	0.1	71.698
Pennsylvania	91,020	90,085	99.0	934	1.0	191.994
South Carolina	78,714	9,740	12.4	68,974	**87.6**	78.408
South Dakota	461,946	460,975	99.8	972	0.2	91.828
Tennessee	115,352	99,609	86.4	15,743	13.6	129.514
Texas	1,816,353	1,812,145	99.8	4,208	0.2	77.638
Virginia	18,617	9,628	51.7	8,990	48.3	118.03
West Virginia	375	314	83.5	62	16.5	145.97
Wisconsin	244,680	202,503	82.8	42,176	17.2	153.142
U.S.	13,826,757	12,796,470	92.5	1,030,287	7.5	107.69

Source: USDA-FSA (2006).

The Iowa farm survey also identified several incentives for the adoption of switchgrass, including expanded use of CRP lands to support production cost savings. The farmers also identified several factors that might discourage adoption, including general distrust of government programs and regulations, including CRP restrictions on land management. Farmers cited recent requirements to mix expensive forages and legumes with switchgrass, despite claimed evidence that they are eventually choked out, as exemplifying unnecessary policy not conducive to biomass production. Also, farmers may be risk averse and prefer to proceed gradually before making a larger commitment. Another potential handicap is scheduling conflicts between new management requirements and off-farm obligations. Farmers were also concerned about a general lack of adequate information and guidance or training. These survey results can provide useful insights for policy promoting large-scale energy crop production.

7.5 Economics of Switchgrass Production

The southern Iowa experience with switchgrass provided the basis for evaluating the economics of switchgrass production and developing production budgets under a CRP system. Brummer et al. (2002) reported production budgets without land rents in order to estimate how much a farmer would have to receive for switchgrass in order to forgo a full CRP payment. Budgets were estimated using a variety of yields and prices for switchgrass.

According to this analysis, an important component of delivered costs for switchgrass biomass is storage and handling. Storage costs for switchgrass in southern Iowa showed that the economics of switchgrass storage depends on switchgrass market prices. Indoor storage (totally enclosed or open sides) only becomes economically viable if the switchgrass price is higher than $44/MT. For a price higher than $55/ton and a yield of 8 dry MT/hectare, delivered costs of switchgrass will range from $75.9/MT to $91.8/MT, depending on storage options and the type of land used for production.

Economics of switchgrass also depend on the type of land on which switchgrass is grown (Brummer et al., 2002). In the Iowa study, delivered costs for switchgrass grown on grassland are $75.9/MT with no storage, $100.1/MT with onfarm storage in a totally enclosed barn, and $104.5/MT with collective storage. For switchgrass grown on cropland, delivered costs are $83.6/MT with no storage, $107.8/MT with onfarm storage in a totally enclosed barn, and $111.1/MT with collective storage. Handling and transportation cost is $11.2/MT without storage and $17.1/MT with storage.

These delivered costs estimates can be compared with previous estimates. Graham et al. (1995) found, for the North Central region including Iowa, an annualized farm cost of $52.4/MT (for 7.38 dry MT/hectare yield) and an annualized delivered cost of $55.7/MT (excluding storage costs). The authors used the present value based on the dollar value in 1993 for cost calculations. They assumed $3.3/MT for transportation cost and used an annual land rental rate of $162.8 per hectare, based on CRP data. Cundiff and Harris (1995) estimated that switchgrass produced and delivered to a conversion facility in Virginia would cost from $50.6 to $59.4/dry MT. They assumed a land charge of $44/hectare and a yield of 8 MT/hectare. Smith et al. (2001) estimated a delivered cost for round baled switchgrass of $89.8/MT, excluding storage costs and considering a 50-mile hauling distance.

Duffy and Nanhou (2001) evaluated the cost of switchgrass production under different yields and land charges for cropland and grassland in southern Iowa (**table 7-3**). The cost of producing switchgrass varies considerably under alternative yield and land charge assumptions (**table 7-4**). Not surprisingly, seeding switchgrass on grassland showed lower production costs (than on cropland) and costs are reduced by more than 50 percent when yields rise from 3.36 to 13.44 MT/ha. Cost of land has the second most significant influence on cost differences. These results suggest that switchgrass production would be most economically viable on marginal land using best-management techniques.

Hallam et al. (2001) compared the production costs of several energy cropping systems including canary grass, switchgrass, and other species in two Iowa locations for 1993 (**table 7-5**). Of the perennial grasses, switchgrass was the highest-yielding crop and had the lowest per-ton costs at both locations. Switchgrass also had slightly lower costs than the intercropping systems (alfalfa-sorghum; reed canary grass-sorghum). The break-even price (cost per hectare divided by expected yield per hectare) estimates ranged from $30.53 to $38.14/MT for switchgrass (versus $44.59 to $73.64/MT for the lower yielding reed canary grass). However, costs per MT of biomass produced were lowest for sorghum (which also produced the highest yields of all crops and systems tested), somewhat higher for switchgrass, higher still for big bluestem, and highest for alfalfa and reed canary grass (**fig. 7-2**). Although the sorghums had the highest yields, they are not well suited for sloping soils because of the high potential for erosion, making sorghum less attractive in certain circumstances.

Table 7-3
Estimated establishment costs for switchgrass: Iowa, 2001

				Switchgrass seeded on:	
				Cropland	**Grassland**
Operating expense	**Unit**	**Price ($)**	**Quantity**	**Cost**	**Cost**
				($/ha)	($/ha)
Seeds (PLS)	kg	8.81	6.72	59.21	59.21
Fertilizer (P and K)[2]	kg			33.83	33.83
Lime (includes application)	MT	13.23	6.72	88.91	88.91
Herbicide					
Atrazine	Liter	3.1	3.5	10.85	10.85
2,4D	Liter	3.45	1.75	6.04	6.04
Roundup	Liter	9.92	4.67		46.35
Total operating cost	$/ha			198.83	245.18
Land charge:					
Cash-rent equivalent	$/ha			185.19	123.46
Total establishment cost	$/ha			435.00	417.77
Prorated establishment cost (11 years @ 8%)	$/ha			60.94	58.52

Source: Duffy and Nanhou (2001).

Table 7-4
Cost of switchgrass under different yield and planting assumptions

Scenario	Yield (MT/ha)	Establishment cost (prorated) ($/ha)	Reseeding cost (prorated) ($/ha)	Yearly production cost ($/ha)	Total cost ($/ha)	Total cost ($/MT)
Spring seeding on grassland with drill	7.392	58.52	8.77	143.8	421.85	125.58
	14.784	58.52	8.77	183.9	520.86	77.53
	19.712	58.52	8.77	210.64	586.86	65.41
	29.568	58.52	8.77	264.11	718.91	53.51
Spring seeding on grassland with no drill	7.392	60.42	22.15	168.8	499.36	148.65
	14.784	60.42	22.15	208.9	598.37	89.06
	19.712	60.42	22.15	235.64	664.4	74.17
	29.568	60.42	22.15	289.11	796.42	59.27
Spring seeding on cropland with drill	7.392	59.19	17.53	143.8	431.78	128.53
	14.784	59.19	17.53	183.9	530.81	79.01
	19.712	59.19	17.53	210.64	596.81	66.63
	29.568	59.19	17.53	264.11	728.86	54.24
Spring seeding on cropland with no drill	7.392	59.73	17.53	143.8	432.32	128.7
	14.784	59.73	17.53	183.9	531.33	79.08
	19.712	59.73	17.53	210.64	597.36	66.68
	29.568	59.73	17.53	264.11	729.41	54.28

Source: Duffy and Nanhou (2001).

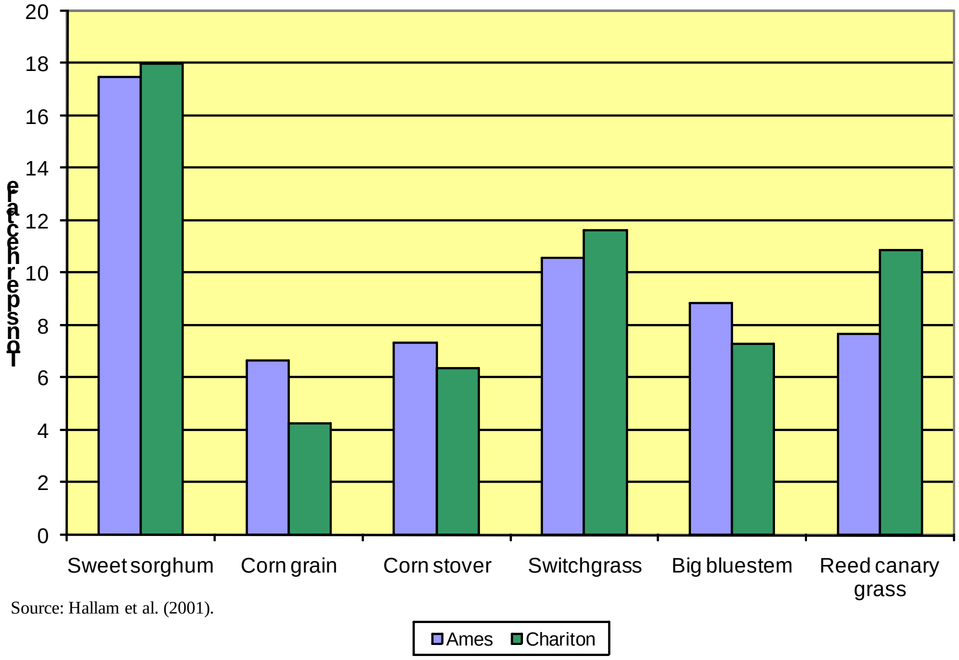
Table 7-5
Comparison of production costs among several grassy crops, Iowa

		Ames, Iowa				Chariton, Iowa			
	Units	Alfalfa	Reed canary grass	Forage sorghum	Switchgrass	Alfalfa	Reed canary grass	Forage sorghum	Switchgrass
Years of production		4	10	10	10	4	10	10	10
Price (1993; hay auction)		71.65	66.14	60.63	60.63	71.65	66.14	60.63	60.63
Total operating expenses	$/ha	166.0	228.4	299.0	309.2	159.6	244.2	307.2	316.6
Total allocated overhead	$/ha	359.1	345.4	357.5	357.5	272.6	258.9	285.9	285.9
Establishment cost	$/ha	158.5	32.0		14.2	125.7	23.1		14.2
Total expenses	$/ha	683.6	605.7	656.5	666.6	557.9	526.2	578.2	587.6
Average yield	MT/ha	10.9	8.2	15.7	17.5	9.3	11.8	17.7	19.3
Break-even price	$/MT	62.9	73.6	41.8	38.1	60.0	44.6	32.8	30.5

Source: Hallam et al. (2001).

Overall, these production budget and delivery cost assessments suggest that switchgrass is a high-cost crop (under current technology and price conditions) and may not compete well with established crops, except in areas with lower opportunity costs (pasture land, marginal lands). Under Midwestern conditions, switchgrass break-even revenue (compared to dominant crops) is estimated at \$110 per ton, for 4 tons/acre and about \$82 per ton for 6 tons per acre (Babcock et al., 2007). According to Babcock et al., processors would pay \$37.50 per ton of switchgrass, with ethanol at \$1.75 per gallon. Given the poor cost competitiveness of switchgrass, large subsidies would be required to induce production in areas where other more lucrative crops are being produced (Babcock et al., 2007). In the long run, only lower cellulosic conversion costs and higher switchgrass yield productivity (through intensified R&D efforts) can guarantee the economic viability and large-scale adoption of switchgrass. Further genetic yield improvements could outpace traditional crops such as corn, but only under the aggressive combined efforts of continuous breeding programs, biotechnology, and improved agronomy practices.

Figure 7-2
Biomass yield for grassy crops and corn in Iowa, 1988-1992 average



Source: Hallam et al. (2001).

Another factor that could swing the economics in favor of energy crops like switchgrass is the consideration of carbon credits and lower greenhouse gas emissions. Switchgrass typically outperforms crops like corn in terms of energy efficiency and carbon balances (Wu et al., 2006).

Bransby et al. (1998) reviewed several studies on carbon balances and concluded that carbon sequestration under switchgrass depends on what crop it replaces and may be positive only if switchgrass is planted after annual crops. Moreover, the amount of carbon sequestered in a switchgrass production system is relatively unimportant compared to reductions in CO_2 emissions when biomass replaces fossil fuels.

Ney and Schnoor (2002) estimated that the substitution of switchgrass for coal in an existing electric generation facility can provide 102 grams of CO_2-eq reduction per MJ of switchgrass combusted. The net greenhouse gas benefit of the project, burning 5 percent switchgrass in place of coal, would be 305,500 metric tons CO_2-equivalent annually.

Kim and Dale (2005a) conducted a life-cycle analysis (LCA) and evaluated the production of ethanol from switchgrass for Hardin County, IA, and its adjacent counties. The analysis included the transportation of switchgrass from field to conversion facility, and showed that ethanol from switchgrass could decrease greenhouse gas by 336 grams CO_2 equivalent per kilometer driven (compared to gasoline) as the result of carbon sequestration and production of electricity and steam from lignin parts of switchgrass.

