U.S. DEPARTMENT OF ENERGY

U.S. BILLION-TON UPDATE

Biomass Supply for a Bioenergy and Bioproducts Industry

August 2011

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

U.S. Billion-Ton Update:

Biomass Supply for a Bioenergy and Bioproducts Industry

A Study Sponsored by
U.S. Department of Energy
Energy Efficiency and Renewable Energy
Office of the Biomass Program

August 2011

Prepared by

OAK RIDGE NATIONAL LABORATORY

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Availability

This report, as well as supporting documentation, data, and analysis tools, can be found on the Bioenergy Knowledge Discovery Framework at http://bioenergykdf.net.

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Additional Information

The U.S. Department of Energy, the Office of Energy Efficiency and Renewable Energy, the Office of the Biomass Program, and Oak Ridge National Laboratory provide access to information and publications on biomass availability and other topics. The following websites are available:

http://www.energy.gov/
http://www.eere.energy.gov/
http://www.eere.energy.gov/topics/biomass.html
http://www.ornl.gov/sci/bioenergy/

DISCLAIMER

Although the authors have made every attempt to use the best information and data available, to provide transparency in the analysis, and had experts provide input and review, the readers need to be reminded that the updated *U.S. Billion-Ton Update* is still a strategic assessment, albeit an improved assessment, of potential biomass. It alone is not sufficiently designed, developed, and validated to be a tactical planning and decision tool. Even though the analysis does provide county by county estimates of the feedstocks at a selected cost, these estimates are only useful for strategic assessments. The users are encouraged to use the website and the associated information to better understand the assumptions and ramifications of using the analysis. Furthermore, the updated *Billion-Ton Update* should only be used with other tools and specific data and information for tactical business decisions. When used correctly, the updated *Billion-Ton Update* is a valuable tool.

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The publication of the original *Billion-Ton Study* in April 2005 was heralded as a significant endeavor, providing quantification to speculation and opening up discussion—if not debate—about a contentious topic, the sustainable supply of biomass. More importantly, the report provided a starting point for the evaluation of underlying data and methods. It also established relevance and use of such an analysis in the burgeoning bioenergy community. The report, a national strategic assessment of biomass resources, has had both supporters and detractors, many of whom have provided insightful comments regarding how to improve the report's usefulness. The study leads greatly appreciate those who have provided input and acknowledge the many solicited and unsolicited comments that provided a basis for this report update. The hope, if not the belief, is that the updated study is a better product because of the efforts of all who took time to analyze and comment on the original report.

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As part of the update process, there became an apparent need to understand and project changes in technologies of the future to better develop scenarios. DOE hosted workshops to solicit input from the industrial, academic, and government sectors to help identify potential technology changes in the future and the impacts of biomass availability. The study leads certainly want to recognize and express our appreciation to those who contributed through this process.

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EXECUTIVE SUMMARY

The report, *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply* (generally referred to as the *Billion-Ton Study* or 2005 *BTS*), was an estimate of "potential" biomass within the contiguous United States based on numerous assumptions about current and future inventory and production capacity, availability, and technology. In the 2005 *BTS*, a strategic analysis was undertaken to determine if U.S. agriculture and forest resources have the capability to potentially produce at least one billion dry tons of biomass annually, in a sustainable manner—enough to displace approximately 30% of the country's present petroleum consumption. To ensure reasonable confidence in the study results, an effort was made to use relatively conservative assumptions. However, for both agriculture and forestry, the resource potential was not restricted by price. That is, all identified biomass was potentially available, even though some potential feedstock would more than likely be too expensive to actually be economically available.

In addition to updating the 2005 study, this report attempts to address a number of its shortcomings. Specifically, the update provides:

- A spatial, county-by-county inventory of primary feedstocks[1]
- Price and available quantities (e.g., supply curves) for the individual feedstocks
- A more rigorous treatment and modeling of resource sustainability.

Furthermore, there have been some significant changes in some of the underlying assumptions and analytical approaches used to estimate both the availability and prices of the various biomass feedstocks. This updated analysis stresses the 2012 through 2030 time period and how it corresponds with the implementation of the Renewable Fuels Standard (RFS) and other initiatives.

The report is organized similarly to the 2005 *BTS*, with separate chapters for forest and agricultural biomass resources. It still excludes Alaska, Hawaii, and U.S. territories. Although energy crops are still part of agricultural resources, they are discussed in a separate chapter because of their potential importance. The 2005 *BTS* combined resources that are currently used for energy production with unused and prospective resources because they all counted toward the billion-ton goal. Whereas, in this update, a clearer distinction is made between currently used resources (e.g., corn grain, soybeans, pulping liquors, mill residues, and fuelwood) and unused and prospective resources available for additional energy (e.g., feedstock needed to meet the 16 billion gallons per year (BGY) of cellulosic biofuels and 4 BGY of advanced biofuels). A general background summary is provided in Text Box ES.1.

The report is similar to the 2005 *BTS* in that it only provides estimates of biomass to roadside or the farmgate. The potential biomass inventory at a given spatial scale is biomass in the form and quality of the production system, which is identified in the report for a specific feedstock. It is important to understand that the estimates in the report do not represent the total cost or the actual available tonnage to the biorefinery. There are additional costs to preprocess, handle, and transport the biomass. There may be storage costs for specific feedstocks. Although the estimates do include losses to roadside, the estimates do not include losses due to continued handling, additional processing, storage, material degradation, and quality separation. In effect, for example, more than one billion tons from estimates in the report would be required to have one billion tons ready to process at a biorefinery. The amount would be dependent on many variables in the continued supply chain and final conversion technology. In addition, the biomass is in varied forms and may not be directly comparable at a biorefinery in either cost or conversion efficiency. Determining such values is outside the scope of the report.

[1] A separate database containing the disaggregated biomass supplies by county and state is available through a Web-based Bioenergy Knowledge Discovery Framework (http://bioenergykdf.net) for users to capture, visualize, and analyze information on the complete bioenergy supply chain and the infrastructure needed to support that chain (ORNL, 2010).

This update evaluates two scenarios—baseline and high-yield. The baseline scenario essentially assumes a continuation of the U.S. Department of Agriculture (USDA) 10-year forecast for the major food and forage crops, and it extends an additional 10 years to 2030. The average annual corn yield increase is assumed to be slightly more than 1% over the 20-year simulation period. The baseline also assumes a continuation in trends toward no-till and reduced cultivation. Energy crop yields assume an annual increase of 1%. The 1% change in annual yield in the baseline reflects learning or experience in planting energy crops and limited gains that can be had through breeding and selection of better varieties. The high-yield scenario is more closely aligned to the assumptions in the 2005 *BTS*. In this scenario, higher corn yields and a much larger fraction of crop acres in reduced and no-till cultivation are assumed. Under the high-yield scenario, the projected increase in corn yield averages almost 2% annually over the 20-year simulation period. The energy crop productivity increases are modeled at three levels—2%, 3%, and 4% annually. These gains are due not only to experience in planting energy crops, but also to more aggressive implementation of breeding and selection programs.

The U.S. Department of Energy's (DOE) Office of the Biomass Program sponsored a series of workshops to obtain expert input on barriers and solutions for securing large quantities of biomass feedstocks in the future (U.S. Department of Energy, 2010a). The overall goal of the workshops was to obtain information concerning the development of industry-based, high-yield alternatives to the baseline assumptions used to develop the update. Experts were invited from industry, academia, and government to help identify and quantify high-yield alternative scenarios.

Overall, results of this update are consistent with the 2005 *BTS* in terms of the magnitude of the resource potential. The forest residue biomass potential was determined to be less than the 2005 numbers due to the removal of unused resources and the decline in pulpwood and sawlog markets. The crop residue potential was determined to be somewhat less than what was in the 2005 *BTS* due to the consideration of managing for soil carbon during crop residue removal and not allowing the removal of residue from conventionally tilled acres. The energy crop potential was estimated to be much greater because of higher planted acreage —a result of the spatially explicit land-use change modeling that was used.

Supply/cost curves were derived for each major feedstock. The cost range that was simulated varied significantly across the curves depending on the type of feedstock. For example, the processing wastes were relatively low and had a narrow range that was roughly between $20 and $40 per dry ton.

TEXT BOX ES.1 | BACKGROUND SUMMARY

- Excludes Alaska, Hawaii, and territories
- Includes all major primary and secondary forest and agriculture residue feedstocks, major waste feedstocks, and energy crops grown specifically for bioenergy
- Based on extension of USDA projections
- Baseline uses 1% per annum average yield increases for corn and 1% for all energy crops
- Yield improvements derived from workshop
- High-yield scenario uses 2% yearly increases for corn yield and 2%, 3%, and 4% annual increases for energy crops
- Baseline assumes a continuation in tillage trends; high-yield scenario assumes a much larger fraction of no-till cultivation
- Collection of crop residues prohibited from conventionally tilled acres
- Covers 2012–2030 with summaries for 2017, 2022, 2030
- Crop residue collection and energy crops modeled using POLYSYS
- Energy crops must offer growers higher net returns than commodity crops and pasture they displace
- Forestry analysis exogenous to POLYSYS
- Energy crop potential estimates limit impact on food, feed, exports, and fiber production

On the other hand, the conventionally sourced wood went as high as $100 per dry ton. In this report, it is difficult to present simple summaries for total potential biomass as a function of cost because the feedstock quantities vary so much under the different cost curves. They could easily be shown at various prices—such as, $30, $40, $50 per dry ton and even up to over a $100 per dry ton. In all cases, the price presented includes biomass available up to that price. For convenience and ease in reading, a decision was made to show all feedstocks quantities and their composite total at the $60 per dry ton level in many of the figures and tables in the report. This price was selected because it brings in most of the available tons from all of the feedstocks and because the price represents a realistic, reasonable price for discussion purposes. For example, this price is comparable to the DOE cost targets for cellulosic feedstocks when adjusted to exclude transportation and handling costs (U.S. Department of Energy, 2011). The selection of this price for presentation purposes does not imply that the feedstocks will necessarily be this high or conversely this low. In fact, the market will decide the price based on many variables.

There will also be great variation among the different feedstock prices. The supply/cost curves will be useful in generating total supply estimates under various, individual feedstock assumptions. The tools in the Web-based Bioenergy Knowledge Discovery Framework (KDF) will be useful in generating composite biomass estimates using the various cost curves, as well as presenting total biomass availabilities at selected prices beyond the $60 per dry ton used in the report.

Results under baseline assumptions are presented in Figures ES.1 and ES.2 for forest and agricultural resources, respectively. The figures show four years (2012, 2017, 2022, and 2030) and three prices—$20, $40, and $80 per dry ton for forest biomass and $40, $50, and $60 per dry ton for agricultural biomass. The forest resources are available over a wider price range than the agricultural resources, with increasing quantities at higher prices. Over the estimated price range, quantities vary from about 33 to 119 million dry tons currently to about 35 to 129 million dry tons in 2030. Primary forest biomass (i.e., logging and fuel treatment operations and land clearing) is the single largest source of feedstock. The resource potential does not increase much over time given the standing inventory nature of the resource and how it is managed. Results also show that very little conventional pulpwood is available for bioenergy at prices below (about) $60 per dry ton. The agricultural resources show considerably more supply, with the quantity increasing significantly over time. This increase is due to yield growth, which makes more crop residue available. The increase is also attributed to the deployment of energy crops. Under current conditions, prospective biomass supplies range from about 59 million dry tons at a farmgate price of $40 per dry ton or less to 162 million dry tons at $60 per dry ton. The composition of this biomass is about two-thirds crop residue and one-third various agricultural processing residues and wastes. By 2030, quantities increase to 160 million dry tons at the lowest simulated price ($40 per dry ton) to 664 million dry tons at the highest simulated price ($60 per dry ton). At prices above $50 per dry ton, energy crops become the dominant resource after 2022.

The high-yield scenario assumes a greater proportion of corn in reduced and no-till cultivation and increased corn yields to about double the current rate of annual increase. For energy crops, the high-yield scenario increased the annual rate of crop productivity growth from the 1% baseline to 2%, 3%, and 4% annually. No high-yield scenario was evaluated for forest resources except for the woody crops. Forest residues come from existing timberlands, and there is no obvious way to increase volumes other than reducing the amounts of residues retained onsite for environmental sustainability or decreasing the merchantable utilization requirements—neither option was considered. Figure ES.3 summarizes the estimated quantities of biomass from forest, agricultural, and energy crop resources under high-yield assumptions at the highest simulated price of $60 per dry ton. Results are presented for different assumptions about the annual increase in the rate of growth of energy crop yields (2%, 3%, and 4%). Agricultural residues and wastes are based on higher proportions of reduced and no-till cultivation, as well as higher corn grain yields. Forest residues and wastes are the same as shown in Figure ES.1 and total 100 million dry tons by 2022.

Agricultural residues and wastes are about 244 million dry tons currently and increase to 404 million dry tons by 2030 at a farmgate price of $60 per dry ton. In 2022, the total agricultural resources (crop residues and energy crops) reach 910 million dry tons at the $60 price. Energy crops are the largest potential source of biomass feedstock, with potential energy crop supplies varying considerably depending on what is assumed about productivity. At a 2% annual growth rate, energy crop potential is 540 million dry tons by 2030 and 658 million dry tons if an annual increase in productivity of 3% is assumed. Increasing yield growth to 4% pushes the energy crop potential to nearly 800 million dry tons. Note that at the lowest simulated price of $40 per dry ton, however, the energy crop potential is only 69 million, 162 million, and 261 million dry tons in 2030 at 2%, 3%, and 4% annual yield, respectively. In general, the farmgate or roadside price for feedstock appears to be a larger driver of biomass availability than yield rate increases, although both are important.

It is important to point out the significant role of energy crops. In the baseline, energy crops provide about 37% of the total biomass available at $60 per dry ton and half of the total potential resource. Energy crops are a much smaller fraction of total available biomass at $40 per dry ton. Overall, energy crops become even more significant in the high-yield scenario—providing over half of the potential biomass at $60 per dry ton.

Under baseline assumptions, up to 22 million acres of cropland and 41 million acres of pastureland shift into energy crops by 2030 at a simulated farmgate price of $60 per dry ton.[2] This land-use change is similar in magnitude to the 40 to 60 million acres in energy crops reported in the 2005 *BTS*. At lower simulated prices, total crop and pasture land-use change is much less—about 5.6 million acres at $40 per dry ton and 27 million acres at $50 per dry ton. At the lowest simulated price, land-use change is limited to cropland. Higher simulated farmgate prices move energy crops onto pasture. At this level of land-use change, total feedstock production in the baseline scenario ranges from 34 to 400 million dry tons at simulated prices of $40 to $60 per dry ton, respectively. Under the high-yield scenario with a 4% annual increase in energy crop yields, greater amounts of cropland and pastureland shift into energy crop production. Up to 30 million acres of cropland and 49 million acres of pastureland shift into energy crops by 2030 at a simulated farmgate price of $60 per dry ton. At the lower simulated farmgate prices of $40 and $50 per dry ton, total land-use change is 33 and 44 million acres, respectively. Over the $20 per dry ton simulated feedstock price range, total energy crop production is 261 million dry tons to nearly 800 million dry tons in 2030.

In sum, potential supplies at a forest roadside or farmgate price[3] of $60 per dry ton range from 602 to 1009 million dry tons by 2022 and from about 767 to 1305 million dry tons by 2030, depending on what is assumed about energy crop productivity (1% to 4% annual increase over current yields). This estimate does not include resources that are currently being used, such as corn grain and forest products industry residues. By including the currently used resources, the total biomass estimate jumps to over one billion dry tons and is even higher with more aggressive assumptions about energy crop productivity. The last two figures (Figures ES.4 and ES.5) in this summary bring in these currently used resources for the baseline scenario and the high-yield scenario shown for the $60 per dry ton price and a 3% annual growth in energy crop productivity. For the baseline, projected consumption of currently used resources, the forest residues and wastes, the agricultural residues and wastes, and energy crops show a total of 1094 million dry tons by 2030. This quantity increases by 400 million dry tons if most of the conventionally tilled acres shift into no-till cultivation, corn yields increase to a national average of about 265 bushel per acre, and energy crop productivity increases 3% annually instead of 1% annually. The quantity decreases significantly as the roadside or farmgate price is decreased to $50 and $40 per dry ton.

[2] This feedstock is assumed to be planted on cropland and pastureland. The POLYSYS model, an agricultural policy modeling framework, was used to estimate potential land-use change and potential economic impacts.

[3] The forest landing or farmgate price mentioned throughout this report is a basic feedstock price that includes cultivation (or acquisition), harvest, and delivery of biomass to the field edge or roadside. It excludes on-road transport, storage, and delivery to an end user. For grasses and residues, this price includes baling. For forest residues and woody crops, this includes minimal communition (e.g., chipping).

The results just discussed, along with estimates of currently used resources are summarized in Table ES.1. One important year highlighted in this assessment is 2022—the year in which the revised RFS mandates the use of 36 BGY of renewable fuels. The feedstock shown in the baseline scenario accounts for conventional biofuels (corn grain, ethanol, and biodiesel) and shows 602 million dry tons of potential resource at $60 per dry ton (100 million dry tons of forest biomass, 221 million dry tons of crop residues and other cropland biomass, and 282 million dry tons of energy crops). This potential resource is more than sufficient to provide feedstock to produce the required 20 billion gallons of cellulosic biofuels. The high-yield scenario demonstrates potential at the $60 price that far exceeds the RFS mandate.

As noted at the outset, the results of this updated assessment are consistent with the 2005 *BTS* in terms of overall magnitude. In fact, the scenario assumptions required to show a "billion-ton" resource (i.e., sufficient feedstock to potentially displace 30% or more of the country's present petroleum consumption) are much more plausible. The forest resources take into account sawlog and pulpwood demands, and they factor in a more explicit accounting of resource sustainability. The agricultural resources now take into account soil organic matter in the assessment of crop residue potential and require less significant shifts of land into no-till cultivation. The energy crop potential is formally modeled and accounts for competition among various competing uses of the land. Although the focus is more on the biomass supply and prices, the assumptions used to derive these estimates are tempered from the sustainability perspective. The update is not a quantitative environmental assessment or a comprehensive sustainability analysis, which means that the study does not evaluate a whole suite of sustainability criteria nor assess changes in the indicators as a function of production scenarios.

It should also be stressed that bioenergy markets currently do not exist for the resource potential identified. The analysis and results are based on very limited data and, as such, require making numerous assumptions, and the results can be sensitive to these assumptions, especially with respect to production response to price. While the methods selected to estimate resources were rigorously applied, the estimates rely heavily on the precision of the underlying data and assumptions. However, an effort was made to be as transparent as possible with the data and methodology, as well as assumptions. The underlying assumptions are based on the best available information and grounded in the expertise of the authors. The major assumptions are outlined in the Appendices and the significance of these assumptions is summarized in Chapter 6. This discussion includes the scenarios; tillage and yield for residue producing crops; management practices and inputs for energy crops; modeling of land-use change; markets for roundwood products; and environmental sustainability. Chapter 6 also discusses a number of factors alluded to earlier about tonnage and final product estimates. Finally, Chapter 6 provides a brief summary of data and research and development needs and opportunities for further analysis.

The Bioenergy KDF provides complementary and reference materials, as well as additional data and explanations (ORNL, 2010). The website also provides tools to help present the results in custom tabular, graphic, and spatial formats, as it is impossible to provide this in a reasonable length report. Hopefully in the future, new data and modeling results, as well as analysis tools, will be made available on the website. Users will also be able to post comments, suggestions for additional analysis, and add links to additional information.

Finally, it should be noted that the intent of this report is to update the 2005 *BTS* and change its focus from a strategic assessment to a comprehensive resource assessment. This report is not an economic assessment of the potential impact large-scale collection, growing, and harvesting of bioenergy feedstocks might have on forestry and agricultural (both commodity crops and livestock) sectors of the economy. For the baseline scenario, results do show a loss of commodity crop acres to energy crops and higher commodity crop prices. For crop producers, the higher crop prices could more than compensate for the loss in crop acres, reflecting greater net crop returns relative to the baseline. Higher energy crop price is one of the factors that affects food and feed prices for end consumers. The large-scale deployment of energy crops could require the displacement of tens of millions of acres of cropland and pasture, especially under the high-yield scenario. These potential changes to commodity crop acres and prices are within historical swings. However, the large projected changes in cropland pasture and permanent pasture acres to energy crops would require additional forage through one or more approaches to pasture intensification. As with the 2005 *BTS*, the feedstock potential identified in this report could be realized, assuming an increased investment in research undertaken by the state or private interests, not only in crop yields, but in new, innovative management and production systems, harvesting and collection technology, and the science for sustainable management.

Figure ES.1 Estimated forest biomass under baseline assumptions

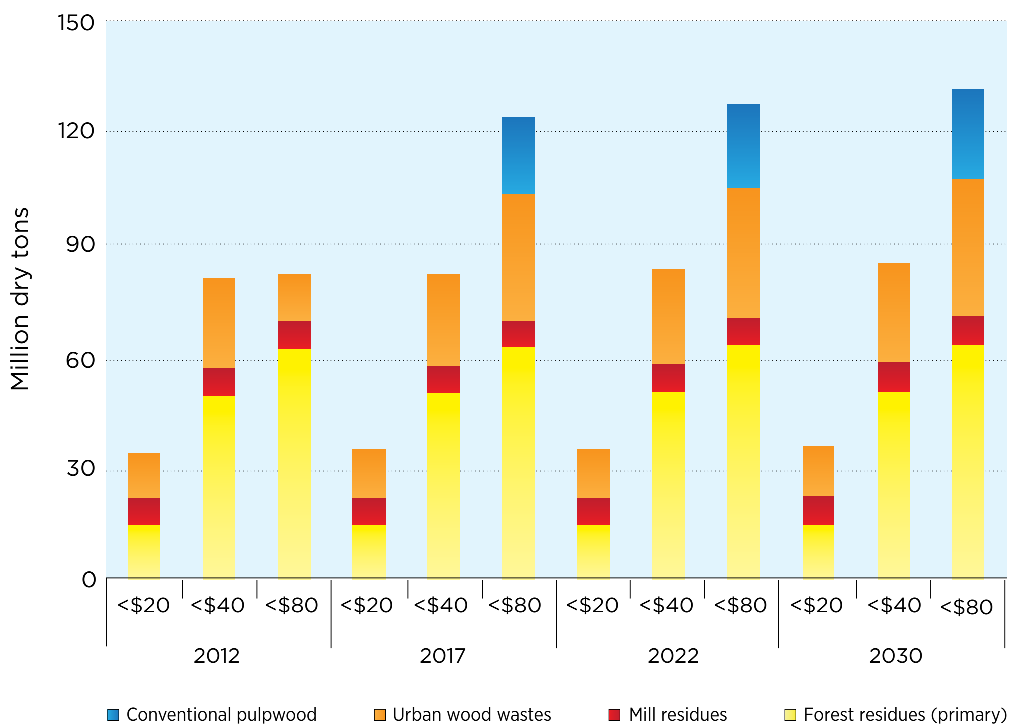

Figure ES.2 Estimated agricultural biomass under baseline assumptions

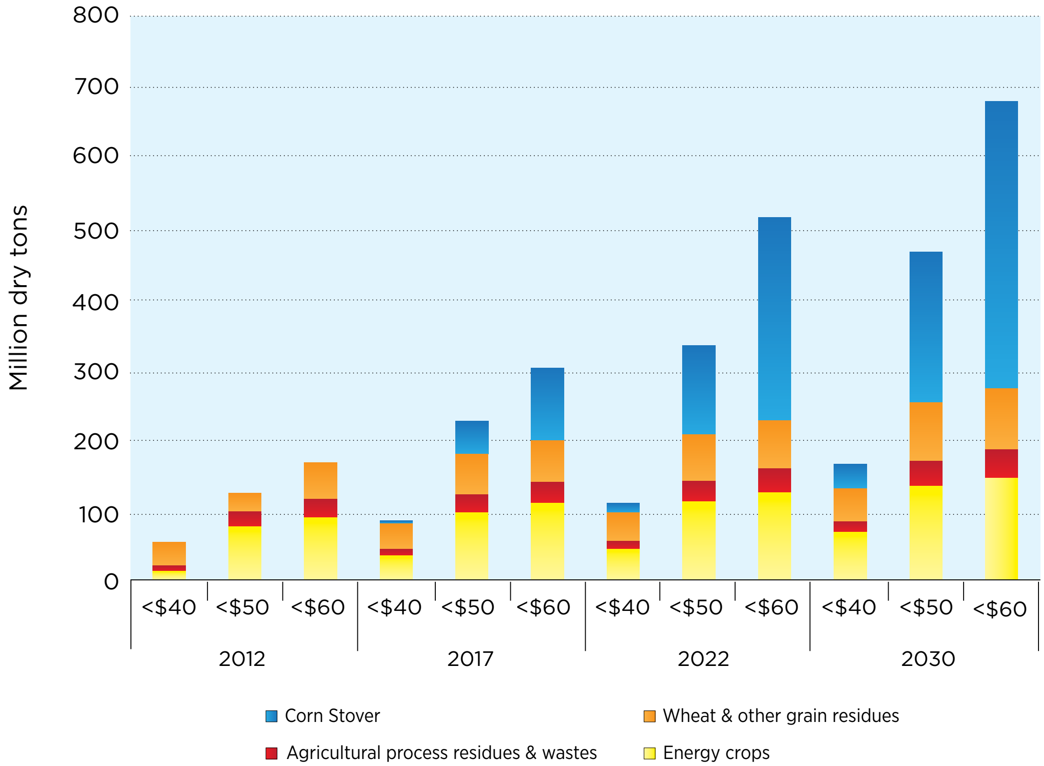

Figure ES.3 Estimated forest and agricultural biomass availability at $60 per dry ton or less under high-yield assumptions

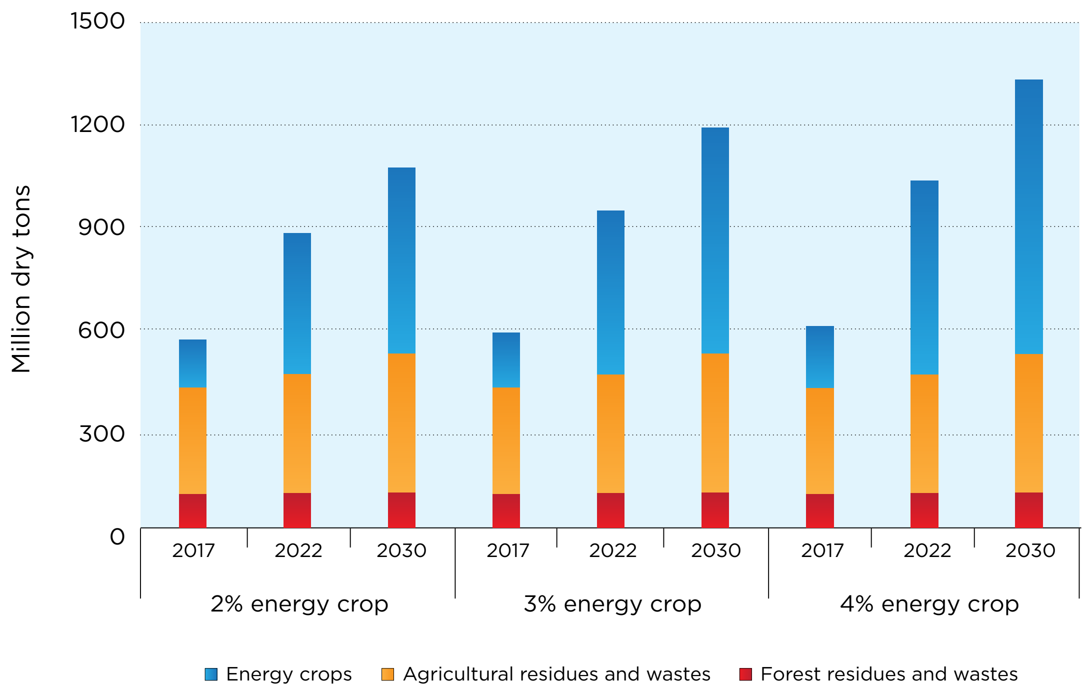

Figure ES.4 Summary of currently used and potential resources at $60 per dry ton or less identified under baseline assumptions

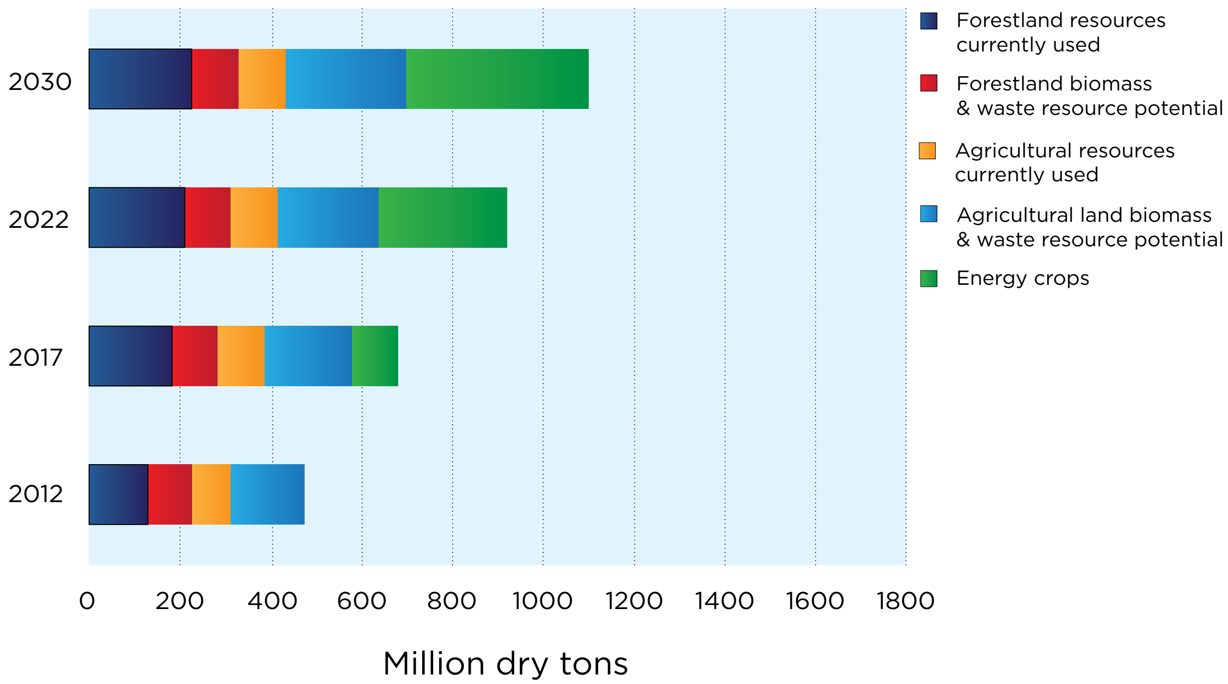

Figure ES.5 Summary of currently used and potential resources at $60 per dry ton or less identified under high-yield assumptions

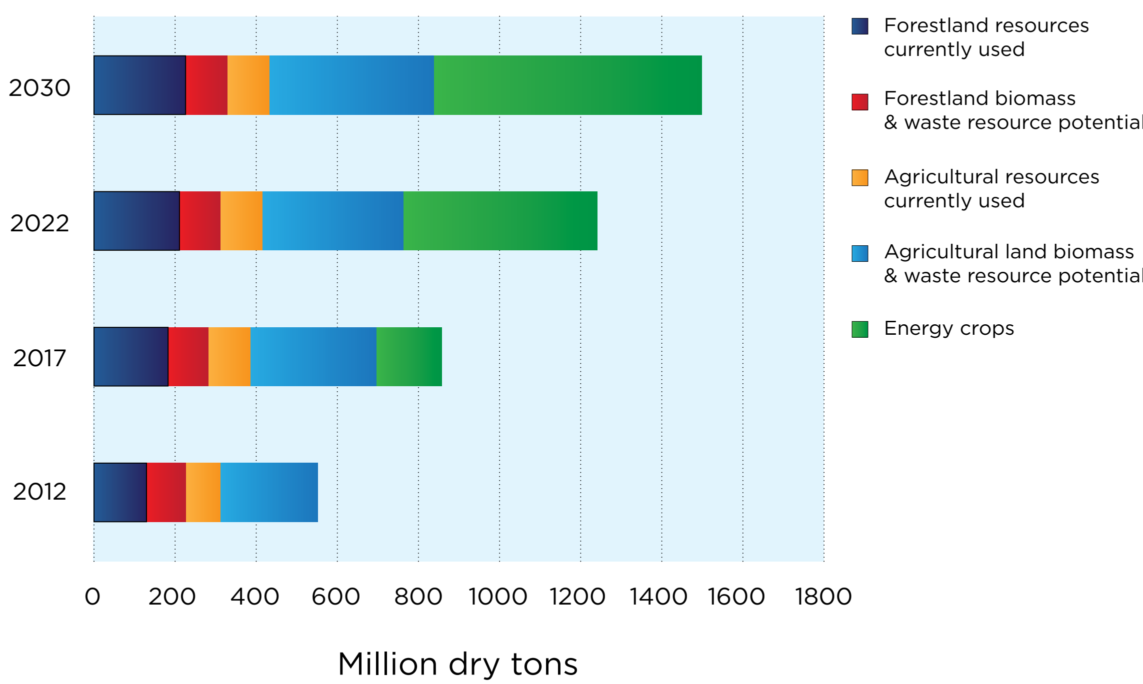

Table ES.1 Summary of Currently Used and Potential Forest and Agriculture Biomass at $60 per Dry Ton or Less, under Baseline and High-Yield Scenario Assumptions

Feedstock	2012	2017	2022	2030
		Million dry tons		
Baseline scenario				
Forest resources currently used	129	182	210	226
Forest biomass & waste resource potential	97	98	100	102
Agricultural resources currently used	85	103	103	103
Agricultural biomass & waste resource potential	162	192	221	265
Energy crops[a]	0	101	282	400
Total currently used	**214**	**284**	**312**	**328**
Total potential resources	**258**	**392**	**602**	**767**
Total – baseline	**473**	**676**	**914**	**1094**
High-yield scenario (2%–4%)				
Forest resources currently used	129	182	210	226
Forest biomass & waste resource potential	97	98	100	102
Agricultural resources currently used	85	103	103	103
Agricultural biomass & waste resource potential[b]	244	310	346	404
Energy crops	0	139–180	410–564	540–799
Total currently used	**214**	**284**	**312**	**328**
Total potential	**340**	**547–588**	**855–1009**	**1046–1305**
Total high-yield (2-4%)	**555**	**831–872**	**1168–1322**	**1374–1633**

Note: *Under the high-yield scenario, energy crops are shown for 2% to 4% annual increase in yield. Numbers may not add up due to rounding.*

[a] Energy crops are planted starting in 2014.

[b] Agricultural residues are generated under a high-yield traditional crop scenario with high no-till adoption (see Table 4.6). Energy crop yield growth follows a baseline growth pattern of 1% annually.

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1 INTRODUCTION

1.1 Background

The report, *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply* (generally referred to as the *Billion-Ton Study* or 2005 *BTS*), was an estimate of "potential" biomass based on numerous assumptions about current and future inventory, production capacity, availability, and technology.[1] The analysis was made to determine if conterminous U.S. agriculture and forestry resources had the capability to produce at least one billion dry tons of sustainable biomass annually to displace 30% or more of the nation's present petroleum consumption. An effort was made to use conservative estimates to assure confidence in having sufficient supply to reach the goal.

The potential biomass was projected to be reasonably available around mid-century when large-scale biorefineries are likely to exist. The study emphasized primary sources of forest- and agriculture-derived biomass, such as logging residues, fuel treatment thinnings, crop residues, and perennially grown grasses and trees. These primary sources have the greatest potential to supply large, reliable, and sustainable quantities of biomass. While the primary sources were emphasized, estimates of secondary residue and tertiary waste resources of biomass were also provided.[2]

The original *Billion-Ton Resource Assessment*, published in 2005, was divided into two parts—forest-derived resources and agriculture-derived resources. The forest resources included residues produced during the harvesting of merchantable timber, forest residues, and small-diameter trees that could become available through initiatives to reduce fire hazards and improve forest health; forest residues from land conversion; fuelwood extracted from forests; residues generated at primary forest product processing mills; and urban wood wastes, municipal solid wastes (MSW), and construction and demolition (C&D) debris. For these forest resources, only residues, wastes, and small-diameter trees were considered. The 2005 *BTS* did not attempt to include any wood that would normally be used for higher-valued products (e.g., pulpwood) that could potentially shift to bioenergy applications. This would have required a separate economic analysis, which was not part of the 2005 *BTS*.

The agriculture resources in the 2005 *BTS* included grains used for biofuels production; crop residues derived primarily from corn, wheat, and small grains; and animal manures and other residues. The cropland resource analysis also included estimates of perennial energy crops (e.g., herbaceous grasses, such as switchgrass, woody crops like hybrid poplar, as well as willow grown under short rotations and more intensive management than conventional plantation forests). Woody crops were included under cropland resources because it was assumed that they would be grown on a combination of cropland and pasture rather than forestland.

In the 2005 *BTS*, current resource availability was estimated at 278 million dry tons annually from forestlands and slightly more than 194 million dry tons annually from croplands. These annual quantities increase to about 370 million dry tons from forestlands and to nearly 1 billion dry tons from croplands

[1] Perlack, R.D., Wright, L.L., Graham, R.L., Turhollow, A., Oak Ridge National Laboratory; Stokes, B., USDA Forest Service; and Erbach, D., USDA Agricultural Research Service. *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply.* ORNL/TM-2005/66, DOE/GO-102005-2135. April 2005.

[2] In this report, primary resources are biomass feedstocks that come directly from either forest or agricultural land and include logging residues and forest thinnings, crop residues (such as stover and straw), and energy crops. Secondary residues are biomass materials that are the result of a processing activity—the generation of residues from sawmills or food processing plants. Tertiary wastes are biomass materials that result from the final consumption of a product, such as urban wood wastes.

under scenario conditions of high-yield growth and large-scale plantings of perennial grasses and woody tree crops. This high-yield scenario reflects a mid-century timescale (~2040–2050). Under conditions of lower-yield growth, estimated resource potential was projected to be about 320 and 580 million dry tons for forest and cropland biomass, respectively. As noted earlier, the 2005 *BTS* emphasized the primary resources (agricultural and forestry residues and energy crops) because they represent nearly 80% of the long-term resource potential.

Since publication of the *BTS* in April 2005, there have been some rather dramatic changes in energy markets. In fact, just prior to the actual publication of the *BTS*, world oil prices started to increase as a result of a burgeoning worldwide demand and concerns about long-term supplies. By the end of the summer, oil prices topped $70 per barrel (bbl) and catastrophic hurricanes in the Gulf Coast shut down a significant fraction of U.S. refinery capacity. The following year, oil approached $80 per bbl due to supply concerns, as well as continued political tensions in the Middle East. The Energy Independence and Security Act of 2007 (EISA) was enacted in December of that year (see Text Box 1.1). By the end of December 2007, oil

TEXT BOX 1.1 | ENERGY INDEPENDENCE AND SECURITY ACT (EISA) 2007

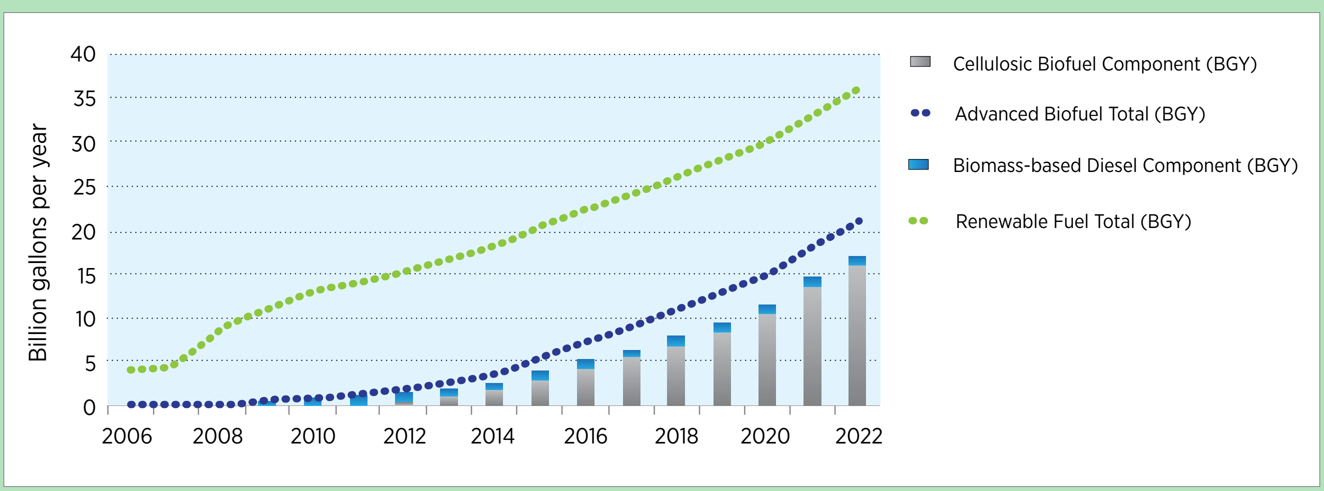
The law contains a number of provisions to increase energy efficiency and the availability and use of renewable energy. One key provision of EISA is the setting of a revised Renewable Fuels Standard (RFS). The revised RFS mandates the use of 36 billion gallons per year (BGY) of renewable fuels by 2022. The revised RFS has specific fuel allocations for 2022 that include use of:

- 16 BGY of cellulosic biofuels
- 14 BGY of advanced biofuels
- 1 BGY of biomass-based biodiesel
- 15 BGY of conventional biofuels (e.g., corn starch-based ethanol).

EISA legislation (see, 42 U.S.C. 7545(o)(2)) also established new definitions and criteria for both renewable fuels (e.g., greenhouse gas reduction thresholds) and the renewable biomass used to produce the fuels. Renewable biomass generally includes:

- Crops from previously cleared non-forested land
- Trees from actively managed plantations on non-federal land
- Residues from non-federal forestland that is deemed not to be critically imperiled or rare
- Biomass from the immediate vicinity of buildings or public infrastructure at risk from wildfires
- Algae
- Separated yard or food waste.

Excluded from the qualifying renewable biomass are resources from ecologically sensitive or protected lands, biomass from federal forestlands, biomass from newly cleared or cultivated land, and merchantable biomass from naturally regenerated forestlands (see, 42 U.S.C. 7545(o)(1)(I)).



prices surpassed $100 per bbl for the first time, and by mid-summer 2008, prices approached $150 per bbl because of supply concerns, speculation, and weakness of the U.S. dollar. As fast as they skyrocketed, oil prices fell, and by the end of 2008, oil prices dropped below $50 per bbl, falling even more a month later due to the global economic recession. In 2009 and 2010, oil prices began to increase again as a result of a weak U.S. dollar and the rebounding of world economies.

Other legislation has had impacts since 2005, as well. The 2008 Farm Bill, also known as the Food, Conservation, and Energy Act of 2008, provides for 11 programs (although not all have been funded) for renewable energy, biobased products, and bioenergy. Furthermore, the Farm Bill provides for "advanced biofuels," which are biofuels other than corn-kernel based, and provides funding for using biomass for power or heat. The Farm Bill also makes incentives available for the production of biomass through the Biomass Crop Assistance Program. The American Recovery and Reinvestment Act of 2009 provided additional funding for biorefineries and other clean energy initiatives. In effect, since the *BTS* was published, America has seen an expansion in financial support for renewable energy and has had both legislative and executive actions that support all types of renewable energy, including biomass. The emphasis has shifted to cellulosic biofuels and to the use of biomass for an array of products, including electricity and thermal applications.

In addition to cellulosic biofuels and the RFS, there has also been interest in developing a national RPS (renewable portfolio standard) to generate electricity from renewable energy, including biomass. A study by the U.S. Energy Information Administration (EIA) (2007a) looked at a combined 25% RFS and RPS by 2025. This analysis suggests that to comply with such mandates, it would require almost a 13-fold increase in non-hydropower renewable generation and more than a 12-fold increase from 2005 levels. Although not all would be biomass based, the likelihood of increased demand for biomass for all energy uses has become very apparent. However, the greenhouse gas reductions are also providing more scrutiny in the use of biomass, especially in emissions accounting. Although this analysis does not address differences in emissions among feedstocks, it does address the basic sustainability aspects of using renewable feedstocks—a non-diminishing supply over the period studied.

In sum, these supply and demand forces have contributed to volatility in oil prices in recent years, and by transitioning toward higher energy efficiency and additional domestic sources of renewable fuels, such as biofuels, there is high potential to reduce U.S. market uncertainty and increase energy security. Legislative and executive actions have occurred at the federal and state levels in support of the use of biomass. There have been increased legislative actions and investments in the use of biomass for biopower. Overall, since the original report, the United States has accelerated efforts in using biomass for energy, and along with that emphasis, new questions have been asked about supply.

1.2 Purpose

The purpose of this report is to update the 2005 *BTS* and change its focus from a strategic assessment to a comprehensive resource assessment, thereby addressing issues raised since its publication. One major criticism of the 2005 *BTS* was that the identified potential biomass was not restricted by price, and some of the potential feedstocks would likely be too expensive relative to other feedstocks under current and prospective technological change (i.e., not be economically available). This update provides estimates of prices and quantities of the

[3] It should be emphasized that this resource assessment is intended to provide an overall indication of resource potential. The report is not an "investment-grade" assessment suitable for evaluating the merits of projects. Project feasibility requires the use of local data and assumptions.

resource potential (i.e., supply curves).[3] This update also treats sustainability much more rigorously, and it focuses on currently unused resources and energy crops. Full analysis of the sustainability of large-scale biomass production is not the intention of this report; however, quantitative projections presented may be useful for further analyses of the environmental and social aspects of using biomass for energy. Many of the sustainability aspects have been discussed in other studies, such as the Biomass Research and Development Initiative (BRDI) (2008) report on economics and environmental implications of meeting the RFS. Further, this update emphasizes the 2012 through 2030 time period coincident with implementation of EISA (see Text Box 1.2) and DOE initiatives, rather than on updating the mid-century projection results in the original study. The original report included biomass that was currently being used for energy production because it counted toward the billion-ton goal. In this update, currently consumed biomass resources, such as wood residues and pulping liquors used in the production of forest products, are treated separately to avoid confusion with the unused potential. The update focuses on deriving estimates of biomass available for additional energy production and bioproducts at different prices and locations across the continental United States. A schematic of the biomass resources considered in this update are shown in Figure 1.1. The resources noted as "currently used" are treated in a separate chapter. Separate chapters are also devoted to forest residues, agricultural residues, and energy crops. Although recent attention has turned to algal feedstocks because of their high productivity, algal feedstocks are not included in this assessment. There is insufficient information and data to estimate and project the availability of algal feedstocks at a county scale with any degree of accuracy. The National Algal Biofuels Technology Roadmap (U.S. Department of Energy, 2010b) reports that many years of research will likely be needed to achieve affordable, scalable, and sustainable algal-based fuels.

A key outcome of this update is to estimate feedstock supply curves by county for all major primary cropland and forest resources at the farmgate or forest roadside. These supply curves include prices to acquire or access the resource and costs for collecting or harvesting the resource and moving it to the field edge or forest roadside to be ready for transport. In this report, only national results are conveyed. A separate database containing the disaggregated biomass supplies by county and state is available through a Web-based Bioenergy Knowledge Discovery Framework (KDF) (ORNL, 2010). This framework is intended for users to capture, visualize, and analyze information on the complete bioenergy supply chain and the infrastructure needed to support that chain.

TEXT BOX 1.2 | KEY DIFFERENCES BETWEEN THE 2005 BILLION-TON STUDY AND THE 2011 UPDATE

2005 *BTS*

- National estimates—no spatial information
- No cost analyses
- Environmental sustainability addressed from national perspective
- No explicit land-use change modeling
- 2005 USDA agricultural projections and 2000 forestry RPA/TPO
- Long-term time horizon (2025–2050)
- Estimates of current availability
- Long-term projections involving changes in crop productivity, crop tillage, residue collection efficiency, and land-use change

2011 Update

- County-level analysis with aggregation to state, regional, and national levels
- County supply curves for major primary feedstocks
- Environmental sustainability modeled for residue removal
- 2009 USDA agricultural projections and 2007 forestry RPA/TPO 2012–2030 timeline
- Land-use change modeled for energy crops
- Annual projections based on a continuation of baseline trends (USDA projections)
- Annual projections based on changes in crop productivity, tillage, and land use

In the 2005 *BTS*, there are three scenarios: (1) current sustainable availability from agricultural lands; (2) technology change with conventional crops only (no land-use change); and (3) technology change with perennial crops and land-use change. Scenario one in the original report is the baseline that used current crops yields, tillage practices (20% to 40% no-till), and agriculture residue collection technology (40% recovery). Scenario two in the 2005 *BTS* has corn yields (*Zea mays*) increasing by 25% to 50% by 2040–2050, with yields of other crops increased at lower rates; these increases are the same as the U.S. Department of Agriculture (USDA) projections (USDA-OCE, 2003). Other assumptions in the scenario are that no-till is practiced on all high-yield acres and that residue recovery is 60% for moderate-yield acres and 70% for high-yield acres. Finally, the 2005 *BTS* scenario three assumes the addition of perennial crops to the landscape, land- use changes, high residue-to-grain ratio for soybean (*Glyine max*), and the same technology changes as in scenario two.

In this update, two scenarios are evaluated. First, there is the baseline scenario that essentially assumes a continuation of the USDA 10-year forecast for the major crops and extends an additional 10 years to 2030. Second, the update provides an opportunity to further evaluate and refine changes in projected improvements, crop yields, and technologies. These projected improvements use underlying assumptions to give the opportunity to estimate availability projections into the future using baseline assumptions (i.e., a continuation of current trends) and to determine the largest feedstock volume potentials over time ("high-yield" scenarios). Impacts of various assumptions are assessed using the POLYSYS model, an agricultural policy modeling framework, to include land-use change and to better understand potential economic impacts on a county-by-county basis for certain feedstocks.

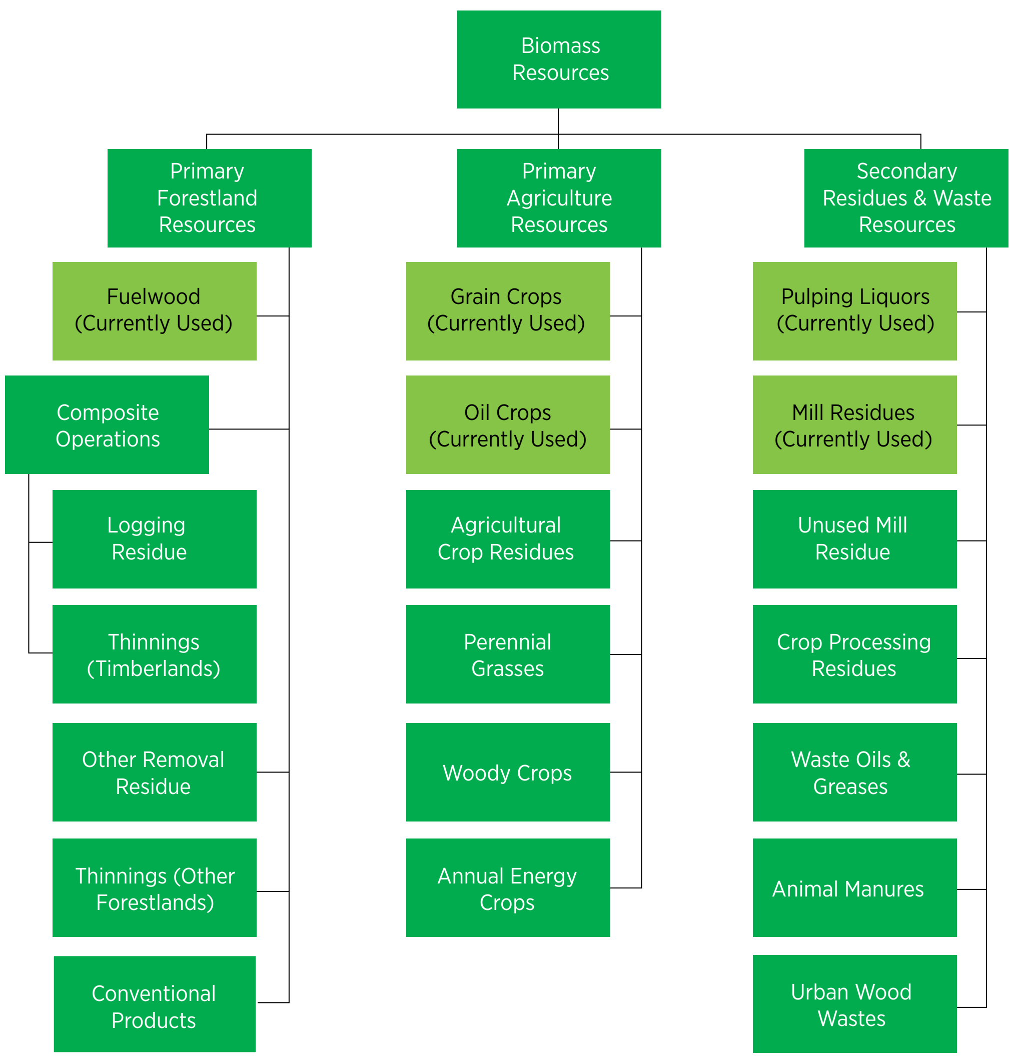
A review of the literature shows a wide range of both qualitative and quantitative projections on crop yield and the management of agricultural feedstocks for enhanced production, but not specifically to energy. The literature is not consistent and does not specifically address energy feedstocks from the industrial perspective—the optimization of current production systems for biomass or the development of new, innovative energy feedstock systems. It was decided that a different approach is needed to quantify feedstock changes in the future. The U.S. Department of Energy's Office of the Biomass Program sponsored a series of workshops to obtain expert input on barriers and solutions for securing large quantities of biomass feedstocks in the future (U.S. Department of Energy, 2010a). The overall goal of the workshops was to develop industry-based, high-yield alternatives to the baseline assumptions that were used to develop the update. Experts were invited from industry, academia, and government to help identify and quantify high-yield alternative scenarios.

The workshops were conducted in December 2009 and were organized by feedstock: corn and agricultural crop residues, herbaceous energy crops, and woody energy crops (U.S. Department of Energy, 2010a). During the workshops, inputs were collected on advancements needed for higher yields, the ranking of the timeliness and likelihood of these advancements, and the projected future yields. Significant input was collected during the workshops and is summarized in three reports. Because of proprietary concerns, participants may have been limited in the amount of quantitative data they could provide and much of the information collected from the workshops is qualitative. Rather than factoring qualitative information into quantified data, which may misrepresent the opinions of workshop participant, the workshop results are analyzed in terms of trends identified within their responses. A synthesis of the yield and other information was used to develop and validate high-yield alternative scenarios in the update. In addition, a literature review was used to gauge the workshop results (Gordon, 2008; Vance et al., 2010).

1.3 Report Organization

The next chapter provides a summary of biomass resources currently used in the production of biofuels, heat, and power. This chapter also provides projections of currently used biomass to the year 2030. Chapter 3 assesses forest biomass and waste resources. This includes all of the resources listed under primary forest resources in Figure 1.1, with the exception of fuelwood, plus unused mill residues and urban wood listed under secondary residues and wastes. Agricultural resources are evaluated in two chapters. Chapter 4 assesses primary crop residues from the major grains, as well as other crop residues, crop processing residues, and animal manures. These latter resources were listed in the 2005 *BTS* as other crop residues and other residues. Chapter 5 contains the assessment of the energy crops and includes perennial grasses, woody crops, and annual energy crops. Chapter 6 provides a summary of the resource assessment update. For convenience and ease in reading, a decision was made to show feedstock quantities and their composite total at the $60 per dry ton level in many of the figures and tables in the report. This price was selected because it brings in most of the available tons from all of the feedstocks and because the price represents a realistic, reasonable price for discussion purposes. This report does not present the county-level information—that information can be found in the Bioenergy KDF (ORNL, 2010).

Figure 1.1 Biomass resources considered in the update to the 2005 *BTS*



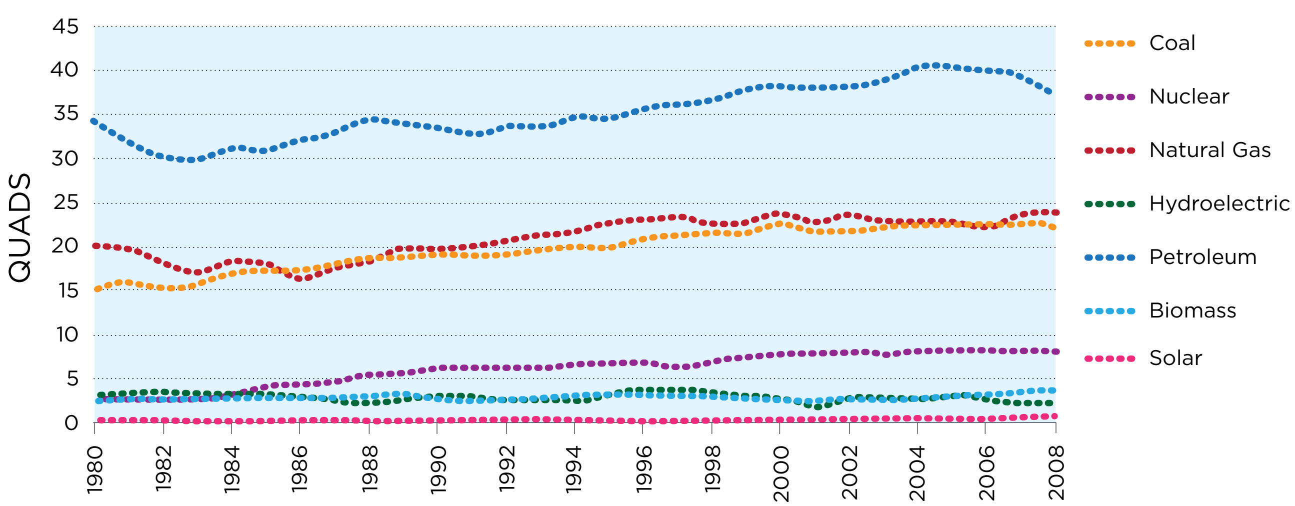
2 BIOMASS IN CURRENT AND PROJECTED ENERGY CONSUMPTION

This chapter reviews currently used biomass resources identified in the 2005 *BTS* as existing uses. These resources are included to provide context for the resource potential identified in subsequent chapters of this report and for comparisons to the 2005 *BTS*.[4] These currently used resources include biomass residues and wastes used in industry for heat and power; wood, and some waste wood used in the residential and commercial sectors for space heating; sugars and starches used in ethanol production; and oilseeds used in biodiesel production. The next section summarizes current consumption of biomass resources followed by projections to 2030.

2.1 Current Consumption of Biomass Resources

A variety of biomass feedstocks are currently used to generate electricity and produce heat and liquid transportation fuels. According to EIA, biomass contributes nearly 3.9 quadrillion British thermal units (Btu) (Quads) and accounts for more than 4% of total U.S. primary energy consumption (EIA, 2010a). Figure 2.1 summarizes energy consumption by fuel source. Although biomass ranks well below petroleum, natural gas, and coal and is about one-half of nuclear, it surpasses hydroelectric and other renewable sources. In 2009, the share of biomass in total U.S. energy consumption exceeded 4% for the first time.[5] Over the last 30 years, the share of biomass in total primary energy consumption has averaged less than 3.5% (EIA, 2010a). However, as shown in Figure 2.1, there has been a gradual increase in biomass consumption that started in the early 2000s. This increase is due to ethanol production.[6]

Figure 2.1 Primary energy consumption by major fuel source from 1980–2008



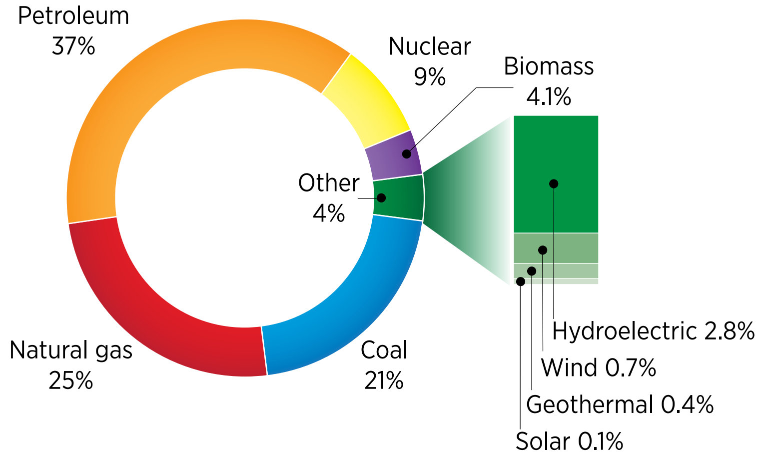
[4] Currently used resources were included in the 2005 *BTS* because they contributed to the goal of displacing 30% of current petroleum consumption.

[5] In the 2005 *BTS*, 2.9 Quads were reported—slightly less than 3% of total energy consumption.

[6] The EIA estimates include the energy content of the biofuels (ethanol and biodiesel) feedstock minus the energy content of liquid fuel produced.

Biomass energy consumption (excluding biobased products) was reported at 184 million dry tons in the 2005 *BTS*. More than 50% of this consumption was estimated to be in the forest products industry, with equal amounts used in other processing industries, electric power generation, and the residential and commercial sectors. A relatively small fraction (less than 10%) was used to make biofuels. Based on the most recent EIA data, current biomass energy consumption is nearly 200 million dry tons, or 4% of total primary energy consumption (see Figure 2.2).[7] About 17% of this consumption is space heating in the residential and commercial sectors. The source of this biomass is nearly all fuelwood. The electric power sector represents a small percentage of total biomass consumption (8%) and uses a variety of biomass feedstocks—fuelwood, MSW biomass, MSW landfill gas, and biosolids (or sewage sludge). In 2009, nearly 60% of biomass-derived electric power consumption was from MSW sources. Transportation accounts for 31% of total consumption, with ethanol used in gasoline blending accounting for most (90%) of the total. Biodiesel accounts for 8%, and the remainder is E85 (85% ethanol fuel) and other biomass liquids. The industrial sector accounts for 44% of total biomass energy consumption. Most of this amount (nearly 90%) is wood and waste wood. MSW, landfill gas, and biosolids account for the remainder.

Figure 2.2 Total primary energy consumption in 2009 – 94.5 Quads



Source: Energy Information Administration, *Monthly Energy Review*, June 2010, http://www.eia.doe.gov/emeu/mer/contents.html.

In the 2005 *BTS*, more than 75% of the biomass consumed was derived from forest sources. The data in this update still shows most of the biomass consumed comes from forest sources; however, the percentage is less (about 65%), owing to the increase in the use of corn grain for ethanol production, a cropland source. Additional aspects of specific forest and cropland biomass resources are discussed below.

2.1.1 Forest-Derived Resources

Biomass originating from forests comes primarily from two sources—fuelwood used in the residential and commercial sectors and residues generated in the manufacture of forest products. There is a relatively small amount of MSW wood that is recovered for energy.

Fuelwood. Fuelwood is wood that is harvested from forests and combusted directly for useable heat in the residential and commercial sectors, as well as power in the electric utility sector. Combined, these sectors account for 30% of current consumption of forest biomass and about 20% of total U.S. biomass energy consumption (Table 2.1). The residential sector is about four times as large as the commercial sector and five times as large as the electric power sector. In the most recent year, these three sectors consumed about 38 million dry tons (Table 2.1), which is approximately the same amount as reported in the 2005 *BTS*. Most of the fuelwood consumed is in the Northeast and North Central regions, and to a lesser extent in the Southeast and Pacific Coast regions and comes mostly from hardwoods (Smith et al., 2009).

[7] This is the total biomass quantity as shown for 2009 in Table A17 (Reference case) of the 2010 Annual Energy Outlook (EIA-AEO, 2010c) excluding losses. It includes the residential, commercial, industrial, electric power, and transportation sectors. Conversion of energy to dry tons was based on a conversion factor of 16 million Btu per dry ton. This factor is used throughout this report.

Forest products industry processing residues. The forest products industry consumes three major sources of residues—primary and secondary mill residues generated in the processing of roundwood, roundwood products, and pulping liquors. Primary processing mills (facilities that convert roundwood into products such as lumber, plywood, and wood pulp) produced about 87 million dry tons of residues in the form of bark, sawmill slabs and edgings, sawdust, and peeler log cores in 2002 (Smith et al., 2009). Very little of this resource is currently unused. According to USDA Forest Service estimates, about 75% of bark is used as fuel, and about 23% is used in other low-valued products, such as mulch, if not used internally for energy or in other markets where it may have a higher value (Figure 2.3). For coarse residues, about 77% is used in the manufacture of fiber products, about 13% is used for fuel, and 8% is used for other applications. About 55% of the fine residues are used as fuel, 25% in fiber products, and 19% in other uses. Overall, only 1.5% of primary mill residue currently goes unused, leaving 1.3 million dry tons for new bioenergy uses.[8]

Residues are also generated at secondary processing facilities—mills utilizing primary mill products. Examples of secondary wood processing mill products include millwork, containers and pallets, buildings and mobile homes, furniture, flooring, paper, and paper products. Because these industries use an already-processed product, they generate much smaller quantities of residues. In total, the secondary mill residue resource is considerably smaller than the primary mill resource (Rooney, 1998; McKeever,1998).

The types of residues generated at secondary mills include sawdust and sander dust, wood chips and shavings, board-end cut-offs, and miscellaneous scrap wood. In total, 32 million dry tons of mill residues are currently used (Table 2.1).

In the manufacture of paper products, wood is converted into fiber using a variety of chemical and mechanical pulping process technologies. Kraft (or sulfate) pulping is the most common processing technology. In kraft pulping, about half the wood is converted into fiber. The other half becomes black liquor, a byproduct containing unutilized wood fiber, lignin, and other chemicals. Pulp and paper facilities combust black liquor in recovery boilers to produce energy (e.g., steam) and, more importantly, to recover the valuable chemicals present in the liquor. The amount of black liquor generated in the pulp and paper industry is the equivalent of nearly 45 million dry tons of biomass (EIA, 2010c). Because the amount of black liquor generated is insufficient to meet all mill needs, recovery boilers are usually supplemented with fossil and wood residue-fired boilers. The pulp and paper industry utilizes enough black liquor, bark, and other wood residues to meet a majority of its energy requirements.

Municipal solid wastes. Currently, about 254 million tons of MSW are generated annually, with slightly more than one-third of this quantity recovered for recycling or composting (EPA, 2008). Another 13%, or 32 million tons, is combusted with energy recovered. Most of the MSW generated originates from households and includes a wide variety of biomass and non-biomass materials. The major forest sources of MSW include newsprint, paper, containers and packaging, yard trimmings, and wood. The quantity of forest-derived MSW currently used is estimated at about 14 million dry tons (Table 2.1).

Figure 2.3 Wood waste

(Courtesy of Rob Mitchell, ARS)

[8] The possibility of residues currently used in making low-value products shifting into bioenergy was not explored in this study. Opportunities may exist to bid away some low value uses (such as mill residue classified as used in other uses, presumably low value) into bioenergy applications.

2.1.2 Agriculture-Derived Resources

Most cropland-derived biomass is used to produce ethanol from corn grain and biodiesel from oilseed crops (Table 2.1). Some MSW (e.g., food wastes and textiles) is also used to produce power.

Ethanol from starch. The primary feedstock for ethanol in the United States is currently corn. Historically, the United States has been a large producer of corn for a number of reasons—chiefly because of its high carbohydrate yield relative to other crops and multiple uses as food, feed, ethanol, and exports. Corn's high starch content and historic presence in the agricultural industry situate it as an accessible feedstock for ethanol production. The highest domestic production occurred in 2009 at 13.4 billion bushels, with about 35% of the total U.S. crop utilized for ethanol production.

As of May 2010, U.S. corn ethanol operating capacity was 12.6 BGY, with production concentrated primarily in the Corn Belt and Northern Plains (Figure 2.5). In July 2011, ethanol operating capacity had increased to 14.2 BGY. Actual 2010 annual production was 13.2 billion gallons, which represents about 4.7 billion bushels or about 112 million dry tons of corn.[9] After fuel is created from the starch in corn, the residual fiber, protein, vegetable oil, and minerals are used as distillers dried or wet grains in livestock feed. Distillers grains account for about one third of total corn grain weight.

Figure 2.4 Harvesting corn in the Great Plains

(Courtesy of Rob Mitchell, ARS)

EISA 2007 mandates the incremental increase of the use of biofuels and is one of the primary drivers in the current increase in the demand for corn grain (Figure 2.6).[10] Specifically, EISA mandates that future Renewable Fuel Standards (RFS) for years 2015–2022 be met with up to 15 billion gallons of corn-based ethanol.

Based on USDA estimates, a more modest rate of increase in ethanol production from corn grain is expected during the next 10 years, compared to production growth over the last 10 years. The projected production in 2020 is about 14–15 billion gallons. The parallel actual and projected corn production for ethanol over the same 20-year period is shown in Figure 2.7. Ethanol corn production increased seven fold in the last 10 years, but is only expected to increase to a little less than 90 million dry tons annually (excluding the fraction recovered as distillers grains) to meet the mandate. About 38% of corn grain produced in 2010 was used in ethanol production (up from 23% in 2007). This corn-to-ethanol proportion is expected to remain stable between 33% and 34% from 2010 to 2020 (USDA-OCE/WAOB, 2010). In spite of increasing demand, USDA estimates that the price of corn is expected to remain stable at around \$3.65 to \$3.90 per bushel (in nominal terms) in the 2011 to 2020 timeframe (USDA-OCE/WAOB, 2010).

Increased corn production may create a number of unintended market and environmental effects (BRDI, 2008). First, a food and fuel use conflict may arise, which suggests that the rise in demand for corn ethanol increases the price and decreases the quantity of corn available for other uses. Because corn is a major cereal grain and primary feed for livestock, increasing corn ethanol requirements could lead to price inflation of

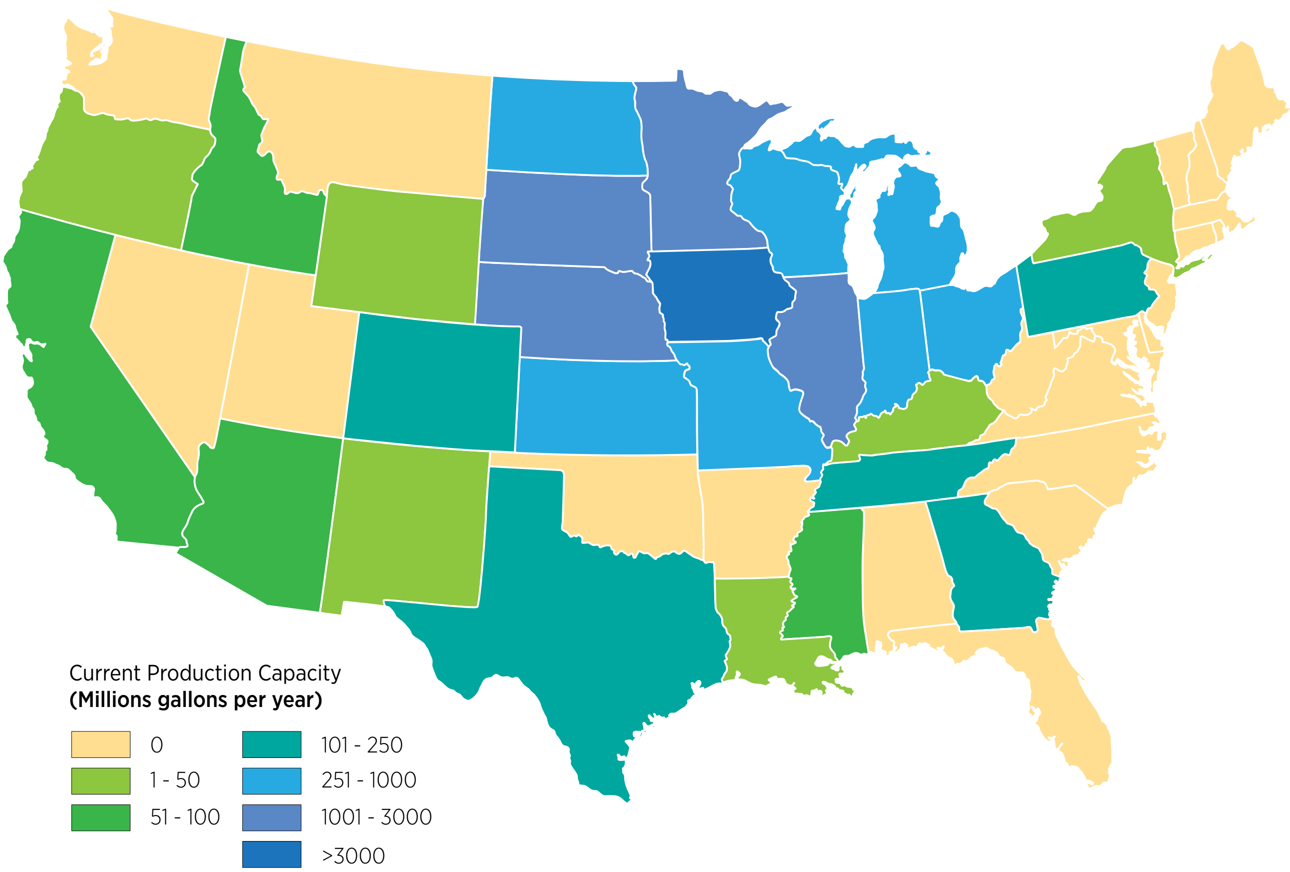
[9] A bushel of corn weighs 56 pounds at 15% moisture. Given current technology, a bushel of corn can produce 2.8 gallons of denatured ethanol. Calculation converts to dry basis and includes distillers dried or wet grains.

[10] Additionally, there is an ethanol blenders' credit, which was reduced to \$0.45 per gallon in 2009.

consumer final goods—primarily food. This upward pressure could be relieved with substitutes for corn-derived foods and livestock feed—a portion of the corn used for ethanol (about one-third) is still available as a feed as distillers grains. Consumers responding to the relatively lower prices of corn substitutes increase the demand for other grains, leading to an increase in prices for other grains. On the supply side, if higher corn prices lead farmers to grow more corn, economic theory suggests the increased land dedicated to corn leads to increased prices and decreased supply for other grains. The outcomes of both demand (consumers switching to consuming other grains) and supply (farmers planting more corn) suggest higher prices for the substitute grains and lower prices for corn, *ceteris paribus*. Careful consideration of other factors is important in identifying inflation in commodity crops, such as international events, weather, and general economic conditions, among other factors.

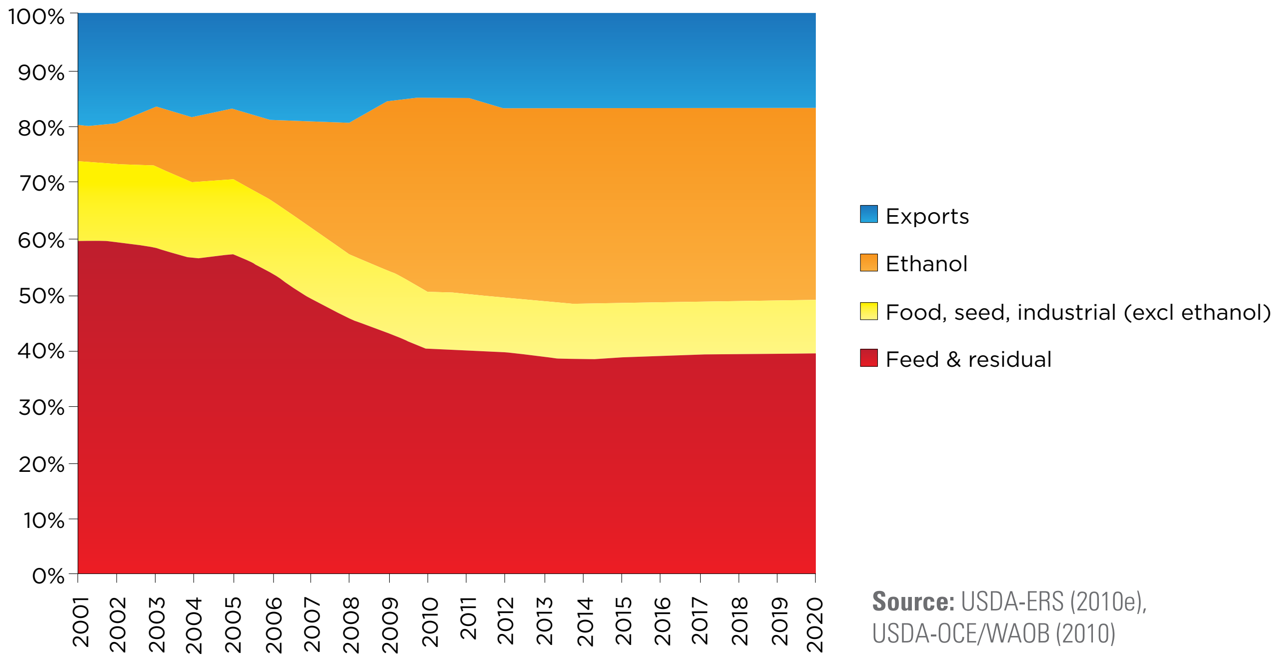
Increasing the corn yields per acre and the efficiency of conversion technologies would help to relieve the economic and environmental pressures related to increased ethanol production. Improving the supply traits (i.e., energy efficiency in production, harvesting, and conversion) of biofuels improves the environmental sustainability of this biofuel.

Figure 2.5 Ethanol operating capacity by state



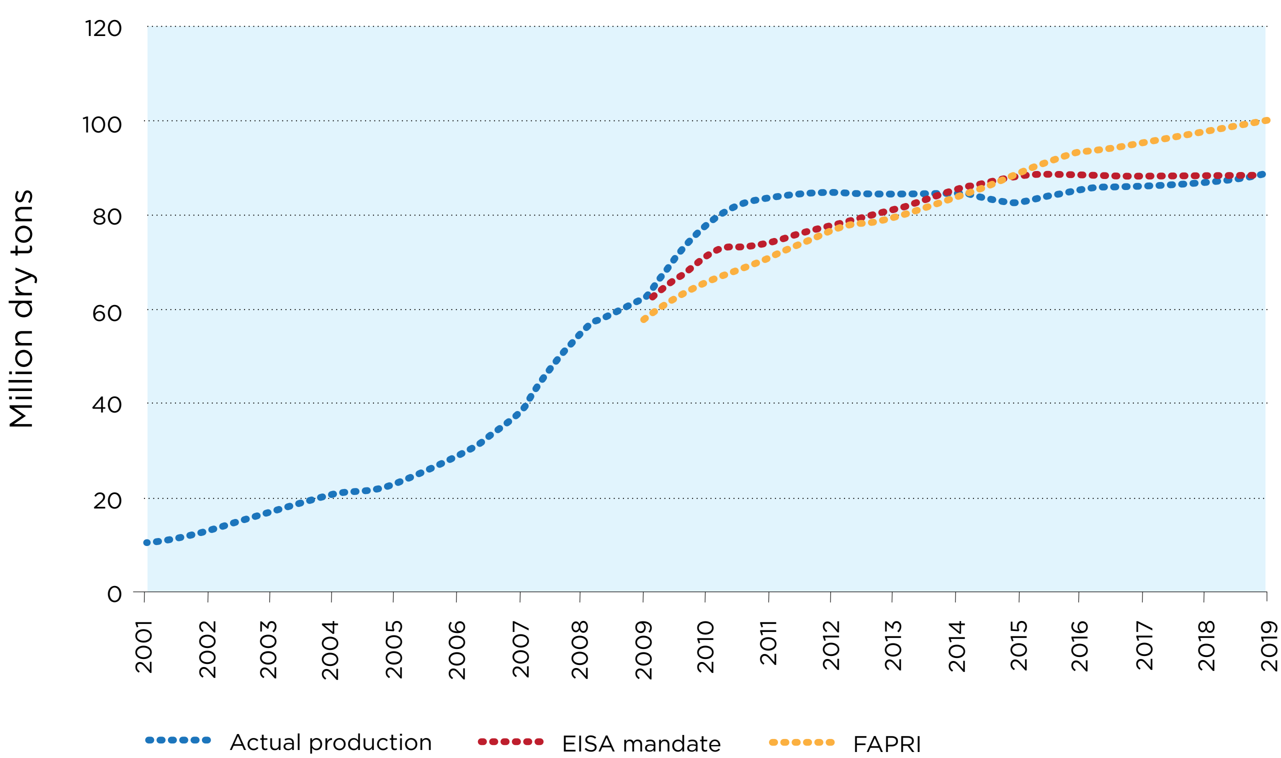
Source: RFA (2010a)

Figure 2.6 Historical and projected corn use, 2001–2020



Source: USDA-ERS (2010e), USDA-OCE/WAOB (2010)

Figure 2.7 Historical and projected ethanol production, 2001–2019

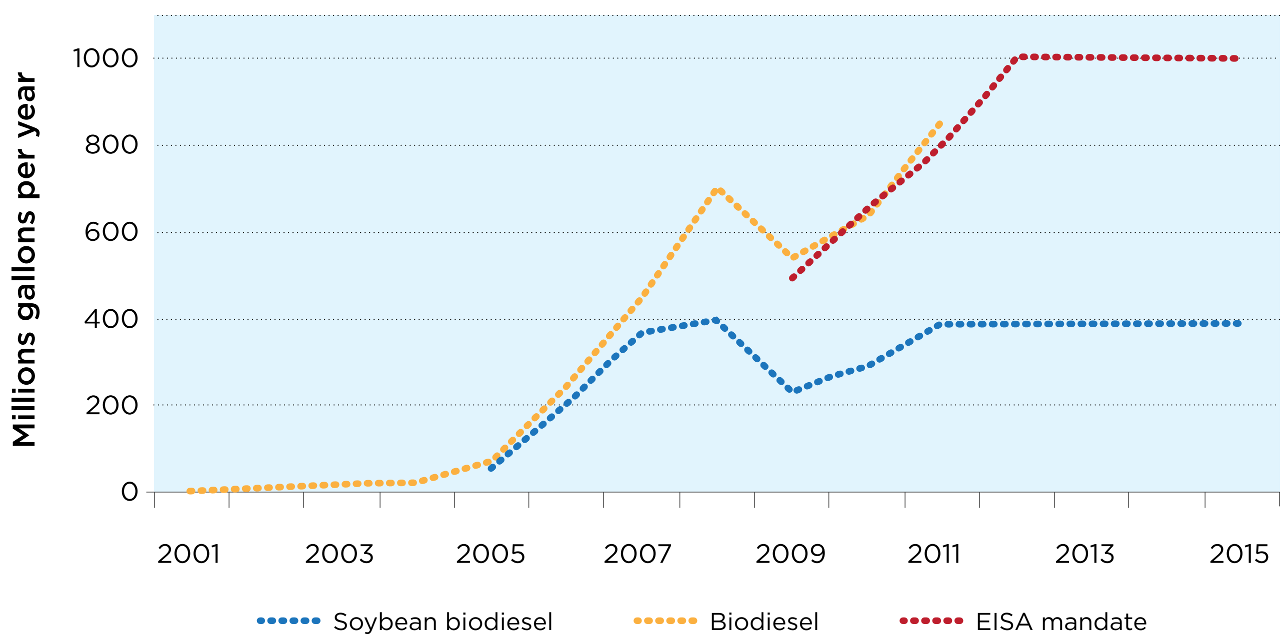


Source: Actual Production (RFA, 2010b); Projected Production based on USDA-ERS, 2010e; USDA-OCE/WAOB, 2010; EISA Mandate, BRDI, 2008; FAPRI, 2010; EIA-AEO, 2010.

Biodiesel. At present, biodiesel is currently produced from soybean, waste fats, and various vegetable oils.[11] Like ethanol, biodiesel production increased rapidly from 2005 to 2008 (Figure 2.7 and 2.8). Historically, soybean oil has been the dominant feedstock (83% of total in 2007) for biodiesel production, but this is changing as animal fats and waste oils are increasingly used. Soybean contribution to biodiesel is expected to decrease and stabilize around 400 million gallons per year after decreasing in 2009 (USDA-OCE/WAOB, 2010) (Figure 2.8). Based on conditions in 2006, by 2015 soybean oil is projected to make up 70% of biodiesel feedstock, as other sources are more widely used (USDA-OCE/OEPNU, 2008). A more recent projection expects that less than half of biodiesel feedstocks will come from first-use vegetable oil with more than half from recycled vegetable oils, or animal fats (USDA-OCE/WAOB, 2009).

Vegetable oils other than soybean oil are projected to make much smaller contributions to biodiesel production in the foreseeable future; this is due to higher relative input prices. The difference between soybean and vegetable oil as inputs to biodiesel and total biodiesel is expected to come from waste fats and recycled oils. Waste fats are generally a less costly feedstock than vegetable oils, however, they contain high levels of saturated fatty acids that results in a lower flow quality than vegetable oil. Yellow grease, a waste product of the food industry, is the least costly available feedstock for biodiesel production. Its supply is limited geographically and lends itself toward smaller capacity production.

Figure 2.8 Historical and projected U.S. biodiesel production with EISA mandate



Source: EIA (2009, 2010a,b) (Biodiesel), USDA-ERS (2007, 2010a,b) (Soybean biodiesel)
Note: *Assume 7.5 pounds per gallon for soybean biodiesel.*

[11] Glycerin, a byproduct, is used in a number of consumer and industrial products.

[12] As of June 2009, biodiesel production capacity was 2.69 BGY, though many facilities had low utilization rates (NBB, 2009). The current tax benefits of biodiesel are provided to the blender at the rate of $1.00 per gallon for all feedstocks (previously, credits for recycled vegetable oils or animal fats was $0.50 per gallon) and was extended through 2009 by the Energy Improvement and Extension Act of 2008.

The U.S. biodiesel industry must meet certain use benchmarks, as mandated by EISA (U.S. Congress, 2007). EISA also requires use levels to reach 500 million gallons by 2009. This requirement increases to 1 billion gallons by 2012.[12]

Municipal solid wastes. Agricultural sources of MSW include food wastes, textiles, and leather. These wastes currently account for about 20% of the total MSW generated (EPA, 2008). The quantity of cropland-derived MSW currently used is estimated at about 7 million dry tons (Table 2.1).

2.2 Projected Increase in Currently Used Biomass Resources

The projected increase in consumption of currently used biomass feedstocks is summarized by feedstock type for selected years in Table 2.1. These data reflect the 2010 EIA reference case projections converted to million dry tons. Consumption of biofuels in the transportation sector increases significantly owing to the EISA 2007 and the RFS. Electric power consumption using biomass feedstocks (shown as fuelwood in Table 2.1) also increases considerably over the next 20 years. As noted by EIA, a large fraction of the biopower increases come from increased co-firing (EIA, 2010c).[13] Modest growth in industrial consumption of biomass is projected with little or no change in the residential and commercial sectors. The key feedstocks contributing to biomass consumption include fuelwood harvested from forests, primary mill residues, pulping liquors, and woody MSW feedstocks. In total, forests currently contribute nearly 130 million dry tons. This is somewhat lower than reported in the 2005 *BTS* due to the economic downturn. By 2022 and 2030, consumption of forest biomass increases to about 210 and 225 million dry tons, respectively. Agriculture sources of biomass include corn and other grains used to produce ethanol; soybean and greases for biodiesel production; and MSW feedstocks, such as food wastes and textiles. These currently used feedstocks total nearly 85 million dry tons. Consumption increases to 103 million dry tons by 2017. Most of 2017 and beyond quantities are grains and soybean used to produce 15 BGY of ethanol and 1 BGY of biodiesel—the assumed maximum available feedstocks for starch ethanol and oils for the RFS under EISA 2007. These estimates do not take into account any liquid production expected from cellulosic sources. The remainder of this report addresses the cellulosic resources that are currently unused and available, as well as energy crops.

[13] Co-firing is a conversion process in which small amounts of biomass are mixed with coal in existing coal-fired plants. The amount of displaced coal can vary from a few percent up to 10% or more depending on the conversion technology and fuel-handling systems.

Table 2.1 Projected Consumption of Currently Used Biomass Feedstocks (Million Dry Tons per Year)

Source	Current	2017	2022	2030
Forest				
Fuelwood	38	72	96	106
Mill residue	32	38	39	42
Pulping liquors	45	52	54	58
MSW sources	14	20	20	20
Total forest	**129**	**182**	**209**	**226**
Agriculture				
Ethanol [a]	76 (109)	88 (127)	88 (127)	88 (127)
Biodiesel [b]	2	4	4	4
MSW sources	7	11	11	11
Total agricultural resources currently used	**85 (118)**	**103 (142)**	**103 (142)**	**103 (142)**
Total currently used resources	**214 (247)**	**285 (342)**	**312 (351)**	**329 (368)**

Notes: *Fuelwood includes the residential commercial sector as well as biomass consumed by the electric utility industry in dedicated biomass plants and co-firing applications. MSW sources are allocated to forest (65%) and cropland (35%) based on EIA (2007b). Ethanol and biodiesel are based on EISA mandates of 15 BGY of biofuels and 1 BGY of biodiesel. Ethanol assumes corn grain at 56 pounds per bushel, 15.5% moisture content, and 2.8 gallons per bushel.*

[a] The first number is the portion of corn consumed to make ethanol. The number in parentheses is the amount of corn required. For example, it takes 127.5 million dry tons to make 15 BGY of ethanol. However, only 88.3 million dry tons are consumed in making the ethanol. The remainder (39.2 million dry tons) is distiller's grain and is excluded from the total.

[b] Includes all sources of biodiesel. Current consumption is 43% from soybeans and 57% from other sources, including animal fats and waste oils. The proportion of sources of future feedstocks will vary and are assumed to have an average conversion rate of 7.5 pounds of oil/fats per gallon of biodiesel.

3 FOREST BIOMASS AND WOOD WASTE RESOURCES

This chapter provides estimates of forest biomass and wood waste quantities, as well as roadside costs (i.e., supply curves) for each county in the contiguous United States (see Text Box 3.1). Roadside price is the price a buyer pays for wood chips at a roadside in the forest, at a processing mill location in the case of mill residue, or at a landfill for urban wood wastes prior to any transport and preprocessing to the end-use location.[14] Forest biomass and wood waste resources considered in this assessment include:

- Forest residues (logging residues and thinnings) from integrated forest operations from timberland[15]
- Other removal residue[16]
- Thinnings from other forestland
- Unused primary and secondary mill processing residues
- Urban wood wastes
- Conventionally sourced wood.

TEXT BOX 3.1 | FOREST FEEDSTOCKS

This chapter provides estimates for forest residues and wood wastes that were reported in the 2005 *BTS*, as well as an additional feedstock, conventionally sourced wood. In the original *BTS*, forest residues include logging residue, other removal residue, and fuel treatments from both timberland and other forestlands. Wood wastes include forest products wood residues (both used and unused), pulping liquors, and urban wood residues. The 2005 *BTS* also included fuelwood.

For this report, fuelwood, "used" wood wastes, and pulping liquors are included in the update, but are not counted as "potential" biomass resources because they are already used for other purposes, primarily energy production. Future prices may shift these "used feedstocks" into new or other energy uses, but for the update, they are still counted as used.

Fuel treatment residues are now "thinnings" obtained using an integrated forest operation, i.e., the production of merchantable products and biomass. A "composite" estimate is determined by combining portions of logging residue and thinning estimates, then by using a ratio to represent the transition from harvesting operations that leave logging residues to harvesting operations that integrate the removal of biomass with merchantable timber. Some conventionally sourced wood (e.g., small-diameter pulpwood) is also considered to be a biomass feedstock. See Chapter 1 for more discussion on the types of feedstocks.

[14] The costs estimated are marginal costs or costs to supply each successively more expensive dry ton of biomass in each county. It is assumed that buyers would be buying from landowners who are aware of the cost for the most expensive units of biomass supply and that there would be enough buyers (a competitive market) such that landowners would only sell to buyers offering the price for the most expensive unit. Prices paid may be less for a given amount of biomass supply, depending on the extent that landowners are not informed about the highest price being offered or are not interested in maximizing profit, or to the extent that there are few buyers to compete for the biomass.

[15] Forestland is defined as land at least 120 feet wide and 1 acre in size, with at least 10% cover (or equivalent stocking) by live trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated (Smith et al., 2009). Forestland is further defined as timberland and other forestland. Timberland is defined as forestland that is producing, or is capable of producing, in excess of 20 cubic feet per acre per year of industrial wood and not withdrawn from timber utilization by statute or administrative regulation. Other forestland is defined as forestland other than timberland and productive reserved forestland. It includes available forestland, which is incapable of annually producing 20 cubic feet per acre per year. Reserved forestland is administratively removed from production.

[16] Unutilized wood volume from cut, or otherwise killed, growing stock from cultural operations, such as precommercial thinnings or from timberland clearing. Does not include volume removed from inventory through reclassification of timber land to productive reserved forest land (Smith et al., 2009).

Forest biomass is a primary resource that consists of a combination of estimates from two sources: (1) removal of a portion of what is called logging residue that is currently generated during the harvesting of timberlands for conventional forest products and (2) removal of excess biomass from fuel treatment (reducing biomass helps forests increase fire resistance) and thinning operations designed to reduce risks and losses from catastrophic fires and improve forest health. This latter component consists of removing merchantable whole trees and excess small trees to the roadside. The tops and branches of merchantable trees, cull trees, cull-tree components, and excess small trees can be used for bioenergy applications. The merchantable tree components can be used for conventional forest products. Both of these resources were considered separately in the *BTS*, but in this update, estimates are made assuming that there will be a transition in conventional harvesting operations from leaving logging residues behind to removing them as part of conventional harvesting. It is projected that access to biomass will come from integrated harvesting operations that provide sawlogs and pulpwood to meet existing market demand, as well as provide biomass for energy. Two other primary resources are considered in this update. Thinnings from other forestland (non-timberland) are conducted to improve forest health by removing excess biomass on low-productivity land. Other removal residue is unused wood that is cut during the conversion of timberland to non-forest uses and unused wood cut in silvicultural operations, such as precommercial thinnings. A description of the forest resource land base is provided in Text Box 3.2.

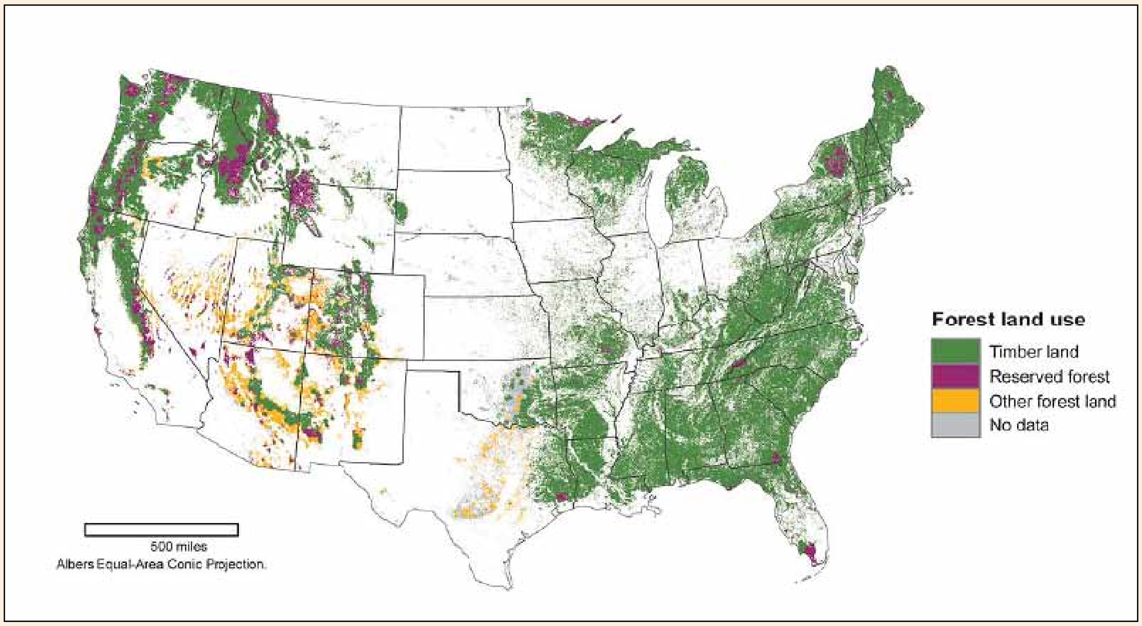
The processing of sawlogs, pulpwood, and veneer logs into conventional forest products generates significant quantities of bark, mill residues (coarse and fine wood), and pulping liquors. With the exception of small quantities of mill residues, these secondary forest products industry residues are currently used in the manufacture of forest products or for heat and power production, and valuable chemicals are recovered from pulping liquors. In addition to pulping liquors, fuelwood—defined as wood harvested directly from forests and used primarily in the residential and commercial sectors for space heating and by some electric utilities for power generation—is also not considered beyond the estimates provided in Chapter 1. Some quantity of these currently used wood wastes could shift to bioenergy applications at the right price. However, estimating how many of these resources could move into bioenergy production is difficult and speculative, as many of these wood wastes are not only used, but are also confined or dedicated to a specific process. Urban wood waste, on the other hand, is largely destined for landfills. The urban wood waste resource includes a wide variety of woody materials, ranging from discarded furniture, landscaping wood wastes, and wood used in the construction, remodeling, and demolition of buildings.

The final resource considered is conventionally sourced wood, which is defined as separate, additional operations to provide pulpwood-sized roundwood for bioenergy applications. Conventional wood was not included in the 2005 *BTS*. Excluded from the forest potential is wood grown under short rotations and dedicated to bioenergy production (see Chapter 5).

The remainder of this chapter discusses the specific woody biomass sources introduced above. The bulk of the chapter focuses on primary forest biomass, including extended discussion of resource sustainability from timberland. This is followed by other removals and thinnings on other forestland. Unused mill residues and urban wood wastes are discussed. The sixth section of the chapter provides estimates of how much conventionally sourced wood could be provided by additional harvest and by a shift of current pulpwood demand to bioenergy applications. The final section provides a summary of forest biomass and wood waste sources. All sections include key assumptions and data used to estimate applicable current and future supplies, as well as prices to access these resources. County-level supply curves are estimated for many of the resources; however, in this report, estimates are summarized by state and nationwide. A complete county-level database with projections of quantities and prices is available in a stand-alone database, the Bioenergy KDF (ORNL, 2010).

TEXT BOX 3.2 | FOREST RESOURCES OF THE UNITED STATES

In the United States, there are about 750 million acres of forestland, with slightly more than two-thirds classified as timberland or land capable of producing 20 cubic feet per acre annually of industrial wood products in natural stands (Smith et al., 2009). Another 22% of this forestland is classified as "other" and is generally not productive enough for commercial timber operations owing to poor soils, lack of moisture, high elevation, or rockiness. The remaining 10% of forestland is withdrawn from timber utilization by statute or administrative regulations and is dedicated to a variety of non-timber uses, such as parks and wilderness. The timberland fraction of U.S. forestlands totals approximately 514 million acres. As noted by Smith et al. (2009), the map below shows forested pixels from the USDA Forest Service map of Forest Type Groups (Ruefenacht et al., 2008). Timberland is derived and summarized from RPA plot data using a hexagon sampling array developed by EPA. Reserved land is derived from the Conservation Biology Institute, Protected Areas Database. Other forestland is non-timberland forests.



3.1 Primary Forest Biomass

Current removals from U.S. forestlands are about 21.2 billion cubic feet annually—nearly 320 million dry tons.[17] This level of harvest is well below net annual forest growth and only a very small fraction of the total timberland inventory. In 2006, the ratio of forest-growing stock growth (wood volume increases) to growing stock removals (harvest, land clearing, etc.) in the United States was 1.71,[18] which indicates that net forest growth exceeded removals by 71% (Smith et al., 2009). The data also suggests a national trend of increasing net growth relative to growing stock removals. However, this trend varies by geographic region, species, and ownership, such as public forests and private industrial forests. In the case of private ownership (excluding Alaska) the growth to removals ratio is 1.3 as compared to a ratio of 5.3 for public lands.

[17] These removals include roundwood products, logging residues, and other removals from growing stock and other sources. Removals refer to removal from standing timber inventory. Some roundwood (logging residue) is actually left on harvest sites. Volume is converted to dry tons using a factor of 30 dry pounds per cubic foot.

[18] The growth to removals ratio is derived by dividing net annual growth of growing stock by annual removals of growing stock on timberland and excludes Alaska (Smith et al., 2009; Tables 34 and 35).

Slightly more than 70% of the volume of current U.S. wood removals is roundwood, with the remainder consisting of logging residues and other removals. Total logging residue and other removals in the United States currently amount to nearly 93 million dry tons annually—68 million dry tons of logging residue and 25 million dry tons of other removal residue (Smith et al., 2009).[19] The logging residue material largely consists of tops, branches and limbs, salvageable dead trees, rough and rotten trees, non-commercial species, and small trees. Most of this residue is left onsite because its small piece size makes it unsuitable and uneconomic for the manufacturing of forest products. However, as markets for bioenergy feedstocks develop, a significant fraction of this residue could become economically feasible to remove, most likely in conjunction with conventional harvest operations where the costs of extraction (i.e., felling and skidding) are borne by the conventional forest product. [Forest biomass compliance with EISA is described in Text Box 3.3.] Other removal residue is wood cut, killed, or burned during the conversion of timberland to non-forest land uses (e.g., cropland, pasture, roads, and urban areas).

Trees killed and unutilized because of silvicultural operations, such as precommercial thinning of commercial forests, are also included in the removal residue category. This woody material is unutilized for reasons similar to the logging residue; it could become available for bioenergy production and other uses as technology, economics, and markets evolve. About 70% of the other removal residue is hardwood, attributable to the clearing of land in the North and Southeast where there is a preponderance of hardwoods.

In addition to forest residues generated by timber extraction and land-conversion activities, millions of acres (one estimate is at least 28 million acres in the West; USDA Forest Service, 2005) of forests are overstocked with relatively large amounts of excess biomass, which have accumulated as a result of forest growth and alterations in natural cycles through successful suppression of fires (USDA Forest Service,

TEXT BOX 3.3 | FEEDSTOCK COMPLIANCE WITH EISA

The Energy Security Act (PL 96-295) of 1980 defines biomass as "any organic matter which is available on a renewable basis, including agricultural wastes and residues, wood and wood wastes and residues, animal wastes, municipal wastes, and aquatic plants" (U.S. Department of Energy, 2010c). This first-ever statutory definition became the standard for some legislative and programmatic purposes. Currently, 16 biomass definitions exist within recently enacted statutes and the Tax Code (Riedy and Stone, 2010). The 2008 Farm Bill Act and EISA definitions are typically regarded as the most comprehensive.

In the enactment of a new national Renewable Fuels Standard, as part of EISA, Title II, Sec. 201(I)(I), a more stringent definition was established that not only defines the types of feedstocks, but also defines the sources of the feedstock. In effect, EISA excludes all biofuels feedstocks from federal lands, except in narrowly defined areas at risk from wildfire.

For the purpose of this report, the original "organic matter" definition without additional statutory or regulatory definitional restrictions is used. This is because:

1. Subsequent laws, such as EISA, are for specific uses and final products—for EISA, it is biofuels. The *Billion-Ton Study* is an evaluation of availability without regard to final use.
2. There are other laws and pending legislation that would have to be included in a comprehensive analysis of available biomass "constrained by definition" that would detract from the goal of this report.
3. Restricting the analysis to definitional biomass availability reduces the usefulness of the information and conclusions if the definition changes.

Therefore, the availability of feedstocks from federal lands is analyzed and included separately. The results are shown by landownership for the convenience of the reader. Outputs are categorized as either public or private ownership. Public ownership includes federal, state, county, and city lands. Private ownership includes industrial and non-industrial lands.

[19] The Forest Inventory and Analysis Program of the U.S. Forest Service conducts annual surveys and studies of industrial users to determine roundwood harvests for primary wood-using mills. Additional studies are also used to determine nonindustrial (i.e., residential and commercial) uses of roundwood. Taken together, these studies provide a comprehensive description of timber product output for a given year (USDA Forest Service, 2007a).

2005; Graham et al., 2004).[20] As part of its Healthy Forest Initiative, the USDA Forest Service identified timberland and other forestland areas that have tree volumes in excess of prescribed or recommended stocking densities. The areas identified require some form of treatment or thinning to reduce the risks of uncharacteristically severe fires and are in close proximity to people and infrastructure. This excess biomass is classified as standing and downed trees in overstocked stands that would leave the forests healthier, more productive, and less susceptible to catastrophic fire hazard if removed.

An initial estimate of the potential supply of this fuel treatment wood was developed for five western states (USDA Forest Service, 2005). The study identified a large recoverable residue and merchantable wood resource ranging from a low of 576 million dry tons to a high of 2.1 billion dry tons that could be removed over a period of years. The low estimate included only 60% of the timberlands in the highest fire risk class and the same high estimate included all timberlands requiring some fuel treatment. About 30% of the total amount was considered residue—tops and limbs of large trees and saplings or trees too small for pulpwood or sawlogs, cull components of merchantable trees, and standing dead trees. [These operations are visualized in Figures 3.1 and 3.2.] A Web-based tool, the Fuel Treatment Evaluator, was subsequently developed to identify, evaluate, and prioritize fuel treatment opportunities that would remove excess biomass and promote a more natural fire regime pattern, with recurrence of less severe fire (Miles et al., 2006; Skog et al., 2006). This tool was used in the *BTS* to estimate the potential availability of fuel treatment biomass across the entire continental United States. The 2005 *BTS* provided an estimate of 60 million dry tons per year, with slightly more than 80% of the biomass on timberland and the remainder on other forestlands. The key assumptions behind this analysis included the exclusion of forest areas not accessible by road and all environmentally sensitive areas, equipment recovery limitations, and merchandizing thinnings into two utilization groups (conventional forest products and bioenergy products).

Figure 3.1 Forest residue operation in northern California

(Courtesy of Han-Sup Han, Humboldt State University)

Figure 3.2 Removal of forest biomass with a skidder

(Courtesy of Han-Sup Han, Humboldt State University)

Although the demand for roundwood, as well as the extent of land-clearing operations, ultimately

[20] In August 2000, the National Fire Plan was developed to help respond to severe forest fires and their impacts on local communities, while ensuring sufficient firefighting capacity for future fires. The National Fire Plan specifically addresses firefighting capabilities, forest rehabilitation, hazardous fuels reduction, community assistance, and accountability. The Healthy Forest Restoration Act (HFRA) of 2003 was then enacted to encourage the removal of hazardous fuels, encourage utilization of the material, and protect, restore, and enhance forest ecosystem components. HFRA is also intended to support research and development to overcome both technical and market barriers to greater utilization of this resource for bioenergy and other commercial uses from both public and private lands. Removing excess woody material has the potential to make relatively large volumes of forest residues and small-diameter trees available for bioenergy and biobased product uses.

determines the amount of forest residue generated, environmental and economic considerations set the amount that can be sustainably removed. The next section of this chapter discusses forest resource sustainability and is followed by a discussion of the methods and data used to estimate county-level quantities and prices for the major forest residue feedstocks.

3.1.1 Sustainability of Extracting Primary Forest Residue Biomass

While the sustainability of harvesting traditionally merchantable roundwood has been studied at great length, the additional harvest of logging residues and small-diameter trees for bioenergy creates new concerns over forest ecosystem sustainability (Janowiak and Webster, 2010). Biomass feedstocks may be harvested from a wide variety of forest management systems, ranging from extensively managed, naturally regenerated forests to short-rotation woody crops (SRWC). Each forest system has its own issues with respect to sustainability. While these issues must be addressed, the sustainable extraction of forest residues can be achieved through either the application of best management practices (BMPs)—that are voluntary or statutory (regulated by states)—or through formal forest certification programs (BRDI, 2008). In all cases, these practices are science based and have the goals of protecting ecological functions and minimizing negative environmental impacts. In the case of fuel treatment operations, biomass harvesting will enhance forest health and vitality as long as some stand structure is left to provide continuous cover, erosion control, and habitat (Figure 3.3) (Graham et al., 2004).

Within the most intensive woody biomass feedstock systems, maintaining site productivity is imperative to efficient management. Nutrient deficiencies that may be present are mitigated as a matter of course through fertilization. The management of these systems in terms of the intensity of soil disturbance; technological inputs to manage water, nutrients, and non-crop vegetation; and harvest intensity, is more intensive than traditional forestry, but usually less intensive than typical agricultural systems. Blanco-Canqui (2010) reviewed the sustainability of these systems in comparison to other agronomic biomass feedstock systems and notes that, in comparison to annual systems, short-rotation woody crops offer several environmental advantages. When sited on marginal agricultural land, these systems improve soil productivity and offer additional environmental benefits, such as improved water quality and wildlife habitat.

Within conventionally managed forest ecosystems, concerns over biomass harvesting involve both operational concerns associated with harvesting and thinning operations, as well as the ecological concerns over the removal of additional wood following conventional stem-only harvests (Page-Dumroese et al., 2010). Some dead woody biomass is left onsite, as it serves several important ecological functions in forest ecosystems (see comprehensive review by Harmon et al., 1986) that are affected by harvesting. Dead woody material serves as a habitat for a variety of organisms, including fungi, mosses, liverworts, insects, amphibians, reptiles, small mammals, birds, and regenerating plants. In cool climates, downed logs act as nurse logs for seed germination and stand establishment. Birds forage, nest, and hunt in and on dead wood. Dead woody material affects ponding, sediment trapping, and aeration in streams; it also impacts site productivity through several mechanisms.

Figure 3.3 Sustainable harvest from managed forest systems

(Courtesy of Evergreen Magazine)

This dead biomass alters site water balance and water quality through storage and release of water and by reducing runoff and erosion. It is commonly used during harvest operations to protect wet soil areas from compaction and rutting, and it is used post-harvest to help limit runoff and erosion from skid trails and forest roads. Finally, dead woody material supports biological nitrogen fixation, thereby increasing onsite levels of nitrogen, and it contains nutrients that are cycled back into the soil.