7.6 Other Herbaceous Crops

Though switchgrass has the potential to be an important biofuels crop, it does have limitations. Being a C4 species, switchgrass performs particularly well in hot environments, but not as well as cool-season grasses in cooler climates typical of the upper Midwest or under wet soils (Cushman and Truhollow, 1991; Wright, 1988). From a long-term sustainability perspective, the reliance on a single species of herbaceous crops for biomass production is risky. Ecological literature clearly favors a multiplicity of grassy species over monoculture in the same area because a diverse set of species improves the temporal and spatial yield stability of the system (e.g., Tilman et al., 1996).

Several grassy or perennial crops could be considered as biomass feedstock and may be better adapted to specific regions and locales than switchgrass. Also, different perennial grasses could be mixed in same region, partly to reduce risk of epidemic pest and disease outbreak and partly to optimize biomass supply to ethanol or biopower plants, since different grasses mature and can be harvested at different times. However, the expansion of these grassy energy crops requires sufficient and sustained technical support and an expanded program of field testing. Promising alternative species include Miscanthus, reed canary grass, bermuda grass, tall fescue, and alfalfa.

7.6.1 Miscanthus

Like switchgrass in the U.S., *Miscanthus* has been extensively researched in Europe as a future bioenergy crop. *Miscanthus* (*M.* × *giganteus*) is a perennial rhizomatous grass species, with great potential for use as a biomass energy crop across a wide range of growing conditions. *Miscanthus* is propagated vegetatively, either by rhizome cutting or in vitro culture, requiring that plantlets be grown in greenhouses (mostly from in vitro micropropagation) and transplanted to the field—an expensive establishment method (Lewandowski et al., 2003). *Miscanthus* is now being grown commercially in the European Union (EU) for direct combustion in local power stations. *Miscanthus* field trials in Europe show very high yields—over 30 tons/ha--for irrigated trials in southern Europe. Also, *Miscanthus* production is characterized by low fertilizer and pesticide requirements, making it a relatively benign crop environmentally.

Weed control is required for *Miscanthus* in the establishment year (and sometimes the second year) and usually consists of one pre-emergent herbicide application and one to two post-emergent applications. *Miscanthus* is nutrient efficient and requires no fertilizers in the establishment year. Fertilizer is applied annually in subsequent years at recommended replacement rates of 2-5 kg nitrogen, 0.3-1.1 kg phosphorus, and 4-8 kg potassium per MT of dry matter harvested; however, on good soils, nitrogen may not be routinely required. Fertilizer is applied in the spring prior to new growth. Typically, *Miscanthus* can be produced successfully without irrigation in north-central Europe, but may need to be irrigated in southern Europe for satisfactory yields.

Heaton et al (2004a), in a side-by-side comparison between *Miscanthus* and switchgrass, found *Miscanthus* to produce significantly more (twice as much) biomass than switchgrass across a range of growing conditions. *Miscanthus* showed the strongest response to water, while switchgrass responded more to nitrogen levels. Heaton et al. (2004b) reported on a sterile variety of *Miscanthus* in Illinois trials to assess its potential under Illinois conditions and its performance compared to traditional row crops. Overall, the results suggest that *Miscanthus* could yield an average of 33 tons of dry matter per hectare. And under high energy prices, the *Miscanthus* crop would be profitable if grown for 4 or more years, even without subsidy (t**able 7-6**).

On the basis of yield per hectare, *Miscanthus* vastly outperforms switchgrass and offers greater energetic efficiency and profitability potential. However, *Miscanthus* has its own limitations, including high establishment costs (vegetable propagation), poor overwintering

Table 7-6

Ten-year projected costs and profits for corn/soybean and Miscanthus in Illinois

	Corn-soybean[1] ***rotation*** ($/hectare)	***Miscanthus***[2] ($/hectare)
Production budget period	10 years[3]	10 year
Fertilizer	621	242
Pesticides	520	15
Seeds	445	316
Crop drying	77	-
Machinery repair, fuel, hire	423	635
Labor	580	562
Total variable cost	2,657	1,770
Machinery overhead, housing, depreciation		
Nonland interest	1,533	360
Land	2,496	2,496
Total other cost	4,029	2,856
Total all cost	6,686	4,626
Gross revenue	5,783	7,527
Net profit[4]	(903)	2,900

Source: Heaton et al. (2004b).

[1] Corn and soybean costs and average yields for central Illinois (Hoeft et al. 2000); prices based on Chicago Board of Trade Dec. 2002 futures.

[2] Miscanthus cost data from Lewandowski et al. (2000). A predicted yield of 35 tons/ha for Central IL is assumed , and a price of $40/ton. This compares to $44 /ton proposed by McLaughlin et al. (2002) for US biomass crops and an EU suggested price of $49/ton (Bullard, 2001).

[3] Total values over 10 years, discounted annually at 3%.

[4] Farmgate price, excluding subsidies.

at some sites, and insufficient water supply in southern regions of Europe (Lewandowski et al., 2003). *Miscanthus* is somewhat sensitive to cold in the first year of production, and winter kills have occurred in areas with cold winters. Two factors seem to disfavor this crop in the U.S.: *Miscanthus* cannot be planted directly through seeds, and it is not native to North America (and is subject to import restrictions to protect against foreign and potentially invasive species). These considerations make this energy crop still highly hypothetical under current conditions despite its many productive advantages. Only cheaper planting methods can improve the realistic prospects of this crop as an energy crop in the U.S.

7.6.2. Reed Canary Grass

Another potential biofuel crop is reed canary grass (RCG), a cool-season grass that is most productive in spring and fall and is highly tolerant to both wet and dry soils. Its strongly rhizomatous growth also makes it appealing, particularly on soils where switchgrass, a bunchgrass, does not form thick stands and erosion is a problem. RCG grows particularly well in the Midwest's wet soils (Carlson et al., 1996). The biomass productivity of reed canary grass exceeded that of switchgrass in northern Ohio (Wright, 1988) and occasionally in southern Iowa (Anderson et al., 1991). Moreover, RCG can be harvested in early summer when warm-season grass is not available, facilitating a constant feedstock flow (Cushman and Truhollow, 1991). However, RCG's high levels of silicon, chlorine, and total ash make it less than ideal for co-firing unless mixed with other biomass such as switchgrass (Rummer et al., 2002).

According to production budgets developed for southern Iowa using 2001 prices, farmgate costs per MT of RCG on grassland ranged from $50.60 to $79.20 at 12 and 6 MT/hectare. On cropland, costs per ton ranged from $55.00 to $88.00 at 12 and 6 MT/hectare (Brummer et al., 2002).

7.6.3 Alfalfa and Other Forages

Another potential source for biomass is the most commonly grown U.S. forage crop: alfalfa (Samac et al., 2007). Under deep and well drained soils, alfalfa is preferred over switchgrass as it offers higher yields and greater value through its high forage protein content. In 2005, Alfalfa was grown on 9.6 million hectares with an estimated hay value of $8.1 billion (just behind corn and soybean in crop economic value) (Bouton, 2007). One possibility tested in Minnesota was to produce under contract a tall alfalfa variety where the stems are baled and sold to bioenergy plants while the leaves are sold as protein-rich forage. However, a farm cooperative project in Minnesota that foresaw the use of alfalfa stems for a local biopower facility in the early 1990s was later aborted for lack of interest on the power utility side (Morris, 2005).

In the Southeast, millions of acres of row crops have been converted to woodland and pasture as a result of soil erosion from overproduction. Pastures were grown mostly with bermuda grass, bahia grass, and tall fescue. Of all major cool-season perennial grass varieties in the U.S., the one grown on the most land area is “Kentucky 31” tall fescue, which occupies most of the 19 million hectares of tall fescue pasture in the country (Bouton, 2007). These species could be converted to biomass feedstock should local biorefineries develop and require a diversified feedstock stream. However, for these grasses to be shifted from feed to energy, prices must be higher than returns from livestock grazing, which can be as low as $20 per ton.

Overall, this literature review of grassy dedicated energy crops reveals several highly suitable perennial crops for energy use. While switchgrass has shown great potential in many regions, several other species could be more suitable candidates depending on the local soil and climatic conditions. More research is needed on how these crops are likely to perform under local conditions and at what price they become feasible as energy crops. Other issues to be sorted out include adaptability of energy crops to existing farming practices, machinery, time allocation, and farming aptitude.

The development of energy crop markets will take time, taking its cue from local feedstock needs at startup or existing biopower facilities or from new cellulosic ethanol plants. The pace at which energy crops will develop will depend on the economic viability of the crops in particular regions and markets, how fast seed’s can be made available, the regional composition of other types of usable feedstocks, the scale and scope of the regional bioenergy industry, contractual arrangements for long-term biomass supply, and whether the local infrastructure can handle large quantities of energy crops moving from field to plant. If a multitude of feedstocks is required to meet biorefinery needs, local energy crops with long-term supply commitments could mitigate feedstock risk and enhance the longrun viability of a local bioenergy market.

Chapter 8

Energy Crops: Short-Rotation Woody Crops

8.1 Advantages of Short-Rotation Woody Crops for Energy

In the U.S., short-rotation woody crops (SRWC) such as willow, poplar, cottonwood, sycamore, and southern pine are considered potential sources of biomass to support cellulosic ethanol and biopower markets. The area in SRWC plantations is expected to increase over time, and would make up one of multiple streams of woody biomass.

SRWC are trees grown on high-density plantations at relatively close spacing (up to 33,000 trees per ha) and harvested under shorter rotation periods than conventional forests (Dickman, 2006). As such, the concept behind SRWC differs sharply from the traditional pine, oak or spruce silviculture and requires foresters to think more like farmers.

SRWC also offer multiple environmental benefits relative to crops. With an extensive root system, SRWC can help reduce soil erosion and nonpoint-source pollution and promote stable nutrient cycling and soil organic matter. Moreover, SRWC provide habitat for a wide range of birds and can enhance landscape diversity, in contrast to agricultural crops (Tharakan et al., 2005).

Among the members of the family of *Salicaceae*, poplars and willows display the fastest growth rates possible in north-temperate climates, and clones are easily propagated. Moreover, both willows and poplars have easily exploitable genetic diversity, enabling continuous yield improvements whether through conventional breeding or molecular biotechnology (Dickman, 2006).

Over the past 20 years, several companies have established SRWC in the U.S. to produce fiber for their paper mills. Among the SRWC, planted poplars dominate. Poplars have been widely used for pulp making since they grow rapidly and can be selected, hybridized, and cloned with ease. Poplar wood also has a high cellulose-to-lignin ratio, and recent advances in pulping technology are helping to increase both the pulp yield and the strength properties of the paper obtained from poplar.

Within the continental U.S., the most likely locations for new SRWC plantations (poplars, willows) are in river bottoms along the Pacific Coast, in the areas of best rainfall between the Cascade and Rocky Mountain ranges (where the terrain is suitable), throughout the Northeast and North-Central States, and in more arid areas where carefully metered irrigation is possible (Arnold, 1996). In the South, cottonwoods can be propagated effectively on sandbanks along river systems, where the trees’ root structures would be under water during the spring floods, but these locations are highly limited. For hardwood species in the South, sycamore, willow, or other fast-growing indigenous species will more likely prove effective (Arnold, 1996). (See Appendix D for an overview of SRWC developments in the Northeast, North Central, Pacific Northwest, Southeast, and subtropical Florida.)

8.2 SRWC Management

Extensive research on poplars and willows in the U.S., Sweden, UK, and Canada has contributed significantly to our understanding of how to grow and manage these trees. A SRWC system entails high-density plantings (5,000-20,000 stems/ha) and short rotations (1-5 years), enabling maximum conversion of solar energy and biomass production.[22] Fertilization is required after successive SRWC harvests. But each combination of species/clone and site requires a different blend of supplemental nutrients for optimum growth. Management of SRWC still faces some hurdles, including high establishment costs because of the many cuttings or seedlings required per hectare, low wood-bark ratio, and lack of efficient mechanical harvesting of dense plantations (Dickman, 2006).

Willow biomass production is likely to be located near end-users. Transportation costs and limited storage time require a short supply chain (Volk et al., 2006). The willow plantations would be established and maintained by farmers, but aggregators (intermediaries between growers and end-users) would harvest and deliver the biomass. Aggregators also supply equipment for planting and harvesting (Tharakan et al., 2005). Typically, biomass end-users, whether utilities or biorefineries, are unlikely to deal directly with individual farmers to secure a supply of biomass fuel and prefer to deal directly with a farm cooperative or independent fuel supplier.

In general, ideal places for planting SRWC are also the best agricultural sites. Highly erodible lands are not preferable, nor are lands with steep slopes or other severe soil limitations (Husain, 1998). Previously cultivated farmlands that are “marginally productive” for conventional agricultural production are generally suitable for SRWC since they do not require the expense of clearing existing forest, which could dramatically reduce the profits of growing SRWC.

8.3 SRWC Breeding, Productivity, and Yields

The potential to increase SRWC yields is vast because of the wide range of genetic diversity across the genus and the lack of cropping history for willow and poplars. Controlled breeding of poplar and related willows is straightforward because excised branches bearing male or female flowers can be easily forced under greenhouse or controlled environment conditions, allowing close regulation of the pollination process (Dickman, 2006).

During the 1980s and 1990s, scientific advances in genetic and physiological biotechnology boosted breeding programs. In the U.S., willow breeding programs were launched around 1995 at the State University of NY-College of Environmental Science and

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[22] Willow is typically harvested every 3-4 years, while hybrid poplars are harvested once every 5 to 7 years.