The loss of nutrient capital and organic matter due to biomass harvesting is of particular concern to sustaining site productivity and carbon sequestration potential. While biomass harvesting includes more sources than just harvest residue from conventional harvest systems, the majority of research in the United States on nutrient removals from biomass harvesting has focused on the impact of whole-tree harvesting relative to conventional harvesting and the removal of small-diameter trees for silvicultural and fire protection purposes. Whole-tree harvest is usually defined as all woody biomass contained in standing trees above ground, where complete-tree harvest removes the stump and large root biomass, as well. More intensive biomass harvesting involves removing existing dead wood from the site. Logging residues, or the remainder of the standing tree after the conventionally merchantable bole is removed, contain a disproportionately high nutrient content relative to the bole. For example, a whole-tree harvesting study of six hardwood and five conifer stands showed the removal of about 23% more biomass than stem-only harvesting, but 49%, 40%, 38%, and 36% more nitrogen, phosphorus, potassium, and calcium (Mann et al., 1988). Similarly, whole-tree harvesting removes about 16% more biomass from Douglas-fir stands, but 65%, 83%, 52%, and 169% more nitrogen, phosphorus, potassium, and calcium (Mann et al., 1988). Small-diameter trees removed in thinning operations or in dedicated short- rotation woody crop systems also have a comparatively high nutrient capital due to higher proportion of high nutrient-concentration biomass (leaves or needles, branches, and bark). Thus, the nutrient removal is much greater in biomass harvesting systems than in conventional harvesting systems relative to the actual amount of biomass harvested. Therefore, it is important to manage the retention of portions of the biomass to ensure long-term productivity through leaving residues or time of harvest.ensure long-term productivity through leaving residues or time of harvest.

However, few long-term studies have followed the growth response of the next rotation following harvest to determine whether site productivity was affected. Johnson and others (2002) found that whole-tree harvesting had no effect on the 16-year growth of an oak-hickory forest compared to stem-only harvesting. Whole-tree harvesting did reduce the 16-year growth of a loblolly pine plantation in South Carolina, which was attributed to the loss of nitrogen and to physical property differences in soil; in stem-only harvested plots, the woody debris significantly improved physical attributes of soil (Johnson et al., 2002). Powers et al. (2005) summarized the findings from 26 installations of the USDA Forest Service Long-Term Soil Productivity (LTSP) study and found that complete aboveground organic matter harvest (including the forest floor) reduced the 10-year growth in aspen stands compared to bole-only harvest, but had no consistent effect for mixed conifers in California and Idaho or southern pine in Louisiana, Mississippi, and North Carolina. Scott and Dean (2006) showed that 7- to 10-year growth of loblolly pine was reduced by an average of 18% on 15 of 19 research blocks across six separate research studies in the Gulf Coastal Plain. Soil carbon sequestration is also rarely reduced substantially by biomass harvesting (Johnson and Curtis, 2001). These scattered results indicate that, in general, intensive harvesting does not universally reduce site productivity, but in some cases, it can cause substantial growth declines if not mitigated. Further research is ongoing at the more than 100 installations of the LTSP study (Powers et al., 2005), and as this study evolves, more information will be available for long-term growth responses and soil carbon sequestration across a variety of forest types and sites.

As noted by the few reports of long-term growth, intensive biomass removals will have no discernible effect across many sites. Numerous sites are well buffered with respect to nutrients, so that even repeated intensive removals over long periods may not induce nutrient deficiencies. Sites with low slope and little susceptibility to compaction do not require much biomass to mitigate erosion and compaction concerns. However, there are some regional-, soil-, and forest-specific origins. Some forests in the eastern United States are at a relatively high risk of calcium loss from harvest (Huntington, 2000). The loss is due to low-calcium geologic parent materials, decades of acid precipitation that have leached much of the natural calcium capital from the soil, and (in the southeastern United States) the high degree of weathering. In southeastern pine forests, certain geologies are markedly low in phosphorus and routinely fertilized to overcome their natural deficiency and to avoid induced deficiency by harvest removals. Nitrogen is a limiting factor throughout the United States, with the exception of the Northeast. However, in dry or cold forests where nitrogen cycling is retarded due to climate, nitrogen losses in harvested materials may substantially reduce productivity by lowering decomposition and nitrogen mineralization rates. Continued research is needed to identify specific forest and soil types where biomass removal may exacerbate potential deficiencies, and mitigation strategies will need to be developed.

Fertilization is a common treatment that is used primarily to increase forest growth, but can also be used to mitigate nutrient removals from biomass harvesting. Application rates for important commercial species (e.g., loblolly pine and Douglas-fir) commonly range from 22–54 pounds per acre of phosphorus and 180–224 pounds per acre of nitrogen. Wood ash, created during wood combustion for energy, can be safely used to replace calcium and other basic cations removed through biomass harvesting (Pitman, 2006). Concerns related to the impact of forest fertilization on water quality have generally been unfounded (Binkley et al., 1999), even in intensively managed systems (McBroom et al., 2008) or when biosolids are applied (Pratt and Fox, 2009).

Based on the ecological- and productivity-related roles of dead woody debris and the fact that some timberland owners may not want to—or be able to—fertilize, in order to mitigate potential productivity loss, some level of woody material should be retained to protect these functions. Some of the material may be present in a stand prior to harvest, while some is created as logging residue or by density-induced natural mortality. Because dead wood is important in many complex functions, and the amount needed to perform these functions varies widely across climatic, geologic, edaphic, and vegetation gradients, a single retention percentage should not be used as an actual guideline. Rather, retention guidelines should be developed at state-to-local geographic scales, by forest type, and by harvesting intensity. Several states and the two largest certification programs in the United States (Sustainable Forestry Initiative® and Forest Stewardship Council) have released guidelines that address the productivity and ecological functions of dead wood (Evans and Perschel, 2009). Most of the guidelines were developed for general timberland conditions, with some additional restrictions for special areas, such as critical plant or animal habitat, shallow soils, or steep slopes. For example, Maine requires all coarse woody material that exists prior to harvest to be retained after harvest, and at least 20% of the logging residues with less than 3-inch diameters should be retained. Minnesota recommends that 20% of the logging residues be retained and scattered throughout the harvest tract. Wisconsin's guidelines require 5 tons per acre of woody material to be retained, but the material can be derived from either logging slash or woody material present prior to harvest. Pennsylvania's guidelines call for 15% to 30% of the harvestable biomass to be retained, while Missouri calls for 33% retention. Sensitive sites and soils are also protected. Minnesota suggests avoiding biomass harvesting in areas with threatened, endangered, or otherwise sensitive plant or animal habitats from within riparian management zones, on certain organic soils, and on shallow soils with aspen or hardwood cover types. In general, the literature and harvest guidelines indicate that retaining 30% of logging residues on slopes less than 30% and 50% retention on steeper slopes is a reasonable and conservative estimate of the amount of material needed to maintain productivity, biodiversity, carbon sequestration, and prevent erosion and compaction.

For the United States, Janowiak and Webster (2010) offer a set of guiding principles for ensuring the sustainability of harvesting biomass for energy applications. These principles include increasing the extent of forest cover, including the afforestation of agricultural, abandoned, and degraded lands, as well as the establishment of plantations and short-rotation woody crops; adapting forest management to site conditions by balancing the benefits of biomass collection against ecological services provided (e.g., old-growth forests provide ecological services and habitat benefits that greatly exceed bioenergy benefits); using BMPs; retaining a portion of organic matter for soil productivity and deadwood for biodiversity; considering forest fertilization and wood ash recycling; and, where appropriate, using biomass collection as a tool for ecosystem restoration. When these principles are applied through state-based BMPs or biomass harvesting guidelines or certification, biomass harvesting can be sustainably practiced with reduced negative impacts on the environment, and harvestingcan be a much-needed tool for achieving forest health restoration objectives.

A summary of the operational sustainability criteria used to estimate primary residue supply curves is provided in Table 3.1.

Table 3.1 Summary of Sustainability Assumptions Used in Developing Forest Residue Estimates

Forest biomass resource	Environmental sustainability	Economic/technical
Logging residues, thinnings, and conventionally sourced wood.	Administratively reserved forestlands excluded. These are lands excluded from timber production by legislative statute and include wilderness and National Parks. Inventoried roadless areas are excluded. These are USDA Forest Service lands identified as possibly qualifying for wilderness or other conservation protections.	Logging residues result from conventional harvests; therefore, assume that there is road access to the biomass and no road building is required. For the thinnings and conventionally sourced wood only, the FIA variable “distance to road” was used to determine road access. If over 0.5 miles, then the high cost excluded biomass because of lack of current road access.
Logging residues from after commercial timber harvesting.	Thirty percent of logging residue is left onsite for sustainability reasons. These residues include non-merchantable trees and tree components, as well as standing and dying trees.	Prices to roadside are assumed to be stumpage price plus chipping (no stumpage cost on federal land). Estimated prices were used to develop supply curves.
Integrated harvesting to produce commercial products and biomass from timberlands and other forestlands.	Estimated biomass amounts are from simulated uneven-age treatments on overstocked stands where treatments are assumed to occur on a 30-year cycle Retention was determined as a function of slope: Slope is less than 40%, then 30% of residue is left onsite Slope is greater than 40% to less than 80%, then 40% of the residue left onsite Slope is greater than 80%, then no residue is removed (no limbs or tops yarded)	Restricted to sites where stand density index is greater than 30% of maximum by forest type Cable yarding sites (slope greater than 40%) are assumed inoperable if yarding distance exceeds 1300 feet Uneven-age management is practiced (selected trees are removed from all diameter classes) Biomass supply is from removal of (1) trees 1 to 5 inches in diameter at breast height (dbh) in the East and 1 to 7 inches dbh in the West and (2) tops and branches of larger trees Whole tree harvesting is assumed (trees are taken to roadside for processing) Costs to provide biomass from tops and branches include only stumpage and chipping (no stumpage cost on federal land) Prices to provide biomass from whole trees include costs for stumpage, harvest, and chipping (no stumpage on federal land)

3.1.2 Logging Residues and Thinnings

There are two major sources of residues from forest stands: (1) the limbs, tops, cull trees and cull tree components, and downed trees from harvesting operations (logging residues), and (2) the non-merchantable components of stands that are thinned as part of fuel treatments and restoration harvests (thinnings). These two forest biomass resources only come from non-reserve forestland, which is land that is not removed administratively or designated as roadless[21] (Table 3.1). These non-excluded resources either have existing roads, as in the case of logging residues, or they could be accessed from existing roads at an acceptable price. The largest source of some of the lowest-cost forest feedstocks is biomass removed along with sawlogs and pulpwood in integrated harvesting operations. This removes fuel that can contribute to fire risks. Integrated harvesting operations are assumed to take the form of removing whole trees to roadside, where tops and branches are removed and chipped for bioenergy feedstock (Figure 3.4). Integrated operations would also remove small trees (less than 5 inches in diameter at breast height (dbh) in the East and 7 inches dbh in the West) to the roadside where they are also comminuted (Figure 3.4). In integrated operations, there is a certain fraction of logging residues left on the site intentionally for retention purposes (see Table 3.1). A minimum of 30% biomass was assumed to be retained on the site, and even more was assumed for steeper slopes.

Two separate methods—recovering logging residues behind conventional harvesting operations and simulated forest thinning with integrated harvesting operations—are used to estimate the quantity and roadside price of the available biomass (see Text Box 3.4). After making separate estimates of county-level supply curves using these two methods, they are combined into a single, composite estimate for a county. This can be done by taking an average of the two supply curves (average of the two supply amounts at each supply price) or a percentage of each, such as 50% logging residue and 50% forest thinnings, which is used in this analysis.

For each of the two estimates, roadside costs and stumpage[22] prices are determined for increasing incremental amounts of supply. Roadside costs include the cost to cut and extract wood to roadside and the cost of chipping at roadside. These estimates were made using the Fuel Reduction Cost Simulator (FRCS) model (Dykstra et al., 2009). Stumpage prices (cost per ton for biomass in standing trees) are estimated as an increasing fraction of baseline pulpwood stumpage prices as the amount supplied increases. Regional pulpwood stumpage prices for 2007 are summarized in Table 3.2. The first step to estimate county-level supply curves is based on estimates of recent amounts of logging residue that are generated, and the second step is based on simulated silvicultural treatments on overstocked timberland that produce biomass, as well as pulpwood and sawlogs.

Logging residue estimates. Logging residue estimates are available from the Timber Product Output (TPO) database (USDA Forest Service, 2007a). The TPO consists of a number of data variables that provide timber product harvested, logging residues, other removal residues, and wood and bark residues generated by primary forest product processing

Figure 3.4 Comminuting forest residue bundles

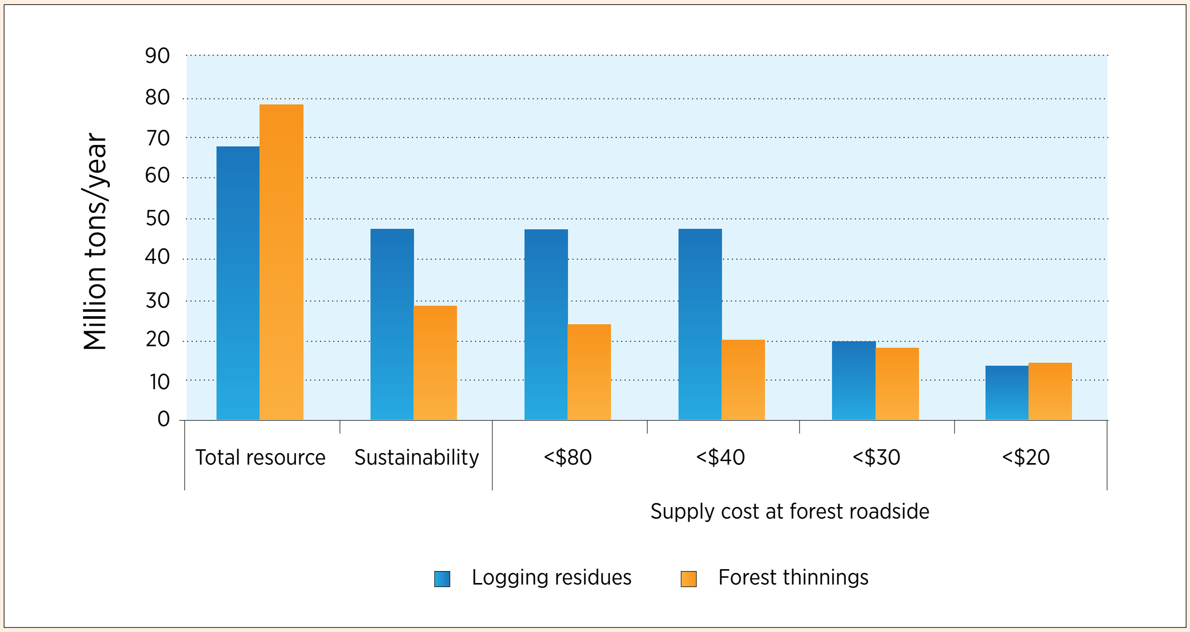
(Courtesy of Han-Sup Han, Humboldt State University)

[21] Roadless areas are defined as lands without constructed roads and have been delineated by government review.

[22] By definition, stumpage is the value of standing trees (i.e., standing on the stump) uncut in the woods.

TEXT BOX 3.4 | LOGGING RESIDUES AND THINNING ESTIMATES

The logging residue-based and simulated forest thinning-based estimates before sustainability and cost restrictions are shown below. Slightly more than 60% of these sources can be harvested once requirements for ensuring sustainability are met. All of the logging residue resources can be harvested at less than $40 per dry ton roadside and more than 90% can be harvested at less than $30 per dry ton roadside. At less than $40 per dry ton roadside, about 70% of the thinnings can be harvested. The higher costs for thinnings generally reflect the presence of small-diameter trees, which incur harvesting and skidding costs in addition to stumpage and chipping.



mills for each county. The TPO Tablemaker, a U.S. Forest Service online tool, was used to access the TPO data. [The Tablemaker is no longer available and has been replaced with other programs (U.S. Forest Service, 2011a).] The TPO database combines forest industry and other private ownership classes into an undifferentiated private class to comply with the Privacy Law. The undifferentiated private class was used in this analysis and will be available on the KDF. The logging residues are estimated using harvest utilization studies and represent the total volume left on the site. It is not economically feasible to actually recover all of the biomass, and due to sustainability reasons, at least 30% of the biomass is left onsite. Therefore, the estimated biomass was reduced by sustainability percentages shown in Table 3.1. Using these reduction factors and cost curves, no further reductions were needed because of economic feasibility, which means that a recoverable factor was not needed as used in the *BTS* (Perlack et al., 2005). The non-recoverable fraction left onsite, which includes leaves, branches, and parts of the tree crown mass, provides nutrients and serves to maintain soil productivity.

An assumption in this analysis is that most logging residue is moved to roadside as part of a whole-tree harvest of merchantable wood, and the only costs will be for stumpage and chipping at roadside. In cases where cut-to-length systems are used, which means that residue is left in the stand where the trees are processed, the assumption is that the biomass will not be recovered (Figure 3.5) (see more complete explanation in thinning section). Chipping costs were determined by the FRCS model (Fight et al., 2006) as modified and expanded to cover the U.S. North and South, as well as the West, by Dykstra and others (2009). Prices average about $13 per dry ton nationwide and are slightly higher in the West and slightly lower in the South due to differences in labor and fuel costs. Stumpage price is assumed to be zero for biomass from federal land because biomass removal is usually part of a fuels treatment or restoration activity. For privately owned timberland, stumpage price is assumed to begin at $4 per dry ton and increase to 90% of the pulpwood stumpage price when 100% of the available logging residue is used. The low entry price is based on a token payment in the likelihood that the biomass is only removed to meet other landowner objectives, such as reducing site preparation costs or fire risks. The higher prices are the result of demand increasing or supply decreasing to the point that biomass is almost competitive with pulpwood.

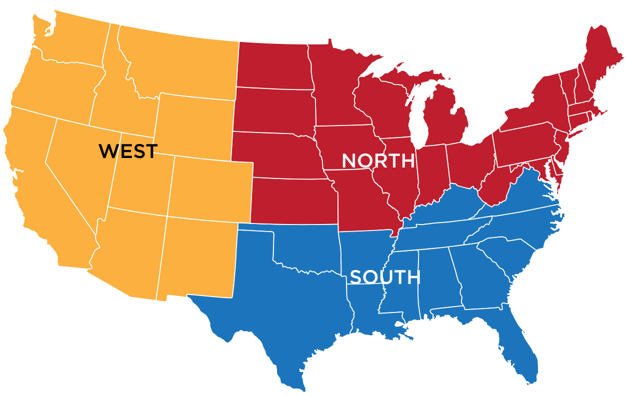


Table 3.2 Pulpwood Stumpage Prices by Region

	Delivered price ($/green ton)	Stumpage price ($/green ton)	Stumpage price ($/dry ton)
Hardwoods			
North	$32.00	$7.70	$15.40
South	$28.80	$6.70	$13.30
Softwoods			
North	$33.60	$10.40	$20.70
South	$29.00	$7.80	$15.70
West	$40.30	$13.80	$27.60

Source: RISI, 2008; Fight et al., 2006; Dykstra et al., 2009 (Includes all types of ownerships)

The supply curve based on logging residue estimates is shown in Figure 3.6 (thinning and composite supply curves shown in Figure 3.6 are discussed in subsequent sections). The logging residue supply curve is generally flat and shows 47 million dry tons per year potentially available at a roadside price of $40 per dry ton or less from all defined forestlands (Table 3.3 in Section 3.7). There is a 9% decrease in available tons per year generally across all prices when the federal lands are removed per EISA definitions. All logging residues are available at this price. State supplies at $40 per dry ton per year are graphically summarized in Figure 3.7. The largest supplies are where pulpwood and sawlog harvests are the greatest, namely the Southeast, Northwest, and Great Lakes. A more spatially explicit summary of logging residues supplies at $20 and $40 per dry ton is shown on the maps in Figure 3.8. Table 3.4 shows that at $60 per dry ton in 2030, about 50 million dry tons are available. These estimates are derived using USDA Forest Service Resource Planning Act (RPA) projections of timber harvests from forestland by region and estimates of logging residue as a percentage of timber product removals (Haynes et al., 2007).

Figure 3.5 Logging residues

(Courtesy of Barry Wynsma, USDA Forest Service)

Figure 3.6 National supply curves for logging residues, thinnings, and composite (50% logging residues and 50% thinnings) from timberland

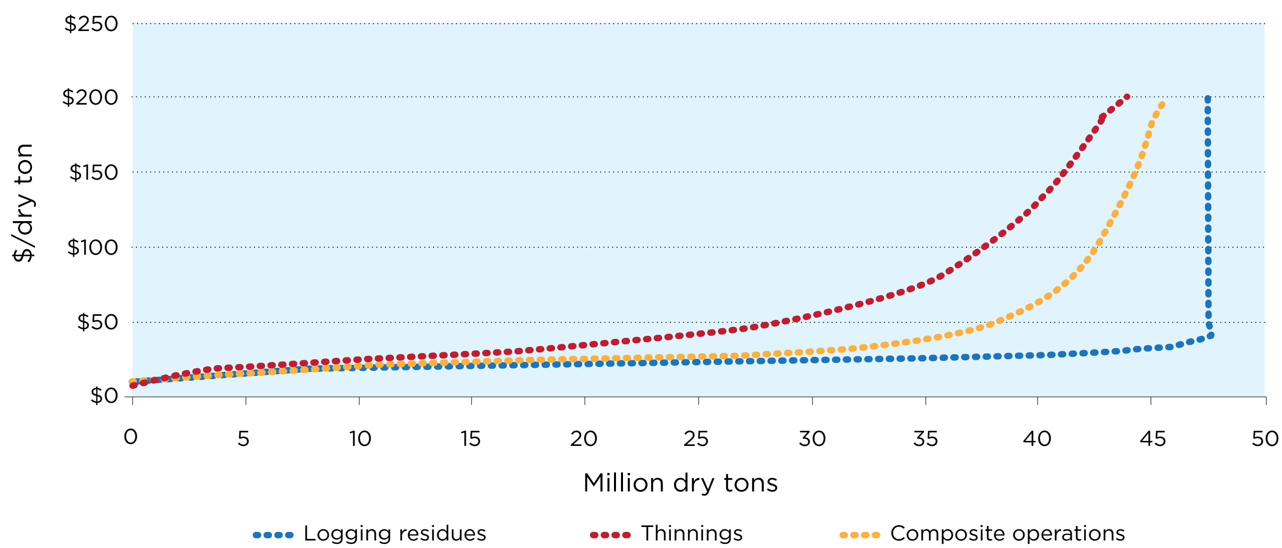


Figure 3.7 Current and year 2030 state quantities of logging residue available annually at $80 per dry ton

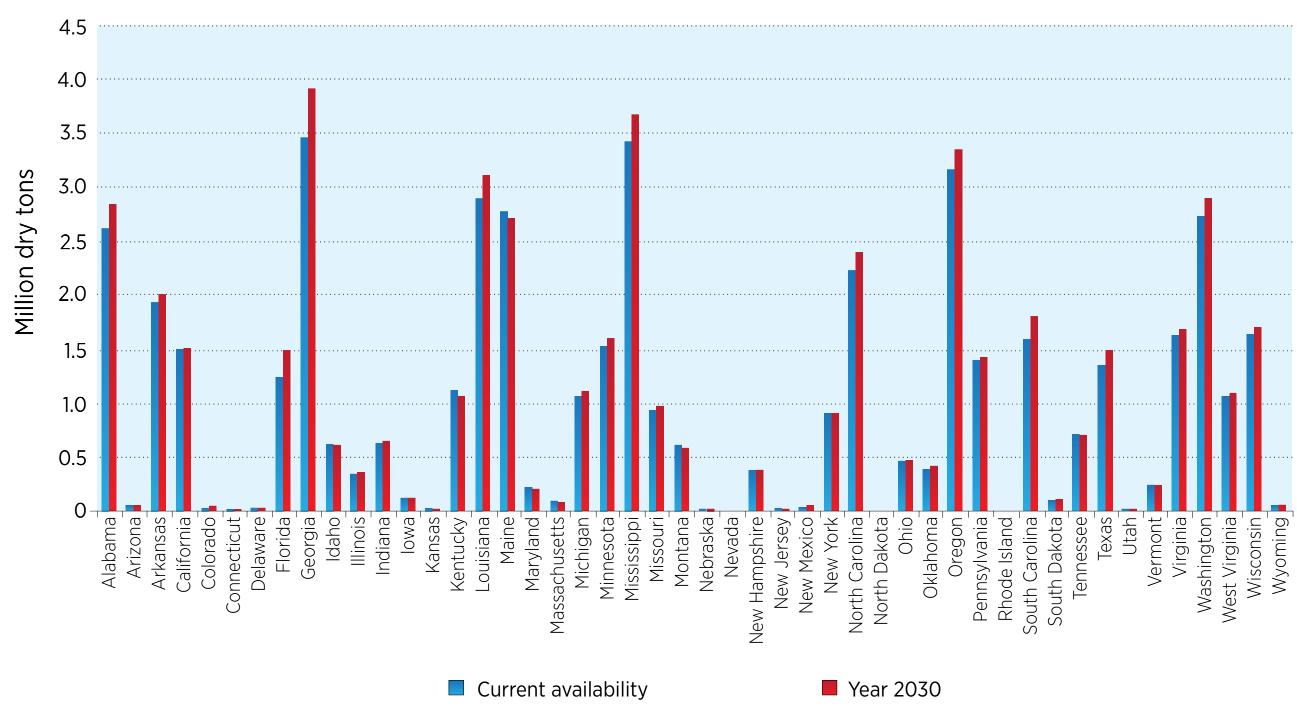
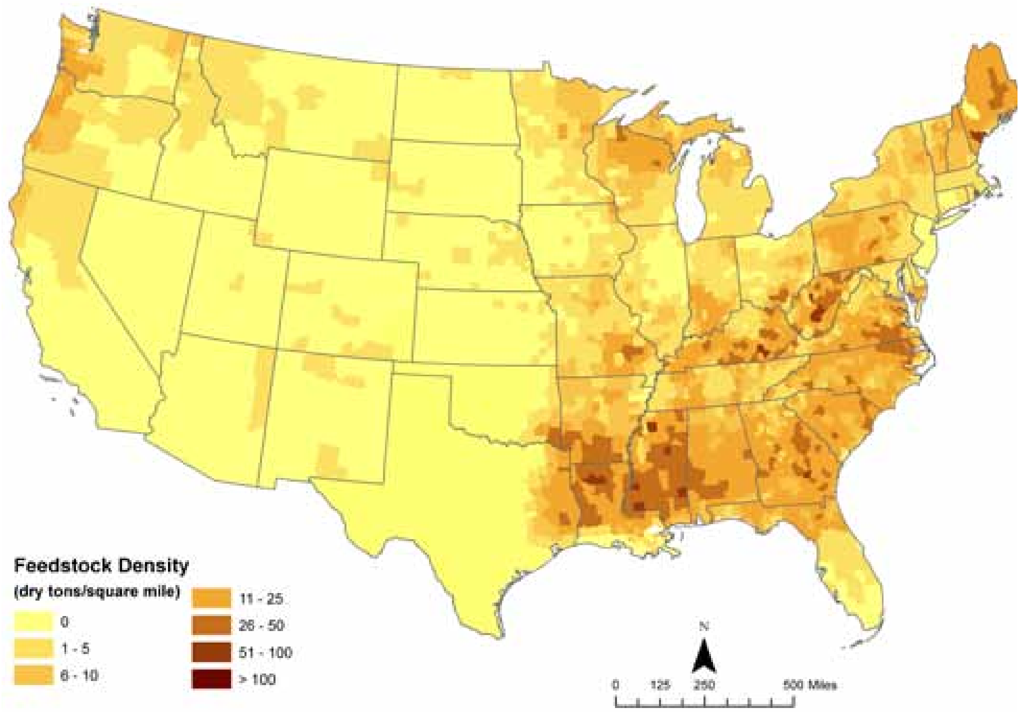
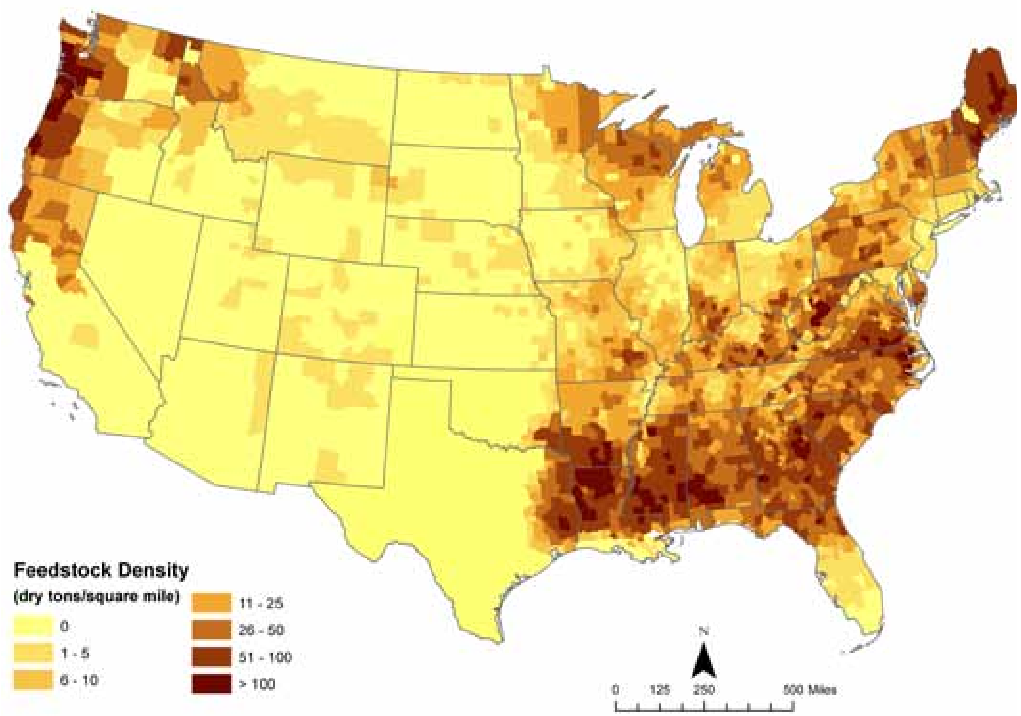


Figure 3.8 Spatial distribution of logging residues at $20 and $40 per dry ton (delivered to roadside)

$20 per dry ton



$40 per dry ton



Simulated forest thinning-based estimates. The second method used to estimate biomass supply by county is to simulate uneven age thinning operations on all non-reserved timberland in the Unites States using USDA Forest Service forest inventory and analysis (FIA) plots (Smith et al., 2009).[23] The data were accessed from the publicly available Forest Inventory Database on February 3, 2010 (USDA Forest Service, 2010a;b). Because the database is dynamic (i.e., is updated as states report new data during the year), accessing the database after that date gives different results. The *BTS* only estimated the biomass from fuel reduction treatments on two specific classes of most overstocked stands that needed mechanical thinnings to reduce fire risk. The new method included all non-reserved forestlands, and if the stands were overstocked above certain densities, the stands were thinned regardless of the fire-risk classification (see Text Box 3.5). Decades of fire prevention and suppression efforts across the United States, especially in western areas, have led to overstocked stands and an accumulation of fuels that are increasing the risk of catastrophic fire. In the past, fire-adapted forests had relatively open canopies due to frequent low-intensity fires and harvestings intervals. Today, many stands have closed canopies and a buildup of high levels of small stems and biomass due to fire suppression and less harvesting. Highly dense forests are also stressed, which is compounded by more frequent and longer drought intervals. These conditions reduce the resistance to insects and diseases.

These forests contain significant levels of carbon sequestered in the biomass of the dense stands. Conducting fuels treatment (i.e., reducing the biomass), can release the stored carbon. If using biomass for energy, there is a displacement of fossil carbon emissions with emissions from renewable feedstocks. Furthermore, the treated stands respond to the lower density, and the trees grow quicker than when stagnated, thus sequestering carbon.

TEXT BOX 3.5 | BIOMASS EQUATIONS IN FIA

The USDA Forest Service Forest Inventory and Analysis Database (FIADB, version 4) as downloaded on February 3, 2010, is used to develop logging residues, thinnings, and conventional wood biomass estimates (USDA Forest Service, 2010a). Logging and other removal residue data is obtained from the 2007 RPA Timber Products Output (TPO) database (USDA Forest Service, 2007a). These estimates include the small tree volumes (1–7 inch diameter at breast height (dbh) in the East and 1–9 inch dbh in the West) and the non-merchantable (limbs, tops, and unmerchantable bole) volumes of the merchantable trees greater than 7 or 9 inches dbh. [Note: the updated *BTS* uses 5-inch dbh limit in the East and 7 inches in the West, which are conservative estimates.]

In August 2009, the Forest Service adopted a new method, the component ratio method (CRM), for calculating the non-merchantable volumes of the merchantable trees. In the original *Billion-Ton Study,* these volumes were calculated using diameter-based, regional prediction equations of tree volumes and biomass in components of the tree. It became apparent in the analysis that the estimated biomass component of the merchantable trees is considerably less using the new database with the CRM method compared to the old method. It is reported that the biomass estimates in tons per acre are consistently lower using the CRM compared to the regional prediction equations (Heath et al., 2009).

The change in biomass methodology to CRM produces total U.S. tree biomass inventory estimates that are 6% to 8% lower compared to estimates using the previous method. More importantly, there are significant reductions—up to 30%—for certain species, stand types, and locations. This change in method also decreased estimates of county-level biomass supply at given prices. The new methodology was used in this analysis. The reason to point out the use of the new methodology is to indicate that change lowers the estimated biomass available from thinnings and conventional harvest for those who may want to make comparisons to the original report.

[23] The FIA program has been in continuous operation since 1928. It collects, analyzes, and reports information on the status and trends of America's forests: how much forest exists, where it exists, who owns it, and how it is changing. The latest technologies are used to acquire a consistent core set of ecological data about forests through remote sensing and field measurements. The data in this report are summarized from over 100,000 permanent field plots in the United States.

Note: The most recent inventories of the 48 states state that there are 300,900 plots of which 117,875 are forested.

Hurteau and North (2009) reported that when including wildfire forecasts in a carbon emissions model, there were more potential greater emissions from untreated stands than treated stands. Their conclusion was that in wildfire-prone forests, tree-based carbon stocks were best protected by fuel treatments.

Thinning is used to reduce density, open up the stands, and improve resiliency to fire and pests. Uneven-aged thinning reduces catastrophic fire risks (Huggett et al., 2008) and provides other values as well, so it was used as a model treatment across all stands. In actual practice, the type of stand treatment is prescribed based on current conditions and desired future conditions.

Uneven-aged thinning removes trees across all age classes. This type of harvesting provides bioenergy feedstocks at the lowest cost because biomass is removed in combination with the removal of larger trees for pulpwood and sawlogs. Otherwise, harvest costs would be considerably more if fuel treatment operations were focused solely on smaller-sized trees. In addition, an uneven-aged treatment appears more likely to achieve fire-risk reductions (Skog et al., 2006). Before simulations are conducted, FIA plots located in reserved and roadless areas were excluded and assumed unavailable for treatment.

The uneven-aged thinning simulation was done on all FIA plots where the plot stand density index (SDI) was greater than 30% of a maximum SDI for that given forest type (Shepperd, 2007).[24] This simulates harvests to reduce fire hazard and to improve forest health on overstocked stands. Uneven- aged thinnings are simulated, and estimates are made of the amounts of biomass, pulpwood, and sawtimber that are removed.[25] Beginning with a 1-inch dbh trees, a treatment successively removes fewer trees from each diameter class where the removals bring the SDI down to 30% of the identified maximum SDI value for that stand type. For the North and South, biomass removals include all wood from trees 1 to 5 inches dbh and tops and branches of trees greater than 5 inches dbh, except for wood left for retention purposes. For the West, biomass removals include all wood from harvested trees 1 to 7 inches dbh and tops and branches of trees greater than 7 inches dbh. It is assumed that all of the small-tree biomass can be extracted to roadside, but only 80% of the volume in tops and branches of larger trees will make it to roadside because of breakage. Again, a percentage of this material is retained onsite.

In estimating the cost of biomass from thinnings, it is assumed that:

- Biomass from federal lands have no stumpage costs
- Biomass from private lands range from $4 per dry ton to 90% of regional 2007 (circa 2006–2008) pulpwood stumpage prices
- Limbs, tops, and cull components of merchantable trees have a chipping cost (harvest cost, i.e., felling and transport to roadside, are borne by the merchantable bolewood) and stumpage cost
- Small, unmerchantable trees and dead trees have harvest, chipping, and stumpage costs.

Harvest costs are estimated by the FRCS model plus costs for chipping and stumpage (Fight et al., 2006; Dykstra et al., 2009).[26] The FRCS estimates the cost of providing biomass at roadside by whichever is the least expensive of three alternative harvesting systems: ground-based, whole-tree harvesting with mechanized felling; ground-based, whole-tree harvesting with manual felling; or cable-yarding of whole trees that have been manually felled. Cable-yarding is used in the model only when the average ground slope exceeds 40%.

[24] SDI (Reineke, 1933) is a long established, science-based forest stocking guide for even-aged stands that can be adapted to uneven-aged stands (Long and Daniel, 1990) using data available from broad-scale inventories.

[25] All the biomass wood is assumed to be residues or byproducts, lacking a higher value than energy wood, except for the conventionally sourced wood. Wood that would normally be used in higher value products (e.g., pulpwood, posts, and piling,) could be used for biofuels when prices for alternate uses are lower. Also, within the lower merchantable limits, small-diameter material can easily shift between conventional, commercial uses and biofuel feedstocks, depending on prices and other factors.

[26] The original FRCS model was designed to simulate harvests in the Interior West. It was substantially revised for this study, including the development of new harvesting procedures designed to simulate harvests in the North and South and in the wetter areas of the West. when prices for alternate uses are lower. Also, within the lower merchantable limits, small-diameter material can easily shift between conventional, commercial uses and biofuel feedstocks, depending on prices and other factors.

To simplify the analysis, it was assumed that all the thinnings would be uneven-aged management treatments with whole-tree harvesting. This combination was determined to be the least-cost means to harvest biomass from small trees, branches, and tops. Currently, some stands are being thinned by cut-to-length systems, where the limbs and tops are processed and left in the stand. It is expected that the use of such systems will continue, if not increase, in the future, and biomass will be recovered in a second pass. This approach could be costly. The assumption of using whole-tree logging, either ground based or cable, is more indicative of how biomass will probably be recovered as part of thinning applications over the next 20 years. Because there are very few cut-to-length systems compared to whole-tree systems, the assumption in the analysis is that all thinning is done by whole-tree systems.

In the 2005 *BTS*, the fuel treatments were assumed to occur where there is road access; reduction factors were used to exclude land without current road access. In this update, the FRCS uses an FIA variable, "distance to road," to estimate harvest cost. Although the biomass that is not near an existing road is not excluded as in the earlier assessment, the biomass is prohibitively expensive—well over $200 per dry ton. (See Text Box 3.6 for more information on federal versus private land estimates.) These high costs occur when biomass is harvested with cable systems over 1,300 feet from an established road and ground-based systems between 0.5 and 1.0 mile from a road.

Stumpage price is developed using the following assumptions: (1) price is zero for biomass from federal land because removal is usually part of commercial sales or treatment contracts, and (2) biomass from private lands begins at a low of $4 per dry ton and increases linearly up to a maximum that was set to be 90% of the derived pulpwood stumpage price for private land (Table 3.2).

Because the simulated thinnings also include the removal of timber for merchantable products, there is a limit as to how much can be harvested depending on mill capacities and markets for the products. This thinning removal limit is assumed to be met when the simulated removal of sawlogs plus pulpwood reaches the 2006[27] level of total sawlog and pulpwood harvests. This state-level restriction is to ensure that the estimated biomass supply from integrated operations can be supported by the recent (2006) level of sawlog and pulpwood harvest in each state. The impact of this assumption can be significant, reducing the amount of available biomass by up to 97%[28] in some states.

In preparing the overall estimate of biomass provided from integrated harvesting, it was assumed that the simulated thinnings would provide half of the harvest needed to meet sawlog and pulpwood needs. The other half of harvest would be done in a conventional way

TEXT BOX 3.6 | FEDERAL LAND ESTIMATES

It is important to note that the "federal land" biomass estimates are not obtained by subtracting "without federal land" from "all land." It is only an approximation because the two values are simulated using composite plots that differ due to costs and sawtimber/pulpwood or sustainable allowable cut cap limits. Biomass estimates for each county were generated based on the lowest cost at the given supply curve costs without either exceeding the mill capacity or the net growth allowance for that county.

Cost differences were primarily dependent on distance from road and stand structure (more merchantable trees reduced costs). In many cases, the biomass from federal land was more costly because of greater distance to road and because of the high volume of small-diameter trees—this resulted in generally more wood from non-federal land. For example, 72% of the biomass less than one-half mile from the road was on private land.

Although there was no analysis completed, it is speculated that the federal lands have less cumulative biomass because of the sawtimber cap. Counties with large amounts of federal land tend to have fewer mills and conversion facilities. There may be high amounts of biomass that could not be harvested because there were no markets for the conventional products.

[27] Harvest data is from 2006 and is taken from Table C5B (USDA Forest Service 2007a).

[28] The U.S. average percentage of biomass from thinnings not available because of not having roundwood markets is about 35%, calculated at $60 per dry ton. Regional percentages are South – 5%; Pacific Coast – 18%; North – 48%; Interior West – 49%. States range from 0–97% of the biomass from thinnings not being counted in the assessment because there was not a market in the state for the associated roundwood.

and generate logging residue, a portion of which can be removed for bioenergy. There is also the potential that the markets for sawlogs and pulpwood will expand as the current 2005 RPA Timber Assessment reflects (Haynes et al., 2007). The amount of estimated biomass supply from integrated harvesting (half from conventional harvesting, half from thinning simulations) is increased over time by the rate of increase in projected sawlog plus pulpwood harvest from the 2005 RPA Timber Assessment. A note about special situations of available biomass is provided in Text Box 3.7.

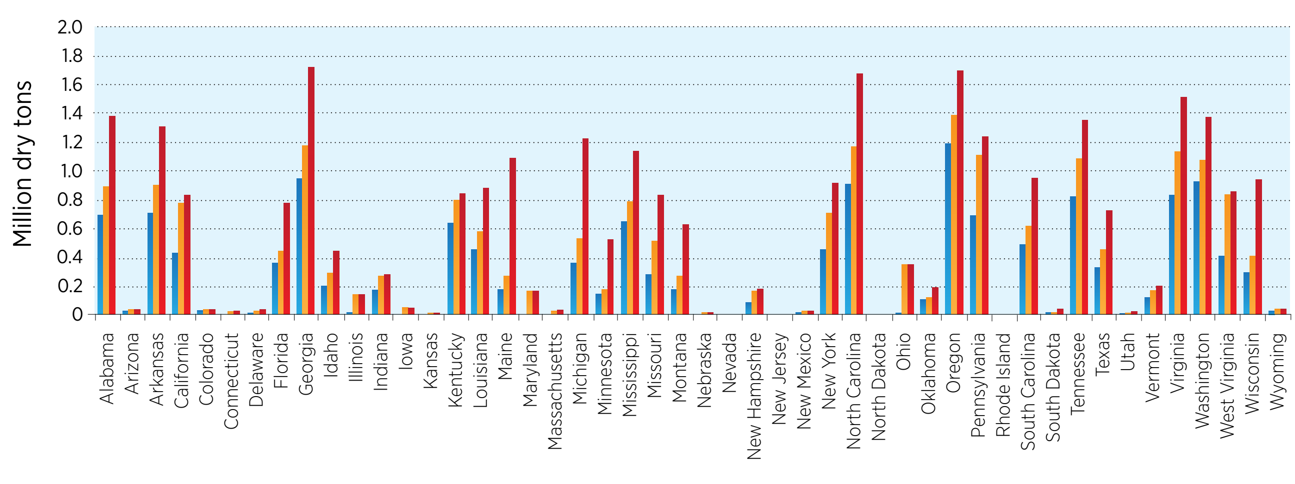
The Biomass Treatment Evaluator was used to estimate county-level supply curves for biomass and industrial roundwood removals on FIA plots by assigning stumpage prices and harvest and chipping costs using the FRCS model.[29] Finally, simulated amounts of biomass supply are assumed to be harvested over a 30-year period. This is the same period assumed for thinnings estimates provided in the 2005 *BTS* report.

The national supply curve for simulated forest residue thinnings on timberland is shown in Figure 3.6. The total simulated quantity is about 37 million dry tons per year at a roadside price of $100 per dry ton or less (Table 3.3). About 24 million dry tons annually are available at a roadside price of $40 per dry ton or less; at $60 per dry ton, about 32 million dry tons are available. Table 3.4 shows that there are no differences over the next 20 years in biomass availability because the thinnings are averaged over 30 years. State quantities are shown in Figure 3.9 at three different roadside costs, with more spatial detail provided in Figure 3.10.

In the 2005 *BTS*, the fuel treatments were assumed to occur where there is road access; reduction factors were used to remove land without current road access. In this update, the FRCS uses an FIA variable, "distance to road," to estimate harvest cost. Although the biomass that is not near an existing road is not excluded as in the earlier assessment, the biomass is prohibitively expensive—well over $200 per dry ton. These high costs occur when biomass is harvested with cable systems over 1,300 feet from an established road and ground-based systems between 0.5 and 1.0 mile from a road.

Stumpage price is developed using the following assumptions: (1) price is zero for biomass from federal land since part of commercial sales or treatment contracts, and (2) biomass from private lands begins at a low of $4 per dry ton and increases linearly up to a maximum which was set to be 90% of the derived pulpwood stumpage price for private land (Table 3.2).

Figure 3.9 State quantities per year of simulated forest thinnings at $20, $40, and $100 per dry ton (roadside)



[29] The Biomass Treatment Evaluator—an SAS® (Statistical Analysis Software) program prepared by Patricia Lebow, USDA Forest Service Forest Products Laboratory—was used to prepare county-level supply curves.

TEXT BOX 3.7 | DEAD AND DYING TREES

A potential feedstock for energy is the dead and dying trees associated with mortality from insects, disease, fire, wind, and other disturbances. In any particular year or period of years, there could be considerable volumes "available" as biomass for energy. A significant issue associated with this feedstock is the inconsistency of the annualized volumes within a designated landscape over a long term and high costs associated with the recovery and utilization of such biomass. There is considerable variation in acres affected annually, especially from pests (Figure 1), and the severity of the damage. In 2008, nearly 9.0 million acres of mortality was caused by insects and disease nationally, a 2.2-million-acre increase from 2007, when 6.8 million acres of mortality were reported (USDA Forest Service, 2009).

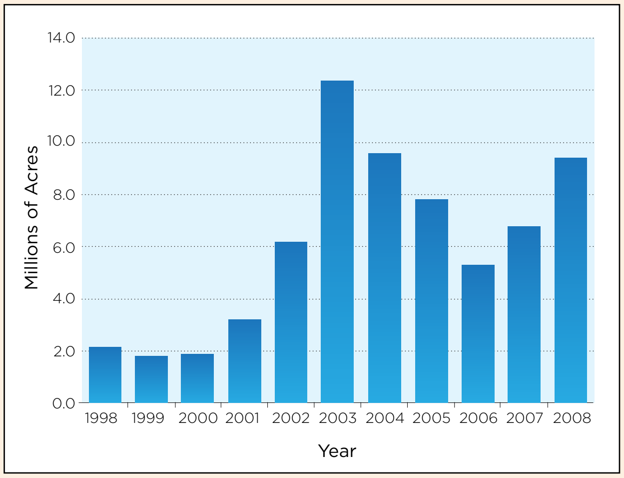


Figure 1 Survey of insect and disease mortality *(Courtesy of USDA Forest Service).*

Figure 2 Pine beetle infestation in Colorado, 2007 *(Courtesy of USDA Forest Service).*

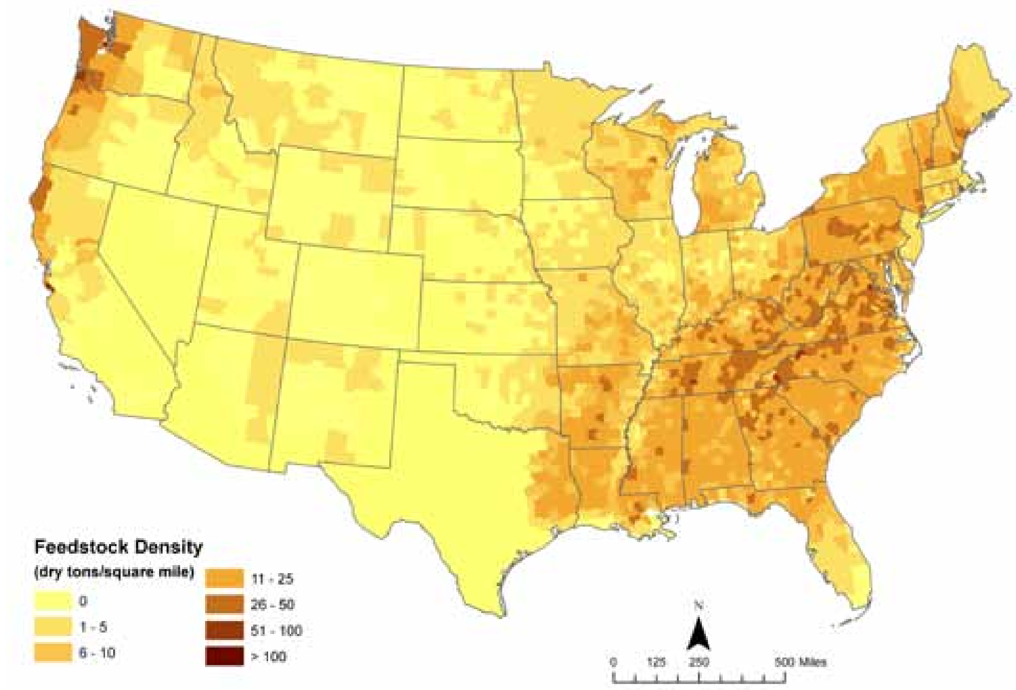
However, there is growing concern about the increasing insect epidemics in the western United States and their transition to other areas of the country. For example, in the reported 2008 insect and disease mortality, nearly 69% of the mortality was caused by just the mountain pine beetle. The mountain pine beetle, Dendroctonus ponderosae, is a native species currently experiencing large-scale outbreaks in western North American pine forests—from Baja California in Mexico to central British Columbia in Canada. It affects primarily lodgepole pine, but also ponderosa and other pines (Figure 2). The beetles have killed more than 2 million acres of lodgepole pines across Colorado and southern Wyoming alone. Cold winters, which Colorado has not seen for years, are needed to kill the larvae and wetter summers are needed to help the trees resist the pests.

Over the past several years, widespread outbreaks of native bark beetles have occurred across the western United States, from pinyon woodlands to spruce-fir forests. The severity and distribution of the recent outbreaks is more than what can be inferred from historical records. The changing climate has given pests the opportunity to invade what has been inaccessible forest habitat (Logan, 2007).

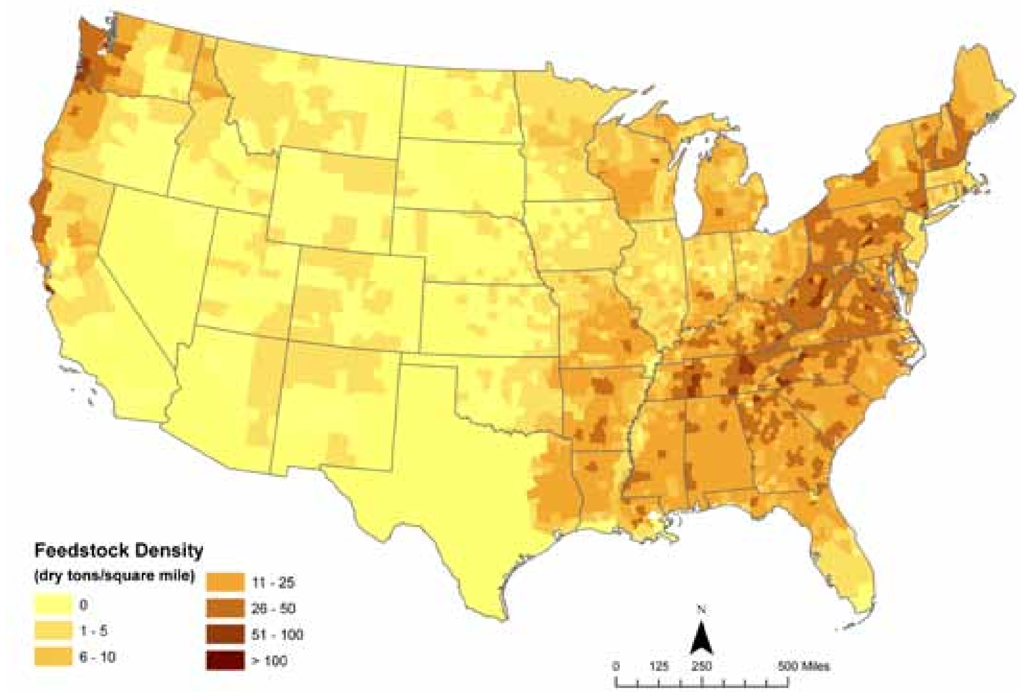
With the known increase in widespread tree deaths from insect epidemics, the issue is whether there should be an additional analysis of the potential wood supply from these epidemics. It was decided that the use of the FIA database and the methodology to address thinnings and logging residues sufficiently included the dead and dying trees. The FIA delineates recently dead and long-standing dead trees on all plots. The current western data averages the number of mortality trees over a 5-year period (Thompson, 2009). A real annual number will not be available until all inventory panels (percentage of all state plots) are completed over 10 years for each state. The "annualized" mortality in the FIA database was thought to be a better estimate of the mortality than an additional analysis, which would be subject to assumptions in both severity and distribution and would have high variability. Because mortality is already incorporated into the assessments using the FIA database, no additional analysis was needed.

Figure 3.10 Spatial distribution of simulated forest residue thinnings at $30 and $60 per dry ton (roadside)

$30 per dry ton



$60 per dry ton



(Courtesy of ORNL)

Composite integrated operations supply estimates. As explained in an earlier section, the logging residue estimates are based on the continuation of current conventional harvesting practices (i.e., merchantable stand and tree components are removed and the residues are left onsite). When estimating both logging residues and simulating integrated thinnings, there will be "double counting of biomass" because the TPO projections used to estimate logging residues do not take into account any reductions in logging residues over time, as more stands are harvested using integrated systems. The conceptual transition from leaving the biomass as logging slash to removing it when the merchantable timber is harvested is likely to occur in response to the development of biomass markets. As it is difficult to model the transition, an assumption had to be made to avoid counting the biomass as both logging residues and integrated thinning biomass. A conservative estimate is 50% of the logging residue supply estimates and 50% of the thinning supply estimates, which means that over the time of the projection, about half will come from the recovery of logging residues and half from thinnings. The composite operations supply curve is shown in Figure 3.6 and Figure 3.11. The curve is generally similar to the logging residue supply, owing to the assumed 50:50 ratio of logging residue to simulated forest residue thinnings. Almost 36 million dry tons per year are available at a roadside price of $40 per dry ton or less (Table 3.3); at $60 per dry ton, the annual potential volume is about 40 million dry tons. When federal land is removed, the amount is reduced by about 5 million tons per year. About 41 million dry tons are available in 2030 at $60 per dry ton from all lands. The residues from integrated operations by state are shown in Figure 3.12 at an example price of $80 per dry ton.

Figure 3.11 National supply curves for integrated harvesting operations

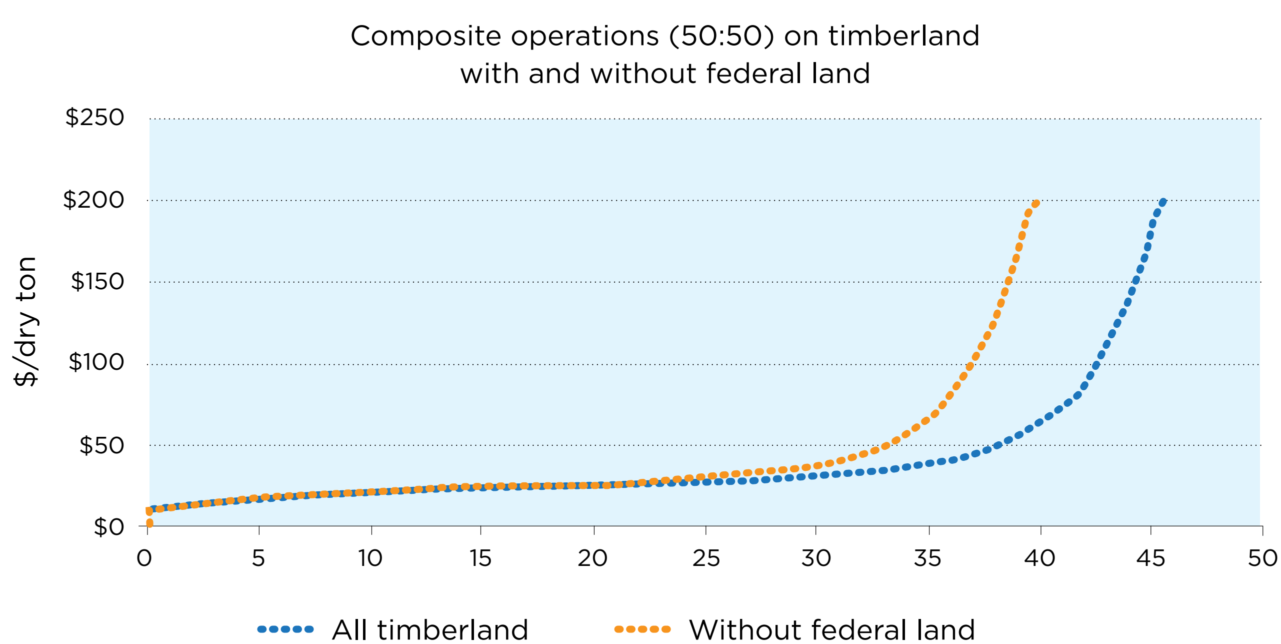
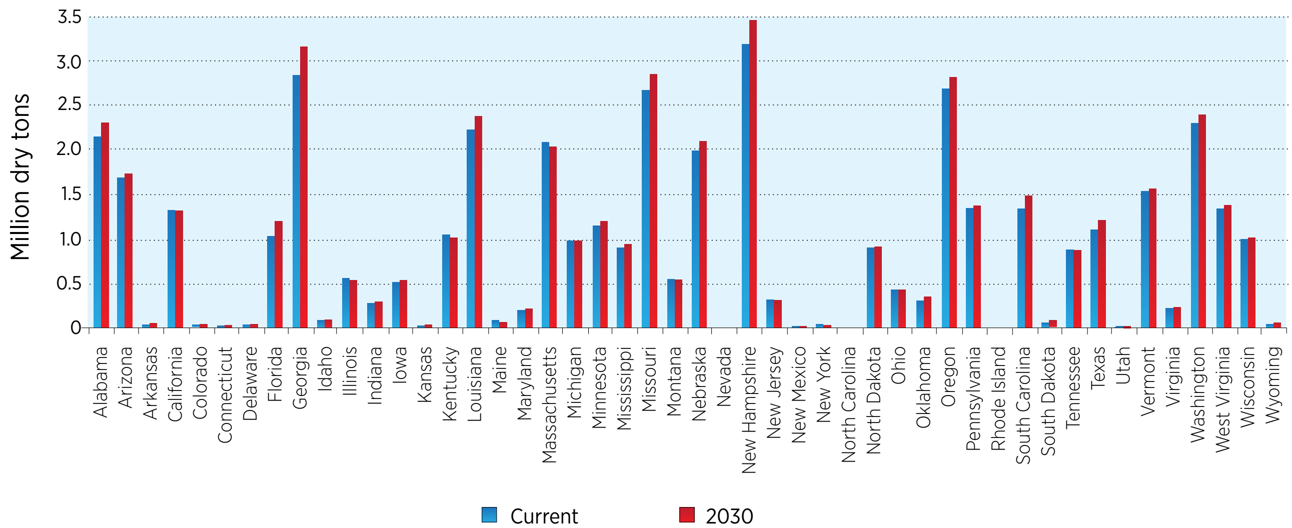


Figure 3.12 Current and year 2030 state integrated operations quantities per year at $80 per dry ton or less at roadside



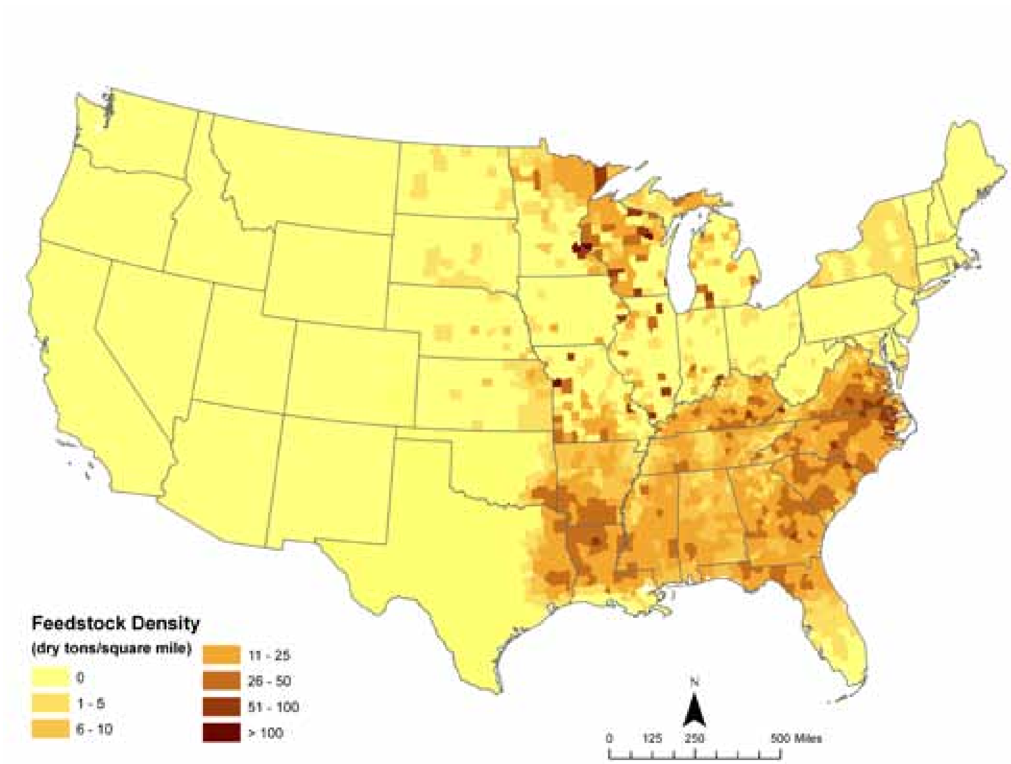
3.2 Other Removal Residues

The conversion of timberland to non-forest land uses (cropland, pasture, roads, urban settlements, etc.) and precommercial thinning operations generates a relatively significant amount of forest residue biomass. These "other removals," especially from land-clearing operations, usually produce different forms of residues and are not generally as feasible or as economical to recover. It is expected that only half of the residues from other removals can be recovered.

Amounts of other forest removals, by county, are obtained from the TPO database for 2007 (USDA Forest Service, 2007a). The 2005 *BTS* report assumed that 50% of the TPO residue estimate is recoverable and available. The original estimate was based on discussion with experts concerning the level of difficulty of recovering this feedstock. Specific characteristics of this feedstock, small land areas, and trees pushed up and piled, trees cut into small pieces, etc., make it difficult to recover them fully. The 50% recoverable assumption is used in this update as well. There is little price data available for these types of feedstocks. Assumptions are made based on the expertise of the contributing authors concerning recovery and transport costs and market prices to derive the stumpage values. Specifically, one-third is assumed to be available at $20 per dry ton (roadside) and the remainder at $30 per dry ton at roadside. So at $60 per dry ton or less, about 12.4 million dry tons are available (see Table 3.3). Future estimates of other removal residue are based on RPA projections of timberland area. Through 2030, total timberland area is projected to decline by about 6 million acres, which could mean that there could be more "other removals." Table 3.4 does not show an increase in recovery of this biomass and keeps potential tons available at 12.6 million per year. Figure 3.13 shows the availability across the United States for residues from other removals.

Figure 3.13 Spatial availability of other removal residues at $40 per dry ton (delivered to roadside)

$40 per dry ton



(Courtesy of ORNL)

3.3 Forest Residue Thinnings on Other Forestlands

Other forestlands are defined as incapable of producing at least 20 cubic feet per acre per year of industrial wood under natural conditions because of a variety of adverse site conditions, ranging from poor soils, lack of rainfall, and high elevation. Many of these woodlands (low-stature or sparse forests) are in the western states and are overstocked, especially with stands of pinyon pine and juniper. As with the fuel reduction thinnings on timberland, removal of the excess biomass could greatly reduce catastrophic fire hazards. FIA data (USDA Forest Service, 2010b: accessed on February 3, 2010) was used to identify overstocked western woodlands. Similar assumptions the 2005 *BTS* report were used for the update. In Table 3.3, the total residue biomass from thinning other forestlands was estimated at 3.2 million dry tons at a price of $60 per dry ton (none are expected to be available below this price because of the high cost of thinning other forestlands). Above $80 per dry ton, 6.4 million dry tons annually becomes available for all lands. When federal forestlands are removed, only 3.6 million dry tons are available, which is a 50% reduction. By definition, these lands do not produce commercial-sized pulpwood or sawlogs, so the cost of removing the thinnings is borne fully by the biomass harvesting operation. An assumption used in the analysis was that about 50% of the biomass could be removed at a price of $60 per dry ton and the remainder at a price of $70 per dry ton. Again, these assumptions are the best estimates by the contributing authors with knowledge in these types of systems. The estimates are considered conservative as they represent the high end of thinning costs because no higher-valued wood is removed with the biomass.

3.4 Fuelwood, Mill Residues, and Pulping Liquors

3.4.1 Fuelwood

All currently used fuelwood is shown in Table 2.1 and is estimated to be 38 million dry tons per year. The quantity of fuelwood used for residential and commercial space heating applications, as well as feedstock for dedicated wood-fired facilities and co-firing applications, is projected to increase to 106 million dry tons per year by 2030.

3.4.2 Primary and Secondary Mill Residues

Amounts of wood and bark residue from milling operations (by county) are obtained from the TPO database for 2007 (USDA Forest Service, 2007a). For the baseline case, it is assumed that only unused mill residues are available (see the discussion in Chapter 2 concerning "used" primary mill residue). Neither the Forest Service nor any other federal agency systematically collects data on secondary mill residue. One of the few estimates of the amount of secondary mill residue available is provided by Rooney (1998) and subsequently revised by Fehrs (1999). Fehrs estimates that about 15.6 million dry tons is generated annually, with about 40% of this potentially available and recoverable. The remaining fraction is used to make higher-valued products, is used onsite to meet some energy needs (such as heat for drying operations), or is not available for other reasons. Table 2.1 provides projected consumption of currently used primary and secondary mill residue. Currently, there are about 32 million dry tons being used, mostly for energy. It is estimated that by 2030, 42 million dry tons will be consumed.

For the unused remaining mill residue, it is assumed that these residues can be purchased at the mill for $20 per dry ton or less, which is comparable to the disposal cost if there are no markets available. Delivered prices could be much higher, especially for secondary mill residue where facilities are small, dispersed, and operate seasonally (Figure 3.14). Table 3.3 shows that there are 1.3 million dry tons of primary mill residues and 6.1 million dry tons of secondary mill residues annually at this mill price. It is assumed that any residue associated with increased future demand for primary and secondary wood products is offset by greater mill efficiencies and a continued increase in the use of this material for byproducts. At a price above $60 per dry ton, the total available used and unused mill residue is about 40 million dry tons. There are no scenarios beyond the baseline.

Figure 3.14 Conversion facility

(Courtesy of ORNL)

3.4.3 Pulping Liquors

As explained in Chapter 2, the combustible chemical byproducts, such as black liquor from pulping facilities, are currently used for energy production and are not counted as an additional feedstock resource. The available amount is 45 million dry tons, with projections to 58 million dry tons in 2030.

3.5 Urban Wood Wastes

The two major sources of urban wood residues are the woody components of MSW and C&D waste wood. MSW source consists of a variety of items, ranging from organic food scraps to discarded furniture, packaging materials, textiles, batteries, appliances, and other materials. In 2007, 254 million tons of MSW were generated (EPA, 2008). About 54% of the total quantity generated was discarded in municipal landfills. The remainder was either recycled, made into compost, or combusted for energy recovery. Containers and packaging are the single largest component of MSW, totaling some 78 million tons, or 31%, of the total. Durable goods are the second largest portion, accounting for 25% of total MSW generated. Yard trimmings are the third largest portion and account for about 33 million tons, or 13%, of the total.

The wood component of containers and packaging and durable goods (e.g., lumber scraps and discarded furniture) is slightly more than 14 million tons (EPA, 2008). According to Falk and McKeever (2004), about 10% of this material is recycled and 22% is combusted for energy recovery. The remaining material is discarded and land filled. About one-third of this discarded material is unacceptable for recovery because of contamination, commingling with other wastes, or other reasons, such as size and distribution of the material (McKeever, 2004). The remainder that is potentially available for bioenergy totals about 5.7 million dry tons annually.

Yard and tree trimmings are the other woody component of MSW. Currently, about 32 million tons are generated annually, with nearly 21 million tons of this amount recovered (EPA, 2008). In this update,an additional 4.3 million dry tons of wood is assumed recoverable and available for bioenergy applications after accounting for quantities that are likely to be composted, combusted, recycled, or contaminated and unavailable. The fractions composted, combusted, and contaminated are based on technical coefficients developed by McKeever (2004).

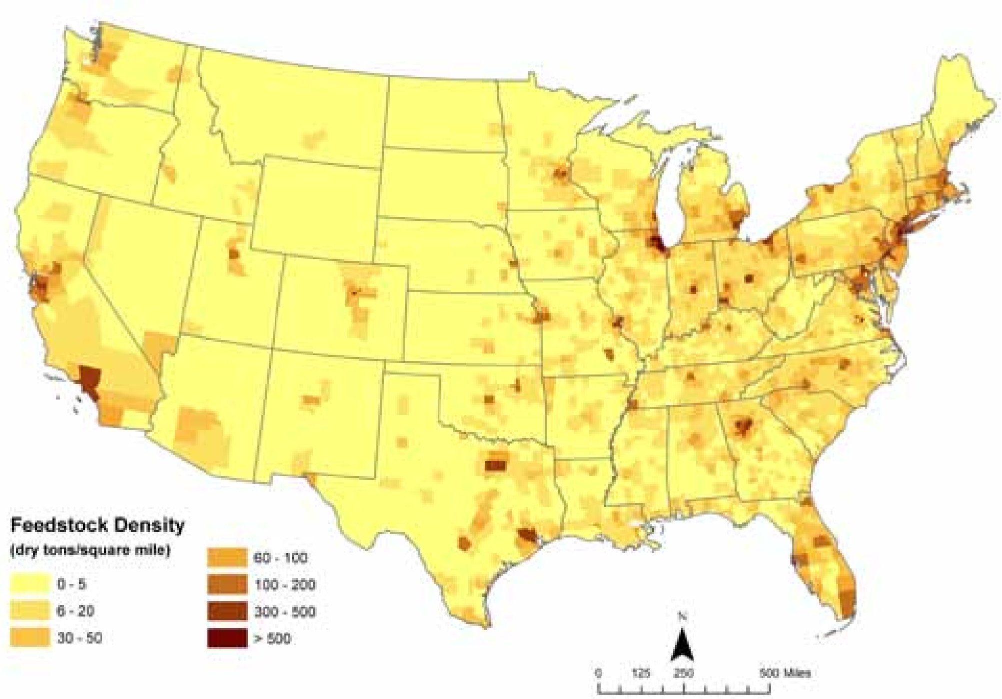
The other principal source of urban wood residue is C&D debris. C&D wood waste is generated during the construction of new buildings and structures, the repair and remodeling of existing buildings and structures, and the demolition of existing buildings and structures (McKeever, 2004). These materials are considered separately from MSW because they come from many different sources. These debris materials are correlated with economic activity (e.g., housing starts), population, demolition activity, and the extent of recycling and reuse programs. The updated estimates of C&D debris wastes total about 21.7 million dry tons. About 9.4 million dry tons are construction debris, and 12.2 million dry tons are demolition debris. These estimates are based on technical coefficients developed by McKeever (2004). They are slightly higher than the 2005 *BTS* estimates because of changes in population and economic activity.

MSW wood waste along with C&D debris together sum to nearly 32 million dry tons per year as potential energy feedstocks. As noted by McKeever (1998), many factors affect the availability of urban wood residues, such as size and condition of the material, extent of commingling with other materials; contamination; location and concentration; and costs associated with acquisition, transport, and processing. A map of urban wood wastes availability is shown in Figure 3.15.

In the previous chapter (Table 2.1), the currently used MSW wood was estimated at 14 million dry tons annually and projected to increase to 20 million dry tons per year by 2030. In this chapter, the unused MSW wood and yard trimming wastes total 10 million dry tons; and, the unused C&D debris wood could provide an additional 21.7 million dry tons. Future quantities of unused urban wood wastes (MSW and C&D sources) will no doubt rise as population increases; however, the increase will likely be less owing to ongoing waste recovery efforts and higher landfill disposal costs. For construction waste, it is likely that higher fractions will be recycled and reused, and there will be greater use of engineered lumber, which will reduce dimensional lumber use and also make less waste available. For demolition wastes, improved recycling and reuse efforts should lead to increases in the number of buildings deconstructed as opposed to demolished, which will tend to lower quantities of waste wood available for bioenergy. For these reasons, future quantities of urban wood wastes are assumed to increase at one-half of the rate of population growth.

Table 3.3 shows the supply schedule for urban wood wastes by MSW and C&D categories. As noted, the total potential resource is estimated at 10 and 21.7 million dry tons for MSW wood wastes and C&D wood waste at prices greater than $60 per dry ton, respectively. As explained by Walsh (2006), the quantity of urban wood wastes available at given prices depends on many factors. Chief factors include whether the materials are collected as mixed wastes or are source separated and the prevailing landfill tipping fees (i.e., the levelized costs of operating a landfill). Prices to acquire these materials could be very low if collected as mixed wastes and where landfill tipping fees (avoided costs) are high. In this update, the prices to acquire urban wood wastes are based on the results of Walsh (2006). The report assumes that about 75% of the MSW wood waste can be acquired for $20 per dry ton or less, 85% at $30 per dry ton or less, and 90% at $40 per dry ton or less. All of the identified MSW wood is assumed to be available at $60 per dry ton or less. For C&D wood wastes, it is assumed that 20%, 50%, 65%, and 100% are available at $20, $30, $40, and $60 per dry ton, respectively. In total, MSW wood is about 24 million dry tons at $60 per dry ton or less. This quantity includes the 14 million dry tons currently used (Chapter 2) and 10 million dry tons of unused MSW wood wastes. In addition, there are 21.7 million dry tons of C&D wood wastes for a total of 45 million dry tons. Table 3.3 shows the urban wood waste supplies and Table 3.4 shows current and future supplies at selected prices and future years.

Figure 3.15 Spatial availability of urban wood waste (municipal solid waste and construction and demolition wood residues)



(Courtesy of ORNL)

3.6 Conventionally Sourced Wood – Pulpwood-Sized Roundwood

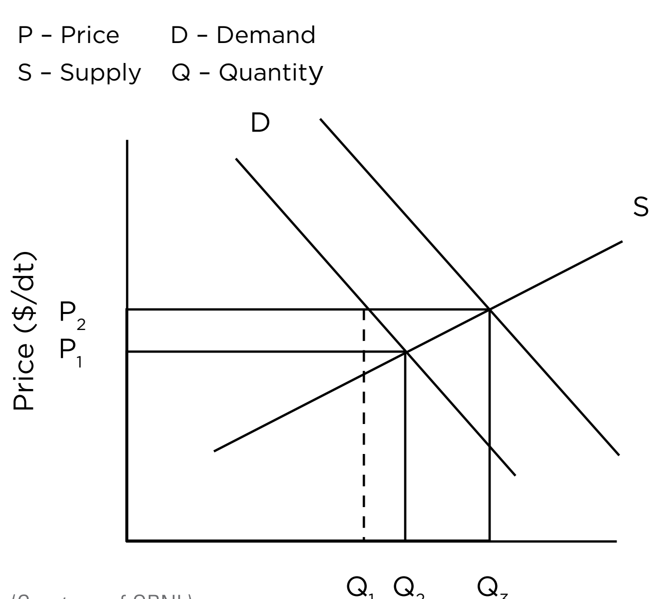
The 2005 *BTS*, as well as most of this update, only considers non-merchantable and waste woody resources. A final resource added to the update is conventionally sourced wood, which is wood that has a commercial value for other uses but is used as an energy feedstock instead because of competitive market conditions. In reality, only the pulpwood-sized roundwood would be used for biomass and probably just the smaller diameter pulpwood-sized trees.

If pulpwood-sized material is used as biomass for bioenergy, it will most likely be obtained through two approaches: (1) from "additional harvests" of pulpwood-sized trees and biomass together in thinning operations that are in addition to the previously discussed thinnings and (2) from a shift of wood being cut for pulpwood from current uses into uses for bioenergy (i.e., "pulpwood supply"). Both are referred to as conventionally sourced wood because the pulpwood-sized trees are usually harvested for conventional products, such as paper and panels. To ensure sustainability in the additional harvests, pulpwood harvests were restricted to only removing the annual growth, which means, not reducing inventory (using the 2006 harvest levels from Smith et al. (2009). When using pulpwood to supply bioenergy, the shift from pulpwood to bioenergy was restricted to 20% of the 2006 pulpwood harvest because of the underlying assumptions in the analyses. The assumptions are explained in the following sections.

3.6.1 Use of Pulpwood Stumpage Supply and Stumpage Demand Curves

To estimate supply from additional harvests, it is assumed that there will be additional thinning operations that are separate from integrated harvesting operations that take pulpwood-sized trees and associated biomass (tops and branches) in a given region. These additional thinning operations, in response to increasing demand for wood for bioenergy, move up the existing pulpwood stumpage supply curve (see Figure 3.16) for each state and increase the marginal stumpage price (Q2 to Q3 and P1 to P2). As the stumpage price increases, an amount of pulpwood previously demanded and used is diverted from integrated harvesting operations to bioenergy use. This corresponds to an amount obtained by shifting stumpage price upward on the pulpwood demand curve (P1 to P2 and Q2 to Q1). The simplifying assumption for the time period covered by the supply estimate is that there is little shift in the pulpwood supply curve or in the pulpwood demand curve for pulp or panel production (see Text Box 3.8). In reality, supply curves will shift with changes in the amount and age composition of timber inventory and technology. Also the demand curve will shift with a number of drivers, including the level of Gross Domestic Product and strength of the dollar relative to other currencies, which will influence demand for pulp, paper, and composite panel exports.

Figure 3.16 Theoretical pulpwood supply model for biomass



(Courtesy of ORNL)

TEXT BOX 3.8 | ESTIMATING FUTURE SUPPLIES OF PULPWOOD FOR BIOENERGY

The conventionally sourced supply curve was developed holding the supply function constant over time, which means that supply does not change in response to changing inventory, changes in pulpwood demand for pulp and panels, or change in product imports. This approach was done for simplicity and convenience, recognizing the lack of a sufficient model to project future supply changes. Future supply of pulpwood for bioenergy will be influenced by the outward shift of pulpwood supply curves (more wood becomes available at a given cost) in each region and by shifts in demand curves (outward shift would mean an increase in demand amount for a given price).

The outward shift in pulpwood supply curves in each region will be influenced in part by increases in available inventory of pulpwood-sized trees. The 2005 RPA Timber Assessment projects increases in some regions and decreases in other regions for pole timber-sapling acres and young sawtimber acres on timberlands privately owned (Haynes et al., 2007, Table 39).

The most notable increase between 2006 and 2020 is for softwood poletimber in the North (13%) and young softwood sawtimber in the West (20%). The U.S. average change in private pole timber acres between 2006 and 2020 is minus 5% and for young sawtimber acres, plus 1%. The changes in acres through 2030 are minus 18% for pole timber and minus 2% for young sawtimber. Volume of timber could be increasing more than the change in acres coming into the timber size class because of a higher density of timber. The total inventory of sawtimber and non-sawtimber for the North, South, and West is projected to increase from 2006 to 2020 by 10%–12% and 15%–19% by 2030. These shifts in acres and inventory of standing timber would tend to shift pulpwood supply curves outward by 2030 in major regions by amounts on the order of 20%. Shifts could be larger in subregions.

The pulpwood demand curves, demand for pulp and panels, in each region will be shifted outward with increases in economic activity that demands paper (e.g., office use, shipping) and composite panel products (e.g., buildings). These outward shifts, shifts that increase demand for traditional products at a given price, will decrease biomass supply available for bioenergy and tend to offset supply increases due to outward shifts in the pulpwood supply curves. Alternately, if pulpwood demand decreases, or more pulpwood, pulp, paper, or composite panels are imported, then more of the pulpwood supply at a given price will be available for bioenergy.

Projections from the 2005 RPA Timber Assessment (Haynes et al., 2007, Table 11) indicate that hardwood pulpwood supply curves for the South would be shifting outward more rapidly than outward shifts in demand curves as evidenced by decreasing pulpwood prices through 2020, but by 2030, the outward supply shift would slow relative to outward shifting demand, and price would increase to the 2006 level. This suggests economic availability of hardwood pulpwood in the South by 2030 could be similar to 2006 if these projections are approximately correct. Projections suggest softwood pulpwood supply curves' outward shift would lag outward shifts in demand through 2020 as evidenced by the increasing pulpwood price by 2020; then, supply shifts would exceed demand shifts as indicated by the decreasing price through 2030 when price may be lower than the 2006 level.

With the current economic downturn of pulpwood demand levels, there may be less demand than projected in the 2005 RPA Assessment through 2020 or 2030. In this case, pulpwood-sized material needed for pulp, paper and panels would be less than projected. Then, more wood would be available for bioenergy, which would result in more conventionally sourced wood going to bioenergy that could match or exceed a 20% increase (for a given price) in response to a 20% increase in timber inventory.

It should be pointed out that the 2005 RPA Timber Assessment was developed without expectations of an economic downturn and notably expanding bioenergy markets. A better analysis of these dynamics will be forthcoming in the 2011 RPA Forest Resources Assessment. The updated *BTS* analysis likely indicates a conservative estimate of pulpwood supply compared to supply in the future.

Estimating pulpwood supply from additional harvest. The initial step (see Figure 3.16) to estimating county-level pulpwood supply curves from additional thinning operations is to specify a new higher regional-level stumpage price; for example, 10% higher than the base price (P1 to P2) and note the quantity obtained will move up the supply curve (Q2 to Q3). Next, the regional-level quantity of pulpwood and biomass is allocated to counties based on lowest harvest and transport costs to roadside. Each county quantity is assigned a roadside price equal to harvest cost plus the state-level stumpage price. The process is repeated for successive increases in the regional-level stumpage price to form county-level supply curves.

The pulpwood harvest prices are estimated by first simulating thinnings on higher-density (higher SDI) FIA plots using diameter-limit aged silvicultural prescriptions that gradually remove diameter classes until the SDI target is met. The thinnings only remove pulpwood-sized and smaller trees, where pulpwood-sized trees are defined as trees 5–7 inches dbh in the North and South, and 5–9 inches dbh in the West. The FRCS model is used to estimate harvest costs to remove pulpwood-sized trees plus biomass. When allocating regional pulpwood supply amount (at a given regional stumpage price) to the county level, the amount is allocated to counties using quantities and harvest costs where harvest costs are the lowest. As more pulpwood is supplied at higher regional stumpage prices, it is allocated to counties where harvest costs are higher.

A cornerstone of this method is a set of estimates for elasticity of pulpwood supply quantity and demand quantity with respect to changes in pulpwood stumpage price (obtained from a review of literature). The elasticity estimates from the literature are made using time series data where quantity and price vary over a certain range and use econometric equation forms, which limit their use and application. Typically, the price and quantity data are annual, and the percentage change in prices over the entire time series is less than 50%. Most of the econometric equation forms do not distinguish between elasticity with respect to price in the short term (roughly a year or less) versus quantity response in the long term (more than one year) where capital investments may occur that will influence supply or demand response to pulpwood price change. Given that short-term elasticities are generally not estimated; the elasticities found in the literature reflect responses to prices that will occur over several years.

Estimated historical average pulpwood supply elasticity with respect to stumpage price for the U.S. South is suggested to be about 0.34, as indicated by results of six studies (Newman, 1987; Carter, 1992; Newman and Wear, 1993; Prestemon and Wear, 2000; Polyakov et al., 2005; Lao and Zhang, 2008). Elasticity estimates from studies that covered the entire South range from 0.23 to 0.49. These are averages for both hardwoods and softwoods for all land where most supply was from private land. While pulpwood supply elasticity estimates are not available explicitly for the North and West, an estimate within this range is consistent with estimates of supply elasticity with respect to stumpage price for all timber from two national studies (Adams and Haynes, 1980; 1996). These two studies estimate that the private timberland area-weighted national average supply elasticity for all timber in the North and West is 0.42 to 0.47. In addition, studies for the South suggest supply elasticity for sawtimber alone to be 0.42 to 0.55 (Lao and Zhang, 2008; Newman, 1987). If elasticity for sawtimber in the North and West is about 0.45, then pulpwood supply elasticity in the North and the West is about 0.3. If the sawtimber supply elasticity in the North and West is 10% higher or lower, the North and West pulpwood supply elasticity could range from 0.16 to 0.44. Given the wide range associated with these estimates, a pulpwood supply elasticity of 0.35 is used for all states.

Given that these estimates are based on large areas and that pulpwood prices are inherently locally driven, it is clear that the estimates of quantity supplied for any given price at the county level could vary notably from actual supply quantities for the given price. The estimates are only intended as an indicator of approximate supply, which may aid in determining when more local estimates are warranted. Given the uncertainty in the supply elasticity estimates and concern about sustainability of increased harvest levels, the possible annual pulpwood supply at the regional level is limited so as not to exceed the level of annual timber (growing stock) growth in each state elasticity estimates and concern about sustainability of increased harvest levels, the possible annual pulpwood supply at the regional level is limited so as not to exceed the level of annual timber (growing stock) growth in each state.

Given the uncertainty in the supply elasticity estimates and concern about sustainability of increased harvest levels, the possible annual pulpwood supply at the regional level is limited so as not to exceed the level of annual timber (growing stock) growth in each state.

Pulpwood supply estimates diverted to bioenergy use. Estimates of average pulpwood and panel wood demand elasticity with respect to stumpage price are found in two studies—for the South as a whole (-0.43) and for Texas (-0.41), respectively (Newman, 1987; Carter, 1992). An elasticity of -0.42 is used for each state. Estimates of potential pulpwood supply are made by using backward shifts along the demand curve for successive increments in pulpwood stumpage price (e.g., 10%). At each price point, the biomass amount is allocated to counties according to lowest harvest costs. Resulting county-level supply curves indicate the quantity supplied at particular total roadside prices.

The methods used to estimate pulpwood supply, although simplified, parallel the methods used to estimate amounts of biomass from integrated harvesting operations. The estimates are based on detailed analyses of harvest quantities and costs from treatments on FIA plots across the United States. The stumpage price to obtain supply amount or a currently demanded amount is estimated using basic information about the elasticities of supply or demand quantity with respect to price. These estimates should be considered only as approximate potential supply in localized areas. The analysis is overly simplified in that it does not take into account potential inventory changes over the longer term because of investments in afforestation or significant disturbances. A model with both spatial detail and time dynamics is not available for this analysis. The estimates are only intended to be both short term and without significant inventory changes.

Given the uncertainty in the demand elasticity estimate for the nation as a whole and a higher uncertainty for a region or county, the possible shift in pulpwood away from current users to biomass is limited to 20% of pulpwood supply, which is reported in 2007 Forest Service TPO database (USDA Forest Service, 2007a). An analysis was conducted to determine the sensitivity to this limit. When the allowable shift from the pulpwood supply is increased to 30% of the 2006 pulpwood supply, the available biomass only increases a few percent at the $90 per dry ton price and only up 9% above $120 per dry ton when the allowable biomass is increased to 30% of the pulpwood supply.

The limitation on shifting of current pulpwood use to 20% was imposed on the recognition that the price elasticity estimate was based on currently available data with a certain variation over time. If prices change substantially, it is possible that demand elasticity could increase, which would cause the pulpwood supply to remain with current users and not be used for biomass. Rather than assume continuing steady shifting in response to increasing prices, a conservative assumption was made to limit the shifting of pulpwood supply from current users to biomass users at the 20% level.

3.6.2 Estimated Conventionally Sourced Wood

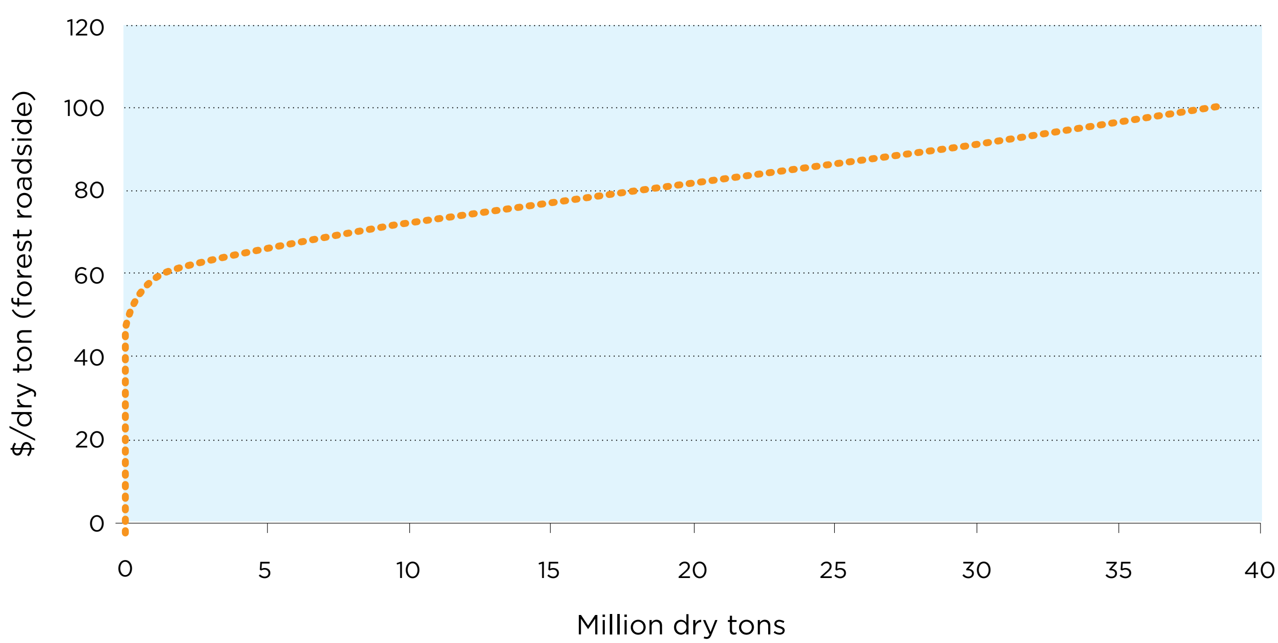
Pulpwood supplied to make pulp and panel products was 4.4 billion cubic feet, or about 66 million dry tons, in 2006. As the price for wood fuel feedstock approaches the price for pulpwood in a locality, there will be additional acres harvested for pulpwood to be used for energy, and some of the pulpwood going to pulp or panel mills will be diverted to wood energy use.

Supply curves (Figure 3.17) for pulpwood-sized roundwood at the county level were developed in several steps using basic concepts about supply and demand curves for existing pulpwood markets for each major region—North, South, and West. In general, it was assumed that regional levels of pulpwood supply can be approximated for bioenergy by starting with recent stumpage prices (Table 3.2), and starting quantities supplied are taken to be equal to recent quantities harvested.

Pulpwood for bioenergy starts to be supplied at current pulpwood stumpage prices, and harvest costs increase as the price that buyers are willing to pay increases. Pulpwood can either come from additional harvesting operations that specifically harvest pulpwood for bioenergy (possibly more expensive than current integrated harvesting) or from a shift in pulpwood use from current users to bioenergy producers. In the first case, additional harvesting operations are analogous to movement along state-level pulpwood supply curves to obtain bioenergy pulpwood. In the second case, it is backward movement along the current pulpwood demand curve, indicating shifts from current pulpwood uses to bioenergy.

At \$60 per dry ton at roadside, the estimated pulpwood supply from additional harvest or shifts from current users is 1.4 million dry tons per year. At a roadside price of \$80 per dry ton, the amount of pulpwood for use as biomass is 18 million dry tons per year; from that total, 13 million tons is the main stem of trees, or a 20% increase over the 2006 harvest level of 66 million dry tons. Such an increased amount would be provided with a stumpage price increase of about 26%.[30] The rest of the price increase is due to increased harvest costs needed to obtain additional pulpwood supply. Supply at \$100 per dry ton or less is 38.6 million dry tons annually, of which 29 million tons is from the main stem of the trees—a 44% increase. This increase would be generated by a stumpage price increase of about 58%. The estimated increases in pulpwood supply are fairly coarse and are particularly uncertain for higher levels of price increase, which are outside the range of prices used to estimate the supply and demand elasticities.

Figure 3.17 Estimated supply of pulpwood for bioenergy annually



[30] It is assumed that percent change in pulpwood biomass supply is equal to (0.34 + .42) x percent change in stumpage price. The quantity includes both additional supply from new harvesting and supply from a shift of current pulpwood harvest away from current users to bioenergy users.

3.7 Total Supply of Forest Biomass and Wood Wastes

Table 3.3 provides a summary of the currently available biomass at a range of prices for the forest biomass and wood wastes feedstocks. There are estimates for the two major sources of forest biomass feedstocks: logging residues and thinnings (shown as a composite), which are based on an assumption of a 50:50 ratio as the transition from logging residues to integrated harvesting occurs. This avoids double counting for both residues and thinnings. At the highest price estimate shown in Table 3.3 of $100 per dry ton, the available biomass from logging residues and thinnings as integrated composite operations is about 43 million dry tons annually. Even at a price of $200 per dry ton (not shown in the table), the additional biomass is much less than 10 million dry tons per year. These levels already account for the biomass that is retained onsite for sustainability purposes. At a price of $60 per dry ton, annual availability is estimated to be about 97 million dry tons. The thinnings portion of these numbers is for all land ownerships and includes federal lands, even though they do not currently qualify under the Renewable Fuels Standard. Removal of the federal lands has little effect on the total biomass availability, reducing the estimated total at the $60 price by only 7 million dry tons. For conventional pulpwood to energy, the higher quantities have considerable uncertainty as they are based only on a 50% change in the current base stumpage price. Volume estimates above $80 per dry ton are outside the model parameters. Figure 3.18 depicts the estimated forestland cellulosic feedstocks by states at an example price of $80 per dry ton.

Future estimates are shown in Table 3.4. Because the thinnings are already averaged across the next 30 years and there is limited data for many of the feedstocks, there is little estimated change over the next 20 years. Assuming a price of $60 per dry ton, the total available tonnage only increases from 97 million dry tons per year in 2010 to 102 million dry tons per year in 2030. Using a forest roadside price of $80 per dry ton, the total quantity of composite residues increases from 1.6 to 2.0 million dry tons for each year (depending on whether federal land is counted). Conventional pulpwood is fairly constant at the prices shown in the table over the time period. Only after prices are higher than $60 per dry ton, conventionally sourced feedstocks start making significant contributions. All other residue quantities at $80 per dry ton are the same as shown at $60 per dry ton. There are no scenario changes with the forest biomass and wood wastes—only the baseline.

Figure 3.18 Current state shares of available forest biomass resources at $80 per dry ton or less

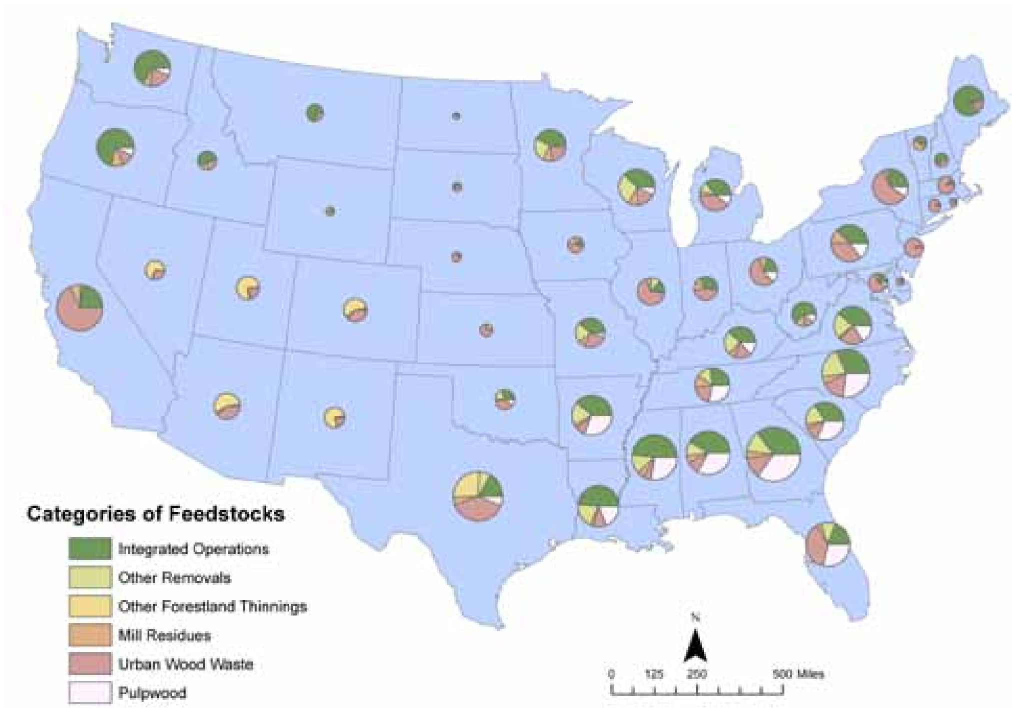


Table 3.3 Summary of Potential Forest Biomass and Wood Wastes (2012)

Feedstock ($ per dry ton)	<$20	<$30	<$40	<$60	<$80	<$100
	Million dry tons					
Other Removal Residue	4.4	12	12	12	12	12
Composite Operations	9.5	30	36	40	42	43
Without Federal Land	8.3	26	31	35	36	37
Treatment Thinnings, Other Forestland	0	0	0	3.2	6.4	6.4
Without Federal Land	0	0	0	1.8	3.6	3.6
Mill residue, unused primary	1.3	1.3	1.3	1.3	1.3	1.3
Mill residue, unused secondary	6..1	6.1	6.1	6.1	6.1	6.1
Urban Wood Waste – C & D	4.4	11	14	22	22	22
Urban Wood Waste – MSW	7.7	8.7	9.2	10	10	10
Conventional Pulpwood to Energy*	0	0	0	1.5	19	40
Total – All Land	**33**	**70**	**79**	**97**	**119**	**142**
Total – Without Federal Land	*32*	*66*	*75*	*90*	*111*	*133*

Notes: *Does not include currently used biomass from Chapter 2. Totals may not add up correctly due to rounding*

* Although shown here for convenience, the estimated conventional pulpwood used as bioenergy above $80 per dry ton is outside the model parameters, which could result in significant errors.

Table 3.4 Summary of Baseline Potential Forest Biomass and Wood Wastes at Selected Roadside Prices

Feedstock ($ per dry ton)	40	50	60	40	50	60	40	50	60	40	50	60
		2012			2017			2022			2030	
	Million dry tons											
Other Removal Residues	12	12	12	12	12	12	13	13	13	13	13	13
Conventional Pulpwood to Energy	0.0	0.1	1.5	0.0	0.1	1.6	0.0	0.1	1.8	0.0	0.1	1.9
Composite Operations	36	38	40	36	39	40	37	39	41	37	39	41
Without Federal Land	31	33	35	32	34	35	32	34	35	32	34	36
Treatment Thinnings, Other Forestland	0.0	0.0	3.2	0.0	0.0	3.2	0.0	0.0	3.2	0.0	0.0	3.2
Without Federal Land	0.0	0.0	1.8	0.0	0.0	1.8	0.0	0.0	1.8	0.0	0.0	1.8
Mill residue, unused secondary	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
Mill residue, unused primary	1.3	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.4	1.4	1.4
Urban Wood Waste – C & D	14	22	22	15	23	23	15	23	23	16	25	25
Urban Wood Waste – MSW	9.2	10	10	9.5	10	10	10	11	11	10	11	11
Total – All Land	**79**	**91**	**97**	**81**	**92**	**98**	**82**	**93**	**100**	**83**	**95**	**102**
Total – Without Federal Land	*75*	*86*	*90*	*76*	*87*	*92*	*77*	*88*	*93*	*79*	*90*	*95*

3.8 Summary

Although a significant amount of effort went into the analysis, the estimates are still only as good as the underlying data and dependent on the underlying assumptions. This concern is further compounded when developing comprehensive cost estimates at county levels. The FIA database brings significant amounts of data to the analyses. However, there are limitations concerning its use for biomass since the primary FIA focus is on merchantable inventory. The use of the data and some of the issues associated with using FIA data at the county level are discussed.

There is very little data on stumpage prices for biomass, and the extrapolation of the available data has limitations. This is especially true when estimating the availability of conventionally sourced biomass, which has high uncertainty at higher prices. Furthermore, the model is developed from historical supply/demand elasticity parameters that may or may not be representative of future market dynamics. There is very little data on biomass harvest systems tailored for handling logging residues, small stems, or integrated production. The largest gap in data is post-consumer wood residues. Limited data are available for C&D wood, and there are large voids for the amounts and costs for recovery of urban wood.

The underlying assumptions are based on the best available information and grounded in the expertise of the authors. The biomass estimates can readily change with them. The primary example is the development of the supply curves. Another considerable example is the recovery of logging residues—whether they will be collected after the original harvest or as part of that harvest. The speculation is that integrated systems will be used to recover residues because of costs. As a last point on assumptions, the use of biomass retention is a primary concern for long-term site productivity and a surrogate for other sustainability criteria, such as habitat. Retention alone, not assuming the use of BMPs and assuming that removals do not exceed growth, does not truly represent the full measure of sustainability. Other considerations are needed. To aid the readers with interpreting the results, they will have access to the KDF for additional analyses using various assumptions.

Finally, the development of this chapter pointed to several needs, as summarized below:

- Improving the biomass portions of the FIA database
- Understanding and modeling the long-term effects of biomass removal under a range of soil, climate, and management schemes
- Improving the databases (e.g., mill residues, urban wastes, and costs)
- Developing and integrating biological and economic models for sustainability assessments.

4 AGRICULTURAL BIOMASS AND WASTE RESOURCES

This chapter provides estimates of quantities and farmgate prices (i.e., supply curves) for agricultural crop residue biomass, as well as residues and wastes generated mostly by food processing industries. Farmgate price is the price a buyer pays for crop residue at the farm, at a mill location in the case of processing residue, or at a landfill or feedlot in the case of waste resources. The agricultural resources considered in this assessment include:

- Crop residues from the major grain-producing crops
- Other crop residues
- Secondary agricultural processing residues
- Waste or tertiary resources (e.g., manures, waste fats, and greases).

For corn stover and other major grain residues, county-level supply curves are estimated using an agricultural policy simulation model. The chapter provides background on each of these resources and explains how estimates are made. The largest quantities are from crop residues. A number of factors are taken into account when estimating available crop residues: soil erosion and soil organic matter constraints, as well as the physical ability of machinery to harvest residues. Included in the price of these residues are the collection costs, a payment to the grower based on the nutrient value of the residue, and a profit. Estimates are made for a baseline and a high-yield scenario.

4.1 Cropland Resources (Corn Ethanol and Soybean Biodiesel)

These resources are accounted for in Chapter 2. The current total feedstocks for corn-based ethanol is 55 million dry tons per year (see Table 2.1). It is estimated that in 2017 the corn production for ethanol will meet the EISA mandate at 88 million dry tons and will be produced at that level through 2030. Soybean biodiesel feedstocks are estimated at 5 million dry tons per year, increasing to 18 million dry tons annually in 2017 and continuing at that level to 2030.

4.2 Agricultural Crop Residues

Crop residues are desirable feedstocks for bioenergy applications because of their low cost, immediate availability, and relatively concentrated location in the major grain growing regions. The most plentiful residues include stalks and leaves from corn (stover) and straw and stubble from other small grains, such as wheat, barley, oats, and sorghum (Figure 4.1). The 2005 *BTS* included a number of crop residue removal scenarios involving changes in crop yields, cropland tillage, and the efficiency of residue collection technology. In the 2005 report, the sustainable quantity of stover and straw residue was estimated at about 210 to slightly more than 320 million dry tons annually, depending on what was assumed about crop yield, tillage, and the fraction collected. If all crops are considered, then the crop residue potential is more than 400 million dry tons.[31] Corn stover, the largest single source of residue, was estimated between 170 and 256 million dry tons, depending on yield and tillage assumptions.

[31] The higher amount for the 2005 study included nearly 50 million dry tons of residues from forage-type soybeans. This potential is not included in this update.

The production of crop residues is significant, with the average annual tonnage between 1998 and 2007 from corn, grain sorghum, winter and spring wheat, barley, oats, and rye exceeding 350 million dry tons; corn stover consisted of about 70% of this total. Residue production is directly related to yield. Projections by USDA indicate yields for corn and wheat will increase approximately 9.5% and 5.2% over the next ten years, respectively. Although significant quantities of residue are produced and will increase over time, how much of this residue can be sustainably collected has been subject to much debate. The next section of this chapter discusses sustainability and provides an overview of the approach used to determine how much residue needs to be retained on fields in order to limit erosion to tolerable levels and maintain soil organic matter.

Figure 4.1 Example of crop residues – stalks and leaves from corn stover

(Courtesy of ORNL)

4.3 Sustainability of Crop Residue Removal

Crop residues provide a number of important soil enhancing and safeguarding functions. These include protecting the soil and controlling erosion from water and wind, retaining soil moisture, increasing or maintaining soil organic matter, adding to the available pool of soil nutrients, increasing biological activity and improving soil structure, and improving crop yields (Andrews and Aschmann, 2006).[32] Soil erosion is an extremely important national issue and most, if not all, agricultural cropland in the United States experiences some degree of soil erosion each year due to rainfall and/or wind. Soil erosion reduces soil productivity and soil organic matter, removes plant nutrients, and has an adverse effect on water quality through the transfer of suspended solids, nitrogen, and phosphorus, both on the surface and in groundwater. Rainfall erosion (sheet and rill) occurs when rain directly strikes the soil, dislodging particles in the top layer of soil.

Degradation of soil quality as influenced by land management is also an extremely important issue to the agricultural and environmental community. Soil quality is defined as a soil's ability to sustain plant growth and contribute to the maintenance or enhancement of air and water quality. Soil organic matter content is particularly important because of its immediate and direct impact on several critical soil functions. Enhancing soil organic matter can improve soil productive capacity, nutrient cycling, filtering and buffering of potential pollutants, water storage, and resistance to compaction and erosion.

Sustainable agricultural residue removal rates must maintain soil quality and future productive capacity. Building from the work presented by Wilhelm et al. (2011), the amount of agricultural residue that can potentially be removed from agricultural cropland is subject to two modeled constraints in this analysis. First, removals cannot exceed the tolerable soil loss limit as recommended by the USDA's Natural

[32] See Andrews and Aschmann (2006) for a primer on crop residue removal and bioenergy production.

Resource Conservation Service (NRCS). Second, removal cannot result in long-term loss of soil organic matter as estimated by the Revised Universal Soil Loss Equation (RUSLE2) and the Wind Erosion Prediction System (WEPS). Both of these programs incorporate a soil quality index referred to as the soil conditioning index (USDA-ARS, 2010; USDA-NRCS, 2008) and are employed by NRCS to help guide farmers, ranchers, and landowners in making their conservation plans.[33] In general, both programs are designed to provide estimates of soil erosion and other pertinent soil tilth parameters due to types of crops, rotations, field management practices (e.g., tillage), and field topography (see Text Box 4.1).

TEXT BOX 4.1 | REVISED UNIVERSAL SOIL LOSS AND WIND EROSION EQUATION

Revised Universal Soil Loss Equation (RUSLE2)

RUSLE2 is intended to describe and estimate the main effects of agricultural cropping practices on soil erosion by rainfall and/or overland flow. It is mainly used as a guide for conservation planning to represent trends demonstrated in field data. RUSLE2 can be, and has been, applied to applications involving cropland, pastureland, rangeland, and disturbed forestland. The equation for RUSLE2, presented below, provides a daily calculation of certain time-varying factors that define soil erosion due to rainfall:

$A = f(r, k, l, s, c, p)$

Where:

r – Rainfall/Runoff
k – Soil erodibility
l – Slope length
s – Slope steepness
c – Cover-management
p – Supporting practices

Average annual soil loss is a function of both erodibility and erosivity, with erodibility related to the susceptibility of the soil to erosion and management. Erosivity is a measure of the force of raindrops, water falling from plant canopy, and surface runoff. Therefore, erodibility and erosivity jointly impact actual erosion rates. RUSLE2 was used to provide average annual estimates of soil erosion on individual soils types for a variety of cropping rotations both with and without residue removal.