Forestry (SUNY-ESF), where researchers developed the genetic resources and technical expertise to perform controlled pollinations, establish nursing trials, and evaluate large numbers of progeny. As a result, many willow species were collected, and through controlled breeding, more than 3,000 progeny genotypes have been produced and maintained (Volk et al., 2006).

In central New York, first-rotation, non-irrigated willow trials have produced yields of 7.6 to 10.5 dry MT/ha, while second-rotation yields were 18-62 percent higher (Volk et al., 2006). Yields of fertilized and irrigated willow grown in 3-year rotations have exceeded 24.5 dry MT/ha in North America and 30 MT in Europe (White, 2007). In North-Central States, poplar yield estimates from a network of research plantations during the 1980s ranged between 4.5 and 11.2 dry MT/ha, depending on soil and climatic conditions (Husain, 1998). Research trials at South Carolina Mead Westavo Center show that yields for loblolly pine can be as high as for (poplar, hardwood) cottonwoods. Loblolly yields of 10 dry MT/ha/year are achievable now, and yields of 16 dry MT/ha/yr or greater are possible on many sites across the southern United States (Allen et al., 2005), illustrating the potential for increased fiber and biomass production in the Southeast.

Overall, early projections of SRWC yields tended to be overly optimistic because they were based on small-plot conditions that were managed more intensively than field plantings could be, and because pest problems were not adequately accounted for. The use of larger plots in trials or operational plantings has yielded more reliable data on growth and yield. Realistic mean annual SRWC yields generally fall within 5-20 MT of biomass/ha/yr, depending on species or clone, site, region, and cultural methods (Dickman, 2006).

8.4 Economics of SRWC: Production and Delivery Costs

There are few estimates of farmgate prices for SRWC feedstock. Numbers from the 1990s show prices from $40.47 to $46.74/MT (Walsh et al., 2000; Sedjo, 1997).[23] However, these price estimates do not factor in delivery costs, which would better reflect SRWC's competitive status. More recently, Gan and Smith (2006) estimated that for a hybrid poplar plantation, at a yield of 11.21 dry MT/ha/yr, biomass production and transport costs stood at $57.19/MT.

The largest cost component in SRWC production is harvest. For willow crops, harvesting and transportation can account for 39-60 percent of the delivered cost of biomass (Volk et al., 2006). The most common harvester system involves a feller-buncher/grapple to skid whole trees to a landing, flail processing at the landing, and a tub grinder for residue combination. Ongoing research at SUNY-ESF and Cornell University is exploring new designs for more efficient and effective harvesters (e.g., Case New Holland FX45) for willow biomass crops (Volk et al., 2006).

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[23] Original costs were given in $/gigajoule (GJ); this was converted to $/MT on the assumption that for poplars/willows, 1 MT contains 19 GJ (according to National Renewable Energy Laboratory, NREL).

Research in Florida focusing on Eucalyptus trees is also looking into harvesting systems. Harvest cost share of total operating costs can reach up to 70 percent with feller-buncher technology on Eucalyptus and up to 50 percent with a high-capacity forage harvester (e.g. Claas) on leucaena trees (Stricker et al., 2000). Research is underway to improve the efficiency of Claas forage harvester systems and reduce harvest cost from 70 percent of total cost for the feller-buncher to 48 percent of total cost (Stricker et al., 2000). As part of a feasibility study conducted with Lakeland Electric Florida, production and delivered fuel costs were estimated at $13.38/green MT for leucaena and $20.17/green MT for Eucalyptus.

8.5 SRWC Economic Viability and Intermarket Competition

Improved yields and more efficient harvesting systems can lower overall delivery costs of SRWC. However, the viability of the SRWC biomass for energy also depends on intermarket competition. SRWC can be used as feedstocks for either bioenergy or the forest industry (pulp mills). In the case of biopower applications, the use of SRWC as feedstock also requires that prices be competitive with alterative fuels such as coal or natural gas (Sedjo, 1997). Most of the evidence suggests that the price of industrial wood exceeds that of coal on an energy (Btu) basis (Sedjo, 1997). Likewise, pulp mills could bid up the price of wood resources away from energy use and into pulp. In this case, biomass price must be low enough to compete with cheaper coal, yet high enough to compete with the pulp industry.

Under current technology and input requirements, SRWC biomass doesn’t seem competitive with alternative feedstock uses. Both willow and poplar market prices are too high to compete with coal for biopower. Most price comparisons find that the delivered coal price is significantly below the break-even price for willow or poplar under current conditions. The cost of coal varies by location, source, transport mode, etc. In one estimate, an energy price of $2.38/GJ would be required to justify that market price for poplar, but the delivered price for coal was only $1.37/GJ and for natural gas $1.74/GJ (Tharakan et al., 2005).[24] In the South, delivered market price of wood was about $49.5/dry MT in 2005, well above the break-even price for the production of fuelwood (Elliott, 2005). This lack of price competitiveness and high cost of producing woody biomass explains why SRWC for bioenergy applications (including biomass co-firing) has not been widely adopted to date (Tharakan et al., 2005) (**table 8-1**).

Future changes in relative prices, either as a result of new policy initiatives (mandates, taxes, subsidies) or market forces can either improve or worsen the competitiveness of biomass as feedstock. If the relative prices of a substitute energy feedstock (coal) rise, due to either taxes or market forces, biomass will become more competitive in the biopower energy market. Likewise, a decline in the relative price of pulp due to market forces would improve the competitive position of biomass vis-a-vis pulpwood and allow biomass to be drawn into energy production rather than as feedstock for industrial wood products.

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[24] Energy or fuel prices are also given in million Btus (MMBtu). In this report, all prices per unit energy are translated to $/gigajoule (GJ). 1 GJ equal 0.946 MMBtu.

Over time, a number of factors could affect the competitiveness of biomass relative to competing feedstocks. Both technology and policy incentives can play a significant role. On the technology side, if the yields of trees grown for biomass could rise significantly faster than those of industrial plantations, the competitive balance could swing toward bioenergy. However, yield increases alone may not be enough to bridge the price gap. Likewise, in areas where industrial wood markets are not heavily present and do not offer serious competition, local wood feedstock could be used for biopower (through co-firing) or for biofuels production (Sedjo, 1997).

Technological innovations might have the greatest effect on scale of operations. Pulp mills must be very large to be technically efficient. Should fuelwood technology take the form of small, more efficient wood-power generating facilities, wood energy operations might find regional niches where a wood feedstock is readily available on a small scale (Sedjo, 1997).

Table 8.1
Willow prices under different yield and CRP payment scenarios

	Fuel price ($/GJ) [$/dry MT]		
	Farmgate Break-even[a] (BEP)	Farm gate[b]	Plant gate[c]
Current yield			
Base case	1.90 [36.5]	2.50 [48.1]	3.0 [57.2]
Base case + CRP	1.17 [22.4]	1.42 [27.2]	1.90 [36.3]
Increased yield			
Base case	1.75 [33.5]	2.23 [42.9]	2.60 [50.1]
Base case + CRP	1.13 [21.7]	1.33 [25.5]	1.70 [33.0]

Source: Tharakan et al. (2005)

[a] Farmgate BEP includes all costs associated with growing and harvesting the willow biomass, excluding a profit to the farmer.

[b] Farmgate price includes the required profit for the farmer.

[c] Plant gate price is the delivered price of willow biomass to the power plant and includes all costs associated with both grower and aggregator, including their profits.

8.6 Policy Incentives for SRWC

Several policy incentives can tip competitiveness in favor of biomass feedstock. These include (1) the Renewable Portfolio Standard, (2) CRP land use for biomass, (3) carbon credits, and (4) and taxes or subsidies favoring biomass feedstock relative to alternatives.

The Renewable Portfolio Standard (RPS) requires that a specified share of electricity production must come from renewable sources (such as wind, biomass, etc.). Currently, 22 States have an RPS in force, requiring that 20 percent of electricity be generated from renewable sources by 2020. An RPS is likely to stoke interest in biomass (SRWC) use for biopower. For example, New York State, whose RPS has been in effect since 2006, has established an aggressive renewable goal of 25 percent. To encourage the use of willow to meet part of that goal, New York is offering several incentives, such as State-based investments in regional breeding research, to improve yields and harvesting methods. In addition, willow growers in New York can take the Federal biomass tax credit for closed-loop biomass.[25]

To date, CRP land status has been approved for several biomass production systems, including both SRWC and switchgrass. Such case-by-case approvals for CRP are required since SRWC do not automatically qualify as conservation systems (because they entail intensive management and produce a marketable crop) but provide some conservation benefits. Examples include willow production in New York, hybrid poplar in Minnesota, and switchgrass in Iowa.

One option to improve the competitiveness of biomass vis-a-vis coal is a carbon credit. Significant carbon credits for using biomass (as replacement of fossil fuels) would change the relative price between wood and coal. In addition to carbon credits, there are other greenhouse emissions that already have market value and are traded as a consequence of the Clean Air Act Amendment (CAAA) of 1990. SO_2 and NOx emission credits can play an important role in improving the economics of biomass co-firing. Estimates put these credits at \$275/MT for SO_2 and \$880/MT for NOx (Tharakan et al., 2005).

Some have argued that because SRWC offer social and environmental benefits (beyond greenhouse gas emission control), such benefits should be factored into the market valuation of woody biomass, with some form of public subsidy introduced to compensate producers for the value of these benefits (Updegraff et al., 2004). Such subsidy payments could be designed to reflect the difference between the market price of biomass and the social value of replacing row crops with trees. The key issue is how to monetize such environmental benefits, and the literature on this is scant. In one study, Updegraff et al. (2004) examined the potential environmental benefits of SRWC in North-Central States. Using a defined watershed (High Island Creek, Minnesota) as the unit of analysis, the author carried out an environmental valuation of a project to establish 5,000 hectares of hybrid poplars. The environmental valuation was derived by estimating the costs to local governments of direct erosion and sediment deposition and the monetary values associated with water recreation, forest conservation, and atmospheric carbon sequestration (**table 8-2**).

Updegraff et al. (2004) concluded that erosion costs reflecting total road/ditch maintenance budget savings (avoided-damages benefit) to communities within the watershed ranged from \$2.18 to \$27.02 /MT avoided sediment with a mean of \$9.07. Total savings across the watershed ranged from \$236,171 to \$369,761 over the 5-year rotation. The monetary carbon offset values ranged from \$1.22 to \$44/MT carbon, with a “most likely” value of

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[25] Closed-loop biomass refers to biomass that is produced in plantations dedicated to its production as feedstock for power generation. This biomass is essentially carbon neutral, and thus ‘‘closes the carbon loop.’’

$6.94. These estimates were based on a study by the Minnesota Public Utilities Commission. For the entire project, the mean value of sequestered carbon ranged from $309,240 to $1,109,676 in the bioenergy scenario (harvested SRWC for electricity) and from $674,688 to $2,411,393 in the forest products scenario (harvested poplar for manufacturing wood). Forest conservation values based on likely willingness to pay of $30/ha and a range of $24-50/ha of preserved forest yielded an estimated annual "forest conservation" value of $4.70 per ha of SRWC at 10 percent conversion and $5.44 at 30 percent conversion. Total annual values for the "forest conservation" part ranged from $22,350 to $79,650 (Updegraff et al., 2004).

Table 8-2

Monetizing environmental benefits from SRWC plantation in Minnesota

Environmental benefits		**Range ($/ton)**	**Median ($/ton)**	**5-year rotation savings for the project ($1,000)**
Erosion costs	Evaluation of direct erosion and sediment deposition-related costs to local governments.	2.18-27.02	9.07	236.2 to 369.7
Carbon sequestration	Corn uptake and fossil fuel expenditures during the 5-year rotation	1.22-44	6.94	
Bioenergy scenario [(a)]				309.2 to 1,109.7
Forest product scenario				674.7 to 2,411.4
Forest conservation	Values associated with water recreation, forest conservation			
10% conversion [(b)]			4.7	22.3
30% conversion			5.44	79.6

Source: Updegraff et al. (2004).

[(a)]: Harvested poplar is used for electricity; under forest product scenario, harvested poplar is used for wood industry.

[(b)] 10% of cropland in watershed is converted to SRWC (hybrid poplar) versus 30% conversion rate.

The overall mean of environmental benefits from this study ranged from $45 to $96 per hectare. However, if offered to farmers as subsidies, these would still not offset their net losses, given current production costs and market prices. The analysis also showed that the carbon sequestration and emissions offset values of tree plantations outweigh other environmental benefits, so the market value of carbon emission offsets will likely play an important role in determining the economic magnitude of SRWC's environmental benefit.

In summary, SRWC have been successfully grown in many parts of the country, but most of these plantations are harvested for uses other than bioenergy. The economics of SRWC are not favorable for bioenergy use under current market prices, yields, and harvesting technologies.

SRWC typically face strong price competition from the pulp/paper industry, which faces a shortage of supply from traditional sources of pulp logs. SRWC also face price competition from lower cost fossil fuels (coal, natural gas) in the biopower market, including biomass co-firing. Only rising energy prices and policy-induced disincentives for fossil energy could tip the balance in favor of biomass and SRWC as the source of fuel for biopower generation. In the long run, improvements in yield and harvest technology are likely to play a bigger role in reducing unit costs of SRWC. However, SRWC markets will evolve slowly given the longer harvest cycles of SRWC relative to other energy crops. Moreover, new business models and contractual arrangements will have to be developed between growers-aggregators and end-users in the bioenergy market.