Wind Erosion Equation (WEQ)

The primary method for estimating the amount of soil loss due to wind erosion on agricultural cropland was to employ the Wind Erosion Equation (WEQ). WEQ is an empirical equation that has been applied to various agricultural and engineering situations to predict annual soil loss from a single, uniform isolated field according to cropping and land management practices. It has been used by the NRCS to predict wind erosion on cropland and to guide and plan wind erosion control practices for the agricultural community. The general functional relationship in WEQ between the independent variable, (E), the potential average annual soil loss, and the variables that directly affect wind erosion is as follows:

$E = f(I, K, C, L, V)$

Where:

I – Soil erodibility index
K – Soil ridge-roughness factor
C – Climatic factor
L – Unsheltered median travel distance of wind across a field
V – Vegetative cover

[33] As summarized by Andrews and Aschmann (2006) "current USDA-NRCS practice standards for residue management do not specify residue quantities but do suggest the use of the RUSLE2 model for guidance (USDA-NRCS, 2005). In the future, specific guidelines for residue harvest could be developed to prevent soil degradation resulting from over-harvest of crop residue, partially based on modeling results from RUSLE2 and the Soil Conditioning Index (SCI)."

4.4 Estimating Crop Residue Supply

In this update, supplies of corn stover and small grain residues are estimated using POLYSYS, a policy simulation model of the U.S. agricultural sector (De La Torre Ugarte and Ray, 2000). The model is anchored to the USDA 10-year projections and includes national demand, county supply, livestock, and income modules. In POLYSYS, supplies of crop residues are estimated simultaneously with energy crops since they must compete with energy crops for land and any changes in land use affects estimated quantities. [More discussion of the POLYSYS modeling framework can be found in the Section 5.2 of this report.] The model estimates potential crop residue supplies from corn, wheat, grain sorghum, oats, and barley by accounting for how much residue is produced (a function of crop yield, moisture, and residue to grain ratio), residue production costs (a fixed per ton grower payment plus collection costs per ton of residue removed), and how much residue that must remain to keep erosion within tolerable soil loss levels and maintain soil carbon levels. For cotton and rice, two of the three other major crops in POLYSYS, residues are estimated separately. For soybeans, it is assumed there is no residue available.[34]

4.4.1 Input Assumptions for Baseline and High-Yield Scenarios

The amount of crop residue produced depends on the crop yield and the harvest index (HI) or ratio of residue to grain (Table 4.1). The amount that can be sustainably removed is governed by the retention coefficients, which are estimated from application of RUSLE2 and WEPS models incorporating the soil conditioning index and tillage (Muth et al., 2011). The amount that can be physically removed depends on the combined efficiency of the collection equipment (e.g., shredders, rakes, and balers). And the amount that can be economically removed depends on grower payments, collection costs, and prices offered for the feedstocks. The remainder of this section discusses these underlying assumptions for the baseline and high-yield scenarios.

Table 4.1 Parameters Assumed for Calculating Crop Residue Production

Crop	Weight (lbs/bu)	Moisture content (%)	Dry weight (lbs/bu)	Residue to grain ratio	Residue (Dry tons/bu)
Corn	56	15.5	47.32	1.0	0.0237
Sorghum	56	14.0	48.16	1.0	0.0241
Oat	32	14.0	27.52	2.0	0.0275
Barley	48	14.5	41.04	1.5	0.0308
Winter wheat	60	13.5	51.09	1.7	0.0441
Spring wheat	60	13.5	51.09	1.3	0.0337

Notes: *Technically a bushel is a unit of volume, 1.244 cubic feet or 32 quarts. Weights for bushels (bu) have been standardized at given moisture contents. For corn (shelled), a bushel has a weight of 56 pounds at 15.5% moisture (Rankin, 2008). The actual weight of a bushel of corn varies with moisture content (Table 3, Murphy 2008), but the standard is 56 pounds at 15.5% moisture.*

[34] Most, if not all, soybean residue needs to be left on the ground to meet conservation practice requirements. Some USDA genetic improvement research has focused on developing varieties that have a higher ratio of straw to beans, grow taller, have improved lodging resistance, and have a better over-winter residue persistence. It is evident from data on the forage soybean varieties that the potential exists to produce 100% more crop residue and thus provide more soil conservation benefits than the conventional varieties (Wu et al., 2004). It cannot be predicted whether farmers will adopt these new varieties, but clearly the technology will be available. Increased use of soybeans in double cropping could also allow for more soybean residue removal. Potentially, with such varieties and/or double cropping, soybean acreage could contribute to the availability of residues.

4.4.1.1 Baseline Scenario

The key residue producing crops are corn and the small grains (wheat, barley, oats, and sorghum). The amount of crop residue produced and potentially available for removal is calculated as a function of crop yield, the grain weight and moisture content, and the HI or ratio of residue to grain. These factors are summarized in Table 4.1. The parameters are the same as used in the 2005 *BTS*.

Crop residue retention coefficients. Removing most of the technically recoverable residue is not warranted because of the importance of such residue in maintaining soil nutrients and soil carbon levels and controlling erosion. The amount of residue that must be left in the field to satisfy these environmental constraints depends on soil properties, field slope, crop rotation, and tillage system (i.e., conventional till, mulch till, or no-till) (see Text Box 4.2).[35]

TEXT BOX 4.2 | SOIL CONDITIONING INDEX AND CROPPING ROTATIONS

Soil Conditioning Index (SCI)

SCI is a tool used by the NRCS in conservation planning to help estimate the effect of certain conservation practices (e.g., residue removal) on maintaining and increasing levels of soil organic matter. Specifically, the SCI expresses the effects of the system on organic matter trends as a primary indicator of soil condition and is an indicator of how modifications of a management system will affect the level of soil organic matter. The index was developed from RUSLE2.

The SCI models the top 4 inches of the soil and combines the effects of three determinants of soil conservation: organic matter, field operations, and erosion. Although 4 inches does not account for all soil characteristics, most soil quality improvements result from changes in the surface layer. Organic material, or biomass factor, accounts for the effect of biomass returned to the soil, including material from plant or animal sources, and material either imported to the site or grown and retained on the site. Field operations factor is directly related to practices that stimulate organic matter breakdown. The erosion factor accounts for the effect of removal and sorting of surface soil by water and wind erosion models.

Cropping Rotations

Previous analyses used very generic cropping rotations, such as continuous corn, corn-soybean, and continuous wheat (Nelson, 2002; Nelson et al., 2003). In reality, these rotations did not really reflect more 'localized' cropping practices. In order to present a more realistic picture of actual cropping practices (crops, rotations, and tillage) and gain a better understanding of sustainable levels of residue removal, specific cropping rotations developed by the NRCS for use in preparing conservation plans at the local, multi-county, state, and/or national levels were utilized in this analysis. These crop management zones (CMZ) tend to represent the major types of agricultural practices employed by farmers in multi-county areas (see Figure 4.2). These divisions combine counties with similar crop production (e.g., corn, winter wheat, etc.), cropping rotations (e.g., corn-soybean-wheat), and field management practices (e.g., conservation tillage, reduced tillage and no-till, etc.).

For each CMZ, NRCS provides common corn and small grain cropping rotations and managements based on experience from field agents and national personnel. For each management and crop, certain residue removal practices were selected. An important note about the selection of the residue removal is that each of the scenarios used is based on actual equipment that would be used in the field in current operations. While this limits the range of removals that can be investigated, it is critical to the soil sustainability analysis that the orientation of the material (stover and straw) be accurately represented. In many cases, the orientation of the material is more important than the quantity of material left in the field. Residue removals were selected using operations from which the orientation of the residue remaining is understood and can be properly represented. Figure 4.1 highlights four no-till cropping rotations for CMZ 4, which is a majority of the Corn Belt.

[35] Conventional tillage involves the use of plowing that disturbs the entire soil surface, leaving a small amount of residue cover—usually less than 15%. No-till leaves the soil surface undisturbed prior to planting or seed drilling. Reduced tillage is defined as the minimal soil disturbance required for crop planting and emergence (e.g., strip or mulch tilling).

In the 2005 *BTS*, residue removal constraints for corn stover were based on Graham et al. (2007); for small grains, the restraints were based on average national estimates corresponding to maintenance of 30% soil cover—roughly 1.6 dry tons per acre. An alternative to using residue retention to ensure sustainable yields is to recover nutrients at the processing facility and recycle them back to the land, along with restoring carbon through organic applications. These are feasible options that will probably be implemented under certain conditions for specific feedstocks. In this update, residue retention coefficients were estimated for erosion and soil carbon in the following sequence of steps:

1. Obtain realistic 1- to 4-year commodity crop rotations from NRCS within the multi-state crop management zones (Figure 4.2)
2. Establish, using RUSLE2 and WEPS, "baseline" erosion and carbon levels for each crop rotation subject to tillage, soils, topography, and climate
3. Identify how much residue can be removed under low-, moderate-, and high-harvesting systems (e.g., windrow pickup, rake and windrow pickup, flail shred, and rake) for the corn stover and small grain straw portions of each rotation (e.g., corn-soybean-winter wheat; stover in year 1, straw in year 3) (Figure 4.3)
4. Obtain, from RUSLE2 and WEPS, the increase in erosion and decrease in carbon as determined levels of residue are removed (consistent with the removal/harvest system)
5. Calculate average retention coefficients by county for wind, rain, and soil carbon for each rotation and tillage combination by crop management zone.

Figure 4.2 NRCS crop management zones

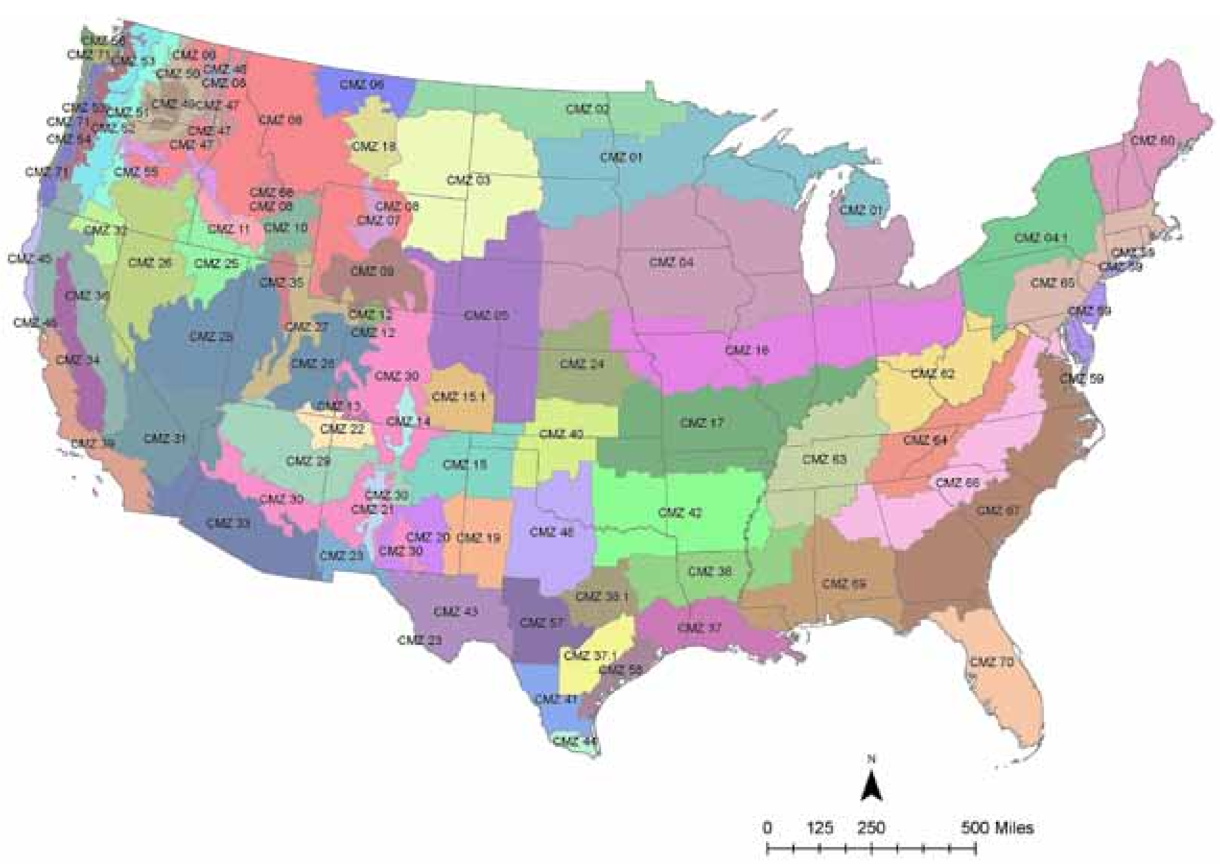


Figure 4.3 Baling corn stover

(Courtesy of ORNL)

The baseline erosion and carbon levels for each crop are yield dependent and were calculated through 2030 to determine retention coefficients. Due to the concern about residue removal and long-term soil fertility, removing residue from conventionally tilled acres was not allowed. For acres under reduced-till cultivation, the Organic Matter subfactor of the SCI (SCI-OM) was used as the carbon trigger; for acres under no-till, the combined SCI was used as the carbon trigger.[36] Figure 4.4 shows national average residue retention coefficients for reduced-till and no-till corn. In this assessment, residue removal is not allowed on conventionally tilled acres. As discussed previously, the estimation was conducted at a county level, with results summarized nationally in this report. County-level output for one particular county is shown in Figure 4.5, with total residue produced and the amount removable under reduced till and no-till represented. The increasing stover yield over time is due to yield growth. To summarize the retention coefficient analysis, the left map in Figure 4.6 shows total corn stover production across the United States in 2030, with the darker shades indicating higher levels of stover (or grain) production. The map on the right in Figure 4.6 shows the sustainable retention coefficient (expressed as a fraction of stover that must remain on the field to meet sustainability requirements) for year 2030. Areas in dark green indicate high levels of stover removal, and areas in dark brown indicate the large fractions of the produced stover that must be retained onsite. Similar results are generated for other years up to 2030, as well as for reduced tillage.

[36] The SCI-OM subfactor is more conservative. Conservation management planning, as implemented by the NRCS, uses the combined SCI as the qualitative carbon metric and allows for more residue removal because the Field Operations (FO) and Erosion (ER) subfactors pull the negative OM subfactor positive when combined across the yield and removal rate spectrum (Muth et. al, 2011).

Figure 4.4 Sustainable corn stover retention coefficients across tillage and selected years

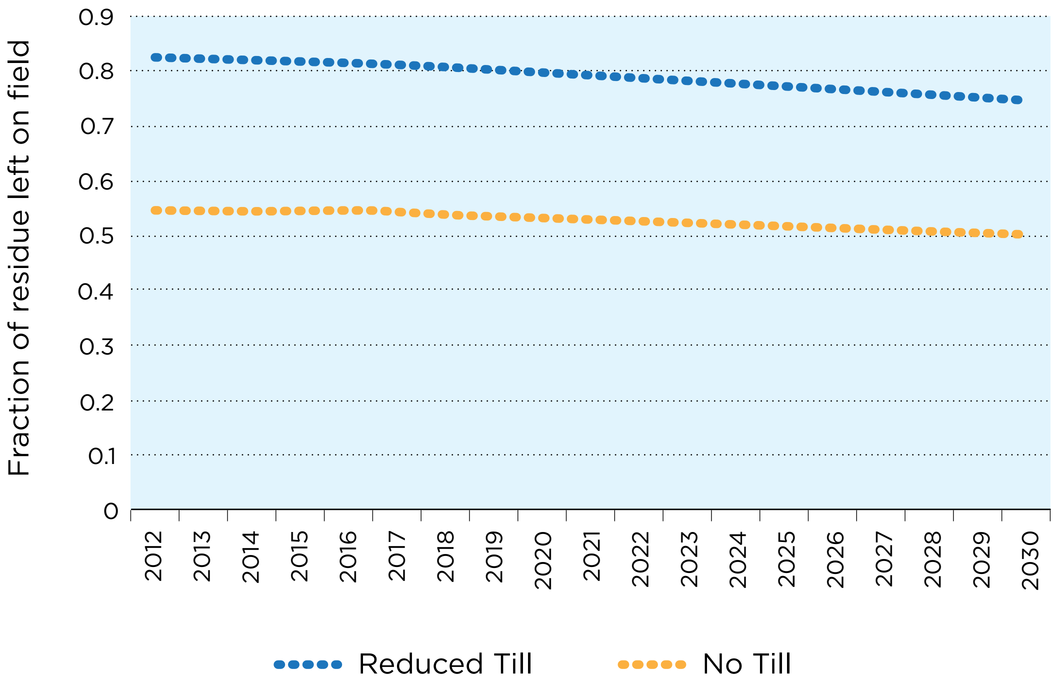


Figure 4.5 Average total standing yield, no-till potential yield, and reduced tillage potential yield of corn stover in Adair County, Iowa

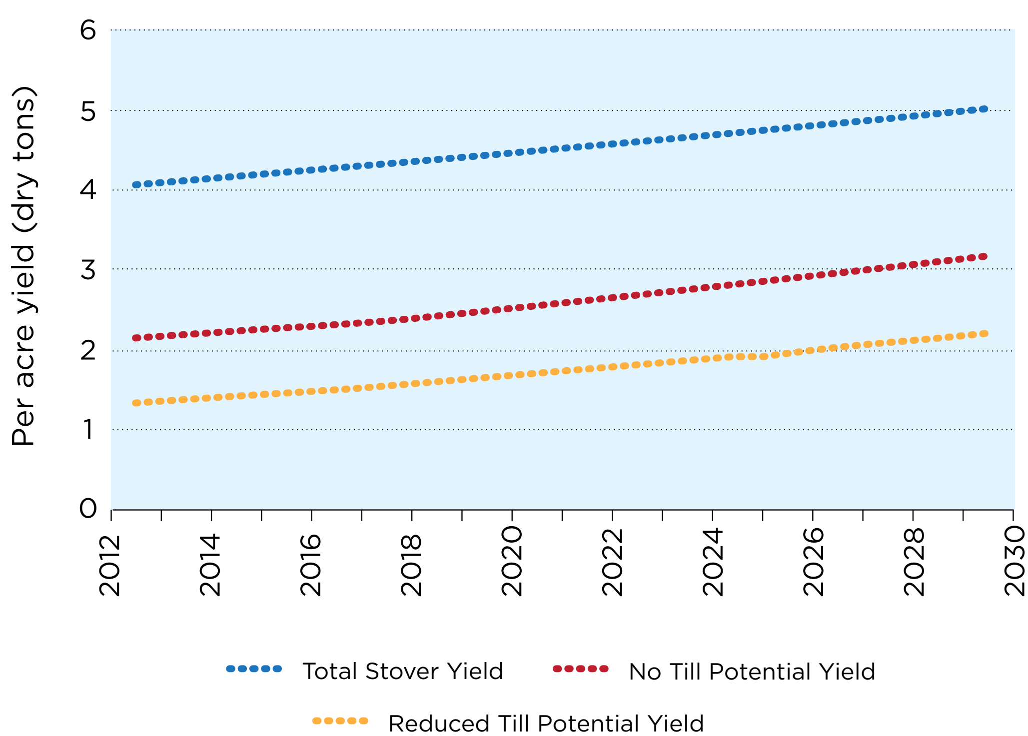
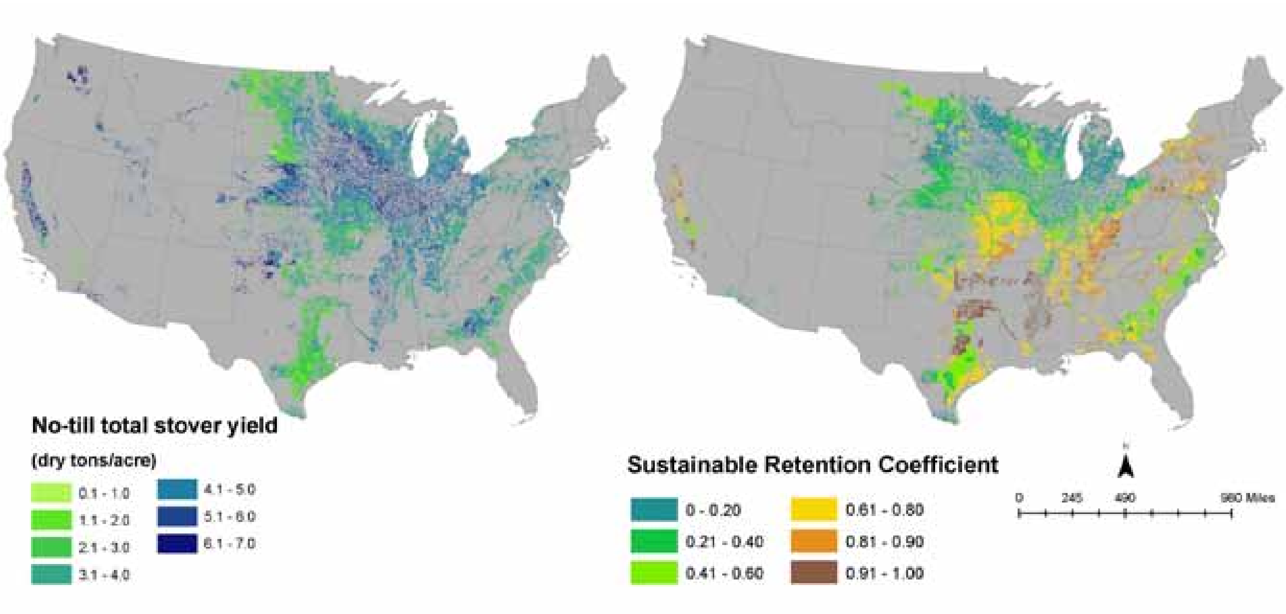


Figure 4.6 Total factor of corn stover yield and sustainable retention coefficients, 2030



Grower payments. Crop residues are a source of nutrients for future crops if left to decompose. When residues are collected, additional fertilizer needs to be applied to compensate for the removed nutrients. Crop residue removal may also affect subsequent field operations and production both positively and negatively. A positive outcome would result if soil that remains wet in the spring has some of its residue removed in the fall; the soil may dry and/or warm more quickly, allowing for earlier spring field work, earlier planting, and earlier seed germination, which would result in higher yields. Residue removal may also make herbicides more effective or require less to be applied (i.e., if less herbicide is intercepted by residues, then more reaches its intended target). However, a negative outcome would occur if residue removal increased soil compaction through additional equipment traffic and reduced organic matter near the soil surface (Wilhelm et al., 2004). Grower payments are determined by valuing the removed nutrients and organic matter and adding a nominal profit. Valuing the competing positive and negative effects of removed nutrients on field operations and production would depend on many site-specific considerations that are difficult to quantify beyond the scope of this report.

The nutrient value is determined as a product of the price of fertilizer and the amount of nutrients in the removed stover. This valuation is not entirely straightforward, given the regional variation in fertilizer prices by nutrient and fertilizer product and the variation in nutrient content of the residue itself. There are many nitrogen sources, with prices varying considerably among these sources. Anhydrous ammonia is the least expensive and generally applied to corn, while ammonium nitrate tends to be the most expensive. The sources of most phosphorus are diammonium phosphate (DAP) and monoammonium phosphate (MAP). For potassium, muriate of potash is used almost exclusively.

Fertilizer prices vary considerably from year to year and by region. However, in 2008, prices increased dramatically due to a combination of factors, including rising energy costs and the energy-intensive nature of production, increased costs for raw materials (e.g., natural gas), higher transportation costs, and a sharp increase in worldwide demand. To account somewhat for year-to-year variability, average regional prices from 2006–2009 were used to quantify the nutrient value of the removed residue. In addition, the nitrogen

Table 4.2 Regional Nutrient Payments per Ton of Stover Removed

Nutrient	Lake States	Corn Belt	Northeast	Appala-chia	Southeast	Northern Plains	Southern Plains	Pacific Northwest
Nitrogen	$9.90	$9.90	$9.50	$9.40	$9.80	$9.30	$8.90	$10.10
Phosphorus	$3.60	$3.60	$3.40	$3.40	$3.50	$3.40	$3.20	$3.70
Potassium	$13.40	$13.40	$12.80	$12.90	$13.30	$12.70	$12.20	$13.70
Total Nutrient Payment	**$26.90**	**$26.90**	**$25.80**	**$25.60**	**$26.60**	**$25.40**	**$24.30**	**$27.50**

embodied in phosphorous fertilizer (18% nitrogen in DAP and 11% nitrogen in MAP) was valued at the 2006–2009 average regional price of anhydrous ammonia, plus a $0.05 per pound application cost.

Data from Nielson (1995), Lang (2002), Gallagher et al. (2003), Schechinger and Hettenhaus (2004), and Fixen (2007) was used to estimate an average nutrient composition of removed corn stover. Nutrient values used were 14.8 pounds nitrogen per dry ton, 5.1 pounds P_2O_5 (phosphate) per dry ton, and 27.2 pounds K_2O (potassium) per dry ton.

Most corn produced in the United States is grown in rotation with soybeans. As corn stover decomposes in the field, nutrients become available. Phosphorous and potassium are not generally lost and are utilized by all crops. For nitrogen, there is a question as to whether it becomes available during the soybean year of a corn-soybean rotation. The question that should be asked is whether the nitrogen that is released during the soybean year (and not used by the soybeans) remains to be used by the following corn crop. The approach taken here was to assume that the nutrients from corn stover become available in a linear fashion over a 10-year period and discounted using a 6% rate. If the nitrogen released during the soybean year is fully valued (in the year of the soybean crop) and discounted, then the worth of the nitrogen is 78% of its undiscounted value.

Corn producers surveyed indicated that they desire to receive a value for their corn stover greater than the nutrient replacement value. Brechbill and Tyner (2008) add 15% of the value of the nutrients, cost of collecting corn stover, dry matter loss, and storage premium. In their second corn stover example, this amounts to $4.32 per dry ton. Edwards (2007) reports that sales of corn stover at hay auctions have resulted in prices that usually range from $20 to $25 per bale. He assumes a bale weighs 0.6 tons, and, if it is assumed that the bale is 85% dry matter, then the stover is worth $39 to $49 per dry ton. Harvest includes baling and may or may not include mowing/shredding and raking

Table 4.3 Regional Nutrient Payments per Ton of Small Grains Straw Removed

Nutrient	Lake States	Corn Belt	Northeast	Appala-chia	Southeast	Northern Plains	Southern Plains	Pacific Northwest
Nitrogen	$10.30	$10.30	$10.40	$10.60	$10.80	$9.90	$10.00	$11.00
Phosphorus	$1.90	$1.90	$2.00	$2.00	$2.00	$1.90	$1.90	$2.10
Potassium	$12.50	$12.50	$12.60	$12.80	$13.10	$11.90	$12.10	$13.20
Total Nutrient Payment	**$24.70**	**$24.70**	**$25.00**	**$25.30**	**$25.90**	**$23.60**	**$23.90**	**$26.20**

(Figure 4.3). Edwards estimates custom baling at $10.35 per bale ($20.29 per dry ton) and total harvest cost (stalk chopping plus raking plus baling) at $13.84 per bale ($27.14 per dry ton). Subtracting the harvest cost and local transport cost (assume $3 per dry ton) from the bale sales price leaves a range of $9 to $19 per dry ton for standing corn stalks. Edwards estimates a nutrient value of $7.53 per bale ($14.76 per dry ton), which leaves a residual (intrinsic) value of $6 to $4 per dry ton. For corn stover left in a windrow behind a combine, a farmer was paid $15 per dry ton in 1997–1998. To give some perspective, in Iowa, non-alfalfa hay prices were $60.50 per ton in the marketing year 1997–1998, and $83 per ton in June 2010. Schechinger and Hettenhaus (2004) estimated the nutrient value of the stover at $6.90 per dry ton. Subtracting this from the $15 per dry ton payment amount leaves a residual (intrinsic) value of approximately $8 per dry ton. From these market-based examples, it would seem reasonable to allow corn stover an intrinsic value of $10 per dry ton. In addition, $1 per dry ton is added to account for the unknown value of the residue for organic matter.

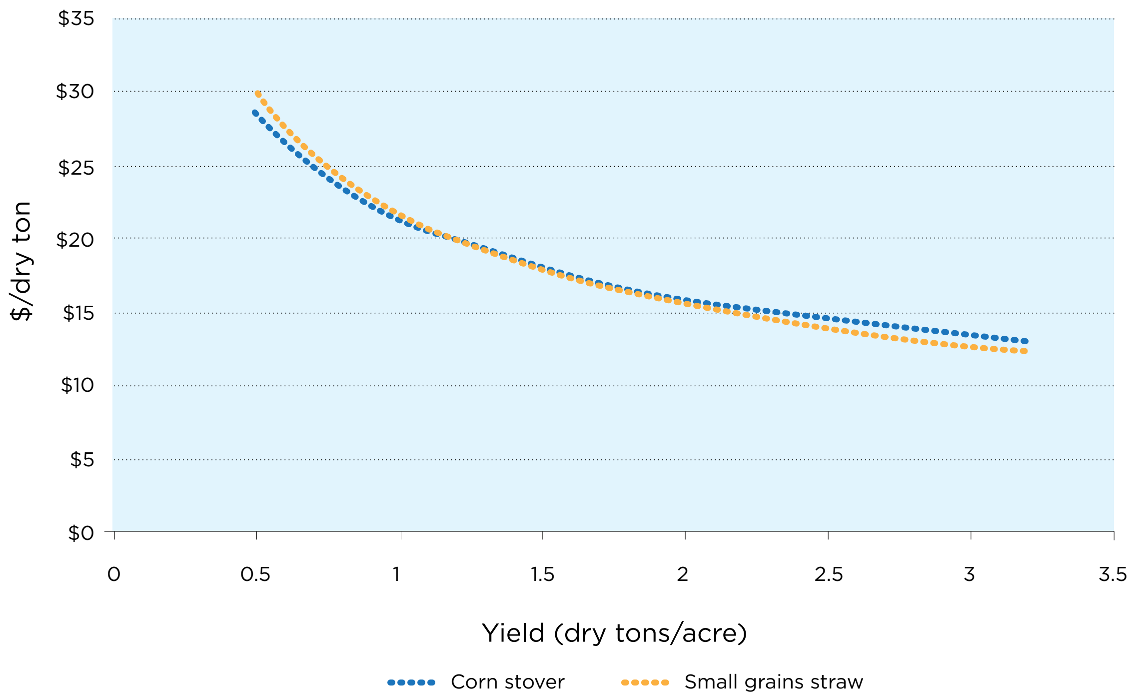
Regional grower payments based on the nutrient content of the removed residue, organic matter, and grower profit (premium or intrinsic value) are summarized in Tables 4.2 and 4.3 for corn stover and small grain straw, respectively. The average grower payment in the United States is $26 per dry ton of removed corn stover and $25 per dry ton of removed wheat straw (using 2006–2009 average regional fertilizer prices). Grower payments are lowest in the Northern and Southern Plains and highest in the Pacific Northwest. For the Corn Belt, the grower payment is about the same as the national average. It should be noted that the occurrence of high fertilizer prices (as experienced in 2008) would increase the value of the grower payment.

Costs of crop residue collection. Corn stover can be collected in a number of ways: (1) turn off the combine's spreader and bale the windrow using a large round baler; (2) after combining, rake and bale the resulting windrow using a large round baler; or (3) shred after combining, rake the shredded biomass, and bale the resulting windrow using a large rectangular baler.[37] For wheat straw, turn off the combine's spreader and bale the windrow using a large round or rectangular baler. To estimate costs for example purposes, shredding is performed using a 20-foot-wide shredder, and raking utilizes a 15-foot wheel rake. Based on data from Shinners et al. (2007), baling wet biomass is assumed, with the round baler producing 0.50 dry-ton bales with mesh wrap, while the large rectangular baler produces 0.49 dry ton bales. Baler capacity is limited by field speed (assumed to be 15.4 and 22.6 dry tons per hour for round and rectangular balers, respectively). Bales are transported to the field edge using self-loading and unloading wagons that are capable of carrying 14 round bales and 8 rectangular bales.

Costs decline with increasing yield. For yields of 1.0, 1.5, and 2.5 dry tons per acre, collection costs up to the field edge are about $21, $18, and $14 per dry ton, respectively. The estimated collection cost function for stover and straw is displayed in Figure 4.7.

[37] In the 2005 *BTS*, estimates assume collection equipment is capable of removing about 35% of the residue under current conditions and up to 75% under the high-yield scenario (assuming the availability of single-pass harvesting systems).

Figure 4.7 Collection costs to the field edge for corn stover and small grains residue



4.4.1.2 High-Yield Scenario

A series of DOE workshops (U.S. Department of Energy, 2010a) was held to provide an opportunity to further evaluate and refine changes in projected improvements in crop yields and in technologies, such as management practices and tools that increase sustainable feedstock availability. For crop residues, the scope of the discussion focused primarily on corn—the most important residue-producing crop with the greatest potential for yield improvements and management of residue production. Participants ranked tolerance to drought, pest, disease, and other stress factors as the greatest barrier to increasing yields. Most thought that the development of genetic potential, biotechnology, and innovations in engineering and management could be leveraged to improve the yield and HI (i.e., maximize both grain and biomass yields) with minimum inputs and sustained soil productivity. A number of participants were optimistic that stover yields could be improved along with grain yields and recommended continued work in genetics, including selective breeding and the application of new biotechnology approaches. However, other participants stressed that without a market pull for higher stover yields relative to grain yields, the emphasis will continue to be on maximizing grain yields. Also, some participants emphasized that the stress factors that are barriers to increasing yields have to be overcome to have consistently higher yields, although there was clear agreement on continued growth of corn yields through 2050.[38] The key divergence in opinions was centered on the extent to which breeding and genetic selection programs can overcome stress factors. A majority of participants supported this perspective, while the remaining participants considered stress factors too significant of a barrier. The consensus high-yield estimate translates into an average annual growth rate of almost 2%. By 2022, corn yield would be 228 bushels per acre in a high-yield scenario compared to the baseline of 183 bushels per acre in 2022. The high-yield estimate of 228 bushels per acre is approximately the same as the 233 bushels per acre value used by EPA in their regulatory impact analysis of the RFS.[39]

[38] The updated *BTS* estimates biomass availability over the 2010–2030 timeframe. The workshop used a longer timeframe as it addressed specific technology developments and implementation.

Participant discussion and opinions relative to HI were even more complex and challenging (more information on the HI is provided in Text Box 4.3). Three themes emerged, depending on the understanding of the variable. A group with considerable experience provided a data-driven case that HI at harvest time is currently increasing with higher yields and genetic selection. Another broad group thought that HI can be improved through breeding and biotechnology. Yet another group held the position that, while harvest-time HI is demonstrably increasing with yield under current production, the HI at physiological maturity is a more important criterion. The conclusions of the participant discussion essentially became: (1) harvest-time HIs are increasing as yield increases; (2) the material balance calculations needed for accurate stover availability analysis require HI at physiological maturity, for which less data exists to construct HI trend analysis; and (3) HI is a crop characteristic that can be engineered to serve market drivers. A summary of the baseline and high-yield assumptions used in the POLYSYS modeling framework is shown in Table 4.4.

In addition to yield and HI, the workshop solicited inputs on environmental sustainability, economic viability, land use, and other technology/ policy advances, although not to the level of detail as yield and HI. For sustainability, the participants listed and ranked factors that currently limit environmentally sustainable increased yields. The workshop resulted in four of the most promising, and likely to be implemented, overarching actions that could "sufficiently be adopted by 2022" in support of sustainability production systems of future high-yield scenarios. The proposed actions are to: (1) improve residue management practices; (2) use a holistic systems approach; (3) implement soil health monitoring; and (4) advance variable rate collection technology.

As with the sustainability-limiting factors, economics and land use were addressed to determine if solutions would be available to support high-yield alternatives in the future. Economic concerns included market access and viability, investments, and risk reduction. Participants suggested that market viability can be supported by prioritizing crop development for both grain and residue yield, maintaining a constant HI, and developing innovative landscape-scale management strategies that reduce inputs and increase yields. Economic returns could be enhanced by producing both grain and biomass as cash crops, using incentives that lower lifecycle GHGs, adopting new technologies that result in higher biomass and grain yields, and reducing equipment costs as "we move down the learning curve." Risks can be better managed through reliable cost models, long-term contracting options, accounting for feedstock variation, considering land tenure, distributing returns between producer and user, and better education. Factors limiting the availability of land for crop expansion include competition for agriculture crops versus livestock production, as well as loss of agricultural lands to urbanization. Participants think there is potential for using other lands, such as public lands and marginal lands, for producing biomass feedstock. The high-yield scenario did not consider the use of public lands for crops or any changes in baseline crop acres. There is strong potential, however, to realize yield increases if a portion of marginally productive lands (including CRP) are brought into production. To continue this expansion, more field trials and data analysis are needed to identify which germplasm combination best responds to increasingly challenging environments.

[39] The EPA higher corn yield scenario of 233 bushels per acre in 2022 (EPA, 2010) was developed in consultation with the USDA as well as industry groups (e.g., Monsanto and Pioneer).

TEXT BOX 4.3 | CROP HARVEST INDEX

HI for corn for grain [ratio of grain to total biomass (grain plus stover)] has long been reported around 0.5 (Kiniry and Echarte, 2005b). [An HI of 0.5 is equivalent to a stover:grain ratio of 1:1.] The best hybrids are in the 0.5 to 0.55 range (MAFRI, 2009). However, whether the corn grain is dry (i.e., 0% moisture) or 15% moisture is not always agreed upon. Pordesimo et al. (2004), for a trial in Tennessee, found that in the range of 18%–31% corn grain moisture (a moisture content they define as the range one would harvest grain at), the HI of corn grain (at its moisture content) with corn stover (on a dry basis), ranged between 0.54 and 0.57. Putting the corn grain on a dry weight basis, the harvest index varies between 0.46 and 0.50 (Table below). Shinners and Binversie (2007), for Wisconsin, found that on a dry weight basis, at corn grain harvest, the harvest index was 0.52. Similarly, Johnson et al. (2006) estimated the mean HI of dry grain and stover to be 0.53 from published literature. Data presented by Wilhelm et al. (2011) results in an HI of .56 for a range of yields.

Ratio of corn stover to corn grain based

Time after planting (days)	Grain moisture content (%)	Stover yield (dry Mg/ha)	Corn grain (wet) yield (Mg/ha)	Harvest index (stover dry & grain wet)	Harvest index (stover dry & grain dry)
118	30.6	15.57	19.05	0.55	0.46
122	25.1	12.02	14.43	0.55	0.47
125	23.4	11.52	14.97	0.57	0.50
132	22.5	12.11	14.64	0.55	0.48
136	18.3	11.48	13.54	0.54	0.49

Note: *Based Table off Pordesimo et al. (2004).*

There are some seemingly contradictory statements in the literature about the effect of plant density on HI. Tollenaar et al. (1994) state that harvest index decreases when plant density increases above a certain critical threshold. Dobermann et al. (2002) examined corn under three different plant densities (ranging from 28,000 to 47,000 plants acre^{-1}) and two management intensities and found that HI decreased with increasing plant density. For their middle plant density (35,000–41,000 plants acre^{-1}), HI over three years was 0.50. Duvick et al. (2004) state that over time there has been very little change when harvest index is averaged over plant densities, but there is a trend toward higher HI as plant densities are increased. Hashemi et al. (2005) present a graph (their Fig. 3) showing HI for three corn hybrids increasing up to a certain point [plant density of 6 to 9 plants m^{-2} (24,000 to 36,000 acre^{-1}) depending on the hybrid] and then decreasing. [In 2008, the major corn producing states of Illinois, Indiana, Iowa, Minnesota, and Wisconsin had about 40% of their acres with plant populations of 30,000+, except Minnesota which was 56%, (Ohio was 34%) with the rest of the acreage with plant populations less than 30,000. Other major corn producing states, with less favorable growing conditions, Kansas, Missouri, Nebraska, and South Dakota, had plant populations over 30,000 plants acre^{-1} at 12% or less (USDA-NASS, 2008).] Over time with the development of newer hybrids, planting densities have increased as yields have increased. Newer hybrids have higher yield potentials, but to reach these higher yields planting density must be increased. What can be said about the effect of plant density on harvest index is that for a given hybrid there is a plant density (or a range of densities) that maximizes harvest index. Over time with changing hybrids this density has been increasing. As Dobermann et al. (2002) show, the HI can be decreased while simultaneously increasing corn yield by increasing plant density. Whether this is economically desirable depends on input prices, corn grain price, and stover price.

Kiniry and Echarte (2005a) provide a brief review of some reported corn harvest indices and suggest that an HI of 0.54 is "reasonable" for modern hybrids at planting densities up to 10 plants m^{-2} (40,000 plants acre^{-1}). [Note that this is planting density and not plant population. Seed mortality of 15% seems reasonable as Farnham (2001) assumes, which would imply that the HI is valid up to a plant density of 34,000.] Above 10 plants m^{-2} harvest index falls linearly to 0.375 at 30 plants m^{-2} (121,000 plants acre^{-1}). For purposes of estimating corn stover potential the suggestion is to use an HI of 0.54 as recommended by Kiniry and Echarte (2005b) (a stover:grain ratio of 0.85). This provides a more conservative (lower by 15%) estimate of corn stover than using an HI of 0.50 (a stover:grain ratio of 1.0). If grain and stover were valuable enough, one might actually manage corn for a lower harvest index, say 0.5, which could potentially give a greater corn stover resource.

Table 4.4 Summary of Baseline and High-Yield Residue Removal Assumptions for Agricultural Crops

Parameter	Baseline	High-Yield
Yield	Uses the 2009 USDA baseline for 2009–2018. Baseline extended to 2030 by extrapolating trends in last 3 years of the baseline forecast. 2009 – 157 bu/acre 2017 – 174 bu/acre 2022 – 183 bu/acre 2030 – 201 bu/acre	Used consensus workshop estimates. 2009 – 157 bu/acre 2017 – 201 bu/acre 2022 – 228 bu/acre 2030 – 265 bu/acre
Harvest index	Assumes an HI of 0.5, which is equivalent to a stover to grain ratio of 1:1.	Workshop HI input ranged from 0.5–0.7 with an assumed harvest index of 0.5 (1:1 stover: grain ratio). Modeling determined that results scale linearly with the stover to grain ratio.
Tillage	Assumes a gradual changing mix of conventional till (CT), reduced till (RT), and no-till (NT) in the following proportions from 2009 to 2030: Corn 2009 – 38% CT, 43% RT, 20% NT 2030 – 34% CT, 43% RT, 23% NT Wheat 2009 – 42% CT, 43% RT, 16% NT 2030 – 35% CT, 43% RT, 23% NT	Assumes a mix of conventional till (CT), reduced till (RT), and no-till (NT) in the following proportions by 2030: Corn 2030 – 7% CT, 37% RT, 57% NT Wheat 2030 – 13% CT, 26% RT, 61% NT
Retention coefficient	Uses RUSLE2 and WEQ for erosion, the SCI (OM factor) for reduced till, and the combined SCI for no-till as carbon triggers.	Same as baseline. Estimated retention different as defined by yields.
Cropping rotation	Uses cropping rotations based on NRCS crop management zones.	Uses cropping rotations based on NRCS crop management zones.
Costs	Same for baseline and high-yield scenarios	

4.5 Crop Residue Supply Results

Estimates of primary residues are presented for two scenarios—a baseline and high-yield. The estimated baseline is an extension of the USDA 10-year projections to 2030. The years outside the USDA projections are based on trends of the last three years of the baseline forecast (2018–2020). The high-yield scenario evaluates the impact of high corn yields and the effect of increased amounts of no-till cultivation, which has less restrictive residue retention requirements.

4.5.1 Baseline Estimates of Crop Residue Potential

Crop residue supply results from the POLYSYS simulation, under baseline assumptions, are summarized in Figure 4.9 for the combined corn stover, wheat straw, oat and barley straw, and grain sorghum stubble residues. The results are for simulated prices ranging from $40 to $60 per dry ton at the farmgate. At the lowest simulated price, about 27 million dry tons of crop residues are profitable to collect. This quantity increases to 80 million dry tons by 2030. The increase is attributable to yield growth, as defined by the USDA projections, and additional acres in no-till cultivation. The additional acres under no-till largely come from converting conventionally tilled acres. As discussed earlier, residue removal is allowed under both reduced-till and no-till cultivation, with the amount removable defined by county estimated retention coefficients (Figure 4.8). The no-till retention coefficients are less restrictive than reduced till. Residue removal is not allowed under conventional tillage. Higher farmgate prices bring in more residue, as shown in Figure 4.9. No residue is available below $35 per dry ton and the significant jump in supply between the price level of $40 per dry ton to $45 and $50 is attributed to the sensitivity of collection costs to per acre potential yield. At the highest price, most of the residue after accounting for sustainability requirements is profitable to collect. Currently, this price ($60 per dry ton) amounts to about 111 million dry tons and increases to 180 million dry tons by 2030.

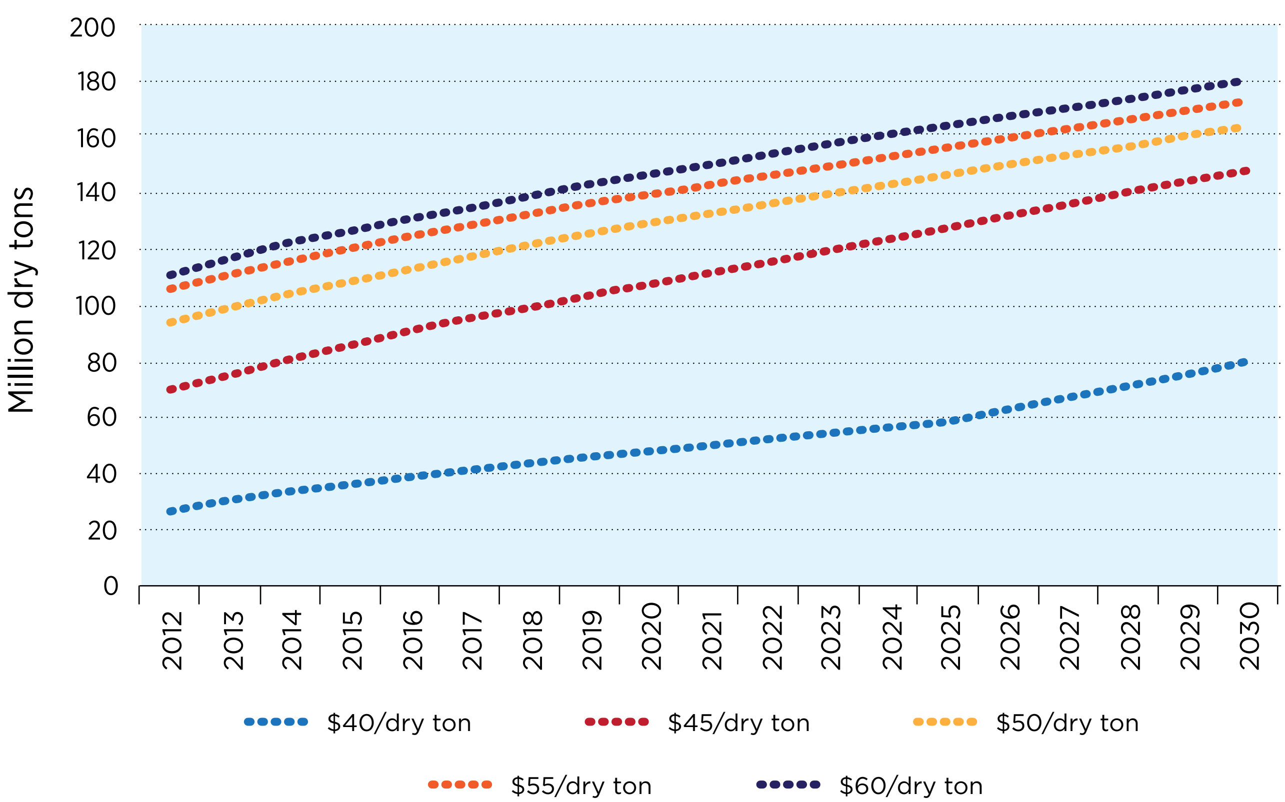
Figure 4.8 ⋮ Crop residue such as corn stover available for energy

(Courtesy of Rob Mitchell, ARS)

The largest fraction of collectable residue is corn stover. At the lower prices, slightly more than 80% of the residue is corn stover. Higher prices bring in proportionately more straw residue. This is due to the smaller amount of collectable straw residue per acre and, therefore, higher collection costs. Specific quantities of residue are shown in Figure 4.10 for selected years and prices. At the median simulated price of $50 per dry ton, about 94 million dry tons of residues are profitable to collect. This quantity increases to 164 million dry tons in 2030 and would be equivalent to an annual production of about 6.2 billion gallons of biofuel.[40] Finally, supply curves for corn stover and wheat and other grain straw for selected years are shown in Figures 4.11 and 4.12. The curves shift outward over time owing to increasing crop yields that more easily offset requirements for sustainability.

The location of potential supplies of corn stover, wheat straw, and other grain straw are depicted in a series of maps in Figure 4.13 through Figure 4.18. The figures show the location residue in 2012 and 2030 and type of tillage. The maps, as expected, show large quantities of stover in the Corn Belt. Higher availability occurs under no-till conditions, as opposed to reduced till, and much larger quantities will be available in 2030 due to yield growth. Similar results should be noted for wheat and other grain residue, with the exception of less supply density and more geographic dispersal.

Figure 4.9 Total available supply of crop residues after sustainability constraints are met at various prices under baseline assumptions



[40] This assumes a conversion rate of 85 gallons per dry ton and about 20% of the total feedstock unavailable due to losses in hauling, storing and handling, and/or some of the feedstock being stranded.

Figure 4.10 Amounts of corn stover and wheat and other grain residue at selected prices and years under baseline assumptions

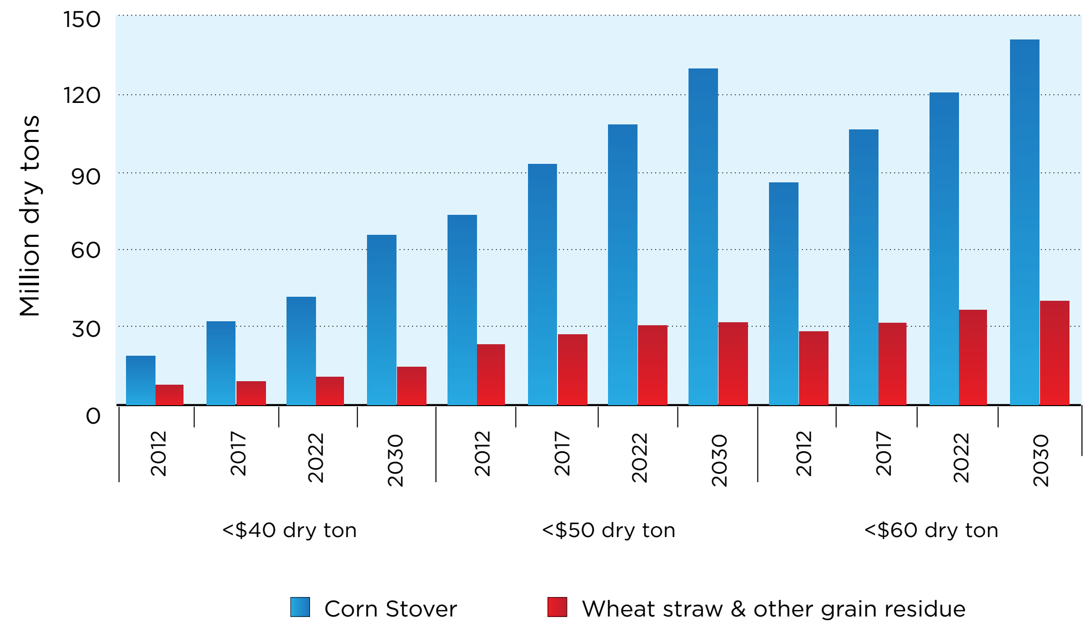


Figure 4.11 Supply curves of potential corn stover production for various years under baseline assumptions

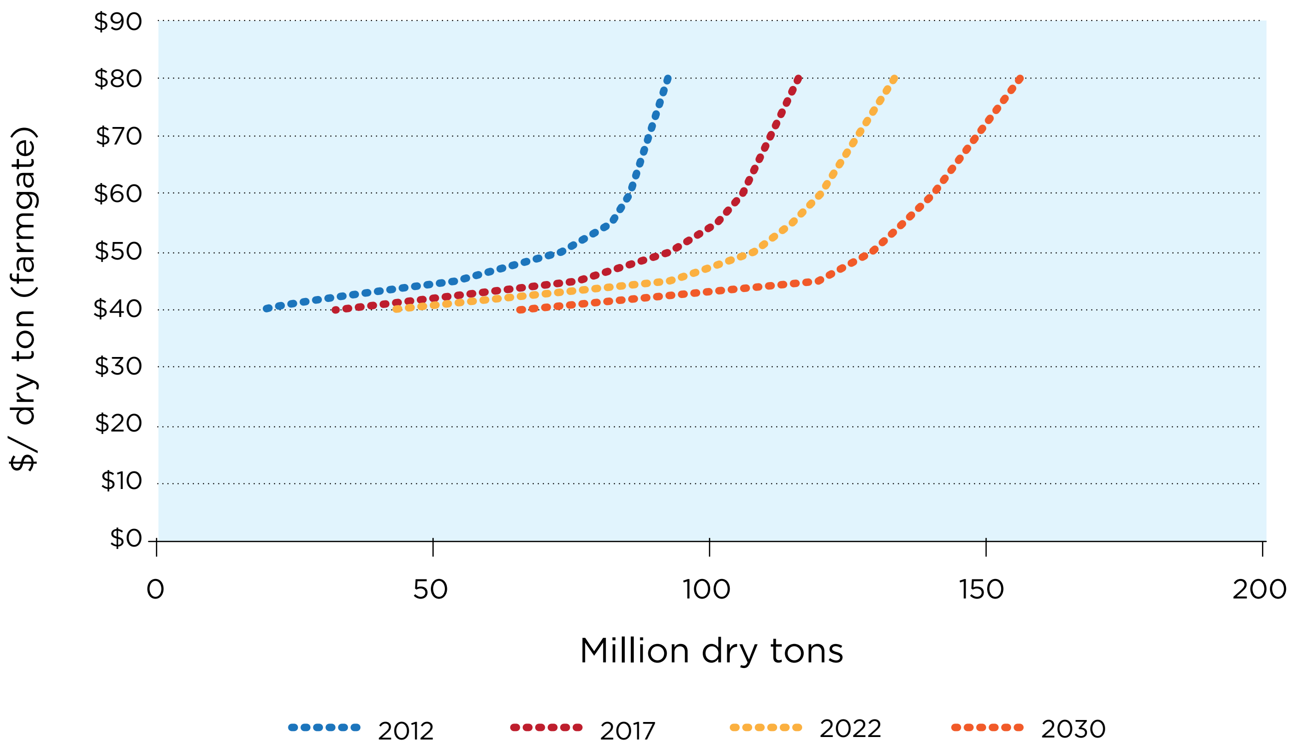


Figure 4.12 Supply curve of potential residue production (wheat, sorghum, oats, and barley) for various years under baseline assumptions

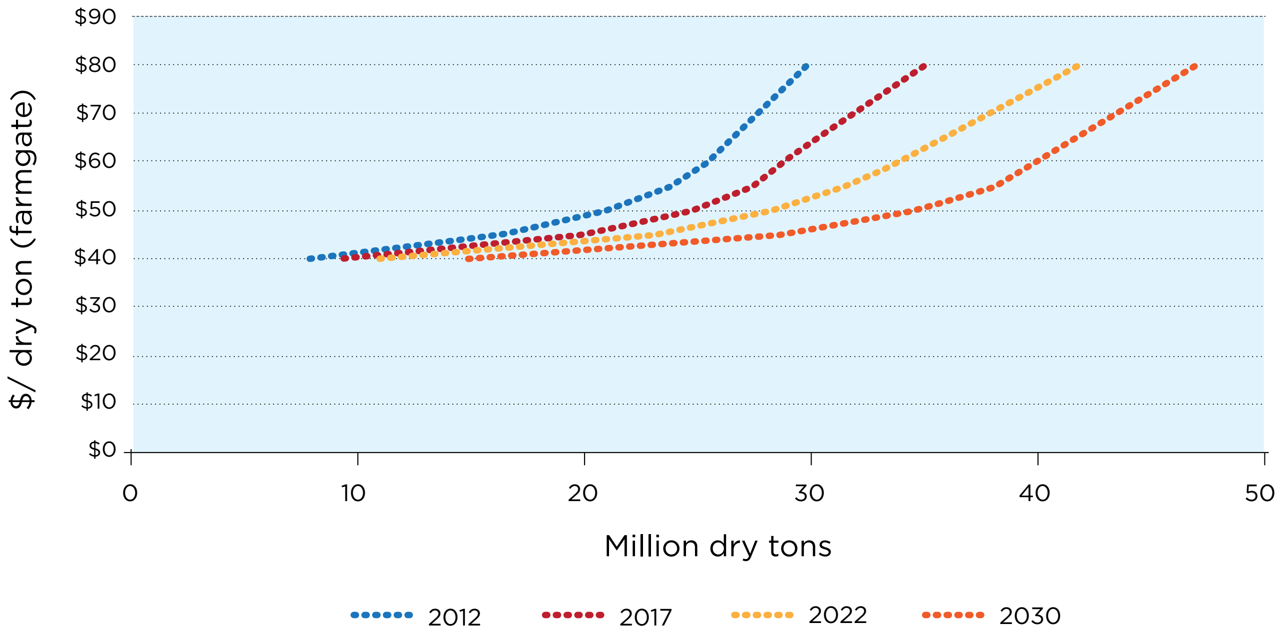


Figure 4.13 ⋮ Corn stover residue yield for reduced tillage and no-till production, 2012

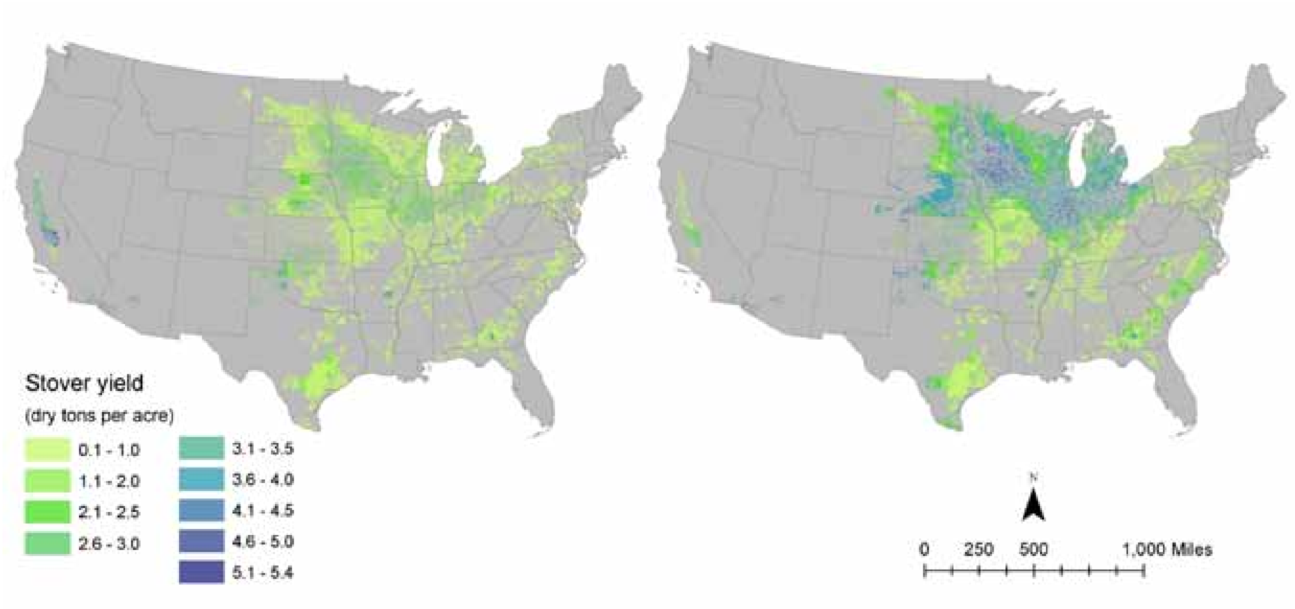


Figure 4.14 ⋮ Corn stover residue yield for reduced tillage and no-till production, 2030

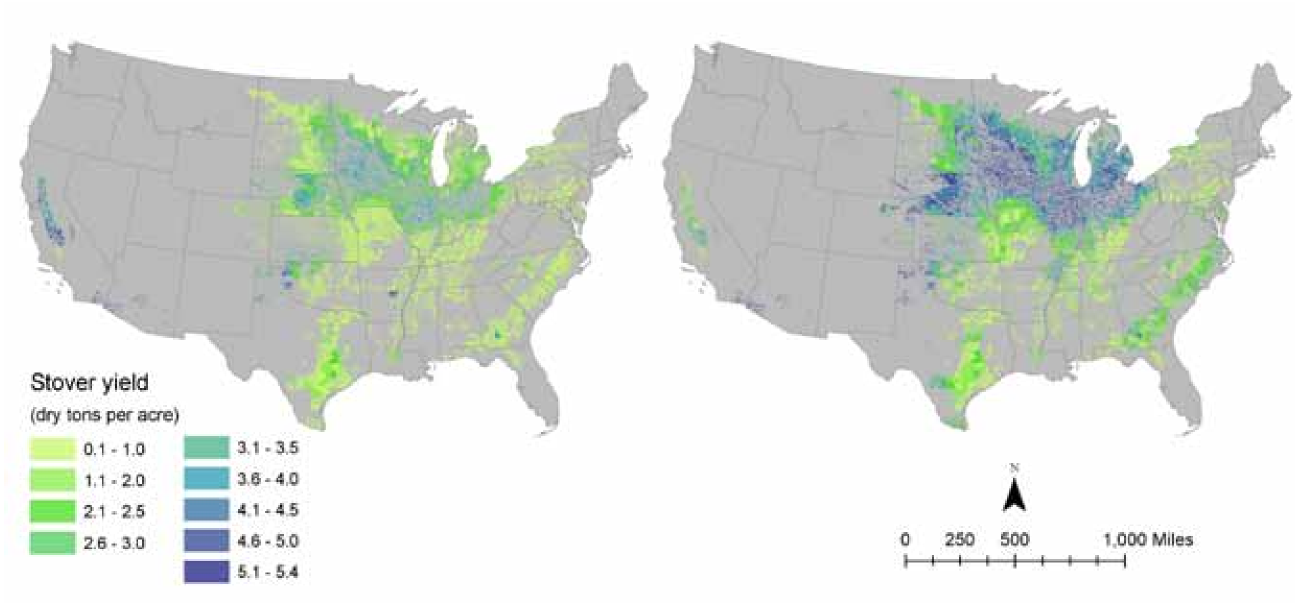


Figure 4.15 ⋮ Wheat straw for reduced tillage and no-till production, 2012

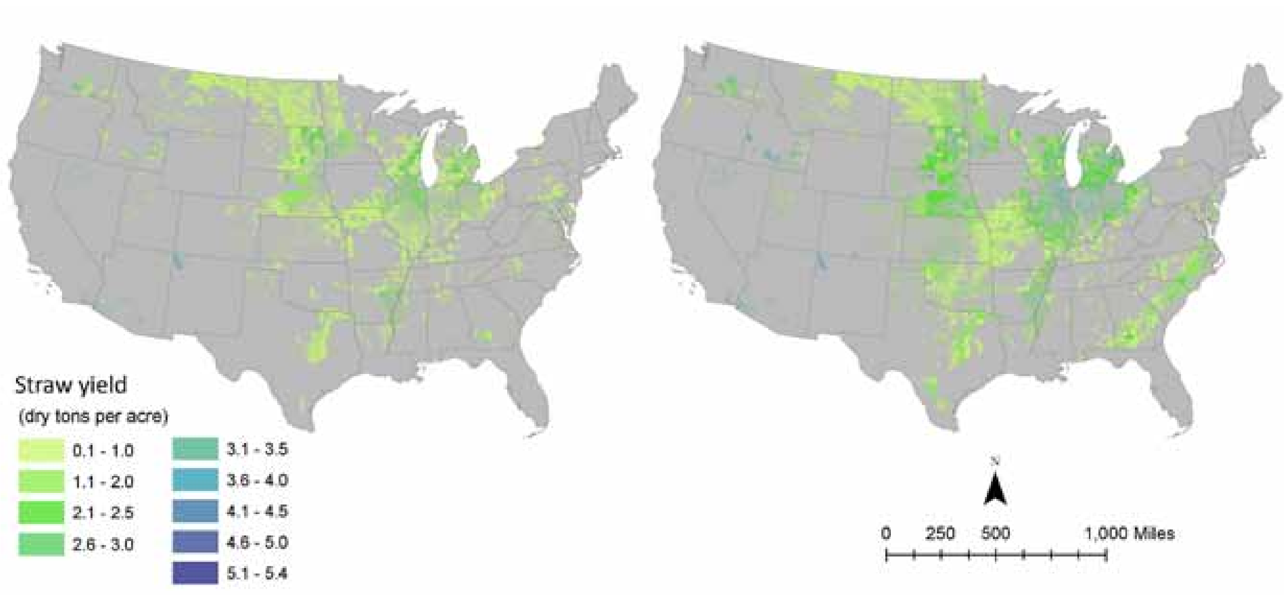


Figure 4.16 ⋮ Wheat straw for reduced tillage and no-till production, 2030

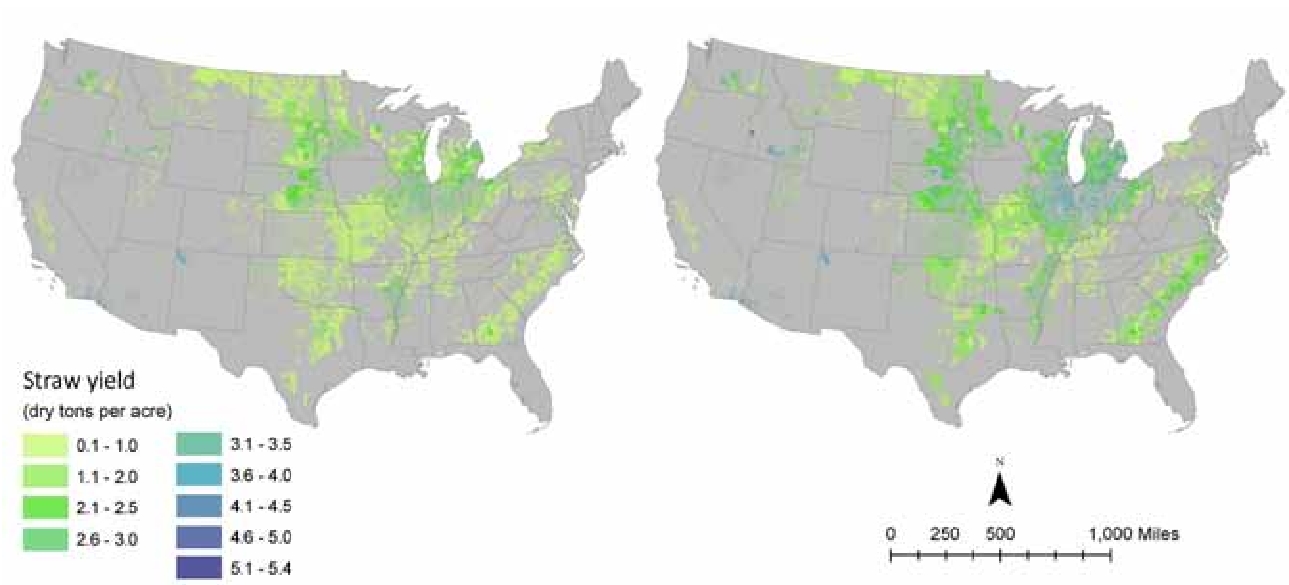


Figure 4.17 ⋮ Small grains and sorghum residues for reduced tillage and no-till production, 2012

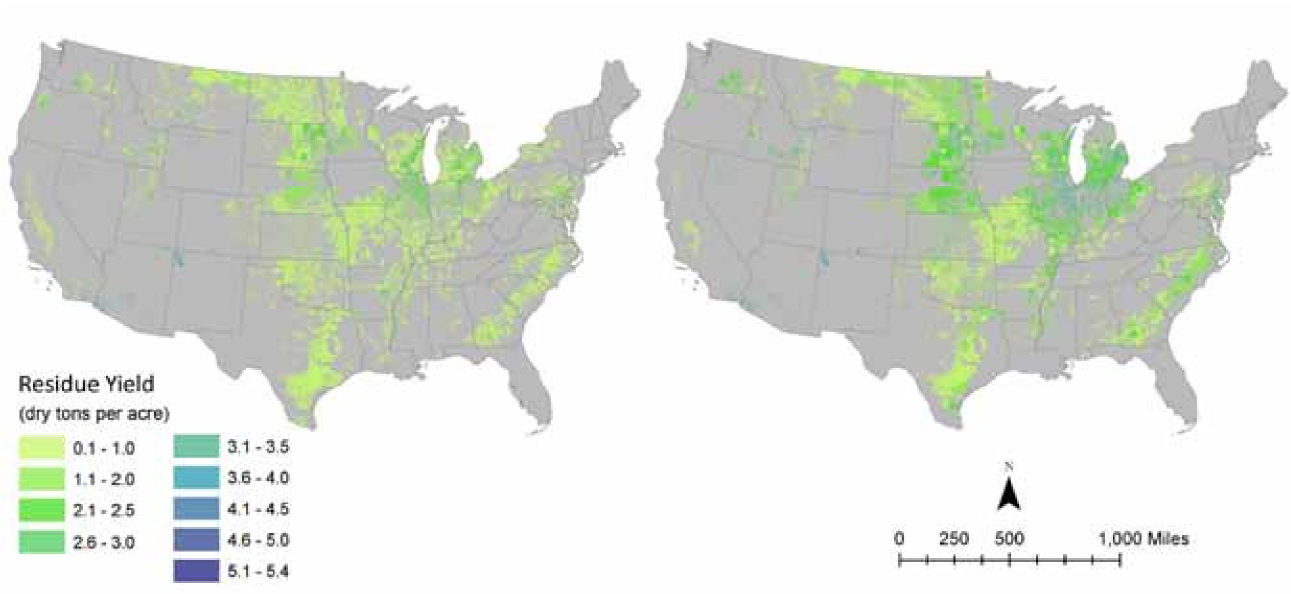
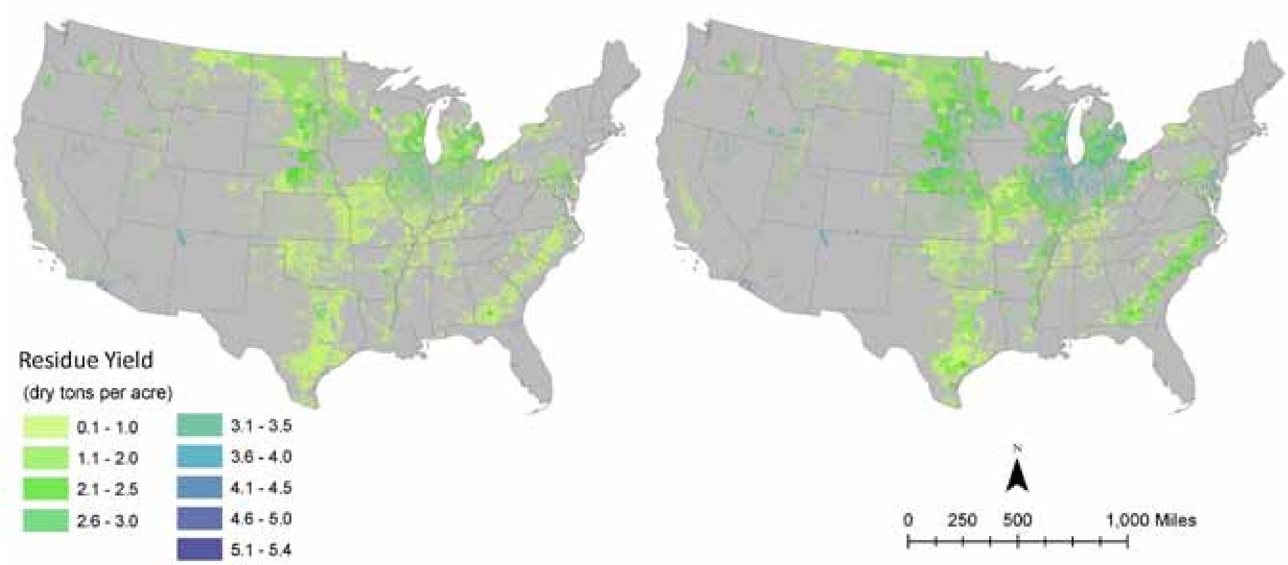


Figure 4.18 ⋮ Small grains and sorghum residues for reduced tillage and no-till production, 2030



4.5.2 High-Yield Estimates of Crop Residue Potential

The high-yield crop residue scenario considers two different assumptions regarding tillage and crop yields over the baseline scenario. The first involves simulating a much larger fraction of corn, wheat, and grains planted into no-till cultivation. These tillage assumptions are summarized in Table 4.4. The second is to simulate a more than doubling of the rate of increase in corn yield growth. The baseline assumes a national average corn yield equal to slightly more than 200 bushels per acre—the equivalent of an average annual increase of about 1%. The high-yield scenario increases corn yields according to the high-yield workshop consensus estimates—about 2% annually—and reaching a national average of about 265 bushels per acre in 2030 .

Results of the POLYSYS simulation under high-yield scenario assumptions about tillage and corn yield are summarized in Figure 4.19 at five alternative farmgate prices. Generally, annual supply quantities are considerably greater than estimates under baseline assumptions about tillage and yield. At the lowest simulated price, an additional 52 million dry tons of stover is profitable to collect in 2012 increasing to 156 million dry tons by 2030. The increase in the amount of wheat straw and other grain residue is much more modest only about 10 to 15 million dry tons over the 2012 to 2030 simulation period at a $50 per dry ton farmgate price. Specific quantities of corn stover and wheat straw and other grain residue under the baseline and high-yield scenario are summarized in Figure 4.20 for selected years and prices.

Under EISA, ethanol produced from corn is limited to 15 BGY starting in 2015. Corn yield has been increasing over time, and corn grain acreage has remained relatively level at about 80 million acres per year. Demand for corn can be divided into the following categories: feed (and residual); exports; ethanol; and food, seed, and industrial uses other than ethanol. Exports and food, seed, and industrial uses other than ethanol have shown modest increases over time and are projected by USDA-OCE/WAOB (2010) to continue modest increases. Feed use has been relatively level but also is projected to show modest increases in the future. Ethanol from corn has been absorbing much of the increase in corn production and is projected to do so between now and 2017.

High-yield-workshop participants projected corn yields to increase to 206, 231, 265, and 318 bushels per acre in 2017, 2022, 2030, and 2050 respectively. One seed company's goal is to increase corn yields 40% in the next 10 years to more than 210 bushels per acre (Perkins, 2009). These are considerably higher yields than the USDA-OCE/WAOB projection. Rick Tolman, Chief Executive Officer of the National Corn Growers, says, "Unless we have growing ethanol production, you can't use all the corn that will be produced by farmers in the future and you'll have a depressing influence on price. We need a growing demand base to keep the incentives in place for farmers to grow more corn. Livestock producers are still our most important customers and exports are important, too, but the only growth piece we have is ethanol to keep up with that increased productivity (Perkins, 2009)." The simulated POLYSYS results under the high-yield scenario are very much consistent with this observation.

Figure 4.19 Total available supply of crop residues under high-yield assumptions

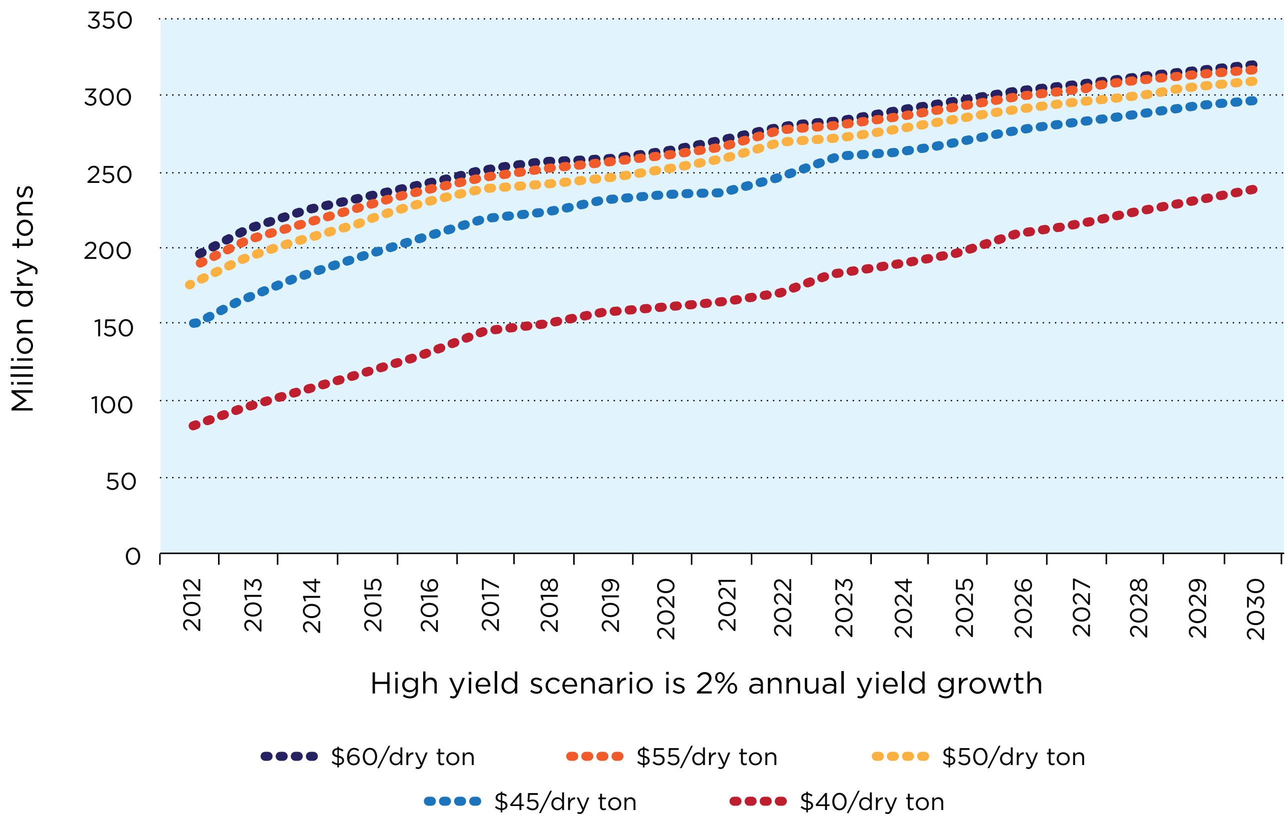
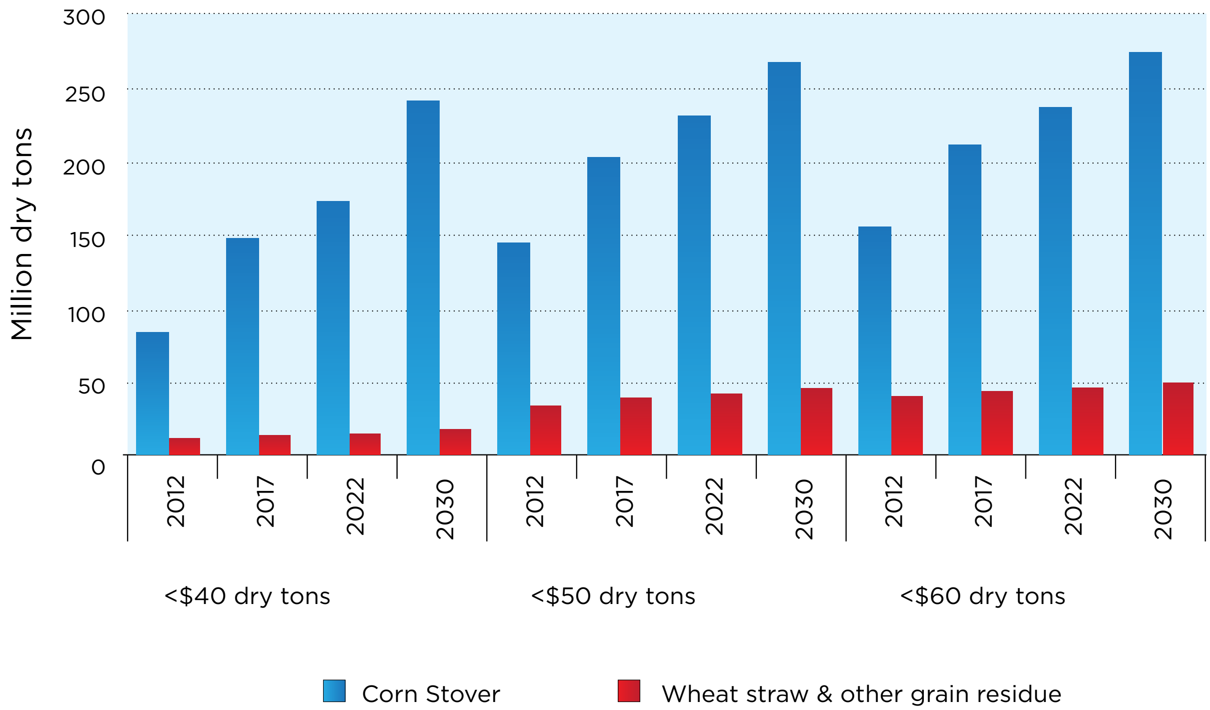


Figure 4.20 Amounts of corn stover and wheat and other grain residues at selected years and prices under high-yield assumptions

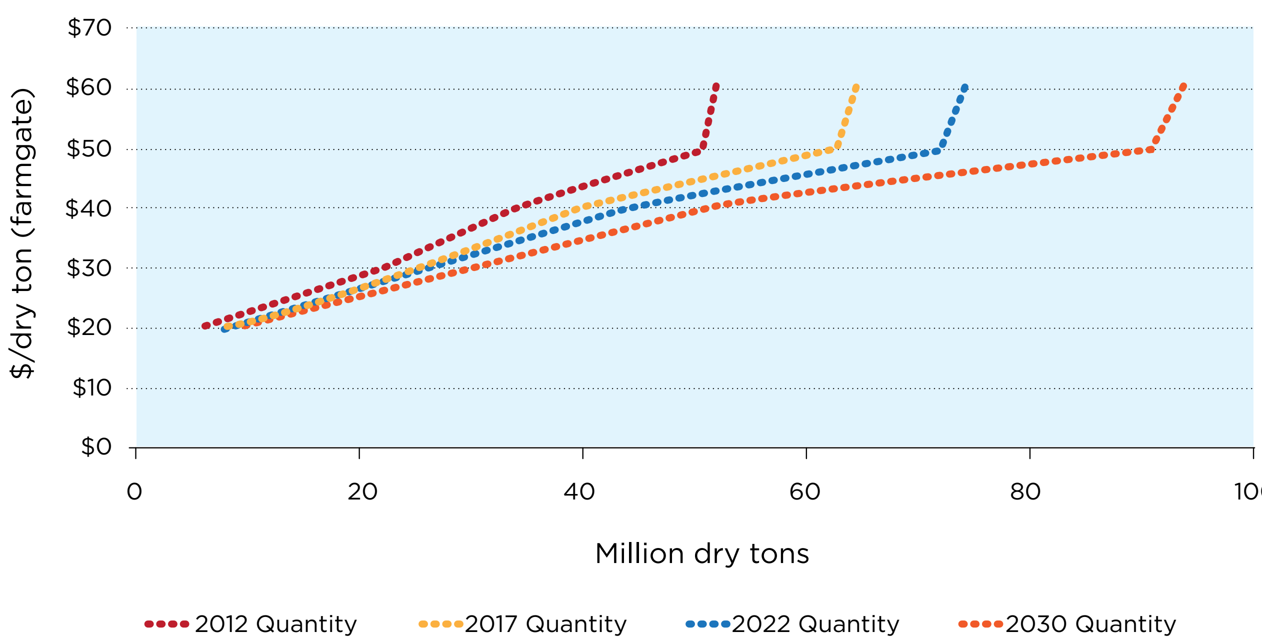


4.6 Secondary Cropland Residues and Waste Resources

A largely unused supply of cellulosic feedstocks for biofuels is categorized as secondary cropland residues and waste resources. These supplies are either the result of crop harvesting and processing or recovered from final consumption (the supply curves are summarized in Figure 4.21 and in Table 4.6). The availability and feasibility of collecting these supplies for biofuels is a function of current use, regional supply, and storage and handling costs. The feedstocks themselves are varied in their quality and availability and may be considered economically feasible and environmentally beneficial with appropriate incentives, logistics, and processing and refining technology.

The residues and wastes considered here include sugarcane trash and bagasse, cotton gin trash and residues, soybean hulls, rice hulls and field residues, wheat dust and chaff, orchard and vineyard prunings, animal fats, animal manures, and MSW. However, this is not an exhaustive list of these resources—there are numerous other secondary processing residues and wastes, although the quantities are much smaller.[41] It is important to recognize that the production levels of the primary products for which these residues are generated crops may be influenced to a high degree by government intervention and international trade, and the current projections are based upon the assumption of continuation of current policies.

Figure 4.21 Current and future secondary processing residues, field residues, and waste resources



[41] The report by Frear et al. (2005) is an example of the wide variety of food processing residues and wastes that are generated in some states.

The price for many of these resources could be considered near zero, at zero, or even negative, indicating producers pay to dispose of these resources. Wheat dust, cotton gin trash, and rice hulls are estimated at zero prices; however, they are assumed to have a price of $20 per dry ton for half of available supply and $30 per dry ton for the other half of supply to cover collection and handling costs. Other resources with little to no costs include field residues of rice and cotton. In this case, collecting and baling to the farmgate were estimated in a similar fashion as corn stover and grain straws. Sugarcane bagasse is assumed used and unavailable. Animal manures are priced according to fertilizer application with an additional cost of $15 per dry ton added for collection and handling costs. Animal fats and waste oils are currently priced in the market, and prices were retrieved from USDA-ERS (2010c). Finally, MSW sources, such as food wastes, are assumed included in the currently used resources reported in Chapter 2 of this report. The overall supply curves for these secondary residues and wastes are summarized by selected year in Figure 4.21.

4.6.1 Sugarcane Residues

Sugarcane is a tall erect plant with a high-sugar-content stalk, leaves, and tops (Figure 4.22). After the sugar is extracted from the stalk, what remains of the stem is bagasse. The leaves and tops, and any parts of the stalk that remain in the field after harvest, are referred to as trash. There are a number of technical coefficients in the literature that relate the amount bagasse and trash produced per ton of sugarcane.[42] In this update, it is assumed that each ton of sugarcane produces 0.14 dry tons of bagasse and 0.075 dry tons of field trash. It is further assumed that one-half of the field trash can be collected.

Sugarcane residues then are the product of sugarcane yield (as reported on a wet basis from USDA-NASS) and the technical coefficient—0.14 for bagasse and 0.0375 for trash. Costs for sugarcane trash collection are based on the use of a rake and a large rectangular baler. Table 4.5 shows estimated supplies of sugarcane residues, which total about 1.1 million dry tons at farmgate prices of $40 per dry ton or less. The bagasse component is not included because it is already used for energy.

Figure 4.22 Sugarcane tassel

(Courtesy of Ed Richard, USDA-ARS)

[42] Assumptions vary in the range of reported moisture, ash, and energy content of bagasse and sugar cane trash. For this report, results from Braunbeck et al. (2005) are adopted. For additional reference, see Deepchand (2005) and Ho (2006).

4.6.2 Cotton Gin Trash and Field Residues

Cotton gin trash is generated from the picking and cleaning processes of cotton harvesting and includes seeds, leaves, and other foreign material, which could include sand and soil. It can have high moisture and nutrient content, and disposal can be costly. Cotton residue refers to the stalks left on the field after the cotton lint has been harvested.

There are two main types of cotton harvesters—spindle pickers and strippers (National Cotton Council of America, 2009). The stripper is a single-pass system that harvests significantly more of the cotton plant and foreign material (sand, soil, etc.) than spindle pickers (0.15 to 0.50 tons per bale versus 0.04 to 0.08 tons per bale for spindlers) and is thus suitable for determinate cotton (e.g., reaches an expected size during the growing season) (Holt et al., 2003; Kim et al., 2004; Mayfield, 2003; Weaver-Missick et al., 2000). Spindle pickers can be used more than once in a growing season to harvest cotton and thus are suitable for indeterminate varieties (e.g., grows continually throughout the season). About 25% to 33% of the U.S. cotton harvest is estimated to be stripper picked, leaving the remaining 67% to 75% to be harvested with spindle pickers (Glade and Johnson, 1983–1985; Mayfield, 2003).

Cotton gin trash is generated in the cotton mill from cleaning the lint and has been estimated at various levels.[43] On average, cotton gin trash is produced at a rate of 0.16 tons of cotton gin trash per bale of cotton (480 pounds) after foreign material is counted.[44] Future production of cotton gin trash is estimated using state level harvesting type percentages and applying cotton production forecasts of upland and pima cotton production (USDA-OACE/WAOB, 2010). These results are shown in Table 4.5 at prices up to $40 per dry ton.

The USDA-OACE/WAOB (2010) projections for 2017 of 17.8 million bales are used for upland cotton; for each year thereafter, upland cotton production increases by 0.2 million bales per year. In addition to upland cotton production, 0.5 million bales of Pima cotton are assumed to be produced each year. Total cotton gin trash production ranges from 1.4 to 1.8 million dry tons on an annual average currently and in 2030, respectively. This residue would be available at central sites and cotton gins and not dispersed in agricultural fields.

Conversely, cotton stalks remain in the field after cotton harvest. The amount in a field will differ according to whether a stripper or spindle harvester is used. The assumptions for calculating cotton gin trash are that spindle and stripper harvesters take around 0.05 and 0.18 tons of residues per bale of cotton with them. These amounts must be subtracted from the amount of residue available in the field. To estimate prices of cotton harvest residue, the following operations are assumed: shredding, raking, and bailing with a large rectangular baler. For cotton, shredding is a typical operation performed even if the residue is not harvested. Therefore, the shredding operation costs are not included in the cost of harvesting residue. The amount of cotton residue available is estimated at 1.2 million dry tons currently, and up to 6.7 million dry tons in 2030 at a price of $40 per dry ton (Table 4.5).

[43] The range of cotton gin trash estimates includes 1.3 million tons (Buser, 2001), 2.5 million tons (Comis, 2002), and 3.2 million tons (Holt et al., 2003). Parnell et al (1994) state that in a typical year gins that handle spindle picked cotton generate 0.5 to 1 million tons and those that handle stripped cotton generate 1 to 1.5 million tons of cotton ginning trash. Their total range of cotton ginning trash produced in a year is 1.5 to 2.5 million tons. Holt et al. (2003) state that in 2001 in the United States 19.8 million bales of cotton [lint] and 3.2 million tons of cotton gin trash were produced, and in Texas 4.2 million bales of cotton and 680,400 tons of cotton gin trash were produced.

[44] Holt et al. (2003) state that about 80% of the cotton gin trash could be used for fuel pellets. Schacht and LePori (1978) report six cotton gins in Texas where 11.1% of the cotton gin waste was cotton lint. According to Holt et al. (2009) previous research shows that the quantity of recoverable fibers in cotton gin trash is between 10% and 25%. Based on the Texas average of cotton gin trash produced as reported by Holt et al. (2003), 0.1806 tons of trash per bale of cotton lint, applying the 11.1% figure of Schacht and LePori (1978), and assuming that cotton gin trash is 90% dry matter, 40 pounds of lint are contained in the trash produced from one bale of cotton lint.

Table 4.5 Summary of Secondary Process Residues and Wastes

	<$20 per dry ton				<$30 per dry ton				<$40 per dry ton			
Feedstock	2012	2017	2022	2030	2012	2017	2022	2030	2012	2017	2022	2030
	Million dry tons											
Rice field residue	0.0	0.0	0.0	0.0	6.3	6.9	7.4	8.0	6.5	6.9	7.4	8.0
Rice hulls	0.8	0.8	0.8	0.9	1.5	1.6	1.7	1.7	1.5	1.6	1.7	1.7
Cotton field residue	1.2	2.1	2.3	3.3	4.1	5.3	5.9	6.7	4.2	5.3	5.9	6.7
Cotton gin trash	0.7	0.8	0.8	0.9	1.4	1.6	1.7	1.8	1.4	1.6	1.7	1.8
Wheat dust	0.3	0.3	0.3	0.3	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Sugarcane residues	0.1	0.1	0.1	0.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Orchard and vineyard prunings	2.9	2.8	2.8	2.8	5.7	5.6	5.5	5.5	5.7	5.6	5.5	5.5
Animal manures	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12	13	16	20
Animal fats	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total secondary residues & wastes	**5.8**	**6.9**	**7.1**	**8.2**	**21**	**23**	**24**	**25**	**33**	**36**	**40**	**46**

4.6.3 Soybean Hulls

When soybeans are processed (crushed), they are separated into three components: meal, oil, and hulls. However, not all soybeans produced in the United States are crushed. Some soybeans are exported as whole beans and processed in other countries. Recently, soybean production has averaged about 3 billion bushels annually. Almost 60% of this total was crushed, which produced 2.74 million dry tons of hulls.[45] Soybean production is expected to increase to 4.4 billion bushels by 2030, and the amount of crushed soybeans is expected to increase to nearly 2.5 billion bushels (USDA-OCE/WAOB, 2010). The corresponding hull residue will increase to nearly 4 million dry tons. Hulls are currently used in livestock feed. Nelson (2010) reports that soybean hull prices ranged between $49 and $175 per ton at five locations (Alabama/Georgia; Central Illinois; Iowa; Minneapolis, Minnesota; and Kansas City, Missouri) between 2004 and 2007. Because hulls are currently utilized, their availability as a cellulosic feedstock would be at or above prices at which they are currently sold. No soybean hull residue is assumed available in this update.

4.6.4 Rice Hulls and Field Residues

When rice is milled, its hull is removed. The hull represents 20% of the mass of rice and generally presents a disposal problem, although rice hulls currently can be utilized as a filter product or as chicken house bedding (Hirschey, 2003). Rice hulls have the potential to be used for energy.[46] Rice is produced in six states: Arkansas, California, Louisiana, Mississippi, Missouri, and Texas. In recent years, total rice production averaged 207 million hundred weight (100 pounds)—nearly 9 million tons, assuming 13.5% moisture content. Some rice is exported as rough rice

[45] In a 60-pound bushel of soybeans, the hulls have averaged 3.48 pounds over 2007 to 2009 (USDA-ERS, 2010d).

[46] A facility in Stuttgart, Arkansas, has plans to convert rice hulls into ethanol at a rate of 50 gallons of ethanol per ton and to produce silica sodium oxide at a rate of 440 pounds per ton (Bennett, 2008).

(i.e., it has not been dehulled)—approximately 35% of total rice production on average. Adjusting for rice that is exported as rough rice and assuming that rice hulls represent 20% of rice, about 1.5 million dry tons of rice hulls per year are currently produced. Rice hull production is projected to increase by 10% to 15%, depending on production and the level of exports. Table 4.5 shows supplies of rice hulls.

Rice field residues (or straw) usually need to be disposed of off the field. In the past burning was common, but it is not allowed now. Because it has such high silica content, it is undesirable as a forage supplement. Sometimes it is incorporated into the soil, or it may be removed and utilized for energy, for example. The HI for rice straw has been reported in ranges of 0.5 to 0.3 (or straw to grain ratios of 1:1 and 2.3:1). Duke (1983) states that rice straw is usually estimated to be two times the grain yield, but goes on to state that for the dwarf varieties, a straw to grain ratio of 1:1 prevails (HI of 0.5). Here, a more conservative harvest index of 0.5 is used to estimate rice straw residues (i.e., the higher HI gives a lower estimate for rice straw). It is assumed that moisture content for grain is 13.5%. Total straw production is estimated at about 6.5 million dry tons increasing to 8 million dry tons by 2030. Rice straw is assumed to be harvested like corn stover and cotton residues with a shredding operation, followed by raking and baling (assumed to be a large rectangular baler for costing purposes). Seventy percent of the rice straw is assumed harvested. All of the rice field straw is assumed to be available at a farmgate price of $30 per dry ton or less (Table 4.5).

4.6.5 Wheat Dust and Chaff

Wheat dust and chaff are produced as wheat is processed at a grain elevator. Approximately 1% of wheat is assumed to become wheat dust and chaff, which could potentially be used as a cellulosic feedstock (Nelson, 2010). Wheat production is currently about 2.2 billion bushels and is projected to increase slightly by 2030 (USDAOCE/WAOB, 2010). Wheat is assumed to be 88% dry matter, and applying the 1% wheat dust and chaff factor to all wheat production results in about 600 million dry tons. Half of the wheat dust resource is assumed available at $20 per dry ton, and all is assumed to be available at $30 per dry ton or less (Table 4.5).

4.6.6 Orchard and Vineyard Prunings

Annual orchard and vineyard prunings (Figure 4.23) are estimated for fruits, citrus fruits, and nuts. The estimated biomass available, according to Nelson (2010), totals 5.7 million dry tons.[47] More than 80% of the orchard and vineyard prunings are from five crops: oranges, grapes, almonds, pecans, and apples. More than half (52%) of the resource is in California, 19% is in Florida, and the remainder is located in Texas, Oklahoma, Georgia, New York, and Michigan. The USDA projections (USDA-OCE/WAOB, 2010) forecast a slight decline in the production area of fruits and nuts. Production estimates from the USDA projections are used to index future orchard and vineyard prunings. Half of the orchard and vineyard prunings are assumed to be available at $20 per dry ton and all are expected to be available at $30 dry ton or less (Table 4.5).

4.6.7 Animal Fats

Animal fats suitable as secondary cropland feedstocks in biodiesel production include edible and inedible tallow, lard, white grease, poultry fat, and yellow grease. Yellow grease is included in the supply estimates, but a description is provided in a following section of the waste cropland resources. When animals are processed for meats, fats are a byproduct of the process. For beef, these fats are separated into edible and inedible tallow. For hogs, these fats are lard and

[47] The fruits included in this analysis are apples, apricots, avocados, cherries, dates, figs, grapes, kiwi, nectarines, olives, peaches, pears, persimmons, pomegranates, and other non-citrus fruits. The citrus fruits are grapefruit, lemons, limes, oranges, tangerines, and other citrus fruit. The nuts are almonds, pecans, pistachios, walnuts, and other nuts (Figure 4.24).

choice white grease. Poultry produces poultry fat. Animal fats are a less costly feedstock than vegetable oils; however, animal fats contain high levels of saturated fatty acids, which result in a lesser flow quality than vegetable oil. Animal fats tend to lose viscosity, causing the formation of crystals that plug fuel filters, especially in colder temperatures. Because biodiesel from animal fat feedstock has the tendency to solidify in colder temperatures, vegetable oil will likely be the feedstock of choice in northern states. The supply of animal fats is limited and will not increase as demand for biodiesel increases.

Nelson (2010) provides estimates of edible and inedible tallow based on cattle processing at 70 locations in 21 states, and lard and choice white grease based on hog processing at 70 locations in 26 states. Edible and inedible tallow are produced at 95 and 90 pounds per cow slaughtered, respectively. Lard and choice white grease are produced at 9 and 10.5 pounds per hog slaughtered, respectively. Edible tallow, inedible tallow, lard, and choice white grease are estimated at 1.49, 1.41, 0.43, and 0.51 million tons according to Nelson (2010). Nelson does not provide an estimate for poultry fat, but Pearl (2002) estimates poultry fat production at 1.11 million tons.

Not all of these fats are necessarily available for energy use. Tallow, lard, and choice white grease are potential biodiesel feedstocks, but each also is used in markets such as edible food, soap, lubricants, and resins and plastics. Edible tallow is used for baking or frying fats and margarine, as well as certain inedible products.

Figure 4.23 Farmer clearing prunings

(Courtesy of ORNL)

Inedible tallow is most often used as a supplement for animal feed—a majority of its market share—followed by use in fatty acids, soap, methyl esters (biodiesel), lubricants, and other uses. Poultry fats are used in soaps, pet foods, and a few other consumer products. Prices for edible and inedible tallow and pork lard and choice white grease have varied from $0.11 to $0.48 per pound in recent years (The Jacobsen Company, 2010). Feedstock price greatly affects the end price of biodiesel, as feedstock price can account for up to 80% of the total biodiesel cost. Because of the high price of animal fats and existing uses, they are not considered further in this update.

4.6.8 Animal Manure

Over the past several decades, livestock operations have experienced a trend toward fewer and more concentrated facilities. As a consequence, manure storage issues have arisen. Often, large confined livestock operations do not have enough cropland or pasture to adequately distribute manure, resulting in excess manure that poses a risk to water quality and human health. Additionally, the land resources are constrained to absorb manure nutrients within proximity to concentrated animal production facilities.

There are 1.3 million livestock farms in the United States (EPA, 2003). In 2003, slightly less than 20%—or 238,000—of these farms were classified as an animal feeding operation (AFO). EPA defines an AFO as a facility where animals are confined and fed or maintained for at least 45 days during a 12-month period, and where crops, vegetation, forest growth, or post-harvest residues are not sustained in the normal growing season over any portion of the facility. AFOs produced more than 500 million tons of manure in 2003 (EPA, 2003). The largest and most polluting AFOs are categorized as Concentrated Animal Feeding

Operations (CAFOs), which make up about 5% of all AFOs but contribute to more than 65% of excess nutrients (Ribaudo et al., 2005).

The EPA defines three different categories of CAFOs that are regulated: large, medium, and small operations. Large CAFOs are generally defined as operations with 1,000 or more animal units (AUs).[48] Medium CAFOs are AFOs that hold between 300 and 1,000 AUs and discharge pollutants through a manmade device that came into contact with the confined animals. AFOs that hold less than 300 AUs are labeled small CAFOs only if they discharge waste into water through a man-made device or directly into waters that originate outside the facility and come in contact with the confined animals.

One possible solution to mitigate pollution created by CAFOs is to use excess manure for production of bioenergy through anaerobic digestion. The nutrients remain in the digester effluent liquid and are usually returned to cropland. Other systems have potential such as capturing some of the nutrients in biochar from thermochemical processes, or even integrating phosphorus crystallization or nitrification recovery systems with energy production from manure.

This report estimates recoverable and available dry tons of manure for a baseline scenario. Recoverable and available manure estimates are based on assumptions by Kellog et al. (2000) reported in pounds of manure phosphorus excreted, recoverable, and available in excess of farm use. Gollehon et al. (2001) estimates the percentage of available manure phosphorus in excess of county potential use, which is used as an estimate for recoverable manure in the baseline scenario. It is assumed that the percent of manure phosphorus that is recoverable and available represents a lower bound estimate (19%) of the amount of total manure that is recoverable and available.

For the baseline scenario, it is assumed that manure from the largest classifications of livestock production is available for bioenergy. For future years, it is assumed that the market for manure will mature and recovery will increase 2% annually, a more conservative approach than Kellog et al. (2000). The baseline scenario assumes the price is equal to its fertilizer substitute value, plus a $15 per dry ton collection and handling fee. The selling price may also be determined by the type of application needed for the individual farm on which the fertilizer is land applied. Prices are computed using the 3-year average price for nitrogen, phosphorous, and potassium.

Animal manure production was identified for beef (cattle and calves), swine, poultry (broilers and layers), and turkeys. Total production of cattle, dairy, and swine was estimated as the product of total AUs (1,000 pounds of livestock) and the percentage of inventory produced on large farms (greater than 10,000 head for cattle; 1,000 head for dairy; 5,000 head for swine) as a proxy for CAFO inventory. Litter available from poultry production was estimated at 70% of total poultry production (chicken broilers, chicken layers, and turkeys). Manure is assumed to have an average moisture content of 82.5%. Using the recoverability and availability percentages described above, the amount available under the base year is 12 million dry tons, increasing to 13, 16, and 20 million dry tons for years 2017, 2022, and 2030, respectively (Table 4.5).

4.6.9 Wastes Resources from Agriculture

Waste resources potentially available from the end consumer are considered tertiary cropland resources. These sources may or may not be currently utilized, and their availability is contingent upon the presence or absence of specific industries that may compete for the feedstock within a particular hauling distance of biorefineries. Common resources within this category are yellow grease and MSW.

Yellow Grease. Yellow grease differs from other animal fat feedstock in that it is the recycled cooking oil from restaurants. It may contain the recycled oils of both vegetables and animals, but the vegetable oil is hydrogenated so that it acts more like animal fat when converted to biodiesel. Yellow grease is the cheapest available feedstock for biodiesel production. Its supply, however, is limited, making it a more attractive feedstock to smaller capacity production facilities that will be located near large population areas where the food service industry is concentrated. Yellow grease

[48] An animal unit is defined as one thousand pounds of live animal weight.

accounted for 1.4 million pounds of U.S. animal fat production in 2004 (USDA-OCE/OEPNU, 2008).

Municipal Solid Wastes (MSW). MSW originates from agricultural sources, such as food wastes and textiles. A large fraction of these resources are combusted into energy as mixed wastes. In 2010, the currently used amount of MSW agricultural wastes is estimated at about 7 million dry tons (see Chapter 2). The estimated amount increases to 10.5 million dry tons per year in 2017 and continues at this level through 2030.

4.7 Total Supply of Agricultural Biomass and Waste Resources

The largest quantities of agricultural residues and wastes are crop residues from the major commodity crops. They range from 27 to 80 million dry tons between 2012 and 2030 at a simulated farmgate price of $40 per dry ton (Table 4.6). Estimated crop residues supplies increase to 111 to 180 million dry tons at the simulated price of $60 per dry ton. The high-yield scenario has potential to double the quantity of collectable crop residue. At the simulated price of $50 per dry ton, total corn stover and total crop residue increase to 264 and 309 million dry tons by 2030, respectively. An additional $10 per dry ton (to total $60 per dry ton) brings in only an additional 7 to 11 million dry tons of residues. Most of the collectable residue can be had for $50 per dry ton or less.

The secondary agricultural processing and other waste products (excluding manure) in the aggregate are in the range of 21 to 25 million dry tons depending on the year and price ($40 to $60 per dry ton), with orchard and vineyard prunings, cotton field residue, and rice straw being the largest individual components. Collectible animal manure production is larger, estimated at 12 and 59 million dry tons between the present and 2030 over the $40 to $60 per dry ton price range. In total, the agricultural processing residues and wastes range from about 33 to 84 million dry tons over the 20-year simulation period.

Combining all of the agricultural residues and wastes totals about 245 million dry tons at $50 per dry ton or less by 2030. An additional 20 million dry tons become available at an additional $10 per dry ton farmgate price. The high-yield scenario adds 146 million dry tons at the $50 per dry ton simulated price and 139 million dry tons at the $60 per dry ton farmgate price.

4.8 Summary

The analysis of primary crop residues from the major grains—corn, wheat, sorghum, oats, and barley—used a relatively sophisticated methodology to determine how much residue needs to remain in-place to meet soil erosion restrictions due to water and wind and maintain soil carbon levels. A number of datasets involving soils, land slope, climate, cropping rotations, tillage, management practices, and residue collection technology were used in the analysis. Of all of these factors the crop rotation and tillage data are two areas where the analysis would benefit from improved and more up-to-date data.

Once crop residue retention was determined, the estimation of crop residue supplies took into account grower payments for removed residue and collection costs as a function of dry tons removed per acre. There is only anecdotal information on grower payments or what farmers would expect from the sale of crop residues. In this update, it was assumed that farmers would accept the value of the removed nutrients plus a fixed amount per ton of removed residue. What farmers will accept for crop residues will depend on a host of factors that are impossible to know with precision in the absence of any significant markets for crop residues.

Included in the agricultural resource analysis are processing residues and wastes. With the exception of animal manure, these supplies are significantly smaller than the primary crop residues, but maybe available at much lower costs. Technical coefficients were used to estimate the amount of available residue to total production and very broad assumptions were made regarding the costs to acquire these resources. Overall, estimated supplies provided in this assessment should be considered somewhat imprecise until additional data are available.

The estimation of agricultural biomass resources identified several needs, these are summarized below:

- There is a need to understand the long-term effects of residue removal on soils and to validate the residue retention coefficients used in this analysis.
- Improved tillage and cropping rotation data would improve the residue retention coefficient analysis.
- As discussed in this chapter, there are differing opinions between an increasing harvest index as yields increase and a harvest index that can be engineered to serve markets. The analysis reported here assumed a harvest index of 0.5 or a 1:1 ratio of stover to grain.
- There is a need to improve the technical coefficients used to estimate available secondary biomass resources and costs to acquire and process these feedstocks.