Conclusions

This report undertook a comprehensive review and synthesis of the literature on biomass feedstock research in the U.S. This effort is the first step toward a broader economic analysis of the cost and availability of biomass feedstock that will be undertaken by the USDA-led Interagency Feedstock Team under the direction of the Biomass Research and Development Board. The report covered all major categories of biomass feedstock, including current (first) generation biofuels (ethanol, biodiesel). However, the bulk of the analysis focused on the second-generation biomass feedstocks.

Biofuel markets already exist for the first generation of feedstocks (corn, vegetable oil), so much of the literature has focused on their economics, relative energy efficiency, and carbon balances. Researchers have also delved into current market trends and future growth prospects, particularly in relation to the emergence of second-generation feedstocks and bioenergy markets.

For U.S. ethanol production, the main technologies currently in use involve the conversion of starchy parts of crops, mostly corn. The recent surge in the use of corn ethanol has been spurred largely by the ban on MTBE, enactment of the Renewable Fuel Standard (Energy Security Act of 2005 and the Energy Independence and Security Act of 2007), and the sharp rise in oil prices. In the next several years, corn ethanol production will surpass the current market limit (for non flex-fuel vehicles) of 10% ethanol blend in gasoline.

Higher targets for renewable fuels would favor continued growth of corn ethanol, as would the spread of flexible-fuel vehicles and E85-capable gas stations. The corn ethanol industry could also benefit indirectly from second-generation conversion technologies (notably biomass gasification) by enhancing its energy efficiency and cost effectiveness. Other factors could disfavor corn ethanol. The economics of corn ethanol may be unfavorable vis-à-vis gasoline once we move beyond ethanol blending and into the neat-fuel market environment. Early success in the commercial development of cellulosic ethanol could significantly shift capital investment toward that market. Development of a market for carbon credits and other GHG credits could favor second-generation fuels that have a more benign environmental impact than corn ethanol. Finally, increasing negative public perceptions of corn ethanol on environmental and social grounds (i.e., impact on food supplies globally) could affect public support for the industry.

The growth trajectory of biodiesel in the U.S. is quite different from corn ethanol. First, biodiesel has clearer environmental benefits compared to diesel and even a small blending share (B2) can make a notable difference. Many factors have combined to stimulate biodiesel production over the last few years (from a very low production base)--the Clean Air Act Amendments of 1990, the Energy Act of 2005, the one-dollar-per-gallon subsidy for soy oil-derived biodiesel, and the potential for export to a high-demand European market. However, once the U.S. market is saturated with B2 diesel blends, attempts to expand toward B5 or B10 blends will likely meet serious soybean oil shortages, with significant implications for the soybean market domestically and internationally. By that time, however, second-generation technologies for generating green diesel from a larger base of alternative feedstocks could open up new production possibilities for the fuel.

Second-generation biomass feedstocks are highly varied with different means of production and procurement and have potential as inputs in several end-use bioenergy options. They can also be divided between short-term feedstocks that are readily available (byproducts of existing production systems and resource streams) and long-term feedstocks that would take time to become established. Among the short-term feedstocks, agricultural residues, forestry biomass and urban waste are expected to play an early role in the development of the cellulosic ethanol industry or could be used for biomass-based power.

Agricultural crop residues are the biomass that remains in the field after the harvest of agricultural crops. Research suggests that corn stover could be a major (if not sole) feedstock source to meet the need of biorefineries in the Midwest. However, most other regions will require more than one source of agricultural residues if and when biorefineries are established. Soil conservation constraints limit the amount of corn stover that can be safely recovered to 30 percent or less of total production, given current practices. This rate could be even lower if constraints other than soil erosion are taken into account. The economics of corn stover depend on whether land rents and transportation costs are included. The infrastructure and logistics required to transport large quantities of crop residues to cellulosic ethanol and biopower plants may be lacking.

Forest resources offer substantial opportunities for biomass applications. Today, forest resources for biomass are mostly used by the pulp and paper industry to produce heat and power for onsite use. The viable and sustainable use of forest residues for energy production faces technical and economic challenges. Depending on the location and available collection/transportation technologies, the economics of forest residue recovery for biomass are not competitive under current market conditions.

As biomass markets develop, the economics of using forest residues for biopower or biofuel plants will vary from one locality to another and will likely be influenced by biomass resource availability in the region beyond just forest biomass. Use of forest residues for biopower is viable only if the cost is competitive with coal fuel. Accounting for social and environmental benefits (carbon credits) could also improve forest biomass competitiveness. Advances in thermochemical conversion efficiency and development of small-scale conversion facilities using gasification and/or pyrolysis may favor the use of forest residues for biofuel production, including the option of onsite densification.

Forest biomass resources from fuel treatments or forest thinnings to protect against wildfire in the Western U.S., still face considerable economic, technical, and resource constraints. This makes it difficult to predict how much of the estimated potential resources are actually recoverable. Future viability of this biomass resource will depend on further advances in harvesting, hauling, and processing machinery and more creative contractual arrangements for recovery of the woody materials.

Urban wood waste and secondary mill residues represent other sources of biomass that can be used for electricity generation, either in stand-alone or co-fired plants. Secondary mill residues are made up of sawdust, shavings, turnings, and trims that are byproducts of the manufacture of wood products. However, despite a number of assessments of urban woody resources, there is still a lack of reliable data on delivered prices for many urban wood resources. Other urban waste resources, like organic materials in landfills, can also serve as biomass feedstock for cellulosic ethanol production, or as sources of methane gas for renewable electricity. All these residues could provide significant supplementary low-cost biomass resources procured locally. In some cases (e.g., organic matter in landfills), these sources could even be free. There are also unresolved issues concerning the quality and usability of municipal solid wastes as feedstocks for bioenergy.

In the long run, a viable option for large-scale biofuels production is the cultivation of dedicated energy crops. A steady supply of uniform biomass of consistent quality is critical to the economic viability of cellulosic ethanol production. Both herbaceous energy crops (such as switchgrass) and short-rotation woody crops (such as willows, poplars) are potential biomass sources.

Research on grassy energy crops in the U.S. has focused on switchgrass, given its demonstrated yield and adaptability potential. However, there are other species that are more suitable candidates under specific local soil and climatic conditions. In addition to basic research on yield and management, more information is needed on conditions for successful adoption of future energy crops by growers. Besides profitability, other adoption factors include adaptability of energy crops to existing farming practices, machinery, time allocation and farming know-how. Moreover, the expansion of herbaceous energy crops such as switchgrass and other species could significantly change the existing crop rotation patterns in some U.S. regions.

Short-rotation woody crops (SRWC) such as willow, poplar, cottonwood, sycamore, and southern pine are considered potential sources of biomass to support cellulosic ethanol, biopower, and bioproduct markets. Hybrid poplars and willows have been studied in the U.S. since the 1980s, and southern pine productivity has been studied for several decades. Thousands of hectares of commercial plantations exist, providing information about yields, propagation techniques, variety development, and best-management practices.

Most SRWC are currently harvested for uses other than bioenergy as the economics of SRWC biomass are not yet favorable compared to alternative uses such as in the pulp and paper industry. Changes in the pulp and paper industry will likely affect the competition for wood from SRWC plantations. Under existing price and market structures, studies have shown SRWC fuelwood to be noncompetitive with coal for power production, the dominant fossil fuel in U.S. electricity generation.

However, continued rises in energy prices and policy incentives that favor renewable over fossil energy sources could favor SRWC, and biomass feedstocks more broadly. Of particular relevance is the implementation of the Renewable Portfolio Standard (RPS) by 22 States. Incorporating environmental benefits such as carbon credits or reduced gas emissions into the market valuation of biomass feedstocks would further improve the competitiveness of SRWC and stimulate its use. But the relative competitiveness of SRWC for biomass will still be dictated by local conditions and will likely vary from region to region. In the long run, yield improvements and more efficient harvest technology are likely to play a bigger role in reducing SRWC unit costs.

Another important consideration for energy crops (e.g., switchgrass, poplar, and willow) is the potential for great strides in increasing yields and developing other desirable characteristics. Future energy crops are essentially unimproved or have been bred only recently for biomass, whereas corn and other commercial food crops have undergone substantial improvements in yield, disease resistance, and other agronomic traits. A more complete understanding of biological systems and application of the latest biotechnological advances will accelerate the development of new biomass crops with desirable attributes. These attributes include increased yields and usability, optimal growth in specific microclimates, better pest resistance, efficient nutrient use, and greater tolerance to moisture deficits and other sources of stress. Agronomic and breeding improvements of these new crops could provide a significant boost to future energy crop development under much improved supply economics.

The development of dedicated energy crops, whether herbaceous or woody, will take time given their long production cycles. Initial acreage expansion--even under favorable market conditions--will still depend in part on how fast seeds, seedlings, or cuttings can be made available. Other considerations include the regional availability of alternative feedstocks, the pace and scale of regional biorefineries and biopower establishments, and the extent of local infrastructure for handling large quantities of biomass from field to conversion facility.

Overall, this report reveals the complexity of multiple biomass feedstocks and their role in future bioenergy systems. While it is important to gain detailed understanding of specific feedstocks, their characteristics, modes of production, and their supply economics, many key issues cut across multiple biomass feedstocks. Among these are transportation and infrastructure, risk management, and business models for feedstock procurement. Consequently, biomass economics can be approached systematically, using a supply-chain model that allows for many feedstock sourcing options.

Feedstock supply is inherently regional. The local distribution of a biomass feedstock, and the relative importance of one type over another, will determine what types of bioenergy opportunities are likely to emerge under favorable market conditions. Other determining factors include regional demand, local resources (e.g. water, soil), enabling infrastructure (e.g., transportation), and competing demands for biomass. A key determinant for biomass supply is an infrastructure that ensures economically viable feedstock logistics and handling from farm to conversion facility.

The starting point for feedstock procurement is the local biorefinery and the type of conversion technology used. Biomass end-users (biorefineries or biopower facilities) are likely to approach feedstock as a stream of different types procured together or at different times. Other factors likely to affect local biorefinery installation include availability of labor and equipment resources in sufficient quantities and at reasonable costs. Given the significance of feedstock production, handling and transportation costs in the economics of bioenergy production, one approach to better understand the supply economics of feedstocks is to carry out an integrated geographic analysis of feedstock cost and availability within a particular region. Such an approach would help identify which feedstocks are available at what price, and whether competing end-use markets would prevail in drawing away these feedstock resources.

Managing risk is another determinant in local biomass market development. Risk mitigation largely dictates where to site the biorefinery to begin with. Factors at play include the relative abundance of local feedstock sources as well as weather conditions that ensure continuity of biomass supply (or ensure alternative feedstocks to prevent supply disruptions). Risk management also dictates the contractual arrangements required between growers and end-users and the role of the intermediary (aggregator). Long-term contracts could reduce supply uncertainty as future price changes could alter the incentives to supply feedstock for biomass.

Well-established local production of a dedicated energy crop with secured long-term supply commitments is an important prerequisite to risk mitigation and overall viability of any bioenergy facility. Even when local biorefineries or biopower facilities have access to locally produced SRWC, feedstock procurement will most likely be based on multiple sourcing of different types of biomass feedstocks as a key lever in risk management. Such multiplicity of sourcing will dictate the nature and shape of the logistic infrastructure likely to emerge regionally.

Sustainability concerns are also important to local biomass markets. Water availability is an obvious consideration: both the quantity of water used and impact on local water quality are important considerations, and in some cases, may prevent a biorefinery establishment. Fertilizer use is a concern because runoff into streams and rivers contributes to eutrophication. The amount of agricultural residue removed is dependent on the residual amount necessary for soil conservation purposes. Forest residue harvests for biomass also need to factor in soil nutrient management for long-term soil productivity. Also, converting CRP or other available lands to croplands can affect conservation goals. To fully gauge the environmental impact, more standardized lifecycle analyses are needed to derive carbon and other greenhouse gas emission reductions, along with the full range of environmental impacts, for various combinations of biomass-bioenergy systems.

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Appendix A

Biomass Conversion Technologies

This appendix provides a brief overview of the various conversion technologies that use biomass. Technologies covered include corn-ethanol, first-generation biodiesels, cellulosic ethanol, thermochemical processes for advanced fuels, and biomass use for power generation such as co-firing, co-generation and bioproducts. The purpose of this overview is to provide a link between the multiple bioenergy applications and the various types of biomass feedstock materials covered in this report.

A.1 Corn Ethanol Process

Ethanol production from dry corn milling follows a seven-step process: milling, liquefaction, saccharification, fermentation, distillation, dehydration, and denaturing (Kim and Dale, 2005b. First, corn feedstock is ground into corn meal (milling); then transferred to a liquefaction tank (slurried with water—mash); enzymes are then added to “mash” to convert starch into a simple sugar (dextrose) (saccharification); after liquefaction, the mash is cooked in a saccharification tank to reduce bacterial levels and placed in a fermenter where sugar is converted to ethanol by yeast (fermentation); the resulting “beer” containing 2-12 percent ethanol is then distilled into ethanol at 95 percent alcohol and 5 percent water (distillation); the remaining solids (stillage) are collected during distillation, dried, and sold as an animal feed called dried distillers’ grains (DDG). The removal of water from ethanol beyond the last 5 percent is called dehydration or drying (ethanol must be dehydrated to below 1 percent water content before blending with gasoline). For dry-corn milling, the distillation uses 56 percent of total energy consumption, followed by liquefaction/saccharification at 29.7 percent.

In the wet milling process, corn grain is first soaked and steeped in water and dilute sulfurous acid; then light steepwater containing soluble carbohydrates and proteins leached from corn is transferred to a dryer to form corn gluten feed (CGF); after steeping, the corn germ is separated from the corn slurry through a series of grinders (degermination) and the germ sent to a germ dryer from which corn oil is extracted onsite or offsite; next, gluten feed is separated from corn starch and both gluten meal and gluten feed are removed by centrifugation; after washing, corn starch is transferred to a liquefaction tank with the rest of the process steps similar to dry-corn milling. Distillation, gluten feed drying, steeping, and liquefaction/saccharification take up 46, 13.2, 9.6, and 9.3 percent of process energy consumption, respectively; other processes take up less than 5 percent.

Current efforts at improving the corn-ethanol conversion technology are focused on fractionation of corn fiber and corn oil extraction. Fractionation of corn fiber aims at producing additional high-value products. Traditionally, the fiber byproduct of the corn wet milling process is sold as corn gluten feed. But new processes are separating fiber via hydrolysis, producing sugars, cellulose, and fermentation extract. These processes increase the amount of starch available for ethanol production, as well as the protein content of DDGs. Corn oil extraction is a new variation to the wet milling process and consists of removing crude corn oil from the syrup before it is mixed with the grains in the dryer. The extracted corn oil can be used as feedstock for biodiesel production. In addition to a new byproduct and higher revenue stream, the process also results in feed co-products with higher protein content and improved flowability.

Another potentially significant change in corn ethanol technology is the improvement of energy efficiency, which is much less than that of alternative ethanol processes such as sugarcane-ethanol in Brazil or the prospective cellulosic ethanol. Currently, some corn ethanol plants in the Midwest are beginning to experiment with onsite biomass gasification facilities to produce steam and power and thus replace the fossil-based process energy (such as natural gas). The Central Minnesota Ethanol Co-op is one example of a corn ethanol plant that has added biomass gasification technology and uses wood waste as biomass feedstock for energy instead of natural gas. Chippewa Valley Ethanol Co. is also building a biomass gasifier, designed to operate on a range of feedstocks including corn stover, distillers dried grains, corn, wheat straw, and wood wastes.

A.2 First-Generation Biodiesel

Biodiesel is an ester that can be made from substances such as vegetable oils and animal fats. The most popular process is *transesterification* (production of the ester) of vegetable oils or animal fats, using alcohol in the presence of a chemical catalyst. About 3.4 kg of oil/fat are required for each gallon of biodiesel produced (Baize, 2006). The transesterification of degummed soybean oil produces ester and glycerin. Glycerin is used in a variety of industrial products such as hand creams, toothpaste, motor lubricants, and aircraft de-icing solvent. For every 100 units of biodiesel fuel, 11 units of glycerin are produced (Coelho and Goldemberg, 2004). A recently developed process transforms glycerin into propylene glycol – a deicer (ice remover) with many applications, including antifreeze for the automobile industry. These developments would open up a large market for the biodiesel byproduct, potentially solving the problem of excess glycerin supply (*Biodiesel Magazine*, 2006).

A.3 Biochemical Conversion to Cellulosic Ethanol

The cellulosic ethanol process converts the cellulosic and hemicellulosic components of trees, grasses, or residues into sugars and then ferments the sugars into ethanol. A wide array of feedstocks could be used, including tree species (poplar, willow, silver maple, and black locust), wood residues (sawdust), construction site residue, municipal solid waste (MSW), paper and sewage residues, agricultural residues (corn stover, corn and sugarcane processing residues, cereal straw), and grasses (switchgrass, sorghum, reed canary grass, Miscanthus).

Biomass feedstock offers the required lignocellulosic material for cellulosic ethanol. Lignocellulose is composed of carbohydrate polymers (cellulose and hemicellulose) that can be hydrolyzed to simpler sugars then fermented to ethanol. A key step of this process is the pre-treatment of biomass (using chemical or acid-based methods) to “soften up” the chemical bonds within the cellulose and hemicellulose to facilitate the enzymatic hydrolysis (breaking down) of the polymers into simpler sugars. The lignin (or woody part) is not fermentable and is typically combusted to produce steam or electricity. Lignin could also be gasified to produce biofuels or processed into biomaterials.

Currently, cellulosic ethanol production is not yet commercially operational, and production costs are still high relative to starch or sugar ethanol processing. More advances in pre-treatment technologies are required to overcome the “recalcitrance” of cellulose and hemicellulose. More broadly, the growth and expansion of cellulosic ethanol technology will hinge on continued R&D to reduce unit costs and improve fermentation rates and yields, with specific efforts geared toward improvement of individual process steps (biomass pre-treatment), further process integration, and reducing the cost of enzymes.

The main barriers to commercially viable cellulosic ethanol production are high capital requirements and feedstock costs. According to plant-level cost estimates for cellulosic ethanol production in 2006, $250-$300 million in capital investment is projected for a 30-million-gallon/year (Solomon et al., 2007). DOE estimates that with current technology, cellulosic ethanol costs over $2.50 per gallon to produce (close to $1 higher than corn-ethanol under modest corn prices), but cost savings due to advances in technology could cut costs by over 50 percent.

Reducing these costs is critical for future economic viability of the cellulosic ethanol industry. Moreover, a viable cellulosic ethanol plant will require not only an affordable supply of feedstock, but also a reliable supply stream, with uniform quality and desirable characteristics. As the industry moves toward commercialization, some biomass feedstock types will become more readily available than others. Agricultural residues, forest residues and urban wood waste are considered “readily” available in the short run, while dedicated energy crops such as switchgrass and short-rotation tree plantations will take time to develop.

A.4 Thermochemical Conversion to Biofuels and Chemicals

An alternative route for turning biomass into advanced fuels, power, and biochemicals is thermochemical conversion, which can come from gasification or pyrolysis.

Gasification is thermal decomposition in an oxygen-limited environment. Gasification technology converts biomass into a fuel gas (syngas) consisting of hydrogen (H_2) and carbon monoxide (CO). The syngas can be burned in a gas turbine to generate electricity or it can be catalyzed to synthesize transportation fuels or chemicals. This conversion process, also known as gas-to-liquid (or Fischer-Tropsch), produces synthetic liquid transportation fuels, including diesel, methanol, di-methyl ether, and hydrogen.

Pyrolysis is thermal decomposition occurring in the absence of oxygen (Bridgewater, 2007). Fast pyrolysis is a variation of the pyrolysis process with the aim to produce a liquid fuel (bio-oil) that is easier to transport than low-density raw biomass. Under the right combination of both temperature (500^oC) and hot vapor residence time, fast pyrolysis can be performed producing bio-oil at a yield of up to 75 percent by weight on dry-feed basis. Fast pyrolysis requires feedstock that is less than 10 percent water and finely ground (to around 2 mm particle size). Virtually any form of biomass can be used for fast pyrolysis, even though most work has been performed on wood materials. Bio-oil can also be upgraded into transportation fuels via gasification or by processing in conventional oil refineries. A key advantage of fast pyrolysis is the scale and decentralized nature of the operation, which can be located near the biomass resources, producing intermediate fuel (bio-oil) that is more economical to transport than bulk and low-density biomass feedstock.

Like the biochemical process for cellulosic ethanol, thermochemical technology also faces technological and capital hurdles. However, thermochemical conversion has several advantages over biochemical conversion. First is the possibility of producing a range of clean transportation fuels. Second, the thermochemical pathway is less demanding on the feedstock side--both in terms of homogeneity and uniform quality (except for the requirement of low-moisture materials)--the biochemical/fermentation process. Third, thermochemical conversion is more readily scalable, enabling small-scale biomass processing (for example, via fast pyrolysis), whereas biochemical conversion is optimal only for large-scale operations. On the other hand, cellulosic ethanol, using the biochemical and fermentation route, holds greater promise for technological strides and cost reductions thanks to the leveraging of advances in biotechnology techniques.

A major potential application of thermochemical conversion technology is the development within the U.S. pulp and paper industry of future gasification-based “biorefineries” (Larson et al., 2006). A biorefinery is where fuels, electricity, and chemicals can be produced optimally from biomass according to technical, economic, and environmental criteria (DOE, 2004). Given the amount of biomass energy used by the U.S. pulp and paper industry, potential biofuel production from this source could be substantial. In 2004, biomass energy consumed at pulp mills in the U.S. was estimated at 1.3 quads (or 10^{15} BTU). Moreover, much of the U.S. pulp and paper industry faces the prospect of renewing its aging current technology (Tomlinson boilers) over the next 10-20 years, offering an opportunity to introduce black-liquor gasifiers (EPRI, 1997; Larson et al., 2006). As such, the U.S. pulp and paper industry has the potential to make a significant contribution toward bioenergy production. Proof-of-concept designs have been carried out in many pulp and paper mills yielding technical performance data, costs of production, and rates of return on investments (Larson et al., 2006). The biorefinery process produces liquid fuels and chemicals via gasification of black liquor or woody residues at pulp and paper mills, along with process steam for the mill, some electricity, and one of several possible fuels (F-T synthetic crude oil, demithyl ether, ethanol-rich alcohol product).

A.5 Biomass Feedstock for Biopower

Beside advanced fuels, biomass can also be used for the production of biopower. This can be done in several ways, including direct combustion of biomass in dedicated power plants, co-firing biomass with coal, biomass gasification in a combined cycle plant to produce steam and electricity, or via anaerobic digestion (EPRI, 1997).

Combustion is the burning of biomass in air. This involves the conversion of chemical energy stored in biomass into heat, mechanical power or electricity (McKendry, 2002). While it is possible to use all types of biomass, combustion is preferable when biomass is more than 50 percent dry. High-moisture biomass is better suited for biological conversion processes. Net bioenergy conversion efficiencies for biomass combustion power plants range from 20 percent to 40 percent. Higher efficiencies are obtained with the combined heat and power (CHP) facilities and with large size power-only systems (over 100 MWe), or when the biomass is co-fired with coal in power plants (McKendry, 2002).

Co-firing biomass with coal is a straightforward and inexpensive way to diversify the fuel supply, reduce coal plant air emissions (NOx, SO_2, CO_2), divert biomass from landfills, and stimulate the biomass power industry (Hughes, 2000). Moreover, biomass is the only renewable energy technology that can directly displace coal. Given the dominance of coal-based power plants in U.S. electricity production, co-firing with biomass fuel is the most economical way to reduce greenhouse gas emissions. Possible biomass fuel for co-firing includes wood waste, short-rotation woody crops, switchgrass, alfalfa stems, various types of manure, landfill gas, and wastewater treatment gas (Tillman, 2000). In addition, agricultural residues such as straw can also be used for co-firing. (e.g., rice straw in California, alfalfa stems in Minnesota).

Gasification is described above under biofuels production. A promising technology development currently at demonstration stage is biomass integrated gasification/combined cycle (BIG/CC), where a gas turbine converts the gaseous fuel to electricity with a high conversion efficiency, reaching 40 to 50 percent of the heating value of the incoming gas (McKendry, 2002). An important advantage of gasification is the ability to work with a wider variety of feedstocks, such as high alkali fuels that are problematic with direct combustion. High alkali fuels such as switchgrass, straw, and other agricultural residues often cause corrosion, but the gasification systems can easily remove the alkali species from the fuel gas before it is combusted. High silica, also a problem with grasses, can result in slagging in the reactor.[1]

Another process route for biomass is the application of anaerobic digestion to produce “biogas” (methane) for electricity generation. Anaerobic digestion involves the controlled breakdown of organic wastes by bacteria in the absence of oxygen. Major agricultural feedstocks for anaerobic digestion include food processing wastes and manure from livestock operations. The Energy Information Agency also projects a significant increase in generation of electricity from municipal waste and landfill gas (EIA, 2006--to about 0.5 percent of U.S. electricity consumption.

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[1] This was one of the reasons rice straw proved a problematic feedstock in gasification reactors (Jeffery Steiner, USDA/ARS, personal communication).

A.6 Biomass for Bioproducts

Current bioproducts are derived mostly from sugars, starch, and lipids. Most current fermentation-based processes use simple carbohydrates like glucose to make specialty chemicals and new polymer blocks. The feedstocks are derived from food processing waste streams and pre-processed starches and are high cost. The growth of fermentation-based polymer building blocks and the production of commodity plastics depends on further technology improvements (Little, 2001).

However, future growth may be through the use of cellulosic materials, the feedstock with the largest potential for chemical production. A key obstacle is the ability to use all constituents of biomass (cellulose, hemi-cellulose and lignin fractions). Research using the tools of biotechnology may enable a broader use of the more recalcitrant fractions of the biomass (hemi-cellulose and lignin) for markets other than biopower (Little, 2001).

The U.S. Department of Energy identified 12 potential biobased platform chemicals for further research and development as part of its “biorefinery” research and development strategy (DOE, 2006). Screened from around 300 substances, these 12 were selected for more focused research to support their perceived role as important building block chemicals that can be produced from sugar biologically and chemically.