Table 4.6 Summary of Baseline and High-Yield Scenarios — Agricultural Residues and Waste Resources

	<$40 per dry ton				<$50 per dry ton				<$60 per dry ton			
Feedstock	2012	2017	2022	2030	2012	2017	2022	2030	2012	2017	2022	2030
	Million dry tons											
Baseline												
Corn	19	32	42	65	73	93	108	129	85	106	120	140
Wheat	6.7	7.8	9.1	12	18	22	26	31	23	26	31	36
Barley, Oats, Sorghum	1.0	1.3	1.6	2.9	2.4	2.5	2.4	3.6	2.8	2.7	2.6	3.7
Total primary residue	**27**	**41**	**52**	**80**	**94**	**117**	**136**	**164**	**111**	**135**	**154**	**180**
Secondary residues & wastes												
Rice field residue	6.5	6.9	7.4	8	6.5	6.9	7.4	8	6.5	6.9	7.4	8
Rice hulls	1.5	1.6	1.7	1.7	1.5	1.6	1.7	1.7	1.5	1.6	1.7	1.7
Cotton field residue	4.2	5.3	5.9	6.7	4.2	5.3	5.9	6.7	4.2	5.3	5.9	6.7
Cotton gin trash	1.4	1.6	1.7	1.8	1.4	1.6	1.7	1.8	1.4	1.6	1.7	1.8
Sugarcane residue	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Orchard and vineyard prunings	5.7	5.6	5.5	5.5	5.7	5.6	5.5	5.5	5.7	5.6	5.5	5.5
Wheat dust	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Animal manures	12	13	16	20	29	34	41	56	30	35	43	59
Animal fats	0	0	0	0	0	0	0	0	0	0	0	0
Total secondary residues & wastes	**33**	**36**	**40**	**46**	**50**	**56**	**65**	**82**	**51**	**58**	**67**	**84**
Total baseline	**59**	**77**	**92**	**126**	**143**	**174**	**201**	**245**	**162**	**192**	**221**	**265**
High-yield scenario												
Corn stover	71	132	157	221	143	200	228	264	153	209	234	271
Wheat Straw	9.8	12	13	16	60	35	38	42	35	39	42	46
Barley, Oats, Sorghum	1.5	1.5	1.4	1.7	3.6	3.4	2.8	3.1	4.0	3.6	2.9	3.0
Total primary residue	**83**	**146**	**171**	**238**	**176**	**239**	**269**	**309**	**193**	**252**	**279**	**320**
Total high-yield	**115**	**182**	**210**	**284**	**226**	**295**	**334**	**391**	**244**	**310**	**346**	**404**

Notes: *High-yield estimates for corn, wheat, barley, oats, and sorghum assume a 1% annual growth in energy crop yields. Increasing the assumed energy crop yield growth rate (e.g. 2 to 4% annually) will slightly change the estimated high-yield resource estimates above.*

5 BIOMASS ENERGY CROPS

Perennial grasses, trees, and some annual crops can be grown specifically to supply large volumes of uniform, consistent-quality feedstocks for biofuel and biopower production. Growing these crops is a natural extension of current farm systems and offers additional profits to farmers and landowners. The 2005 *BTS* included scenarios that assumed a relatively large shift of land into the production of energy crops. It was reasoned that energy crops could displace as many as 40 to 60 million acres of cropland and pasture and produce 150 to nearly 380 million dry tons of biomass sustainably, provided average annual yields of 5 to 8 dry tons per acre could be attained. Demands for food, feed, and exports would still be met under these *BTS* scenarios because of projected yield growth and other technological advances in U.S. agriculture.[49]

Implicit in the 2005 *BTS* was an assumption that energy crops are economically competitive and offer risk-adjusted net returns at least as high as what could be earned from growing conventional agricultural crops or from existing uses of the land. In this update, an agricultural policy simulation model (POLYSYS) is used to assess the economic competitiveness of energy crop production and determine how much cropland and pastureland could possibly shift to energy crops. The next section of this chapter provides background on energy crops. Included in this discussion are crop biology and adaptation, agronomics, production costs and yields, and requirements for sustainability. This energy crop background section is followed by a summary of key assumptions and data used to estimate potential supply and land-use change. The final part of this chapter provides results under baseline and high-yield scenarios.

5.1 Background on Energy Crops

Beginning in the late 1970s, numerous woody and perennial grass crops were evaluated in species trials on a wide range of soil types across the United States.[50] One key outcome of this research was the development of crop management prescriptions for perennial grasses and woody crops. Some highlights of this research are presented below for representative energy crops deemed to have high potential. These crops include three perennial grasses, an annual energy crop (high-yield sorghum), and four woody crops, managed either as a single rotation (i.e., harvest before replanting) or managed as a multi-rotation (i.e., coppicing) crop.

5.1.1 Switchgrass and Other Perennial Grasses

Breeding and selection research on native perennial grasses such as switchgrass (*Panicum virgatum*), big bluestem (*Andropogon gerardii)*, and indian grass (*Sorghastrum nutans*) started in 1936 when the USDA at Lincoln, Nebraska, began breeding native grasses to revegetate land damaged by the drought of the 1930s. In 1949, the first cultivar, 'Nebraska 28' switchgrass, was released jointly by the USDA and the University of Nebraska. Since that time, USDA and other scientists have evaluated native collections and selected and bred

[49] In addition to the *BTS*, many other analyses conclude significant quantities of energy crops can be grown on abandoned, idle, and marginal cropland or other agricultural land without impacts to food and forage supply. For example, see BRDI (2008).

[50] Much of the research was conducted under the Department of Energy's Biomass Feedstock Development Program. More than 150 woody and 35 herbaceous crops including nearly 20 perennial grasses were screened and evaluated as potential energy crops. A historical perspective on herbaceous and woody crops can be found in Wright (2007) and Wright et al. (in press).

improved cultivars for most areas of the United States. These initial cultivars were developed for forage and conservation purposes. A full array of establishment and management practices has been steadily refined and improved. Millions of acres of these grasses have been planted. Past and continuing genetic research is leading to the development of bioenergy-specific cultivars with substantial genetic gains. Switchgrass is widely considered the model perennial grass for bioenergy production.

Several characteristics make switchgrass, big bluestem, and indian grass desirable biomass energy crops. They are broadly adapted and native to North America, which reduces the concerns for becoming invasive species. Each has consistently high yields with minimal inputs and is well-suited to marginal land. Additionally, they are relatively easy to establish from seed, and a seed industry already exists. Long-term plot trials and farm-scale studies indicate switchgrass is productive, enhances and protects environmental quality, and is potentially profitable given the establishment of a viable cellulosic biofuels market. Although stands can be maintained indefinitely, they are expected to last at least 10 years, after which time the stands could be renovated and replaced with new, higher-yielding cultivars (Figure 5.1). Currently there are additional public and private breeding programs throughout the United States.

Biology and adaptation. Switchgrass, big bluestem, and indian grass are perennial warm-season grasses that are native to most of North America, except for areas west of the Rocky Mountains and north of 55°N latitude. They grow 3 to 10 feet tall with most of the root mass located in the top 12 inches of the soil profile, according to the long-standing literature. There is variation by species, but the root depth can reach 10 feet with new varieties even deeper. More than 70 years of experience with these grasses used as hay and forage crops demonstrates that they are productive and sustainable on rain-fed marginal land east of the 100th Meridian (Mitchell et al., 2010). This meridian matches the western boundary of Oklahoma (excluding the panhandle), and bisects North Dakota, South Dakota, Nebraska, Kansas, and Texas. They are adapted to a wide range of habitats and climates and

Figure 5.1 Switchgrass research plot

(Courtesy of SD State University)

have few major insect or disease pests. In addition to potential bioenergy production, these grasses are used for pasture and hay production, soil and water conservation, and wildlife habitat.

Switchgrass has distinct lowland and upland ecotypes and two primary ploidy levels (chromosome numbers). Tetraploid plants have 36 chromosomes, while octaploid plants have 72 chromosomes. All lowland ecotypes are tetraploids, whereas upland plants can be tetraploids or octaploids. Tetraploids and octaploids do not cross. Additionally, switchgrass ecotypes are differentiated by the latitude of their origin. Ecotypes from the southern United States are not well adapted to the northern United States because of winter kill, and northern ecotypes moved to the southern United States have low productivity. Upland ecotypes occur in upland areas that are not subject to flooding, whereas lowland ecotypes occur on flood plains and low-lying areas (Vogel, 2004). Generally, lowland plants have a later heading date and are taller with larger and thicker stems. Tetraploid lowland and upland ecotypes have been crossed to produce true F1 hybrids that have a 30% to 50% yield increase over the parental lines (Vogel and Mitchell, 2008). These hybrids are promising sources for high-yielding bioenergy cultivars. The lowland ecotypes and the lowland x upland hybrids have the most potential for bioenergy production because of their high yields.

Production and agronomics. In perennial grasses, successful stand establishment in the seeding year is mandatory for economically viable bioenergy production systems (Perrin et al., 2008). Weed competition during establishment is a major reason for stand failure. For example, acceptable switchgrass production can be delayed by at least 1 year due to weeds and poor stand establishment (Schmer et al., 2006). No-till planting has significant cost and environmental benefits. After the establishment year, well-established switchgrass stands require limited herbicides. Nitrogen fertilizer is not recommended during the planting year since nitrogen encourages weed growth, increases establishment cost, and increases economic risk associated with establishment if stands should fail (Mitchell et al., 2008; 2010). In most agricultural fields, adequate levels of phosphorus and potassium will be in the soil profile (Mitchell et al., 2010). Good weed management and favorable precipitation will produce a crop equal to about half of potential production, which can be harvested after frost at the end of the planting year with 75% to 100% of full production achieved the year after planting.

Although switchgrass can survive on low-fertility soils, nitrogen fertilizer is required to optimize yield. The optimum nitrogen rate for switchgrass managed for biomass varies (Mitchell et al., 2008; 2010), but biomass declines over years if inadequate nitrogen is applied, and yield will be sustainable only with proper nitrogen application. Vogel and others (2002) found that for one variety, applying 100 pounds of nitrogen per acre per year optimized biomass, with about the same amount of nitrogen being applied as was being removed by the crop. A general nitrogen fertilizer recommendation for the Great Plains and Midwest region is to apply 20 pounds of nitrogen per acre per year for each ton of anticipated biomass if harvesting during the growing season, with nitrogen rate reduced to 12 to 14 pounds per acre per year for each ton of anticipated biomass if harvesting after a killing frost. The nitrogen rate can be reduced when the harvest is after a killing frost because less nitrogen is removed from the system and some nitrogen is recycled. Nitrogen is applied as switchgrass greens up in the spring to minimize cool-season weed competition. Spraying herbicides to control broadleaf weeds is typically only needed once or twice every 10 years in established, well-managed switchgrass stands (Mitchell et al., 2010).

Figure 5.2 Baling switchgrass

(Courtesy of ORNL)

Switchgrass can be harvested and baled with commercially available haying equipment (Figure 5.2). Self- propelled harvesters with rotary heads are preferred for harvesting high-yielding (greater than 6 tons per acre) switchgrass fields. Harvesting switchgrass within 6 weeks before killing frost or leaving a stubble height shorter than 4 inches can reduce stand productivity and persistence, whereas harvesting after a killing frost will not damage stands. A single harvest per growing year generally maximizes switchgrass yields, and harvesting after a killing frost ensures stand productivity and persistence. Proper management maintains productive stands for more than 10 years. Round bales tend to have less storage losses than large square bales when stored outside uncovered, but square bales tend to be easier to handle and load without road width restrictions. After harvest, poor switchgrass storage conditions can result in storage losses of 25% in a single year and can reduce biomass quality. Covered storage is necessary to protect the harvested biomass.

Potential yield and production costs. Switchgrass yield is strongly influenced by precipitation, soil fertility, location, and genetics. Most plot- and field-scale switchgrass research has been conducted on forage-type cultivars, selected for other characteristics in addition to yield. Consequently, the forage-type cultivars in the Great Plains and Midwest are entirely represented by upland ecotypes which are inherently lower yielding than lowland ecotypes. Yield data comparing forage-type upland cultivars like Cave-In-Rock, 'Shawnee,' 'Summer,' and 'Trailblazer' do not capture the full yield potential of switchgrass. For example, high-yielding F1 hybrids of 'Kanlow' and Summer produced 9.4 tons per acre annually, which was 68% greater than Summer and 50% greater than Shawnee (Vogel and Mitchell, 2008). New biomass-type switchgrass cultivars will be available soon for the Great Plains and Midwest. In a 5-year study in Nebraska, the potential ethanol yield of switchgrass averaged 372 gallons per acre and was equal to or greater than that for no-till corn (grain + stover) on a rain-fed site with marginal soils (Varvel et al., 2008). These results were based on switchgrass cultivars developed for grazing. Significantly greater yields are expected by the next generation of biomass-specific cultivars.

An economic study based on the 5-year average of 10 farms in Nebraska, South Dakota, and North Dakota indicated producers can grow switchgrass at a farmgate price of $60 per ton (Perrin et al., 2008). Producers with experience growing switchgrass had 5-year average costs of $43 per ton, with a low of $38 per ton. These costs include all expenses plus labor and land costs. This research from nearly 50 production environments indicates that growing switchgrass for cellulosic ethanol could be economically feasible in the central and northern Great Plains, with sufficiently cost-effective fuel conversion and distribution. Fuel and land prices have increased since this study, so the cost increases for those inputs need to be considered when determining switchgrass production costs.

Sustainability. Sustainability is crucial for biomass energy crops. Switchgrass protects soil, water, and air quality, sequesters atmospheric carbon, creates wildlife habitat, increases landscape diversity, returns marginal farmland to production, and could potentially increase farm revenue. In a 5-year study, Liebig et al. (2008) reported that switchgrass stored large quantities of carbon (C), with four farms in Nebraska storing an average of 2,590 pounds of soil organic carbon (SOC) acre/year when measured to a depth of 4 feet across sampled sites.

The energy-efficiency and sustainability of cellulosic ethanol from switchgrass has been modeled using net energy value (NEV), net energy yield (NEY), and the petroleum energy ratio (PER) (Schmer et al., 2008). Switchgrass fields in the Midwest produced 540% more renewable energy (NEV) than non-renewable energy consumed in production over a 5-year period (Schmer et al., 2008). The estimated on-farm NEY was 93% greater than human-made prairies and 652% greater than low-input switchgrass grown in small plots in Minnesota (Tilman et al., 2006). The on-farm study had an estimated PER of 13.1, equivalent to producing 93% more ethanol per acre than human-made prairies and 471% more ethanol per acre than low-input switchgrass in Minnesota (Schmer et al., 2008).

Implementing switchgrass-based bioenergy production systems will require converting marginal land from conservation plantings or annual row crops to switchgrass. Growing switchgrass on marginal sites likely will enhance ecosystem services more rapidly and significantly than on productive sites. There is concern of soil carbon loss associated with converting conservation grasslands such as those in the Conservation Reserve Program to bioenergy crops such as switchgrass. Recent research on converting grasslands to no-till corn demonstrates that using no-till revegetation practices results in no measurable soil carbon loss (Follett et al., 2009; Mitchell et al., 2005).

Switchgrass is the leading perennial grass biofuel feedstock option for the Great Plains and Midwest. Some have questioned if switchgrass is the best choice from an ecological perspective, and contend that diverse mixtures of native plants are ecologically more beneficial and should be considered for biomass production. However, feedstock selection will be determined by the amount of available land and the ability of producers to profit by its production. Managed switchgrass monocultures can produce 1.5 to 5 times more biomass than native tallgrass prairies and seeded polycultures (Table 5.1), which translates into less land being required to produce the necessary biomass and more profit potential for the producer.

An Oklahoma study compared monoculture and polyculture feedstock production managed in a low-input system (no nitrogen fertilizer) (Griffith et al.,

Table 5.1 Reported Perennial Grass Yield and Acres Required for a 50-Million Gallon Cellulosic Ethanol Plant

Feedstock	Yield, dry tons/acre	Acres need to grow 588,000 dry tons/year	Percent of land in 25-mile radius
LIHD prairie[a]	1.75	336,000	27
Managed native prairie[b]	2.5	235,200	19
Shawnee switchgrass[c]	5	117,600	9
Bioenergy switchgrass[d]	7.4	79,500	6
Hybrid switchgrass[e]	9.4	62,600	5

Note: *Feedstock requirements for a 50 million gallon biorefinery require 588,000 dry tons of feedstock at a conversion rate of 85 gallons of ethanol per dry ton. Ethanol conversion rate from Biomass Multi-Year Program Plan (U.S. Department of Energy, 2011).*

a. Low-input, high-diversity man-made prairies (Tilman et al., 2006).
b. Native tallgrass prairie burned in late spring (Mitchell, 1992).
c. Shawnee is an upland forage-type switchgrass cultivar released in 1995.
d. Lowland bioenergy-specific switchgrass in the cultivar release process.
e. F1 hybrid of 'Summer' and 'Kanlow' switchgrass (Vogel and Mitchell, 2008).

2011). The monocultures were switchgrass, sand bluestem (*Andropogon hallii* Hack.), Old World bluestem (*Bothriochloa ischaemum* L. Keng), and big bluestem. The polycultures were four grasses, four grasses and four forbs, eight grasses and eight forbs, and Old World bluestem with alfalfa (*Medicago sativa* L.). Average yield was 2.8 tons per acre for the monocultures and 2.4 tons per acre for the polycultures. For each polyculture, a dominant species emerged by year three, indicating that over time polycultures may be similar to monocultures. These low-input systems produce about half the biomass of managed systems.

Adding perennial grasses into a landscape provides habitat improvements over corn and soybeans, even if the areas are mowed every year. If the grasses fill the landscape, special management practices can be used to optimize the habitat value. These include early summer harvest with regrowth prior to dormancy, or leaving some material standing during winter to provide winter cover and spring nesting habitat.

Conclusions. Characteristics that lead to potential adoption of new crops include profitability for the producer, ability to fit within existing farming operations, ease of storage and delivery to the end user, and availability of extension information on best management practices. Each of these exists for switchgrass. Switchgrass can be harvested after frost when many farmers have completed corn and soybean harvests. The operational aspects of perennial herbaceous cropping systems are fully developed and accepted by farmers, and the economic opportunities on small, difficult to farm, or marginally productive fields are attractive to many farmers (additional considerations are provided in Text Box 5.1).

Large-scale switchgrass monocultures evoke concerns of potential disease and insect pests and the escape of switchgrass as an invasive species, especially since little research has been conducted on these topics. However, the genetic diversity available to switchgrass breeders, the initial pathogen screening conducted during cultivar development, and the fact that switchgrass has been a native component of U.S. grasslands for centuries will likely limit negative pest issues.

Available cultivars and production practices reliably produce 5 tons per acre in the central Great Plains and Midwest, and 10 tons per acre in the Southeast. Improved cultivars and agronomics will increase yields similar to the yield increases achieved in corn in the last 30 years.[51] Hybrid switchgrass makes producing 10 tons per acre a reality in the central United States. The availability of adequate land area and the profit potential in a region will determine the success of growing switchgrass for bioenergy. Production practices and plant materials are available to achieve sustainable and profitable biomass production.

TEXT BOX 5.1 | IRRIGATION OF ENERGY CROPS

Irrigation of energy crops can be a contentious issue. Water in the western United States has to meet a number of competing off-stream uses, such as municipal, agriculture, and industrial, as well as providing for hydropower generation and minimum in-stream flows for fisheries. In the West, the majority of water comes as winter precipitation, as rain or snow, and usually water for summer use comes from snow melt or storage.

In the western United States, most crops, including hay crops, are grown under irrigation. Irrigated energy crops will never compete economically with high-value irrigated crops, such as fruits and vegetables, but may be able to compete with lower valued crops such as hay and small grains. One potential energy crop species for irrigation in the western United States is switchgrass (*Panicum virgatum*) (Fransen, 2009). It is a C plant, and as such has higher water use efficiency than C3 plants such as wheat. It is native to many western states except for the Pacific Coast states.

An arena where energy crops may be able to utilize water in the West, without competing with food crops is to utilize water that cannot be used for crops for human consumption, such as from treated sewage waste, food processing, and mining and other industries. Significant quantities of produced water are extracted with the oil, gas, and coalbed methane. Produced water can range from being nearly fresh to being hypersaline brine. There are opportunities to improve the quality through treatment or use the better quality water for synergistic energy co-production (U.S. Department of Energy, 2006). Some of the produced water could be used in feedstock production, especially as new fossil-related extraction systems are developed that use less recycled water in enhanced recovery. In Wyoming, a coal bed methane well produces about 15,000 gallons (0.046 acre-feet) of wastewater per day. This may result in over a million acre-feet of wastewater produced per year in Wyoming. In California, 240,000 acre-feet of municipal waste water was used for agriculture in 2003. There is a goal of utilizing an additional 1 million acre-feet by 2020 and 2 million acre-feet over 2002 levels by 2030. Energy crops may be able to utilize marginal lands, including saline-affected land. In addition to the issue of water use, there is the issue of land competition. In California, 200,000 to 300,000 acres are classified as saline.

For high-valued crops, it may not be desirable to grow these crops 2 years in a row on the same land. While energy crops will not displace high valued crops, there may be opportunities to rotate some annual energy crops with some high-valued crops. Large irrigated acreages in the West are devoted to traditional agronomic crops (e.g. small grains, oilseeds, and forages) that often have low profit margins for the grower. For example, in California, low-value crops are grown on 5.5 out of 9 million acres. There may be opportunities to integrate energy crops into forage/grain/oilseed/sugar crop rotations. Some grasses may be able to produce biomass under limited irrigation, when other traditional crops might not produce a product (e.g. feed suitable for livestock feed). Grasses response to limited irrigation is species specific. Of course, the decision by producers as how to utilize their land and water will be market- and value-based.

Because irrigated lands can be highly productive, land rents are high (e.g. can be $200 per acre in the Columbia basin). This requires high yield from energy crops. For switchgrass, a yield of 11 dry tons per acre is achievable in the Columbia Basin. Water can cost $15 to $50 per acre plus costs for repairs, labor, and energy. Total irrigation costs can be in the range of $120 to 140 per acre. Presupposing the availability of water, profitable and competitive energy crop production requires high yields to offset irrigation costs.

[51] Corn grain yields have risen at an average annual increase of 1.7 bushels per acre even while fertilizer inputs have declined (Dobermann et al., 2002).

5.1.2 Giant Miscanthus – *Miscanthus x giganteus*

High levels of biomass production shown in U.S. studies are a major reason that *Miscanthus x giganteus* (Greef & Deuter ex Hodkinson & Renvoize; hereafter referred to as *Mxg* or Giant Miscanthus) is an attractive feedstock (Figure 5.3). *Mxg* also exhibits many other characteristics that allow it to meet or exceed the criteria for desirable biomass crops. As a perennial, it typically requires fewer yearly agronomic inputs than annual row crops. After establishment, time spent in the field is usually limited to a single annual harvest. In some years, in some locations, additional field time may be spent applying fertilizer, but applications have neither been shown to be required every year, nor in every location. For example, Christian et al. (2008) reported no yield response to nitrogen applications to a 14-year-old stand in England, while Ercoli et al. (1999) did see a nitrogen response when nitrogen was applied to *Mxg* in Italy. Thus, *Mxg* crops have not needed annual planting, pest controls, or fertilization in ongoing studies. Its perennial growth also controls soil erosion. As it becomes established and grows, *Mxg* develops an extensive layer of rhizomes and mass of fibrous roots that can hold soil in place. Finally, the belowground growth can contribute soil organic carbon levels as shown in Germany (Schneckenberger and Kuzyakov, 2007) and Denmark (Foereid et al., 2004).

Biology and adaptation. Giant Miscanthus is a sterile triploid hybrid resulting from the cross of the diploid *M. sinensis* and tetraploid *M. sacchariflorus* (Scally et al., 2001). Originally discovered in Japan, *Mxg* was thereafter introduced into the United States as a landscape plant (Scally et al., 2001).

M. sinensis and *M. sacchariflorus* are native to regions in eastern Asia with overlapping ranges in the same areas of Japan (Stewart et al., 2009). There are several forms of *M. sinensis* and the species can be found in mountainous areas, mid-level grasslands, and in low-lying waste areas (Clifton-Brown et al., 2008). It is usually a rhizomatous clump-former of variable size that spreads by seed. *M. sacchariflorus* is a vigorously rhizomatous species that can spread both by seed and

Figure 5.3 Miscanthus growth in August

(Courtesy of the University of Illinois) by rhizomes and is often found on the margins of rivers or marshes (Barkworth et al., 2007). It has escaped cultivation and individual clumps can cover more than 20–32 square feet in escaped roadside settings.

The *Mxg* clone used in University of Illinois feedstock research originated from rhizomes obtained from the Chicago Botanic Gardens in 1988 and has been part of a landscape demonstration planting at the University since that time (Pyter et al., 2009). In addition to this common landscape clone, there are now other Giant Miscanthus types being developed and marketed specifically for biomass production. For example, 'Freedom' Giant Miscanthus was developed at Mississippi State University and is being produced for commercial planting by SunBelt Biofuels of Soperton, Georgia. Cantus Bio Power Ltd. of North Leamington, Ontario and Vancouver, British Columbia, Canada lists 'Amuri' Giant Miscanthus and 'Nagara' Giant Miscanthus as very cold-tolerant, high-yielding grasses. Both Mendel Biotechnology, Inc. of Hayward, California, and Ceres, Inc. of Thousand Oaks, California, have included feedstock types of *Miscanthus* spp. as part of their research activities.

Also of importance is the fact that *Mxg* grows efficiently in a variety of settings. Established *Mxg* stands have survived air temperatures of -20°F in Illinois (Pyter et al., 2009). The temperature for optimum photosynthesis is 86°F (Naidu et al., 2003; Naidu and Long, 2004), but it has the ability to photosynthesize at temperatures as low as 47°F (Naidu et al., 2003; Farage et al., 2006). While both are C4 grasses, *Mxg* produced 61% more biomass than maize in an Illinois study (Dohleman and Long, 2009) even though maize has a higher photosynthesis rate in midsummer. This was due to the ability of *Mxg* to begin growing earlier in the growing season and continue later in the season.

Established plants have exhibited tolerance to summer drought. While substantial water is necessary for high yields (Beale et al., 1999), soils—given adequate moisture—have not shown to effect *Mxg* biomass production (Pyter et al., 2009), but have affected establishment rates. In fertile soils, establishment is usually 2 to 3 years, while it may take 3 to 5 years in less fertile sites (Pyter et al., 2009).

Production and agronomics. In Illinois, new shoots emerge from scaly underground stems (rhizomes) in April, and the grass grows to approximately 6.6 feet by the end of May (Pyter et al., 2007). Growth continues through summer into autumn with sterile flowers emerging in late September, and it goes dormant with the onset of killing frosts, usually in October after it has reached approximately 13 feet (Pyter et al., 2007). With the onset of freezing temperatures, leaves drop and minerals are returned to the belowground portions of the plant. The senesced stems are harvested from mid-December through late March; however, the standing biomass can be harvested before a killing frost if necessary.

In established *Mxg* plantings, there are approximately 5 to 10 shoots per square foot (Pyter et al., 2009). Harvestable stems resemble bamboo and are usually 0.5 to 0.78 inches in diameter and approximately 9.5 feet long (Pyter et al., 2009). Given that the original University of Illinois demonstration plot was planted in the late 1980s and has continued to produce large amounts of biomass for the past 20+ growing seasons, it is anticipated that commercial plantings of *Mxg* will provide good yields for at least 10 to 15 years

A major drawback to *Mxg* is increasing the planting stock. Because it is sterile, seed propagation is not an option, and *Mxg* is typically propagated by tissue culture, plugs, or by rhizome division. In Europe, tissue culture-produced plants were more expensive and less winter hardy during the initial growing season than rhizome-produced plants (Lewandowski, 1998). Thus, tissue culture has not been widely used to propagate large numbers of *Mxg* in Europe, nor in the United States.

Rhizome propagation entails digging dormant root-rhizome (underground stem) clumps, separating the rhizomes into smaller pieces, and replanting the newly divided rhizomes. Healthy, 1- or 2-year plants work well for propagation. In central Illinois, a 1-year plant usually yields 7 to 10 rhizomes and a 2-year plant normally yields 25 or more usable rhizomes (Pyter et al., 2009). Thus, 2 years after planting, an acre of well-tended *Mxg* can produce enough rhizomes to plant 25 or more acres. An acceptable planting rate is 4,250 rhizomes per acre (Pyter et al., 2009). A planting depth of 4.0 inches is recommended (Pyter et al., 2010) for both propagation and final planting. There are ongoing efforts to develop seed sources because of the high cost of vegetative propagation. These would be crosses of various varieties. The costs are expected to be significantly lower, as much as half and even more over time.

Lastly, there appears to be little or no insect or disease pest problems associated with *Mxg*. There have been no reports of pests in commercial plantings in Europe. In the United States, however, several aphids (Bradshaw et al., 2010) have been reported recently and *Mxg* may be a site of oviposition and emergence for the western corn rootworm, a major pest of corn in the Midwest (Spencer and Raghu, 2009). Also, a leaf spot disease (Ahonsi et al., 2010) has been reported on *Mxg* plantings in Kentucky. It remains to be seen if these recently identified pests develop into commercial problems.

Harvesting *Mxg* biomass usually begins after the grass is fully senesced and should be completed prior to the onset of spring growth (Pyter et al., 2009). There is not enough first-year growth to warrant harvesting, and second-year crops usually deliver yields of about half of fully established plantings. In quality soils, established *Mxg* in the third and subsequent years usually reaches plateau yields.Several commercial manufacturers are evaluating and developing equipment specifically designed to harvest and handle *Mxg* biomass, but at present, hay mowers, conditioners, and balers are used. In Illinois production, hay equipment from several different manufacturers has worked well, but slowly, due to stem toughness and density. There is a need for specialized harvesting equipment that can handle *Mxg* more efficiently than commercial hay equipment.

Potential yield and production costs. European study (Lewandowski et al., 2000) of 3-year-old and older stands from 19 variously distributed sites reported that dry-matter yields of spring-harvested *Mxg* ranged from 1.8 to 15.2 tons per acre. The lowest reported yield was obtained from Central Germany (50–52° N)—the site is similar latitude of Saskatoon, Saskatchewan. The highest yield was from northwest Spain (43° N) at 15.2 dry tons per acre, latitude similar to Saginaw, Michigan. This high-yielding site was fertilized with nitrogen, although there was no fertilizer effect. Another European site with a high yield was in Southern Italy (37° N – 15.2 tons per acre). This site's latitude is similar to that of Lexington, Kentucky.

Plot yields in 2004, 2005, and 2006 at three Illinois sites have varied depending on the latitude and weather during the growing season. In replicated studies of unfertilized *Mxg* planted in 2002 using small potted plants, the average hand-harvested yields over the 2004, 2005, and 2006 growing seasons were 9.8 tons per acre in northern Illinois (latitude 41.85N), 15.4 tons per acre in central Illinois (latitude 40.12N), and 15.5 tons per acre in southern Illinois (latitude 37.45) (Pyter et al., 2007). In the same 3-year period, yields for unfertilized upland switchgrass, 'Cave in Rock', seeded in 2002 were 2.2, 5.2, and 2.7 tons per acre at the same northern, central, and southern Illinois sites, respectively. A separate demonstration plot in Urbana, Illinois, yielded approximately 14.1 tons per acre of dry *Mxg* biomass in 2006 at the end of the third growing season (Pyter et al., 2007). Based on average yields of 13.2 tons per acre, it would require approximately 31.2 million acres of *Mxg* to produce 35 billion gallons of ethanol in the United States, compared to 83.5 million acres of switchgrass producing 4.6 tons per acre (Heaton et al., 2008).[52]

Figure 5.4 Harvesting miscanthus

(Courtesy of the discoversolarenergy.com)

[52] Assuming an ethanol yield of about 85 gallons per dry ton (U.S. Department of Energy, 2011).

Mxg yield data were collected after 2 years at the DOE/Sun Grant Herbaceous Partnership sites in Kentucky, Nebraska, and New Jersey (Table 5.2). The plots at these sites receive 0, 54, and 107 pounds of nitrogen per acre. Second-year biomass yields increased at the New Jersey site with fertilization, but it did not increase yields in Kentucky or Nebraska. In fact, Nebraska yields of *Mxg* went down with increasing nitrogen levels. Further analysis will likely reveal that the differences were the result of native soil fertility or climate differences. These yields are impressive given that yields usually increase until the grass is fully established, which takes 3 to 5 years (Lewandowski et al., 2000).

Table 5.2 2009 (Second-Year) *Miscanthus x giganteus* Biomass Yields (Tons per Acre)

Nitrogen Fertilization	Lexington, KY	Mead, NE	Adelphia, NJ
0 lbs/acre	7.5	7.1	4.9
54 lbs/acre	7.8	6.9	6.6
107 lbs/acre	7.5	6.5	6.4

Developing a crop of *Mxg* will likely be expensive. Jain et al. (2010) estimates a cost of $1,197 to establish an acre of *Mxg* planting rhizomes at a rate of 4,000 rhizomes per acre in Illinois. Following establishment, Lewandowski et al. (2000) estimated the annual breakeven cost of producing *Mxg* in Denmark to be approximately $85 per ton (based on an exchange rate of $1.35 per Euro). In 2008, Khanna and others estimated the annual breakeven farm-gate price to produce *Mxg* to be between $37 and $52 per ton in the United States. Finally, Jain et al. (2010) most recently estimates the annual breakeven cost to produce *Mxg* to be between $46 per ton in Missouri and $139 per ton in Minnesota.

Future plantings may involve a seeded option closer to the establishment costs of grasses. Miscanthus from seed may reach maturity in the second year and have a higher yield because of higher plant density. Finally, because the variety is fertile (as opposed to the sterile rhizomes), risk of invasion would need to be managed if planted on any scale.

Sustainability. Most investigations of *Mxg* grown as a biomass feedstock have been positive because it is a long-lived perennial, produces high biomass yields, and has been shown to require minimal inputs in some studies. In fact, Heaton et al. (2004) summarized that *Mxg* stores carbon in the soil, has low fertilizer requirements, high water-use efficiency, dries in the field, and has the ability to stand in the field during winter prior to harvest. While these positive attributes make *Mxg* an attractive feedstock, there are concerns about the invasiveness of *Mxg* and other Miscanthus species. A search of the literature revealed no substantiated settings where *Mxg* has been invasive. Other types of Miscanthus, including the parents of *Mxg*, have been reported to be invasive. Czarapata (2005) lists *M. sinensis* as a lesser invader of natural grasslands and prairies in the northeastern, southeastern, and eastern Midwest and Kaufman and Kaufman (2007) indicate that it will take over in roadsides and burned pastures in areas of the United States where soils are naturally moist. The Minnesota Department of Natural Resources (2009) has identified *M. sacchariflorus* to be invasive in moist areas of the upper Northeast and Midwest, where it can be found in roadsides and openings or edges of wooded areas.

Conclusions. *Miscanthus x giganteus* is receiving much attention as a potential biomass crop. In Europe, work using the grass as a feedstock began in the 1980s. While a great deal of research has been conducted recently, there are still barriers to commercial production. For example, developing low-cost, reliable, commercial-scale propagation methods are critical to developing the crop. Identifying the genotypes best suited to a given region is also critical. Gaining a better understanding of the relationships between the grass and mineral fertilization and the grass and pests and pest controls is also necessary. Finally, developing efficient harvesting methods and equipment will be necessary to remove the crop from the fields and into storage in a low-cost, timely fashion (Figure 5.4).

Mechanical equipment is becoming available that will plant more than 25 acres per day. Improvements in *Mxg* genetics, agronomy, and harvesting are also coming quickly. Long-term production from a single planting, modest-input requirements, and carbon capture, coupled with realistic commercial biomass yields of 9 to 16 tons per acre per year, makes *Miscanthus x giganteus* a candidate feedstock for addressing the U.S. renewable bioenergy demand.

5.1.3 Sugarcane

Sugarcane is a large-stature, jointed grass that is cultivated as a perennial row crop, primarily for its ability to store sucrose in the stem, in approximately 80 countries in tropical, semi-tropical, and sub- tropical regions of the world (Tew, 2003). It is one of the most efficient C4 grasses in the world, with an estimated energy in: energy out (I/O) ratio of 1:8 when grown for 12 months under tropical conditions and processed for ethanol instead of sugar (Bourne, 2007; Macedo et al., 2004; Muchow et al., 1996). Under more temperate environments, where temperature and sunlight are limited, I/O ratios of 1:3 are easily obtainable with current sugarcane cultivars if ethanol production from both sugar and cellulosic biomass is the goal (Tew and Cobill, 2008). In addition, sugarcane ethanol cuts GHGs at least 60% compared to gasoline—better than any other biofuel produced today. EPA has confirmed sugarcane ethanol's superior environmental performance by designating it as an advanced renewable fuel. Most of the sugarcane grown in the United States is dedicated to the production of sugar. As an energy cane industry has not developed to date, one can assume that the production practices of the mature sugarcane industry can be modified to ensure the sustainable production of energy cane as well.

Biology and adaptation. Sugarcane (*Saccharum* spp.) is a genetically complex crop with a genomic makeup that results from successful interspecific hybridization efforts, primarily involving *S. officinarum* and *S. spontaneum* (Tew and Cobill, 2008). Improvement of sugarcane for increased energy efficiency and adaptability to a wide range of environments is considered by many geneticists as synonymous with "genetic base broadening" (i.e., utilization of wild Saccharum germplasm), particularly *S. spontaneum* in sugarcane breeding programs (Ming et al., 2006). *S. spontaneum*, considered a noxious weed in the United States, can be found in the continents of Africa, Asia, and Australia in environments ranging from the equator to the foothills of the Himalayas. This makes it an excellent source of a number of valuable genes (Mukherjee, 1950; Panje and Babu, 1960; Panje, 1972; and Roach, 1978). The USDA-ARS's Sugarcane Research Unit (SRU) at Houma, Louisiana, in the 1960s took on the role of introgressing desirable genes from sugarcane's wild and near relatives (Miscanthus and Erianthus) to build new parents for utilization in its commercial sugarcane varietal development program in what is referred to as the SRU's basic component of its breeding program. Because these wild accessions contain only small amounts of sugar, three or four rounds of backcrossing to elite sugarcane varieties must be done to obtain a commercially acceptable sugarcane variety, which has high-sugar yields with minimum amounts of fiber.

Production and agronomics. Sugarcane is grown as a monoculture with fields being replanted every 4 or 5 years. This type of culture is conducive to the development of perennial weeds like johnsongrass and bermudagrass, since the row top (i.e., raised bed) remains relatively undisturbed for the 5-year crop cycle. The selective control of these weeds within the crop is difficult with currently registered herbicides once these weeds produce rhizomes. To minimize this risk, growers disk the old stubble fields in the winter or early spring and fallow the fields until they are planted to sugarcane again. Frequent disking and/or the use of multiple applications of glyphosate are used to deplete the soil of weed seed and rhizomes during the fallow period.

Sugarcane is vegetatively planted by laying 6- to 8-foot long stalks end-to-end in a planting furrow along rows spaced 5 to 6 feet apart and covering the stalks with 2 to 4 inches of soil. The wide row spacing is needed to accommodate mechanical harvesting. One acre of seedcane can plant 6 to 10 acres of sugarcane, depending on the length and number of stalks at the time of harvesting the "seedcane" for planting, and the number of stalks per foot of row being planted. When

Figure 5.5 Energy cane research plots

(Courtesy of Ed Richard, USDA-ARS)

harvesting seedcane for planting, stalks are cut at the soil surface and at the last mature node at the top of the stem. An alternate method of planting is to plant 12- to 18-inch stalk pieces (billets) that can be harvested with the same chopper harvester used to harvest sugarcane for delivery to sugar mills. Once the stalks are planted, a broad spectrum preemergence herbicide is applied to control seedling weeds. New plants emerge from the axillary buds located in the nodal regions along the stalk. Growers produce most of their own seed cane for planting; hence, planting is generally done a few weeks prior to the beginning of the harvest season to ensure that stalks are plentiful and tall (Figure 5.5).

Vegetative planting of sugarcane is often considered a drawback by growers who are accustomed to planting large areas of seeded crops relatively quickly with one tractor and one planter. It is an expensive process as it requires considerable labor and equipment, is relatively slow, and requires that the grower plant sugarcane that would normally be sent to the raw sugar factory for processing. However, with energy cane, 20% to 30% higher planting ratios can be expected, because stalk numbers and heights are higher. In addition, at least two additional harvests per planting can be expected, significantly lowering the number of acres requiring planting each year. It is estimated that the cost to plant one acre of sugarcane is about $500 when the grower uses seedcane from the farm. Because planting costs are spread over four annual harvests, the annual cost would be approximately $125 per acre. With energy cane, one acre of seedcane would plant about 13 additional acres reducing per acre planting costs to $346. If spread over the anticipated six annual fall harvests, annual planting costs would be $58 per acre.

Vegetative planting also has advantages, especially when planting must be done under conditions of less than ideal seedbed preparation. The crop emerges 14 to 21 days later and continues to grow until the first heavy frost of the fall. The first production year (plant-cane crop) actually begins in the spring following planting with the emergence of the crop from winter dormancy. Herbicides are applied each spring to the subsequent ratoon crops (first- through third-ratoon crop) to minimize early weed competition. Nitrogen is applied at rates of 70 to 90 pounds per acre to the plant-cane crop (first growing season) and 90 to 120 pounds per acre to the subsequent ratoon crops. These applications are generally made in the spring about two months into the growing season.

The crop is susceptible to the rapid spread of a number of bacterial, fungal, and viral pathogens that can be spread easily by machinery and wind currents. These pathogens can affect the yield and ratooning ability (number of yearly harvests per planting) of the crop. Race changes of some of these pathogens are common and the industry is always susceptible to new diseases. Insects, primarily stalk borers, grubs, and aphids also plague the industry. The compactness of the industry and the fact that the crop is grown continuously as a monoculture makes sugarcane especially vulnerable to the rapid spread of diseases and insects. The planting of resistant varieties is the predominant means of managing diseases in sugarcane. For insects, mainly stalk borer, an effective integrated pest management program that involves field scouting, the use of tolerant varieties, and insecticides when established infestation thresholds are exceeded, is used. Additional research is exploring the use of multiple crop-production systems for year-round delivery of feedstocks and to respond to biotic stresses (McCutchen and Avant, 2008).

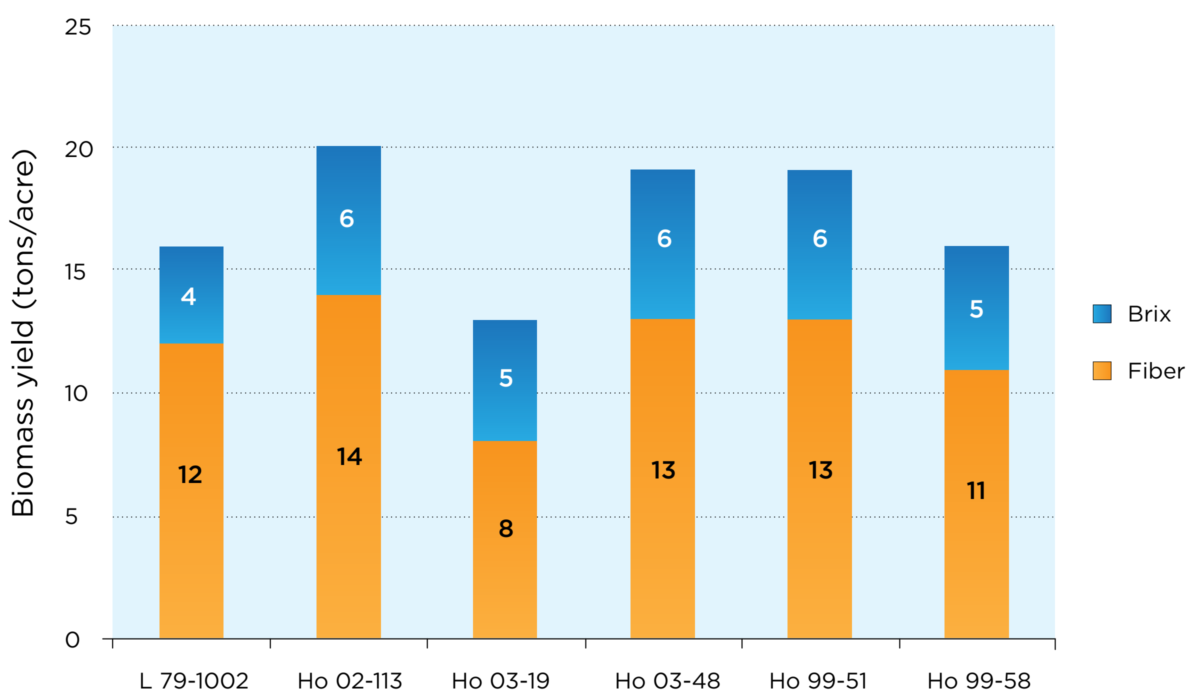
With each successive fall harvest during the crop cycle, yields tend to decline to the point that it is not practical to keep the old stubble for another year. The milling season in the more sub-tropical climates, like Louisiana, lasts about 100 days beginning in late October and ending in late December or early January. Given that the crop emergence in the spring depends on the date of the last killing frost, it is obvious that sugarcane harvested in December will produce higher yields than sugarcane harvested in September. For this reason growers try to have a balance in ratoon crop ages from 0 (plant cane that was never harvested) to 3 (third ratoon that was harvested three times previously) and begin the harvest with the third-ratoon fields that would lack the vigor of the plant-cane crop. In addition, early harvested crops tend not to yield as much the following year. A similar scenario is anticipated for energy cane with the exception that fourth- and fifth- ratoon crops would also be harvested.

In Louisiana, some energy cane varieties have produced average yields of 56 green tons per acre, with 8 to 14 tons per acre being fiber and 4 to 6 tons per acre being brix (soluble sugars) on a dry weight basis (see Figure 5.6).

Potential yields and production costs. The theoretical maximum for aboveground sugarcane biomass (total solids) yield is estimated to be 62 green tons per acre annually (Loomis and Williams, 1963). This is dependent on temperature and sunlight, and would probably occur under tropical conditions. Sugarcane breeding programs have reported sugar yield gains in the order of 1% to 2% per year (Edme et al., 2005). The economic sustainability of growing energy cane in non-traditional cane growing regions will require yearly biomass yield gains of this magnitude or greater, with a goal of ensuring that the I/O ratio of 1:8 projected for tropical countries can be met and ultimately exceeded under the sub-tropical cane growing conditions of the southeastern United States.

The "sun-dried crop" concept of allowing the crop to desiccate in the field and perhaps devoid itself of some of its leaves and moisture, as is proposed for many of the perennial grasses being considered for biofuels, is not an option for energy cane as the stalks are thick with a waxy coating on them and the new growing season should begin as soon after

Figure 5.6 Average yields from four successive fall harvests of several candidate sugarcane varieties as compared to the standard variety, L 79–1002



(Courtesy of Ed Richard, USDA-ARS)

Figure 5.7 Harvesting sugarcane

(Courtesy of Ed Richard, USDA-ARS)

harvest as possible. Consequently, energy cane, like sugarcane, will have to be harvested green and dewatered if the fiber is to be stored and processed later in the year. The value of this liquid is in question because it will add to transportation costs. However, if water is needed for the digestion of the fiber or the maintenance of the bagasse under anaerobic conditions to minimize deterioration during outside storage, it would be present at no additional charge. What is also overlooked is the fact that the water contains sugar that is easily and much more cheaply converted to ethanol. Furthermore, in some conversion processes the yeast used in fermentation needs a substrate to grow and multiply on, and sucrose is an ideal substrate. Conceivably the biorefinery would have two processes for the production of biofuel, with one having sugar (brix) obtained from de-watering at the biorefinery as the feedstock and the other the fiber (bagasse). Economics would have to be considered with these options especially because of the very short cut-crush interval needed for sugar recovery and to prevent spoilage.

Sustainability. Green cane harvesting of sugarcane deposits 2.7 to 3.6 tons per acre of a mixture of brown and green leafy material and fragments of the stalks (Richard, 1999; Viator et al., 2006; 2009a;b). The fibrous extraneous matter generated during harvest has an energy value; however, the greatest value may be as mulch to: limit soil erosion, depress weed development, conserve moisture, and as a means to recycle nutrients. All are potential contributors to the sustainable production of energy cane (de Resende et al., 2006). It is estimated that the extraneous residue generated during the green cane harvesting of sugarcane contains 0.7% of N, 0.07% of phosporous, and 0.7% of potassium by weight. Using 2009 USDA economic data (USDA-ERS 2010b), 2.7 tons of residues would equate to a savings of approximately $50 per acre.

The critical amount of post-harvest residue that can be removed from the field has not been determined for energy cane. Sugarcane is harvested mechanically with a chopper harvester (Figure 5.7). These harvesters chop the sugarcane stalks into small 6- to 8-inch long pieces (billets) and use wind currents from an extractor fan to remove the leaves attached to the stalks. If used to harvest energy cane, the speed of the extractor fans could be adjusted to deposit a percentage of the extraneous matter on the soil surface while the remainder is collected with the stalks and used as an additional source of fiber.

Production cost estimates are complicated by the first-year production of seedcane crop and the number of ratoon crops before re-establishment. For example, different costs are associated with fallow field and seedbed preparation, seedcane planting and harvest, plant cane, and ratoon operations and harvest over multiple years (Salassi and Deliberto, 2011). Using the most common sugarcane assumptions from the production costs from Salassi and Deliberto, an extrapolated cost to produce and harvest the energy cane is estimated to be about $34 per dry ton. The assumed yield is about 14 dry tons per acre.

Energy cane will be grown as a perennial. Commonly discussed disadvantages of perennial feedstocks include the difficulty of establishing a perennial crop from seed and rhizomes, the control of weeds during the establishment period, and the fact that an economic return will not be realized the first year. Energy cane, like sugarcane, is vegetatively planted by placing the stalks in a planting furrow in mid- to late summer. Herbicides are labeled for at-planting preemergence applications in sugarcane; presumably, these herbicides can also be applied to energy cane with similar results. These herbicides are reapplied each spring during the course of a 3- to 4-year sugarcane production cycle. Because of the vigor (e.g., early spring emergence and high stalk population) of energy cane, use of these herbicides beyond the first spring after planting is not anticipated. The vigor of energy cane is also advantageous due to the fact that when the crop is planted in the summer, it emerges and produces a uniform stand quickly. The crop continues to grow until the aboveground portion is winter-killed in the fall. This aboveground material, which can equate to 2 to 4 dry tons per acre, could be harvested and converted to fuel in the first year of establishment.

The final consideration in the sustainability of energy cane production is the utilization of biorefinery byproducts to supply nutrients and reduce the impact of crop removal on soil health. These byproducts can include vinasse from the fermentation process, biochar from pyrolysis, and filter press mud and boiler fly ash from the squeezing of stalks. A positive synergistic response was observed when the application of fertilizer was combined with an application of filter press mud in Florida (Gilbert et al., 2008). In Brazil, vinasse from the ethanol distillery is typically returned to the recently harvested fields to supplement fertilizer requirements.

Conclusions. Looking to the future, the greatest needs to make energy cane a suitable feedstock for the cellulosic industry and extend its range of geographic distribution outside of the traditional sugarcane growing areas are cold tolerance for expansion outside of tropical areas; drought and flood (saturated soil) tolerance, as this crop will probably be grown on marginal soils that may be prone to flooding or where irrigation is difficult; insect and disease resistance; and a further exploitation of some varieties of sugarcane that encourages symbiotic relationships with nitrogen fixing bacteria.

The success of the sugarcane industry has been, and continues to be, dependent on the development of new hybrids with superior yields and increased resistance to many of the abiotic and biotic stresses previously mentioned. This formula will not change if the crop is grown as a dedicated feedstock for the production of liquid biofuels or electricity. Successful hybridization begins with the introgression of desirable traits from the wild relative of sugarcane, *Saccharum spontaneum*. Early generation progeny from these crosses with elite sugarcane clones exhibit high levels of hybrid vigor, which translates into increased cold tolerance, greater ratooning ability, enhanced levels of tolerance to moisture extremes, increased insect and disease tolerance, and more efficient nutrient utilization (Legendre and Burner, 1995). Much of the vigor of these early generation hybrids is lost in a conventional breeding program for sugar, as progeny from these crosses must be backcrossed with elite high-sugar-producing clones three to four times before a commercial sugarcane variety can be produced. These early generation hybrids would be considered ideal candidates as dedicated cellulosic biomass crops like energy canes. Most of these varieties can average over 15 dry tons per acre annually over at least four annual fall harvests.

By enhancing the level of stress tolerance through the conventional breeding techniques being employed by the basic breeding program of the USDA-ARS SRU, the geographic area of distribution could be expanded to more temperate regions of the United States to include those states in Hardiness Zone 8 (regions within Texas, Louisiana, Arkansas, Mississippi, Alabama, Georgia, South Carolina, North Carolina) and perhaps the extreme southern end of Hardiness Zone 7 (regions within Oklahoma, Tennessee, Virginia), where the annual low winter temperatures can approach 1º F. With this in mind, it is conceivable that the area devoted to this crop could be tripled, thus making it a more attractive feedstock for biotech companies with proprietary genes to further enhance the level of stress tolerance, or introducing genes for the production of saleable byproducts without the labeling restrictions encountered in food crops.

5.1.4 Sorghum

Of the crops recently identified for their potential bioenergy production, sorghum (Sorghum bicolor) has historically had the most direct influence on human development (Figure 5.8). Sorghum was domesticated in arid areas of northeastern Africa over 6,000 years ago (Kimber, 2000). Sorghum is traditionally known for grain production; it is the fifth most widely grown and produced cereal crop in the world (FAO, 2007). However, in many regions of the world, sorghum is just as (if not more) important as a forage crop. In addition to forage and grain, sorghum types high in stalk sugar content and extremely lignified types (for structural building) have been grown throughout the world.

Given the demands for renewable fuel feedstocks, sorghum is now being developed as a dedicated bioenergy crop. This designation is not new; sorghum was mentioned prominently as a bioenergy crop over 20 years ago (Burton, 1986). The interest in the crop is justifiable based on several independent factors that separately indicate good potential, but when combined, they clearly designate sorghum as a logical choice for bioenergy production. These factors include yield potential and composition, water-use efficiency and drought tolerance, established production systems, and the potential for genetic improvement by using both traditional and genomic approaches.

Biology and adaptation. Whether measured in grain yield or total biomass yield, sorghum is a highly productive C4 photosynthetic species that is well adapted to warm and dry growing regions. While sorghum is technically a perennial in tropical environments, it is planted from seed, then grown and managed as an annual crop. Sorghum has a long-established breeding history through which the productivity, adaptation, and utilization of the crop has continually been improved. These efforts have resulted in numerous cultivars and hybrids of sorghum that are used for various purposes.

The optimum type of sorghum to be grown for biofuels production is dependent on the type of conversion process that will be used. Sorghums are divided into distinct types based on the amount of different carbohydrates they produce.

Figure 5.8 Sorghum hybrid tests

(Courtesy of W. Rooney, Texas A&M University)

Grain sorghum hybrids produce large quantities of grain (approximately 50% of total biomass); the grain is composed primarily of starch (approximately 75%) and may be used as a food grain, feed grain, or ethanol substrate via starch hydrolysis and fermentation. If mechanically harvested, these hybrids are usually less than 2 meters tall. Residue is typically returned to the soil, but it is used as forage under drought conditions, and it could be used as a biomass feedstock as well.

Forage sorghums are usually one of two types. Sorghum-sudangrass hybrids are tall, leafy, thin-stalked hybrids used for grazing or hay production. Silage-sorghum hybrids are typically taller and thicker-stalked with high grain yield (25% of total biomass), and they are chopped and ensiled for animal feeding (Figure 5.8). Both of these types of sorghum have been highly selected for optimum forage production, palatability, and conversion in an animal system. There have been significant breeding efforts to enhance the forage quality of this material by incorporating the brown midrib trait into many forage hybrids. These brown-midrib hybrids have lower lignin and are more palatable, which increases conversion efficiency and consumption rate in ruminant feeding programs (Aydin et al., 1999; Oliver et al., 2004). These types may have application in certain energy sorghum applications where lower lignin content is desirable.