Even though several bio-materials have been commercially produced[2], the high cost of these products compared to petroleum-based substitutes is a serious hindrance to market viability.

A.7 Demonstration Plants for Second-Generation Fuels and Feedstock Choices

A close look at the feedstock makeup of the first cellulosic plants currently under construction with DOE financial assistance shows what type of feedstocks are considered initially. In February 2007, the U.S. DOE announced funding of up to $385 million over 4 years for 6 projects to produce more than 130 million gallons/year of cellulosic ethanol. This announcement was heralded as a significant initiative to bring the commercial cellulosic industry into existence. These plants (plus other firms currently operating cellulosic post-pilot scale-up operations) represent the first-generation of the emerging cellulosic ethanol industry.

The plants are dispersed across several regions of the U.S. and use a range of feedstock types (**table A-1**) including agricultural residues, byproducts of food processing, easily accessible wood residues, and urban waste including landfill material. Location and feedstock mix used by these plants reflects availability and proximity of supply.

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[2] Examples of commercial products that use bioenergy or are biobased include biopolymers (PLA, PDO, PHAs) and chemicals (Ethyl lactate, succinic acid, and lactic acid).

Choice of conversion technologies and feedstock mix for each plant are briefly described below:

- POET plans to expand a corn dry-mill facility in Emmetsburg, Iowa to add biochemical conversion (enzyme hydrolysis and fermentation) to produce cellulosic ethanol from corn stover and cobs. Given its location in the heart of the Corn Belt and given that this plant is an expansion of an existing conventional dry corn ethanol operation, POET is tapping into one of the largest feedstock sources currently available in the U.S. Therefore, POET is less concerned about diversifying feedstock types outside corn.

- Abengoa Bioenergy plans to build a plant in Hugoton, Kansas, for cellulosic ethanol using enzymatic hydrolysis/fermentation and a mix of feedstock--corn stover, wheat straw, milo (sorghum) stubble, switchgrass and other feedstocks. Initially, the company considered building a plant in the heart of the Corn Belt, but weather variability and the 1-in-7 probability of a wet harvest season raised the concern about supply disruption for corn stover. The company then settled for a drier area in Kansas with sufficient alternative agricultural residues. The inclusion of switchgrass in the feedstock mix reflects a long-term strategy to add a dedicated energy crop as well as recognizing switchgrass suitability in Kansas, particularly in areas too marginal for traditional cropland production.

- Alico Co. proposed a plant in LaBelle, Florida, to produce cellulosic ethanol and biopower using gasification and fermentation technology from a mixture of feedstock types--urban yard waste, wood waste, vegetative waste, and sugarcane bagasse. In this case, proximity to metropolitan areas will ensure a steady supply of cheap wood waste and help to improve the economics of feedstock input. Including bagasse in the feedstock mix was meant to take advantage of the local sugarcane industry--Florida has 4 cane mills that process more than 2.04 million MT per year. In mid 2008, the project was taken over by one of Alico’s partners, New Planet Energy Florida.

- BlueFire Ethanol, Inc. (Irvine, California), proposes a plant on an existing landfill in Corona, California. The plant will produce cellulosic ethanol through acid hydrolysis and fermentation from landfill biomass, enabling it to tap into a feedstock source virtually cost free. The company’s strategic plan is to specialize, over time, in cellulosic ethanol using landfill feedstocks from various sites within the country. Such a strategy can tap into a potentially large pool of woody and other waste biomass discarded in landfills (Themelis and Ulloa, 2007).

- Iogen’s (Ottawa) plans to build a cellulosic ethanol plant in Shelley, Idaho were suspended in mid 2008; the company now will focus attention on a possible site in Saskatchawan because of attractive Canadian government incentives. The proposed plant will produce ethanol using enzymatic hydrolysis and fermentation from a variety of crop residues, including wheat straw, barley straw, corn stover, rice straw, and eventually switchgrass. This mix of feedstock reflects both the makeup of major crops produced in the area and the need for Iogen to leverage its longstanding expertise in enzymatic fermentation processes specializing in wheat and similar cereal crops. Iogen is set to test and commercially prove its cellulosic technology developed over the years specifically for wheat straw.

- Range Fuels of Bloomfield, Colorado, began construction in November 2007 on a commercial-sized plant in Soperton, Georgia to produce both ethanol and methanol from gasification and catalytic conversion using wood chips and residues from the State's indigenous Georgia pine and other dedicated woody tree plantations.

In summary, three conclusions emerge from the review of these plants. First, unless the plant is located in an area with abundant supplies of a single feedstock type (corn stover in Iowa, pine trees in Georgia), the common strategy is to work with multiple feedstocks. Second, the choice of location may also be dictated by the need to minimize risk (e.g., against weather variability) or to optimize the selected conversion technology. Third, most of the potential feedstocks listed by these plants are immediately available. At the same time, companies are planning to add dedicated energy crops to ensure a sustainable long-term feedstock supply.

Table A-1
DOE-supported cellulosic ethanol plants and feedstock choices

Plant	Location	Size (Mgpy)	Feedstock	Conversion technology	Completion date	DOE funding ($ million)	Observations
POET	Emmetsburg, Iowa	31	Corn stover (cob, stalks)	Enzyme hydrolysis and fermentation	2009	80	corn fractionation; lignocellulosic conversion package developed by Dupont; also collaborating with Novozymes
BlueFire Ethanol	Southern California	19	Waste wood	Acid hydrolysis and fermentation	2009	40	Plant to be located on existing landfill in Corona, California 700 tons per day of sorted green waste and wood waste from landfill as feedstock
New Planet Energy Florida (took over project from DOE grantee, Alico, in mid 2008)	South Central, Florida	20	Wood, ag waste	Gasification and fermentation	2010 or early 2011	33	13.9 million gallons of ethanol to be produced; 6,255 kilowatts of electric power; 8 tons of hydrogen and 50 tons of ammonia per day For feedstock, the plant will use 770 tons per day of yard, wood, vegetative waste, and eventually cane (bagasse)
Abengoa Bioenergy	Hugoton, Kansas	11.4	Corn stover, wheat sraw, etc	Enzyme hydrolysis and fermentation	2011	76	Produce power and feed excess energy to adjacent corn dry mill Use 700 tons per day of corn stover, wheat straw, millo stubble, switchgrass, and other feedstocks
Iogen	Saskatchewan, Canada	18	Ag waste	Enzyme hyrdolysis and fermentation	2010	Will not pursue DOE funding,	Feedstock will include corn stover, wheat straw, barley straw, rice straw, and switchgrass
Range Fuels	Soperton, Georgia	50	Waste wood, energy crops	Gasification and catalytic conversion	2011	76	40 MGPY of ethanol and 9 MGPY of methanol; as feedstock the plant will use 1,200 tons per day wood residue of Georgia pine and other wood energy crops

Appendix B

Sugar-Cane Ethanol: The Brazilian Experience

B.1 Overview

In Brazil, the second largest ethanol producer after the U.S., sugarcane is the dominant feedstock. Production of ethanol in Brazil comes mainly from fresh sugarcane juice (79 percent), with the balance coming from molasses byproducts. The conversion of sugarcane to ethanol has proven least costly compared to other feedstocks used for ethanol. Kojima et al. (2007) reported the financial costs of ethanol production in Brazil ranging from $0.87 to $1.10 per gallon for 2005. Out of a total cost of $1.10, variable costs are 89 cents and fixed costs are 21 cents. One contributing factor to the low fixed cost is that many installations were built with subsidies in the 1980s and are now completely depreciated. These ethanol cost levels are equivalent to gasoline prices when crude oil is $35-$50 per barrel. By comparison, variable costs of corn ethanol in the U.S. average $0.96 per gallon, and fixed costs range from $1.05 to $3.00 per gallon.

Feedstock costs account for 55 to 65 percent of the cost of ethanol production in Brazil (**table B-1**). The cost of sugarcane production is thus critical, and Brazil boasts the lowest production costs for this crop in the world. The simpler processing of sugarcane (compared to starch crops) and the availability of free fuel in bagasse (left over from the sugarcane after sugar juice is extracted) also contribute to the cost advantage of producing ethanol from sugar cane versus other feedstocks. Bagasse can be used as a fuel for heat and power generation, and is significant in the economics and energetics of producing ethanol from sugarcane (**fig. B-1**). The processing of 1 ton of sugarcane produces about 260 kg of bagasse, with 13 percent dry fiber and 50 percent average moisture. Also, about kilojoule (KJ) of steam is obtained from each kilogram of burned fiber. As a result, sugarcane mills and distilleries are nearly entirely self-sufficient in energy, and a few plants sell surplus electricity (Martines-Filho et al., 2006).

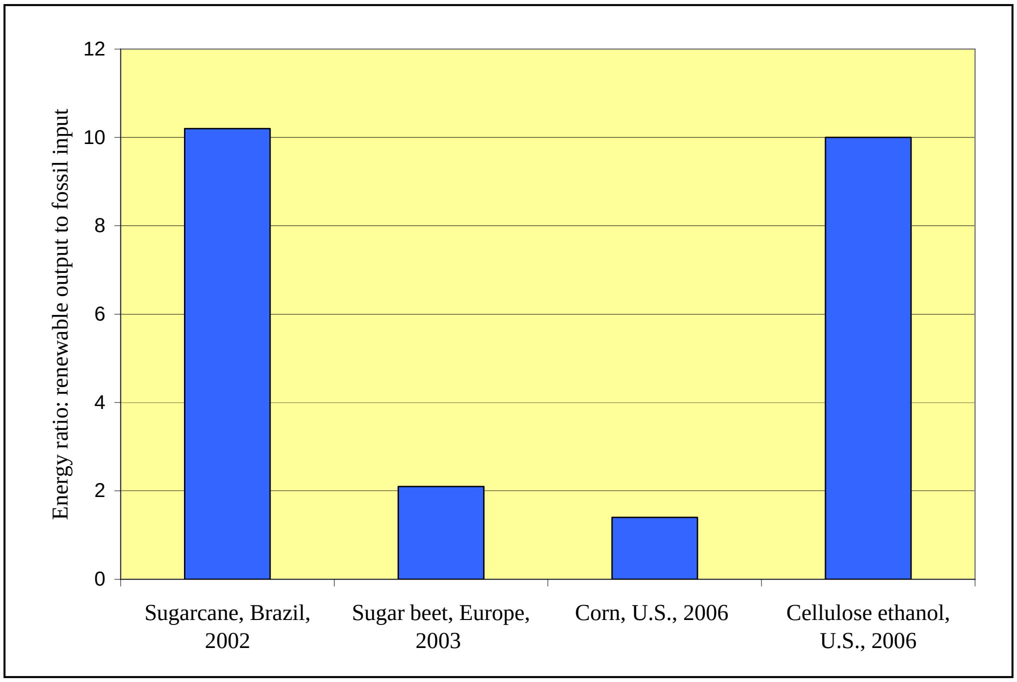
Another feature of sugarcane-based ethanol is the production and disposal of vinasse (the residue liquid from the distillation of ethanol, rich in potassium and organic matter). For each gallon of ethanol sugarcane, distilleries produce 37.9 to 53.1 gallons of vinasse rich in biochemical oxygen. The discharge of so much vinasse into streams is detrimental to the environment. However, applying vinasse to the soil through irrigation has become more common since Brazil has toughened laws against discharge into streams. Filtercake, another sugarcane waste, is also recycled as fertilizer. These practices have resulted in reduced application of fertilizers in Brazil.

Table B-1
Brazil sugar cane processing costs, 2002

	($/gallon)
Operating costs	
Labor	0.0228
Maintenance	0.0152
Chemicals	0.0076
Energy	0.0076
Other	0.0152
Interest payments on working capital	0.0836
Feedstock (sugarcane)	0.4826
Total	0.6346
Fixed Costs	
Capital at 12% depreciation	0.1938
Other	0.0418
Total	0.2356
Total	0.874
Total per gasoline-equivalent gallon	1.292

Source: Fulton (2005).

Figure B-1
Energy balance for ethanol production, by feedstock



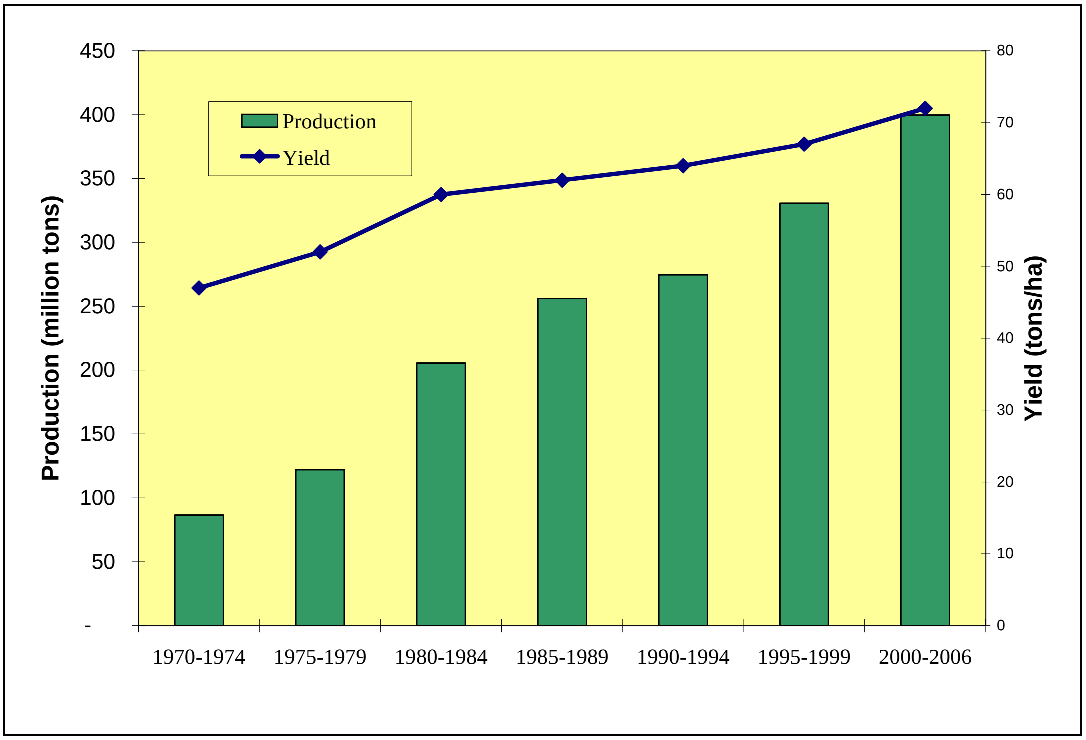
B.2 Brazilian Sugarcane Industry

Ethanol production from sugarcane in Brazil was 4.2 billion gallons in 2006, requiring around 3 million hectares out of a total sugarcane crop area of 5.6 million hectares (for sugar and ethanol) (or 10 percent of total cultivated land in Brazil) (Goldemberg, 2007).

Sugarcane plantations in Brazil are concentrated in the Central South (State of Sao Paulo) and Northeast and have been increasing since the 1970s, mostly through crop substitution (from coffee plantations to sugarcane) and conversion of pasture (Macedo, 2005). In 1975, 91 million tons of sugarcane was produced, yielding 6 million tons of sugar and 145.1 million gallons of ethanol. In 2002, sugarcane production reached 320 million tons, yielding 22.3 million tons of sugar and 3.32 billion gallons of ethanol (Goldemberg et al., 2004).

Sugarcane yields have also been increasing, reaching an average of 70 green tons/ha in 2002[3], compared with 50 tons/ha in the mid-1970s (**fig. B-2**). Nearly all cane fields in the Center-South of Brazil are rainfed. This is a marked advantage over other cane growers that rely on irrigation, such as in Australia and India. Productivity in Brazil has also benefited from decades of research and commercial cultivation. For example, cane growers in Brazil use more than 500 commercial cane varieties that are resistant to many of the 40 or so crop diseases found in the country.

Figure B-2
Brazil sugarcane production and yield, 1970-2006



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[3] With 70 percent moisture level at harvest, 70 green tons/ha amount to 21 dry tons per hectare.

Sugarcane in Brazil also benefits from cheap labor and manual harvesting. Once harvested, the fields are burned to eliminate pests and remove weeds. While burning also makes movement through the field safer and easier, it produces significant greenhouse gases, ash, and other airborne particulates. The harmful environmental effects from sugarcane field burning have prompted the Government to enact laws that will phase out burning in favor of mechanized harvests. Such a shift in sugarcane management will not only ease environmental and air pollution problems, but will also likely change the sugarcane cost structure and displace many workers.[4]

B.3 Brazilian Ethanol Industry

In Brazil, ethanol is used either as an octane enhancer in gasoline[5] in the form of anhydrous ethanol (99.6 percent alcohol and 0.4 percent water) or as fuel in the form of hydrated ethanol (95.5 percent alcohol and 4.5 percent water) for neat-ethanol engines (Martines-Filho et al., 2006). Around 330 sugarcane mill/ethanol plants (with another 89 planned) (Unica, 2006) offer an annual ethanol production capacity of 4.75 billion gallons per year (actual ethanol production in 2005 was 4.43 billion gallons). Of these plants, 50 produce only ethanol and 22 only sugar.

Most plants are sugar mill/distillery complexes, capable of shifting production from 60/40 to 40/60 sugar/ethanol depending on market conditions (Nastari, 2005). Sucrose from sugarcane typically yields 17 percent molasses and 83 percent sugar. Molasses earns only about 10 to 35 percent of the price of sugar. Converting molasses to ethanol, the price of which tends to equal that of sugar, enables the producer to earn the sugar-equivalent price for molasses. In this case, the processor is more likely to extract molasses from sugar, thereby improving sugar quality.

The average ethanol plant in Brazil is about three times smaller than in the U.S., largely because of technical constraints on the storage of sugarcane, which must be processed shortly after harvest to avoid deterioration of the sugar content. A 1.5-million-ton sugar mill will need around 27,000 hectares of sugarcane, most of it within 40 kilometers (25 miles) from the mill (Martines-Filho et al., 2006).

Technological innovations have enabled a nearly three-fold increase in the yield of ethanol produced from sugarcane in Brazil since 1975, when yield was about 527.7 gallons per hectare of sugarcane. By 2004, yield was 1,556.7 gallons of hydrous ethanol, an annual increase of 3.8 percent over 1975-2004 (Nastari, 2005).

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[4] Close to 135,000 or 11 percent of the 1.2 million workers employed in the sugarcane industry (Unica, 2006).

[5] In March 2006, the country's fuel blenders had to cut the ethanol content to 20 percent because of ethanol shortages.

Appendix C

Methane from Manure and Landfills

C.1 Livestock Manure for Methane

Manure represents one of the largest biomass sources from food or feed processing activities. Manure can readily be collected from confined animal feeding operations (CAFOs). On the other hand, manure will need to be handled differently than most other biomass resources, and conversion to methane is closely tied to the manure source (farm). USDA publishes data on manure production on CAFOs (USDA-ERS, 2001.) Using that in addition to studies that estimate the amounts of recoverable nitrogen and phosphorus (Kellogg et al., 2000; Gollehon, 2001), it is possible to determine collectible and recoverable dry weights of manure. Manure quantities available as biomass are the residual in excess of amounts applied onfarm (within EPA mandated criteria). Using this approach, Perlack et al. (2005) conclude that up to 35 million dry tons of manure may be available as biomass each year.

Milbrandt (2005) estimated resource availability for manure in the U.S. using a GIS-based county assessment (**table C-1**). In this analysis, all major livestock categories were included (dairy, beef, hogs, sheep, chickens, and turkey) and data on animal populations by county were obtained from the 2002 ARMS (USDA-NASS). All emissions were calculated by animal type and manure management system using EPA (2005) guidelines. Methane emissions were estimated by county and State, with a U.S. average of 2.2 million metric tons of methane produced annually.[1]

C.2 Methane From Landfills

Part of the methane generated in landfills can be captured and used as a renewable energy source. In contrast, when methane is allowed to escape to the atmosphere, it has a global warming potential that the Intergovernmental Panel on Climate Change (IPCC) estimates to be 23 times greater than that from the same volume from carbon dioxide (Energy Information Agency, 2003).

In 2003, there were 1,767 U.S. landfills (EPA, 2003). In 2000, an estimated 75 percent of the U.S. municipal solid waste was deposited in the 500 largest landfills [U.S. EPA, 2000]. As of December 2005, there were 425 landfills with energy projects producing 10 billion kilowatt-hours of electricity and 230 million cubic feet of landfill gas for direct use per year (U.S. EPA, 2006). Of these, 355 landfills are equipped to recover biogas (methane) (Willumsen, 2003).

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[1] DOE also has thermochemical technology that can directly convert manure slurry to methane and from there to liquid fuels through gasification and running through Fischer-Tropsch conversion.

Table C-1
Estimated quantities of methane from livestock and landfills, 2005

State	Methane from manure mangement	Methane from landfill
	--------------- (1,000 tons/year) ------------------	
Alabama	94	236
Alaska	0	11
Arizona	14	151
Arkansas	145	38
California	142	1,359
Colorado	28	273
Connecticut	0	66
Delaware	0.5	58
District of Columbia	0	0
Florida	19	457
Georgia	139	201
Hawaii	3	58
Idaho	31	7
Illinois	76	974
Indiana	77	526
Iowa	142	137
Kansas	22	139
Kentucky	34	250
Louisiana	6	166
Maine	0.2	27
Maryland	6	204
Massachusetts	0.1	206
Michigan	30	446
Minnesota	71	148
Mississippi	72	93
Missouri	120	273
Montana	4	21
Nebraska	102	48
Nevada	0.4	76
New Hampshire	0	40
New Jersey	0.3	497
New Mexico	60	31
New York	10	885
North Carolina	370	427
North Dakota	4	5
Ohio	41	647
Oklahoma	47	153
Oregon	17	125
Pennsylvania	23	642
Rhode Island	0	28
South Carolina	30	181
South Dakota	36	10
Tennessee	20	274
Texas	58	845
Utah	10	76
Vermont	3	21
Virginia	23	275
Washington	39	240
West Virginia	1	47
Wisconsin	19	273
Wyoming	2	8
U.S.total	**2,192**	**12,379**

Source: Milbrandt (2005).

In 2002, the Earth Engineering Center of Columbia University collaborated with *BioCycle* journal in a nationwide survey of the amount of municipal solid wastes (MSW) generated in the U.S. and its method of disposal. The survey showed that of 305.4 million MT of MSW generated, 26.7 percent was recycled and composted, 7.7 percent was made into energy, and 65.6 percent was landfilled. By comparison, EPA in 2001 estimated total MSW production of 191.8 million MT distributed between recycling (30.8 percent), energy use (12.8 percent), and landfill (56.4 percent) (Themelis and Ulloa, 2007).

The methane emissions from landfills depend on landfill size, total waste, and aridity of location (Milbrandt, 2005). EPA defines a large landfill as containing more than 1 million MT of waste. In assessing the amount of methane emissions from landfills, Milbrandt used data on landfill locations and total waste from 2003. Since methane emissions are higher in non-arid regions, Milbrandt estimated methane emissions separately for arid and non-arid States (**table C-1)**, arriving at an estimated 12.38 million MT of methane emissions for 2003.

New advances in solid waste landfill management, such as bioreactor landfills, are leading to more economical methane utilization. A bioreactor landfill is an MSW landfill that is manipulated with the addition of liquid to facilitate the rapid decomposition of solid waste. EPA research has demonstrated that the rate of methane generation from bioreactor landfills is more than four times higher than from conventional ones. Coupled with an effective gas collection system, bioreactor landfills can enhance energy generation and potentially lower greenhouse emissions.

Appendix D

Regional Developments of Short Rotation Woody Crops

D.1 North Central: Willow

In New York, willow plantations are grown in the central and western part of the state. The biomass is produced for use in coal-fired facilities. The cultivation of willow was revived in upstate NY in the mid-1980s at the SUNY-Environmental Science and Forestry, with the goal of supplying locally produced renewable feedstocks for bioenergy and bioproducts (Volk et al., 2006). About 280 ha of willow were established between 1998 and 2000 in western and central NY. The first commercial harvests of willow biomass crops in North America began in winter 2001-2002. First-rotation commercial-scale harvests of the most consistent clones resulted in average yields of 6.8 MT/ha/year (Volk et al., 2006). A new commercial willow nursery started production in 2005 and is rapidly increasing capacity to meet future demand. New commercial willow biomass crops were planted in 2006 for combined heat and power (CHP) and biorefinery applications, and plans were to plant an additional 136-227 hectares in 2007.

D.2 North Central: Hybrid Poplar

Today, the wood products industry across the Great Lakes States is heavily dependent on aspen and balsam poplar for the production of pulp and oriented strand board, a widely used building material. Minnesota has 14 paper or oriented strand board mills and aspen is the primary feedstock in many of these mills (CRPD, 2001).

But Minnesota has recently begun to experience a shortage of harvest-age aspen. This, plus the potential emergence of a biomass industry that will use SRWC to generate electricity, is favoring the growth of hybrid poplar, considered a suitable substitute for aspen in the manufacture of paper and oriented strand board. The aspen shortage is already being felt as stumpage prices in wood have been rising sharply in the North Central U.S. (from $12.9/MT in 1991 to $103.5/MT or more in 2004) (Berguson, 2005). Price trends for aspen pulp in Minnesota indicate a recent leveling off, though prices are much higher than 8-10 years ago (http://files.dnr.state.mn.us/forestry/um/minnesotaforestresources_rt2007.pdf).

These changing market conditions have stimulated interest in hardwood plantations (poplar) to supply feedstock for paper production. The Minnesota Hybrid Poplar Research Cooperative has an established poplar breeding and field testing program. The program breeds and selects poplar and willow clones. Field trials are conducted at 11 sites, testing over 1,200 clones. Minnesota has also developed best-management practices for hybrid poplar (Updegraff et al., 2004).

Hybrid poplar plantings in the area cover nearly 13,636 hectares, two-thirds of it established by International Paper Company, and 909 hectares are added each year. In addition, 2,727.3 hectares of poplar plantations were established as part of the Department of Energy's Biomass Feedstock Development Program, as well as the Oaklee Project in northwestern Minnesota. In southwest Minnesota, hybrid poplar is also grown in the Minnesota River watershed, and the trees are used for biopower in a 50-MW whole-tree energy power plant in St. Peter. By contrast, plantings in Iowa, Michigan, and Wisconsin have been limited primarily to research and demonstration plantings, with little large-scale commercial activity.

D.3 Pacific Northwest: Hybrid Poplar

The largest hybrid poplar plantations in the U.S. have been established along the Columbia River in northeastern Oregon and southern Washington and are a unique example of intensive wood-crop cultivation (Spinelli and Hartsough, 2006). Hybrid poplar cultivation began in 1993, when the Potlatch Pulp Mill in Lewiston, Idaho, planted 7,818.2 hectares of hybrid poplar to produce pulp logs in response to environmental regulations limiting the supply of public timber (Eaton, 2000). Hybrid poplars are also commercially grown in eastern Oregon and by the GreenWood Resources plantations in western Oregon. A total of 27,273 hectares have been planted in the Pacific Northwest and British Columbia, most of them on sites previously used to provide short fiber for pulp mills.

However, current market conditions favor the shift of hybrid poplar use from pulp into higher value markets such as production of saw logs and veneers. Other opportunities include the market for certified wood and the production of poplars for environmental cleanup. The bioenergy market is still viewed as insufficiently competitive to bid SRWC away from these other uses, without subsidies or technological development (Eaton, 2000).

D.4 Southeast: Pines

The southern pine plantations are the largest intensively managed fast-growing tree crop in the world. Over 9.7 million hectares of plantation pine are currently under management in the U.S. South. Three species dominate in the Southeast: sycamore, sweetgum, and loblolly pine (*Pinus taeda*). Loblolly is the most widely planted tree in the U.S., and its outstanding growth rates place it in contention for SRWC culture in temperate regions. Both sycamore and loblolly seeds are produced in seed orchards, so genetic improvement is highly advanced. Clonal planting stock of sycamore, sweetgum, and loblolly pine will become available as micropropagation techniques become operational, most likely by genetic engineering.

About 15,000 hectares of eastern cottonwoods are grown on relatively short rotations. In the U.S. South, cottonwoods can be propagated effectively in sandbanks along river systems where their root structures are underwater during the spring floods, but these locations are highly limited. For hardwood species in the South, sycamore, willow, or other fast-growing indigenous species will more likely prove effective. A recent revival of hardwood interest is focusing on sweetgums, but pines are getting more attention as a short-rotation crop.

Until recently, there was little interest in growing wood for bioenergy because large amounts of low-grade wood were available at low cost, with no incentives to grow SRWC specifically for bioenergy. However, interest in bioenergy is building--more utilities are using forest residues, and groups such as the Southern Alliance for Utilization of Biomass formed to promote biomass use (Stanturf et al., 2001).

D.5 Florida: Eucalyptus and Pine

Florida's long growing season and abundant moisture favors highly productive short-rotation woody crops. Among the most promising species are cottonwood, slash pine, Leucaena, castor bean, and intensively managed *Eucalyptus* (Stricker et al., 2000). Of the species that can be grown as SRWC in Florida, only cottonwood and slash pine are native. However, Eucalyptus trees grow faster than native tree species in peninsular Florida. Slash pine requires relatively well drained sites and would not be recommended for phosphate clay or poorly drained flatwood soils (Eaton, 2000). In the near term, opportunities for SRWC in Florida and areas with similar climate and soil include two Eucalyptus species (*E. grandis* and *E. amplifolia*), and eastern cottonwood (*Populus deltoids*), all of which regenerate by coppicing[1] after harvest.

Much of the land with potential for biomass production in Florida is presently being used for other economic activities. This includes the construction boom that is bidding land away from agricultural uses. In addition, some of the land is in State and National forests, and other land belongs to timber and paper companies. For land to be shifted to biomass production, the value of biomass would need to rise enough to outbid other uses.

Even so, there are thousands of hectares of land that are potentially available for growing SRWC and other biomass crops in Florida. Two of the most abundant soil types capable of supporting biomass production are the flat and often poorly drained flatwoods and reclaimed phosphate-mined lands in central Florida. Both are primarily used for cattle grazing, but would also be suitable for SRWC (Eaton, 2000). Opportunity costs for much of these lands are low, ranging from $37 to $61.78/ha/yr in central and parts of south Florida, and from $86 to $160 in north and west Florida.

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[1] A method of encouraging regrowth by cutting the stem to near ground level; often used as a method of regeneration that enables the grower to obtain three or four rotations before replanting.

Glossary

Acid hydrolysis: A chemical process in which acid is used to convert cellulose or starch to sugar.

Alcohol: A general class of hydrocarbons that contain a hydroxyl group (OH). There are many types of alcohol (butanol, ethanol, methanol).

Anaerobic digestion: A biochemical process by which organic matter is decomposed by bacteria in the absence of oxygen, producing methane and other byproducts.

Biochemical conversion: The use of fermentation or anaerobic digestion to produce fuels and chemicals from organic sources.

Biodiesel: Transportation fuel derived from transesterification of fatty materials. Biodiesel can be made from rapeseed or other vegetable oils, animal fats, waste vegetable oils, or microalgae oils.

Biofuels: Liquid fuels derived from organic sources (corn, vegetable oil).

Biogas: A combustible gas derived from decomposing biological waste. Biogas normally consists of 50 to 60 percent methane.

Biomass: Any organic-based material that can be processed into energy/biomaterials.

Biomaterials: Products derived from organic (as opposed to petroleum-based) products.

Bio-oil: Intermediate fuel derived from fast pyrolysis.

Biopower: The use of biomass feedstock to produce electric power or heat through direct combustion of the feedstock, through gasification and then combustion of the resultant gas, or through other thermal conversion processes. Power is generated with engines, turbines, fuel cells, or other equipment.

Biorefinery: A facility that processes and converts biomass into value-added products. These products can range from biomaterials to fuels such as ethanol or important feedstocks for the production of chemicals and other materials. Biorefineries can be based on a number of processing platforms using mechanical, thermal, chemical, and biochemical processes.

Black liquor: Solution of lignin-residue and the pulping chemicals used to extract lignin during the manufacture of paper.

Bone dry: Having zero-percent moisture content.

British thermal unit (Btu): A unit of heat energy equal to the heat needed to raise the temperature of one pound of water one degree Fahrenheit at one atmosphere pressure (sea level). 1 Btu = 1055 joules.

Bulk density: Weight per unit of volume, usually specified in pounds per cubic foot.

Carbon dioxide (CO_2): A product of combustion; the most common greenhouse gas.

Carbon monoxide (CO): A colorless, odorless gas produced by incomplete combustion. Carbon monoxide is poisonous if inhaled.

Carbon sequestration: The absorption and storage of carbon dioxide from the atmosphere by naturally occurring plants.

Cellulose: The main carbohydrate in living plants. Cellulose forms the skeletal structure of the plant cell wall.

Cellulosic ethanol: Ethanol derived from cellulosic and hemi-cellulosic parts of biomass.

Chips: Woody material cut into short, thin wafers. Chips are used as a raw material for pulping and fiberboard or as biomass fuel.

Clean Air Act (CAA): National law establishing ambient air quality emission standards to be implemented by participating states. Originally enacted in 1963, the CAA has been amended several times, most recently in 1990. The CAA includes vehicle emission standards, regulating the emission of certain pollutants (lead, ozone, carbon monoxide, sulfur dioxide, nitrogen oxides, and particulate matter). The 1990 amendments added reformulated gasoline (RFG) requirements and oxygenated gasoline provisions.

Closed-loop biomass: Crops grown, in a sustainable manner, for the purpose of optimizing their value for bioenergy and bioproduct uses. This includes annual crops such as maize and wheat, and perennial crops such as trees, shrubs, and grasses such as switchgrass.

Co-firing: Practice of introducing biomass into the boilers of coal-fired power plants.

Conservation reserve program (CRP): Provides farm owners or operators with an annual per-acre rental payment and half the cost of establishing permanent land cover in exchange for retiring environmentally sensitive cropland from production for 10 to 15 years.

Combined heat and power (CHP): A plant designed to produce both heat and electricity from a single heat source.

Combined-cycle power plant: The combination of a gas turbine and a steam turbine in an electric generation plant. The waste heat from the gas turbine provides the heat energy for the steam turbine.

Densification: A mechanical process to compress biomass (usually wood waste) into pellets, briquettes, cubes, or densified logs.

Externality: A cost or benefit not accounted for in the price of goods or services. Often "externality" refers to the cost of pollution and other environmental impacts.

Fast pyrolysis: Thermal conversion of biomass by rapid heating to 450-600 degrees Celsius in the absence of oxygen.

Feedstock: Any material that is converted to another form or product.

Feller-buncher: A self-propelled machine that cuts trees with giant shears near ground level and then stacks the trees into piles to await skidding.

Fermentation: Conversion of carbon-containing compounds by micro-organisms for production of fuels and chemicals such as alcohols, acids, or energy-rich gases.

Fischer-Tropsch fuels: Liquid hydrocarbon fuels produced by a process that combines carbon monoxide and hydrogen. The process is used to convert coal, natural gas, and low-value refinery products into a high-value diesel substitute.

Flexible-fuel vehicle: A vehicle with a single fuel tank designed to run on varying blends of unleaded gasoline with either ethanol or methanol.

Gallon: A volumetric measure equal to 4 quarts (231 cubic inches) used to measure fuel oil. One gallon equals 3.785 liters; 1 barrel equals 42 gallons.

Gasification: A chemical or heat process to convert a solid fuel to a gaseous form.

Gasohol: A motor vehicle fuel that is a blend of 90 percent unleaded gasoline and 10 percent ethanol (by volume).

Gigajoule (GJ): A measure of energy equal to 1 billion joules.

Gigawatt (GW): A measure of electrical power equal to one billion watts (1,000,000 kW). A large coal or nuclear power station typically has a capacity of about 1 GW.

Greenhouse gases: Gases that trap the heat of the sun in the Earth's atmosphere, producing the greenhouse effect. The two major greenhouse gases are water vapor and carbon dioxide. Other greenhouse gases include methane, ozone, chlorofluorocarbons, and nitrous oxide.

Heating value: The maximum amount of energy that is available from burning a substance.

Hectare: Common metric unit of area, equal to 2.47 acres. 100 hectares = 1 square kilometer.

Herbaceous: Non-woody type of vegetation, usually lacking permanent strong stems, such as grasses, cereals and canola (rape).

Higher heating value (HHV): The maximum potential energy in dry fuel. For wood, the range is 7,600 to 9,600 Btu/lb (17.7 to 22.3 GJ/ton).

Joule: Metric unit of energy, equivalent to the work done by a force of one Newton applied over a distance of one meter (= 1 kg m_2/s_2). One joule (J) = 0.239 calorie (1 calorie = 4.187 J).

Kilowatt (kW): A measure of electrical power equal to 1,000 watts. 1 kW = 3,413 Btu/hr = 1.341 horsepower.

Kilowatt hour (kWh): A measure of energy equivalent to the expenditure of one kilowatt for one hour. For example, 1 kWh will light a 100-watt light bulb for 10 hours. 1 kWh = 3,413 Btu.

Landfill gas: A type of biogas that is generated by decomposition of organic material at landfill disposal sites. Landfill gas is approximately 50 percent methane.

Life-cycle analysis: Analysis focused on the environmental impact of a product during the entirety of its life cycle, from resource extraction to post-consumer waste disposal. It is a comprehensive approach to examining the environmental impacts of a product or package.

Lignin: Structural constituent of wood and (to a lesser extent) other plant tissues, which encrusts the cell walls and cements the cells together.

Lower heating value (LHV): The potential energy in a fuel if the water vapor from combustion of hydrogen is not condensed.

Megawatt (MW): A measure of electrical power equal to one million watts (1,000 kW).

Methane: An odorless, colorless, flammable gas with the formula CH_4 that is the primary constituent of natural gas.

Methanol: Also known as methyl alcohol or wood alcohol, having the chemical formula CH_30H. Methanol is usually produced by chemical conversion at high temperature and pressure. Although usually produced from natural gas, methanol can be produced from gasified biomass (syngas).

Methyl tertiary butyl ether (MTBE): An ether manufactured by reacting methanol and isobutylene. MTBE has high octane and low volatility. Used as a fuel oxygenate.

Metric ton: 1,000 kilograms. 1 metric ton = 2,204.62 lb = 1.023 short tons.

MBtu: One million British thermal units.

Municipal solid waste (MSW): Garbage and refuse offering the potential for energy recovery; includes residential, commercial, and institutional wastes.

Neat fuel: Fuel that is free from admixture or dilution with other fuels.

Pyrolysis: The thermal decomposition of biomass at high temperatures (greater than 400° F, or 200° C) in the absence of air. The end product of pyrolysis is a mixture of solids (char), liquids (oxygenated oils), and gases (methane, carbon monoxide, and carbon dioxide) with proportions determined by operating temperature, pressure, oxygen content, and other conditions.

Pulp wood: Roundwood, whole-tree chips, or wood residues that are used for the production of wood pulp.

Quad: One quadrillion Btu (10^15 Btu) = 1.055 exajoules (EJ), or approximately 172 million barrels of oil equivalent.

Syngas: A synthesis gas produced through gasification of biomass. Syngas is similar to natural gas and can be cleaned and conditioned to form a feedstock for production of methanol.

Tipping fee: A fee for disposal of waste.

T value: Tolerable soil loss limits (from erosion) as determined by USDA-NRCS.

Whole-tree harvesting: A harvesting method in which the whole tree (above the stump) is removed.