Sweet sorghum is a unique type of sorghum that accumulates high concentrations of soluble sugars. Traditionally, these sorghums were grown for the stalk, which was milled to extract the juice. The juice was then cooked down, and the resulting syrup was used as sweetener. While these types of sorghum continue to be grown for syrup on an artisan level, there has been significant interest in the development of sweet sorghum as a dedicated bioenergy crop using a sugarcane system model. In the mid-1970s, significant research was conducted to explore the development of sweet sorghum as a bioenergy source for biofuels and energy production, and breeding programs were initiated to develop high-yielding sorghum specifically for ethanol production (McBee et al., 1987).

Dedicated biomass sorghums are the most recent class of sorghum that has been developed in response to the interest in bioenergy crops. These sorghums are highly photoperiod sensitive, meaning that they do not initiate reproductive growth until well into the fall season of the year. Consequently, in temperate environments like most of the United States, these sorghums will not mature. This absence of reproductive growth reduces sensitivity to periods of drought and allows the crop to effectively photosynthesize throughout the entire growing season. This results in higher yields of primarily lignocellulosic biomass that is completed in a single annual season. While phenotypically similar to forage sorghums, these biomass sorghums are distinctly different in that they are not selected for animal palatability, which results in plants with larger culms and flexible harvest schedules, which minimizes nitrogen extraction at the end of the season.

Production and agronomics. Biomass yield potential of sorghum is strongly influenced by both genetic and environmental factors. For example, grain sorghum is commonly grown in more arid regions of the country, and the plant itself is genetically designed to be shorter to facilitate mechanical harvesting. Alternatively, specific dedicated biomass sorghums are very efficient at producing large amounts of lignocellulosic biomass. Finally, both sweet sorghum and forage sorghum are prolific when the environmental conditions allow the plants to reach full genetic potential. Hallam et al. (2001) compared perennial grasses with annual row crops and found that sweet sorghum had the highest yield potential, averaging over 15.6 tons per acre (dry weight basis) and also performing well when intercropping with legume species. Rooney et al. (2007) reported biomass yield of energy sorghum in excess of 44.6 tons per acre (fresh weight) and 13.4 tons per acre (dry weight). They reported that potential improvements could extend the potential of these types of hybrids to a wide range of environments. Under irrigation in the Texas panhandle, McCollum et al. (2005) reported yield of commercial photoperiod sensitive sorghum hybrids as high as 36 tons per acre (65% moisture) from a single harvest. In subtropical and tropical conditions, single cut yields are generally lower, which is likely due to increased night temperatures, but cumulative yields are higher due to the ratoon potential of the crop. Total biomass yields as high as 13.4 tons per acre (dry weight basis) were reported near College Station, Texas (Blumenthal et al., 2007).

Composition of sorghum is highly dependent on the type that is produced, such as grain sorghum, sweet sorghum, forage, and cellulosic (high biomass) sorghum. Sorghum grain is high in starch, with lower levels of protein, fat, and ash (Rooney, 2004). Significant variation in the composition of grain is controlled by both genetic and environmental components, making consistency in composition a function of the environment at the time of production; consequently, these factors influence ethanol yield (Wu et al., 2007). Juice extracted from sweet sorghum is predominantly sucrose with variable levels of glucose and fructose, and in some genotypes, small amounts of starch are detectable (Clark, 1981; Billa et al., 1997). In forage and dedicated biomass sorghums, the predominant compounds that are produced are structural carbohydrates (lignin, cellulose, and hemicellulose) (McBee et al., 1987; Monk et al., 1984). Amaducci et al. (2004) reported that the environment influences sucrose, cellulose, and hemicellulose concentrations, while lignin content remains relatively constant.

Potential yield and production costs. Sorghum has a long history as a grain and forage crop, and production costs range from $200 to $320 per acre (USDA–ERS, 2010a). This history provides an excellent basis for estimating crop production costs for energy sorghums with a few modifications. Seed costs, planting costs, and production costs will be similar to grain and/or forage sorghum. Fertilizer rates will likely be less than forage sorghum on a production dry-ton basis (due to the reduced nitrogen content in the mature culm), but it is expected that yields will be higher, so total nitrogen requirements will be equalized. Production is expected under rain-fed conditions; therefore, no additional costs are added for irrigation. On a dry ton basis, given an average production of 10 dry tons per acre and assuming $400 per acre cost of production for dedicated biomass sorghums, biomass sorghum will cost $40 per dry ton at the farmgate.

Production practices for dedicated biomass and sweet sorghum are similar to traditional sorghum crops with some minor modifications. For both types of energy sorghums, it is expected that plant populations will be lowered relative to grain and certainly compared to forage sorghum. This drop will allow the plants to produce larger culms and reduce the potential for lodging and interplant competition. Pests and diseases of sorghum are well known and described, and there are some that will require management plans and effective deployment of host plant resistance for control. Of particular note is the disease anthracnose (caused by *Colletotrichum graminicola*), which is prevalent in the southeastern United States and is capable of killing susceptible sorghum genotypes. Fortunately, there are many sources of genetic resistance to the disease, and effective control relies on effective integration of these anthracnose resistance genes.

Harvesting and preprocessing of energy sorghums is an area of significant research and will likely require the greatest amount of modification compared to grain sorghum. Sweet sorghum will be harvested and moisture extracted for soluble sugars at a centralized location. For dedicated biomass sorghums, the forage harvest systems work very well, but there is a need to reduce moisture content to minimize transportation and storage costs.

The range of sorghum production varies with the type being produced. Both sweet sorghum and dedicated biomass sorghums grow well throughout the eastern and central United States as far north as 40° latitude, and the range of dedicated biomass sorghums is considered to be composed of most of the eastern and central United States. In the western United States, productivity will be directly related to available moisture from rainfall or irrigation. It is unlikely that the crop (or any crop) will be economically viable as a biomass crop in regions with less than 20 inches of available moisture annually. Dedicated biomass sorghums have shown yields of 7–13 dry tons per acre in the northern areas of the United States, with even higher yield potential possible in a southern environment due to the longer growing seasons. Therefore, dedicated biomass sorghum should find wide adaptation throughout most of the country that is suitable for herbaceous biomass production from an annual crop.

While sweet sorghum is productive at northern latitudes, the logistics of processing make the production of the crop unlikely in more temperate latitudes. Because soluble sugars are not stable for long periods, a processor requires a long harvest and processing window for effective use of capital equipment. The farther north the production, the shorter the growing season; hence, the harvest season is further reduced and the ability to consistently grow the high-yield potential sweet sorghum varieties is limited (Wortmann et al., 2010). Consequently, the areas of the United States that process sugarcane are also ideal locations for the production of sweet sorghum. Production in other regions will be dependent on detailed economic analysis of the cost of processing versus the length of the processing season.

Sustainability. Sorghum is unique among the dedicated bioenergy crops because it is an annual crop. The general opinion is that bioenergy crops should be perennial for sustainability purposes. While most of the bioenergy crops are perennial, there are several reasons why annual bioenergy crops are necessary. First, annual crops deliver large yields in the first year, as compared to most perennial crops, which typically increase annual yield in subsequent years following establishment. Given the challenges of propagating and establishing perennial crops, annual crops can provide insurance and production stability to industrial processors in the early phases of bringing a new processing facility online if perennial crop stand failures or establishment problems are encountered. Second, for the most part, the U.S. farming system has been based on annual crop production systems. Farmers, bankers, and processors are much more familiar and accepting of these systems, and while this will eventually be overcome, annual energy crops will be needed for that transition. Finally, annual crops are much more tractable to genetic improvements through breeding due to the simple fact that breeding is accelerated by multiple generations per year.

There are several traits of specific importance to sorghum improvement, as it relates to bioenergy production. These include, but are not limited to, maturity and height, drought tolerance, pest tolerance and/or resistance, and composition and/or quality. Improvements in these areas will increase yield potential, protect existing yield potential, and enhance conversion efficiency during processing.

While the reason for producing bioenergy feedstock is to produce renewable fuel, one of the critical components in their production will be water. Thus, both drought tolerance and water-use efficiency are critical, as many of these feedstocks will be produced in marginal environments where rainfall is limited and irrigation is either too expensive or would deplete water reserves. Sorghum is more drought tolerant than many other biomass crops. Depending on the type of biomass production in sorghum, both pre- and post-flowering drought tolerance mechanisms will be important. In sweet sorghum, both traits are important, but there has been little research regarding the impact of drought stress on sweet sorghum productivity.

For high-biomass, photoperiod-sensitive sorghums, preflowering drought tolerance is critical because, in most environments, this germplasm does not transition to the reproductive phase of growth. Each type of tolerance is associated with several phenotypic and physiological traits; these relationships have been used to fine map QTL (quantitative trait loci) associated with both pre- and post-flowering drought tolerance. Traits that have been associated with drought resistance include heat tolerance, osmotic adjustment (Basnayake et al., 1995), transpiration efficiency (Muchow et al., 1996), rooting depth and patterns (Jordan and Miller, 1980), epicuticular wax (Maiti et al., 1984), and stay green (Rosenow et al., 1983). Combining phenotypic and marker-assisted breeding approaches should enhance drought tolerance breeding in energy sorghums.

Unlike perennial bioenergy crops, sorghum will require crop rotation to maintain high yields and soil conditioning. Continuous cropping studies of sorghum have confirmed that yields will drop in subsequent years unless additional nitrogen is provided to maintain yields (Peterson and Varvel, 1989). Therefore, it is critical to consider rotations when accounting for potential land area needs in energy sorghum production. The exact rotation sequence and timeframe will vary with locale, but sorghum production once every 2 or 3 years will be acceptable in most regions. Failure to rotate may result in reduced yields and quality, as well as increased weed, insect, and disease problems. Research is needed to determine the appropriate rotation for energy sorghum in the target regions for production.

The molecular genetic resources available in the sorghum species are the most advanced among all of the potential energy crops. Combining these molecular genetic resources with traditional breeding approaches, it should be possible to rapidly develop and deploy improved, dedicated energy sorghum that meets the needs of both crop and biofuel producers.

Conclusions. Sorghum benefits from a long-established production history, existing research infrastructure, and a relatively simple genetic system. All of these factors allow for the rapid modification of the crop and delivery of specific sorghum types that are developed specifically for bioenergy and adapted to the target areas of production. The future of energy sorghum is based on development of energy-specific genotypes in which composition and productivity are optimized, while minimizing inputs like insecticide and fertilizer. In this scenario, resistance/tolerance to both biotic and abiotic stresses is critical. Fortunately, adequate genetic resources and technology are available to make these modifications in an efficient and timely manner. Composition and yield are obviously important, and continual enhancement of these factors will rely on the full use of genomic technology.

5.1.5 Poplar

The following section provides a brief description of the genus *Populus*, with attention to the biology, potential yield, production costs, and sustainability issues related to deploying an efficient, biomass-producing woody crop. Much more extensive information is available in other resources [e.g., Stettler et al. (1996) and Dickmann et al. (2001)].

Biology and adaptation. Today, the genus *Populus* includes almost 30 species and represents several taxonomic sections distributed throughout the northern hemisphere. Poplar species are an ancient and well-established component of the native North American landscape. Hybrids within and among species belonging to two sections, *Aigeiros* and *Tacamahaca* (cottonwoods), are commonly referred to as "hybrid poplars" (Figure 5.9).

Commercial deployment of hybrid cottonwood plantations for the production of fiber for paper and other products and biofuels and for the purpose of environmental remediation (e.g., phytoremediation) is a reality in many forested and agricultural landscapes, including those that lie within the temperate regions of the United States. Genotypes of eastern cottonwood (*P. deltoides* Bartr. ex Marsh) and hybrids between eastern cottonwood and Asian black poplar, European black poplar, and western black cottonwood (*P. suaveolens* Fish. subsp. maximowiczii A. Henry, *P. nigra* L., and *P. trichocarpa* Torr. & Gray, respectively) capable of producing in excess of 7 tons per acre per year by age 6-years have been identified by field tests, even in the harsh climate of the North Central region of the United States (Riemenschneider et al., 2001a; Zalesny et al., 2009).

The susceptibility of the cottonwoods to vegetative propagation was, and continues to be, in large part, a factor to their commercial value and domestication. One of the most economical means of plantation establishment is to plant dormant hardwood cuttings capable of developing adventitious roots (Heilman et al., 1994; Zalesny et al., 2005). As needed, rooted cuttings can be used to enhance survival. Thus , the vegetative propagation of poplars can confer significant genetic advantage during all stages of the breeding and selection strategy to an aggregate phenotype with high commercial utility and stability (Eriksson, 1991; Orlovic et al., 1998; Zalesny et al., 2005).

There are many possible breeding strategies that can be applied to the development of a hybrid poplar woody biomass crop (Riemenschneider et al., 2001b). Yet, all breeding strategies derive from the need for a commercial variety to possess several attributes simultaneously such as an adventitious root system, rapid growth, and resistance to pests. Eastern cottonwood, when planted in the southern United States, is an example of such a species.

Figure 5.9 Hybrid poplar plantation in Pacific Northwest

(Courtesy of ORNL)

Elsewhere, interspecific hybridization may be necessary. For example, in the upper Midwest, eastern cottonwood cuttings root erratically in the field, and hybridization between that species and another more easily rooted species is necessary to achieve an economical silvicultural system (Zalesny and Zalesny, 2009). This need for an aggregate genotype possessing all required commercial attributes gives rise to the several breeding programs found throughout North America and elsewhere in the world. Commercial genotypes in use today have most, if not all, of the important traits affecting production. However, the number of commercial genotypes in use today is relatively low, and diversification, as well as yield improvement, is a goal of breeding programs.

Production and agronomics. Plant propagation for commercial plantation establishment is generally via cuttings, which are produced in densely planted "stool beds." In the South, eastern cottonwood roots readily under field conditions, which makes for economical commercial deployment. In the North, eastern cottonwood roots erratically under field conditions, and it is more common to utilize a hybrid between eastern cottonwood and European black cottonwood (*Populus nigra*) or one of the *Tacamahaca* poplars. Of these, *Populus nigra* is preferred as a hybrid parental species because of the reduced probability of stem canker disease. Cuttings are harvested from stool beds in the winter during the dormant period, stored under refrigeration, and then planted in the field when soil temperatures reach levels appropriate to specific regions and genotypes.

Poplar can be managed in a number of ways, depending on the desired end product and target rotation age. Plantations grown for the production of larger-diameter trees used in the manufacture of paper and lumber are typically planted at spacings ranging from 8 feet by 8 feet (680 trees per acre) to 12 feet by 12 feet (302 trees per acre). Plantations of this type are currently managed commercially in Minnesota for pulpwood production and Oregon and Washington for a mix of products, including sawtimber and pulpwood. Poplar has the ability to resprout from established stumps after harvest, and thus could be managed on repeated coppice rotations. In light of the development of new genotypes and increased interest in dedicated energy feedstock production systems, the repeated coppice management option is a subject of renewed interest, and field research is recommended to identify optimal plant spacing and biomass production of such systems.

After planting, it is necessary to eliminate weed competition. As poplar plantings are mostly established on marginal agricultural land that has been under prior cultivation, weeds are mostly herbaceous and can be managed by preemergence herbicides, contact herbicides, or by cultivation. Weed control is needed until tree canopy closure—usually by the end of the second or third year of tree growth.

It is important to protect poplar plantings from insects and diseases. Various chemicals are available to control common pests, such as the cottonwood leaf beetle (Mattson et al., 2001; Coyle et al., 2008) and other insects, and the possibility of genetic selection for resistance, landscape-level deployment strategies, and other integrated pest management strategies can be considered (Mattson et al., 2001). Disease incidence and severity often depend on region (Newcombe et al., 2001). For example, Septoria stem canker is a serious problem in the Midwest on some hybrids, while much less of a concern in the Northwest, which places serious constraints on parental poplar species selection in the Midwest. Genetic selection among parental poplar species, among specific parental genotypes, and

Figure 5.10 Harvesting poplar plantation

(Courtesy of B. McMahon, University of Minnesota) within hybrid poplar breeding populations is practiced in nearly all breeding programs (Newcombe et al., 2001).

Harvesting of poplar plantations can be accomplished by using the same timber harvesting equipment found in standard forest pulpwood systems or by using purpose-designed equipment that combines felling and chipping or bundling in a single machine (Figure 5.10). Selection of equipment and method of harvest depends on average tree size and age at harvest, which are, in turn, determined by plantation density. A wide array of possibilities can be envisioned.

Potential yield and production costs. Yields from commercial plantations are proprietary and not readily available; therefore, most yield data is from research plots (Figure 5.11). A series of plot (10 x 10 tree square plots) yield trials conducted in Wisconsin, Minnesota, North Dakota, and South Dakota from 1987 demonstrated yields as high as 5.0 tons per acre per year by age 7 years (Netzer et al., 2002). Yields of newly selected genotypes in smaller plot experiments have exceeded 7.0 dry tons per acre annually on good agricultural soil in southern Wisconsin and Iowa (Riemenschneider, 1996; Zalesny et al., 2009). In general, sustainable average yields of 4.5, 6, and 9 tons per acre annually (dry weight, stem, and branches) are expected in the midwestern, southern, and northwestern United States, respectively. With appropriate research and development investment, over time these yields could be significantly increased, even doubled (Volk et al., in press) (Figure 5.11).

Using cash flow models of production costs and expected yields, costs of poplar biomass are comparable to other dedicated biomass production systems and range from $25 to $60 per dry ton depending on site quality and site-specific inputs. Using cash flow models developed by the University of Minnesota for the north-central United States, the total discounted cost of all inputs (assuming a 12-year rotation pulpwood-oriented system) is $450 per acre or roughly $36 per acre annually. Breakeven price of biomass in this system is approximately $16 per dry ton, including input costs only. The question of where woody energy crops will be deployed depends less on the breakeven price of the energy crop itself and more

Figure 5.11 Minnesota poplar plantation

(Courtesy of ORNL)

on the profitability of the crop being replaced. Based on data from a survey of production costs conducted by the University of Minnesota (2010), per-acre profits are estimated to range from $50 per acre in the case of wheat to $200 per acre in the case of corn production. Thus, energy crops will have to be priced at a level in which profits to growers are at least equal to competing crops.

Sustainability. Perennial woody crops provide multiple benefits when managed sustainably, such as biological diversity, conservation of soil and water, maintenance of site productivity, carbon sequestration, and socioeconomic values (Ruark et al., 2006). In a summary paper on the subject published by Tolbert et al. (2000), several trends are identified. Soil structure, total organic content, and infiltration rate is shown to the agricultural system being replaced. Inputs of leaf litter and lack of annual site disturbance are thought to be contributing factors. Nutrient content and water yield of short rotation poplar plantations were found to be similar to older, natural aspen stands in Minnesota. Increased soil carbon has been documented under short rotation systems, particularly in those regions of the country where inherent soil organic content is low, like it is in the South. Over the long term, soil carbon is expected to increase under perennial woody crops due to inputs of leaf and root biomass and lack of disturbance of the soil surface. Oxidation of carbon from upper soil layers has been shown to be a major factor, accounting for differences between perennial energy crops and annually tilled agricultural crops. Studies of wildlife effects of hybrid poplar plantings in Minnesota have shown increased diversity in bird populations compared with row crops (Hanowski et al., 1997). Small mammal abundance was found to be a function of canopy closure, with younger plantations being more similar to grasslands. Research done to date indicates that perennial woody crops will not mimic natural forest stands, but will contribute to diversification of habitat in agriculturally dominated landscapes.

Conclusions. The widespread natural range of eastern cottonwood, plus the possibility of extending the adaptive range by interspecific hybridization, points to the fact that poplar is one of the most promising species groups for woody crops development nationally. High rates of biomass productivity, amenability to clonal propagation and agricultural management, as well as coppicing ability, are factors that make poplar a desirable crop to produce biomass for energy as well as other products. Past research has documented acceptable yields of these systems using genetic material that is essentially one generation away from native populations. Genetic improvement research underway in Iowa, Minnesota, and the Pacific Northwest has demonstrated significant gains in biomass yield and the benefits of a concerted breeding and field testing effort. Continued research in genetics and stand management is needed to improve yield and extend the range of high-yielding varieties to all regions where biomass crops may be planted.

Figure 5.12 Harvesting willow with a one-pass cut and chip forage harvester

(Courtesy of T. Volk, SUNY)

5.1.6 Willow

Interest in shrub willows (*Salix* spp.) as a perennial energy crop for the production of biomass has developed in Europe and North America over the past few decades because of the multiple environmental and rural development benefits associated with their production and use (Börjesson, 1999; Volk et al., 2004; Rowe et al., 2008). Initial trials with shrub willows as a biomass crop were conducted in the mid-1970s in Sweden with the first trials in the United States starting in 1986 (Volk et al., 2006). Since the initial trials in upstate New York in the mid-1980s, yield trials have been conducted, or are underway, in 14 states (Delaware, Indiana, Illinois, Maryland, Michigan, Minnesota, Missouri, New Jersey, New York, Pennsylvania, South Carolina, Virginia, Vermont, and Wisconsin) and six provinces in Canada.

Biology and adaptation. Willow shrubs have several characteristics that make them an ideal feedstock for biofuels, bioproducts, and bioenergy: high yields that can be sustained in 3- to 4-year rotations, ease of propagation from dormant hardwood cuttings, a broad underutilized genetic base, ease of breeding for several characteristics, ability to resprout after multiple harvests, and chemical composition and energy [3-year-old willow stems averaged 8,340 Btu per dry pound (Miles et al., 1996)], similar to other northern hardwood species.

Production and agronomics. The shrub willow cropping system consists of planting genetically improved varieties in fully prepared open land where weeds have been controlled. The varieties of shrub willow that have been bred and selected over the past two decades in New York can be grown successfully

Figure 5.13 Spring resprout after fall cutting of willow

(Courtesy of T. Volk, SUNY)

on marginal agricultural land across the Northeast, Midwest, and parts of the Southeast. This range could be expanded with the development of new varieties. Weed control usually involves a combination of chemical and mechanical techniques and should begin in the fall before planting if the field contains perennial weeds, which is often the case with marginal land. Willows are planted as unrooted, dormant hardwood cuttings in the spring as early as the site is accessible at about 6,070 plants per acre using mechanized planters that are attached to farm tractors and operate at about 2.0 acres per hour. To facilitate the management and harvesting of the crop with agricultural machinery, willows are planted in a double-row system with 5 feet between double rows, 2.5 feet between rows, and 2 feet between plants within the rows. Following the first year of growth, the willows are cut back close to the soil surface during the dormant season to force coppice regrowth, which increases the number of stems per stool from 2–4 to 8–13 depending on the variety (Tharakan et al., 2005). After an additional 3 to 4 years of growth, the stems are mechanically harvested during the dormant season after the willows have dropped their leaves (Figure 5.12). Forage harvesters with a specially designed cutting head cut the willow stems 2–4 inches above the ground, feed the stems into forage harvester, and produce uniform and consistent sized chips that can be collected and delivered directly to end users with no additional processing (Abrahamson et al., 2002; Volk et al., 2006). The chipped material is then delivered to end users for conversion to bioenergy, biofuels, and/or bioproducts.

The plants will sprout again the following spring when they are typically fertilized with about 90 pounds per acre (Figure 5.13) (Abrahamson et al., 2002; Adegbidi et al., 2003) of commercial fertilizer or organic sources like manure or biosolids. The willows are allowed to grow for another 3- to 4-year rotation before they are harvested again (Figure 5.12). Projections indicate that the crop can be maintained for seven rotations before the rows of willow stools begin to expand to the point that they are no longer accessible with harvesting equipment. At this point the crop can be replanted by killing the existing stools with herbicides after harvesting and the killed stools are chopped up with a heavy disk and/or grinding machine followed by planting that year or the following year.

Potential yield and production costs. A rapid growth rate is one of the attributes that makes shrub willows an appealing biomass crop. Yields of fertilized and irrigated, unimproved varieties of willow grown for 3 years have exceeded 12 dry tons per acre per year (Adegbidi et al., 2001; Labrecque and Teodorescu, 2003). Due to the costs associated with irrigation and the relatively low value for biomass, irrigation will probably not be used for most large-scale production operations, with the exception of situations where willow crops could be irrigated with wastewater as part of a nutrient management plan. First-rotation, non-irrigated research-scale trials, with unimproved varieties in central New York, have produced yields of 3.8 to 5.2 dry tons per acre per year (Adegbidi et al., 2001; 2003; Volk et al., 2006). Second rotation yields of the five best-producing varieties in these trials increased by 18% to 62% compared to first-rotations (Volk et al., 2001), and in subsequent rotations, yields are maintained and largely dependent on weather conditions. The most recent yield trials using improved varieties of willow that have been bred and selected for biomass production in New York are showing yield increases of 20% to 40%.

The large genetic diversity across the genus Salix and the limited domestication efforts to date provide tremendous potential to improve yield and other characteristics, such as insect and disease resistance and growth form of willow biomass crops. The species used in woody crop systems are primarily from the subgenus *Caprisalix* (*Vetrix*), which has over 125 species worldwide (Kuzovkina et al., 2008). Breeding and selection of willow biomass crops in the United States began in the mid-1990s and has continued with various levels of effort since that time (Smart et al., 2008). Selection trials of new varieties from the initial rounds of the breeding programs in the late 1990s have produced yields that are up to 40% greater in the first rotation than the standard varieties used in early yield trials. Second rotation results from these same trials indicate that the yield of some of the new willow varieties is more than 70% greater than the standard varieties. These results indicate that there is a large potential to make use of the wide genetic diversity of shrub willows to improve yields with traditional breeding and selection.

The economics of willow biomass crops have been analyzed using a cash flow model (EcoWillow v.1.4 (Beta) that is publically available (Buchholz and Volk, 2011). The model incorporates all the stages of willow crop production from site preparation and planting through harvesting over multiple rotations to transportation of harvested chips to an end user. For the base case scenario in EcoWillow, the internal rate of return of willow biomass crops over seven 3-year harvest cycles (22 years) is 5.5%, and the payback is reached in the 13th year at assumed sale price of $60 per dry ton. Harvesting, establishment, and land rent are the main expenses associated with willow biomass crops over their entire lifespan, making up 32%, 23%, and 16% of the total undiscounted costs. The remaining costs, which include crop removal, administrative costs, and fertilizer applications, account for about 29% of the total costs.

The development of new harvesting technology is reducing costs by optimizing productivity. Another approach is to reduce the frequency of harvesting operations. Increasing the rotation length from 3 to 4 years reduces harvesting costs by 14% (from $14.79–$12.70 per dry ton) and increases the IRR by 11% (from 5.5%–6.2%).

Establishment costs are the second largest cost in the willow biomass crop production system and account for 23% of the total cost. Over 63% of these costs are for planting stock, so decreasing this input cost will affect the overall economics of the system. For instance, decreasing costs from a cutting from $0.12 to $0.10 reduces establishment costs by $106 per acre and increases the IRR of the system from 5.5% to 6.5%.

Several other components of the system need to be developed to improve the overall economics of willow biomass crop systems, and one of the main ones is yield. Increasing yields from the base case of 5.4 dry tons per acre annually by 50% to 8 dry tons per acre per year increases the IRR from 5.5% to 14.6%. With ongoing breeding and selection, as well as efforts to improve crop management, these levels of yield increases should be possible in the near future.

Sustainability. Willow biomass crops are being developed as sustainable systems that simultaneously produce a suite of ecological and environmental benefits in addition to a renewable feedstock for bioproducts and bioenergy (Volk et al., 2004; Rowe et al., 2009). The perennial nature and extensive fine-root system of willow crops reduce soil erosion and non-point source pollution relative to annual crops, promote stable nutrient cycling, and enhance soil carbon storage in roots and the soil (Ranney and Mann, 1994; Aronsson et al., 2000; Tolbert et al., 2000; Ulzen-Appiah, 2002). In addition, the crop is constantly in its rapid juvenile growth stage, so the demand for nutrients is high, which results in very low leaching rates of nitrogen, even when rates of applications exceed what is needed for plant growth (Adegbidi, 1999; Mortensen et al., 1998; Aronsson et al., 2000). The period with the greatest potential for soil erosion and nonpoint source pollution is during the first 1.5 years of establishment of the crop when cover is often limited because weeds need to be controlled and the willow canopy has not closed. The use of a winter rye cover crop has proven to be effective at providing cover for the soil without impeding the establishment of the willow crop (Volk, 2002). Since herbicides are only used to control weed competition during the establishment phase of willow biomass crops, the amount of herbicides applied per hectare is about 10% of that used in a typical corn-alfalfa rotation in upstate New York.

Nutrient removal from willow biomass crops is limited because only the aboveground woody portion of the crop is harvested during the dormant season after the leaves have dropped and most nutrients have been translocated to the root system. Nutrients not translocated from the foliage are returned to the system in litter. For most soils in the region where willow is being deployed, the only nutrient addition that is recommended is nitrogen, which is typically added at the rate of about 100 pounds of nitrogen per acre once every 3 to 4 years in the spring after the crop is harvested. However, research is ongoing to address concerns about nutrient management across a range of sites with new varieties of willow.

The recommended planting scheme for willow biomass crops is designed to maintain both genetic and structural diversity across a field and the landscape. Blocks of four or more willow varieties from different diversity groups should be planted in each field so that the structural and functional diversity of the system across the field is improved and any potential impact associated with pests and diseases in the future is reduced (Figure 5.13). At the landscape level, willow biomass crops will be in different stages of growth each year because they are managed on a three-year coppice cycle, which will further increase the structural diversity of the system.

Birds are one indicator of the biodiversity supported by willow biomass crops that have been studied in the United States. A study of bird diversity in willow biomass crops over several years found that these systems provide good foraging and nesting habitat for a diverse array of bird species (Dhondt et al., 2007). Thirty-nine different species made regular use of the willow crops and 21 of these species nested in them. The study found that diversity increased as the age of the willows and the size of the plantings increased.

It also found that birds have preferences for some varieties of willow over others (Dhondt et al., 2004). The number of bird species supported in willow biomass crops was similar to natural ecosystems, such as early succession habitats and intact eastern deciduous forest natural ecosystems. Willow biomass crops will increase diversity, especially in contrast to the open agricultural land that it will replace, rather than creating monocultures with a limited diversity across the landscape Lifecycle analysis of willow biomass crops has shown that they are low carbon fuels because the amount of CO_2 taken up and fixed by the crop during photosynthesis is almost equal to the amount of CO_2 that is released during the production, harvest, transportation, and conversion of the biomass crop to renewable energy (Heller et al., 2003). The cycle is balanced for all the CO_2 inputs into the atmosphere from the system because only the aboveground portion of the willow biomass crop is harvested and used in the conversion process. When willow biomass is used to offset fossil fuels, it can help reduce the amount of CO_2 emitted to the atmosphere. If the 99 million acres of available land in the United States were planted and harvested with short rotation woody crops to offset coal use for power production, up to 76% (11 quadrillion tons carbon per year) of the carbon offset targets for the United States under the Kyoto Protocol could be met (Tuskan and Walsh, 2001).

The low input intensity of willow biomass crops relative to agricultural crops and their perennial nature result in a large, positive net energy ratio for the biomass that is produced. Accounting for all the energy inputs into the production system, starting with the nursery where the planting stock is grown through to the harvesting of biomass, converting it to chips and delivering it to the side of the field, results in a net energy ratio of 1:55 (Heller et al., 2003). This means that for every unit of nonrenewable fossil fuel energy used to grow and harvest willow, 55 units of energy are produced and stored in biomass. Replacing commercial nitrogen fertilizers, which are produced with large inputs of fossil fuels, with organic amendments, such as biosolids, can increase the net energy ratio to 73–80 (Heller et al., 2003). Transporting the woody biomass 24 miles from the edge of the field to a coal plant where it is co-fired with coal to generate electricity results in a net energy ratio of 1:11. If a gasification conversion system is used, the net energy ratio is slightly higher (Keoleian and Volk, 2005).

Conclusions. Shrub willows have the potential to be grown on marginal agricultural land as a dedicated energy crop across a large range in the United States. The decades of research in Europe and North America provide a solid foundation for the large-scale deployment of the crop. This transition has begun with new varieties of shrub willow being scaled up in commercial nurseries in the United States and Canada, and the engagement of agricultural equipment manufacturers, like Case New Holland, in the development of harvesting systems. The continued optimization of the willow crop production system, a strong breeding and selection program, and quantification of the environmental and socioeconomic benefits associated with the crop are important for the effective and successful expansion of willow biomass crops. The proper deployment of willow biomass crops has the potential to put millions of acres of marginal agricultural land back into production, annually produce millions of tons of biomass, create thousands of rural jobs, and produce an array of environmental benefits.

5.1.7 Eucalyptus

Eucalyptus spp. is the world's most widely planted hardwood species. Its fast, uniform growth, self-pruning, and ability to coppice (regrow after harvest) make it a desirable species for timber, pulpwood, and bioenergy feedstocks (Figure 5.14). It has been domesticated for various products and has been widely commercialized in the tropics and subtropics.

In the United States, eucalyptus was introduced as early as the 1850s on the West Coast to produce dimension lumber and has been produced commercially in Florida since the 1960s. Though eucalyptus has naturalized in areas of the Southwest raising concerns of invasiveness, there is no evidence of spreading in the Gulf South. In anticipation of an increased role in biomass production, ongoing efforts aim to develop eucalyptus cultivars for improved yield and frost resistance in the southern United States.

Biology and adaptation. There are over 700 species of eucalyptus, adapted to various ecological conditions across its native range of Australia. Less than 15 species are commercially significant worldwide. In the South, genetic improvement programs are selected for fast growth, cold tolerance, desirable growth form, and reduced lignin. Genetic improvement programs aim to improve varieties for various growing conditions (Gonzalez et al., 2010; Rockwood and Carter, 2006a).

Production and silviculture. Eucalyptus production practices in different parts of the world vary with site conditions, desired products, and scale of commercialization. Genetic selection has led to commercialization of genotypes with unique advantages in different applications. They are commercially propagated by both seed and cloning of tissue culture. For conventional pulpwood production, stands are typically established at a planting density of 600–1,000 trees per acre, and harvested every 6–10 years. They may be replanted at harvest, which can benefit from improved genetic material, or regenerated from coppice growth, which eliminates the cost of replanting. Economically optimum time between harvests may be 3–4 years, with replanting after 2–5 harvests, on stands with initial densities of 3,400 trees per acre in Florida (Langholtz et al., 2007).

Figure 5.14 Eucalyptus plantation in Florida

(Courtesy of ArborGen and R. Gonzalez, NCSU)

Silvicultural strategies in the United States continue to evolve with changing markets, genotypes, and applications.

Because of high growth rates and tolerance to a range of growing conditions, eucalyptus can be produced in innovative ways, providing non-market benefits. For example, research trials demonstrate that *E. grandis* and *E. amplifolia* can be used for restoration of phosphate-mined lands (Rockwood and Carter, 2006b, Langholtz et al., 2007; 2009). *Eucalyptus* spp. has been shown to be effective at phytoremediation of reclaimed wastewater, municipal waste, storm water, and arsenic- and trichloroethylene-contaminated sites (Rockwood et al., 2004; Langholtz et al., 2005). Eucalyptus plantations that provide these types of environmental services may be viewed more favorably by the public, and compensation for non-market environmental services would improve the profitability of these systems.

Potential yield and production costs. Eucalyptus yields are influenced by precipitation, fertility, soil, location, and genetics. *Eucalyptus* spp. yielded 7.6–14.3 dry tons per acre annually after 3–5 years of growth on a clay settling area in central Florida, comparable to 8.9–13.8 dry tons per acre estimated for eucalyptus in Florida (Rahmani et al., 1997), but higher than the estimated 4–7.6 dry tons per acre estimated by Klass (1998), who observed that yields could be improved with SRWC development in the subtropical South. *E. grandis* is a high-yielding species in southern Florida, while *E. amplifolia* has the advantage of being more frost tolerant, with current trials as far north as South Carolina. The subsequent analysis in this report assumes a conservative annual yield average of 6.0 dry tons per acre.

Sustainability. Intensive management of eucalyptus, characterized by short rotations of genetically uniform monocultures, has dramatically increased yields over recent decades. These tree plantations maintain some sustainability attributes associated with forested landscapes, while at the same time facing sustainability challenges common in agriculture (Binkley and Stape, 2004). Infrequent tilling in tree plantations reduces risk of soil erosion associated with annual crops, and carbon sequestered in eucalyptus stand biomass exceeds the amount of carbon sequestered in herbaceous crops.

Conclusions. Eucalyptus has proven to be one of the most productive and economically viable biomass crops in the world, with expansive commercialization on all populated continents. As with other biomass crops, high yields require fertilization and water. Intensively managed plantations offer both environmental benefits over conventional agricultural systems and potential environmental downsides if native ecosystems are displaced. It is expected that eucalyptus will continue to be produced commercially in the United States and will play an increasing role as a feedstock for bioenergy systems.

5.1.8 Southern Pines

Pines comprised 32% of the tree species planted for production purposes around the world in 2005 (FAO, 2007) and 83% of tree species planted in the southern United States (USDA Forest Service, 2007b). Softwoods in the southern United States already contribute 40% of the total annual industrial wood supply of roundwood (USDA Forest Service, 2007c) and 40% of southern softwoods are used for pulpwood and composites. Because the fiber industry has long used both bark and black liquor to produce energy for running the pulp mills, southern pines are already a significant contributor to U.S. biomass energy.

Biology and adaptation. Loblolly pine (*Pinus taeda* L.) is the most important and widely cultivated timber species in the southern United States. Because it grows rapidly on a wide range of sites, it is extensively planted for lumber and pulpwood (Figure 5.15). This tree is dominant on 30 million acres and comprises over half of the standing pine volume in the South (USDA Forest Service, 2007c). A medium lived loblolly matures in about 150 years, with select trees reaching 300 years in age. Other pine species are found in the South, including slash pine (*Pinus elliottii* Englem), longleaf pine (*Pinus palustris* Mill), and shortleaf pine (*Pinus echinata* Mill); hybrids of loblolly

Figure 5.15 Pine plantation

(Courtesy of William M. Ciesla, Forest Health Management International)

and the three other species are also found (Peter, 2008). Of these, loblolly and slash pine are most frequently planted, and loblolly is the most important southern pine for bioenergy feedstock production. Loblolly shows a strong growth response to management inputs and is the best choice on good sites with better-drained soils where hardwood competition is a problem.

Production and silviculture. Improvements in pine silviculture have resulted in improving southern U.S. pine productivity by a factor of about 6 since the 1940s and increasing the number of planted acres of all pines from zero in 1940 to 37,664 million acres by year 2006 (USDA Forest Service, 2007a). The change from relying on natural pine stands to establishing and intensively managing pine plantations for fiber production is one of the major success stories in plantation forestry (Fox et al., 2007b). Loblolly pines are now deemed to be one of the most productive species that could be used in the southern United States for supplying bioenergy resources (Gonzalez et al., 2009).

Loblolly pines are normally planted as 1-year-old bare-root seedlings, though the more expensive containerized seedlings offer several advantages, including better survival (Taylor, 2006). Production of bare-root seedlings involves planting seed in specialized beds with controlled conditions for 8–12 months, top pruning, lifting, and grading. Currently 0.8 to 1.0 billion loblolly and slash pine bare-root seedlings are sold annually for forest planting. Essentially all of the seed is genetically improved for growth and disease resistance, with 70% of the seedlings being loblolly pine and 30% slash pine (Peter, 2008).

Many steps have contributed to improving the productivity of loblolly pine in the South (Stanturf et al., 2003a; Fox et al., 2007a). Naturally regenerated forests were the common practice from the 1920s through the 1950s, with very low annual productivity. Improved nursery and field planting practices began in the 1950s with continued improvement through the 1970s, and as a result, whole tree aboveground yields tripled. Seed orchards dedicated to seed improvement were first established in the late 1950s. The first generation improved seeds increased value of plantation wood by 20%, and second generation improved seeds being used now are adding another 14%–23%. The importance of hardwood competition control was recognized by the early 1970s. First methods of control were entirely mechanical, but by the late 1970s herbicides were added, and by 1990, chemical site preparation was predominate with limited mechanical site preparation involved. Fertilization of pine plantations was initiated in the late 1960s, but was implemented slowly during the 1970s and 1980s (Albaugh et al., 2007). Average productivity increased rapidly from the 1970s to 1990s primarily as a result of implementing use of improved site preparation, hardwood competition control, and genetically improved seeds.

Implementation of silviculture and genetic improvements very much accelerated in the 1990s as a result of the non-proprietary research conducted by university-industry cooperatives. In 1999, there were 23 research cooperatives at nine southern universities (Stanturf et al., 2003b). During the 1980s and 1990s, cooperative research clearly confirmed the benefits to pine productivity of fertilizing with both nitrogen and phosphorus, especially in mid-rotation. Further research published since 2000 has shown the need for micronutrients on certain soil types (Fox et al., 2007a;b; Kyle et al., 2005). Other recent studies have compared the effects of management intensity levels (Borders et al., 2004; Cobb et al., 2008; Martin and Jokela, 2004; Roth et al., 2007; Samuelson et al., 2008; Will et al., 2006), clearly showing the potential for much higher yields. Since third generation seeds from selected parents were beginning to be deployed in the early 2000s (McKeand et al., 2003), several of the recent research trials have included a higher performing genotype that resulted in enhanced yields.

At present, most loblolly pines stands in the South are managed for a combination of pulp and timber so that thinning is incorporated into the management. The stands are planted on average at about 600 seedlings per acre (~1480 seedlings per hectare), planning for a 25-year rotation with a thinning at age 15 (Gonzalez et al., 2009). With many studies showing the benefits of weed control and fertilization, mid- rotation fertilization has become considerably more common (Albaugh et al., 2007). Average operational yields in the southeastern United States were reported in 2003 to be about 4 dry tons per acre annually total aboveground oven-dry weights (Stanturf et al., 2003b). Current yield potential is assumed to be higher with the recent deployment of third generation loblolly pine seedlings on sites with site preparation treatments that ensure adequate survival and rapid early growth. Future management techniques are predicted to include "clonal plantations, whole rotation resource management regimes, use of spatially explicit spectral reflectance data as a major information source for management decisions, active management to minimize insect and disease losses, and more attention to growing wood for specific products" (Allen et al., 2005).

Potential yield and production costs. Loblolly pine research plots managed with site preparation and weed control but no fertilizers have produced total aboveground biomass yields (stem, branches, and foliage) of 3.3 to 3.8 dry tons per acre per year. Research plots with site preparation, weed control, and fertilization only at planting have produced total yields in the 3.6 to 5.2 dry tons per acre per year range. Addition of higher levels of fertilizers plus irrigation in some cases has bumped yields to 5.1 to 7.3 dry tons per acre per year of biomass. Very intensive management with selected loblolly pine genotypes, annual fertilization, irrigation (in some cases), excellent site preparation, and weed control has increased biomass yields to 5.4 to 8.5 dry tons per acre per year. Based on recently reported research results, companies are predicting future operational yields of 6 to 8 dry tons per acre per year when greater management intensity is used. However, it is unlikely that yearly fertilization will be economically viable or indeed it may not be necessary for high-yield achievement.

Various ideas have been proposed on how to manage southern pines for bioenergy production. Both Gonzalez et al. (2009) and Scott and Tiarks (2008) have recently described management plans for producing both timber and bioenergy products. Both involve a combination of rows of widely spaced trees and tightly spaced rows for bioenergy. The bioenergy rows would be harvested in 5 to 8 years and a widely spaced row for lumber production to be harvested at 18 to 22 years. While this might be a reasonable transition strategy, an efficient harvesting strategy for removing the bioenergy trees has not been discussed. Planting and harvesting can be much more efficient when pine plantations are dedicated entirely to supplying bioenergy feedstocks. Such plantations are likely to be planted at higher densities and managed on shorter rotations similar to poplars and eucalyptus.

The age of optimal stand harvest has not yet been determined for higher density loblolly pine plantings. Recent intensive management studies planted at stand densities of 454 to 670 trees per acre show total aboveground biomass continuing to increase between 10 and 15 years of age (Samuelson et al., 2008; Borders et al., 2004). However, those same studies also show density-dependent mortality beginning at basal areas of about 153 square feet per acre on fertilized wet sites, which correlates to an age range of about 9 to 10 years. The highest density study with 1,210 trees per acre showed a slowing of the current annual increment by age 5, but the mean annual increment was still increasing (Roth et al., 2007). The cost of planting will depend on initial planting density and the amount of replanting needed (Taylor et al., 2006). Advanced generation, bare-root seedlings were reported to cost $47.50 per thousand seedlings in 2006. Over the planting ranges mentioned above, and including culls and extra seedlings needed for replanting, seedling costs could be expected to range from about $40 to $60 per acre. Planting with current planting equipment is expected to cost about $65 to $100 per acre.

Harvesting of small-diameter trees has been a significant cost barrier to using southern pines for energy (Peter, 2008) but the results of intensive management studies are showing that excellent growth can be achieved at densities low enough to allow individual trees to achieve an economically harvestable size. Consequently, harvest and handling costs (to roadside) using currently available equipment should be similar to current pulp harvesting costs or about $20 per dry ton.

Economically optimal fertilization strategies will vary for each planting site. Intensive culture studies produce higher yields with high annual fertilization fairly consistently, while financial returns depend on the magnitude of the growth response obtained, the product mix, stumpage prices, cost of fertilization, and the length of time before harvest (Fox, 2007b). As with hardwoods, first fertilization with nitrogen and phosphorous should be delayed a year or two to avoid stimulating weed competition, but no later than stand closure. Mid-rotation fertilization applications of both nitrogen and phosphorous (at 200-pound nitrogen per acre and 25-pound phosphorous per acre applied at time of stand closure) have shown very positive stand responses lasting for several years in lower density stands, but more frequent fertilization at lower levels may be needed in higher density loblolly stands.

Sustainability. Use of intensive management to produce wood specifically for bioenergy is generally only economically viable when the total aboveground portions of the trees are removed. This has raised concern about long-term site productivity impacts. Research and analysis of intensive pine production has shown that good site preparation, chemical control of non-crop vegetation, and fertilizer application at levels and times that optimize utilization by the trees, increases biomass yields in an energy-efficient manner, while maintaining or improving long-term site productivity (Scott and Dean, 2006). Allen et al. (2005) argue for use of a fully integrated management approach starting with good site selection followed by excellent early competition control and additional inputs, as needed. Such management practices will not only create economically sustainable woody production systems, but will also minimize the potential for adverse environmental effects.

Conclusions. In the near term, pine bioenergy feedstocks are most likely to be obtained by thinning existing loblolly pine stands that are planted for multiple uses (fiber and energy). If loblolly pines are planted specifically for energy, then they will be grown at relatively dense spacings and short (8–10 year) rotations. Research studies suggest that the lowest planting density under intensive management that might be expected to achieve an economically harvestable size within that time period is about 726 trees per acre. Average yields of about 5.5 dry tons per acre annually in the Southeast, Atlantic Coast, and Delta regions are obtainable with appropriate management. This includes plowing, disking, and application of a total kill herbicide once or twice before planting. Non-crop vegetation is controlled during the first 2 years, primarily with herbicide applications. In the southern United States, phosphorus and potassium are usually added to high-yield stands in the planting year, and nitrogen additions of about 89 pounds per acre are added in years 2 through 6, based on foliar analysis studies showing nitrogen demand levels (Will et al., 2006). Economically viable harvest is expected to occur as early as the eighth year. Both traditional and molecular genetics need to continue to be aggressively pursued to improve the productivity potential of loblolly and other pines, and substantial yield improvements are expected between now and 2030.

5.2 Estimating Future Crop Supply

The economic potential of energy crops is estimated using POLYSYS, a policy simulation model of the U.S. agricultural sector that includes four interdependent modules—crop supply disaggregated to 3,110 counties, national crop demand and prices, national livestock supply and demand, and agricultural income (De La Torre Ugarte and Ray, 2000). The model is anchored to the USDA 10-year projection of the U.S. agricultural sector and is extended 10 years to 2030 by extrapolating crop yields, exports, and population. The USDA and extrapolated projections are further disaggregated to county levels.[53] The projections include production and consumption for agricultural commodities, agricultural trade and exports, commodity prices, and aggregate indicators of the sector, such as farm income and food prices (USDA-OCE/WAOB, 2009). By varying prices offered for biomass feedstocks, POLYSYS estimates potential energy crop supplies and changes in land use, which can include acreage changes among crops and conversion of cropland and pastureland to energy crops. The model also estimates changes (i.e., deviations in the agricultural projections) in crop prices for the eight major crops (corn, grain sorghum, oats, barley, wheat, soybeans, cotton, and rice); production quantities for food, feed, and industrial uses; exports; crop and livestock income; and government payments throughout the 20-year simulation period (De La Torre Ugarte and Ray, 2000).[54] The version of POLYSYS used in this assessment includes three energy crop options—a perennial grass, short-rotation woody crops, and an annual energy crop. The grasses and non-coppice woody crops (e.g. poplar and pine) were evaluated for 10- and 8-year rotations, respectively. The rotation length for the coppice woody crops (e.g., willow) was 20 years with a 4-year cutting cycle.

5.2.1 Input and Yield Assumptions for Baseline and High-Yield Scenarios

Baseline scenario. The land base in POLYSYS includes about 250 million acres planted to the eight major crops, 61 million acres of land in hay production, 23 million acres of cropland used as pasture, and 117 million acres of non-irrigated permanent pasture.[55] Land enrolled in the Conservation Reserve Program (CRP) is another potential source of land.[56] The CRP was enacted through the Food Security Act of 1985 and compensates farmers for acres that they retire from crop or pasture use that are highly erodible or otherwise environmentally sensitive. Farmers sign into multi-year contracts when enlisting in CRP. As these contracts expire, farmers have the option of keeping their land enrolled in the CRP or converting it back into crop or forage production. In this update, it is assumed that the approximately 32 million acres currently enrolled remain in the CRP. The USDA projections also assume acreage enrolled in the CRP will remain close to the legislated maximum of 32 million acres.

POLYSYS allocates available land in each county to the competing crops, including energy crops based on the maximization of expected returns above variable costs of production. Energy crops will displace conventional crops in the model, provided

53 The county-level data provide a non-unique, representative reference scenario, which is consistent, in the aggregate, with the national level projections.

54 Alternatively, a bioenergy feedstock production target can be set, such as an EISA 2007, the RFS and a price solved to meet the production target. BRDI (2008) is an example of the latter application of POLYSYS.

55 Total U.S. acreage in cropland pasture and permanent pasture is approximately 36 and 409 million acres, respectively (USDA-NASS, 2009). POLYSYS explicitly excludes pasture in counties where there is extensive use of supplemental irrigation and pasture west of the 100th Meridian.

56 The primary goal of the CRP is to mitigate soil erosion (USDA-FSA, 2008). Compared to pre-CRP erosion rates, the CRP reduced erosion by 470 million tons in 2007. Other benefits of the program include creating wildlife habitat, reducing sedimentation, improving water quality, preventing excess crop production, and providing a stable source of income for farmers.

they are more profitable.[57] (Text Box 5.2 provides more information on regional land-use) In the case of pastureland, however, POLYSYS allows conversion to energy crop production only if lost forage can be made up by intensifying pasture production.

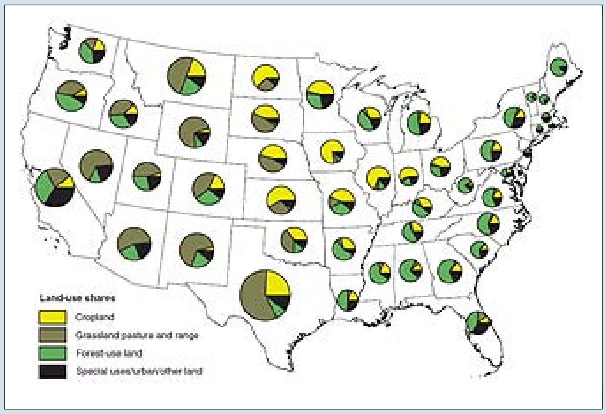
The availability of pasture (permanent pasture and cropland pasture) for conversion to perennial grasses and woody crops is constrained to counties east of the 100th Meridian (for reference, this parallel runs through Dodge City, Kansas). Counties east of the 100th Meridian are assumed to have sufficient rainfall to replace lost forage through intensification. That is, POLYSYS assumes no loss of forage production. Further, it is assumed that intensifying cropland currently used as pasture will cost $50 per acre the first year and an additional $10 per acre in subsequent years. For permanent pasture, first-year costs are assumed to be $100 per acre and $15 per acre in following years. First-year costs are for additional investments, such as fencing. Costs in subsequent years are for management. Energy crops must overcome these additional costs plus the pasture rental rate to come into production.

A set of restraints are used to limit the amount of land switching to new energy crops in a given year. These restraints are imposed to simulate the relative inelastic nature of agriculture in the near-term. These restraints include:

- 5% of permanent pasture can convert to energy crops each year. The total amount of permanent pasture in a given county that can convert to energy crops is limited to 50% (i.e., assumed doubling of forage through intensification)
- 20% of cropland pasture can convert to energy crops each year. The total amount of cropland pasture in a given county that can convert to energy crops is limited to 50% (same assumption as permanent pasture)
- 10% of cropland can convert to energy crops each year. The total amount of cropland in any given county that can convert to switchgrass or woody crops energy crops is limited to 25%. This restraint serves to maintain crop diversity. Energy sorghum, the annual energy crop, is much more limited due to rotation and land suitability considerations (non-erosive land only).

TEXT BOX 5.2 | RELATIVE PROPORTION OF MAJOR LAND-USE TYPES BY STATE

The land base dictates regional emphasis on primary feedstock availability. For example, the Southeast has considerable potential to supply forestland biomass, but more limited capability to produce energy crops given cropland and pastureland availability, even though energy crop productivity is potentially high relative to other regions. The Central and Southern Plains have greater potential to produce energy crops despite lower productivity potential because of the high proportion of cropland and pastureland. The Corn Belt and Plains are dominant suppliers of crop residue biomass.



Map source: Lubowski et al., 2005.

[57] In practice, POLYSYS first determines the amount of land in each county that can enter into production, switch to a different crop, or move out of production (De La Torre Ugarte and Ray, 2000; De La Torre Ugarte et al., 2003). This determination generally depends on relative crop profitability in preceding years. The model also contains allocation rules or flexibility constraints that limit the amount of land a given crop can lose or gain each year. These rules or constraints serve to simulate the relatively inelastic nature of short-run agricultural supply. Once supply is solved, POLYSYS estimates market prices and demand quantities for each crop and use (food, feed, and industrial), exports, and carryover stocks.

In POLYSYS, energy crop production costs include seed or planting stock, fertilizer, herbicide, insecticide, machinery services, custom operations, fuel and lube, repairs, handling, paid labor, and technical services. Factor input costs are specific to broad farm production regions due to regional differences in labor rates, fertilizer prices, and other inputs. Energy crop production inputs, assumptions, and prices are summarized in Tables 5.3 and 5.4, for herbaceous and woody crops, respectively. They were developed based on the general crop guidelines provided earlier in the background section. For perennial crops, such as grasses and trees, establishment costs and harvesting are most important. (Field trials are conducted as a result of the Feedstock Partnership described in Text Box 5.3)

Perennial grasses are generally planted, managed, and harvested like a traditional hay crop and use existing agricultural equipment. Conventional establishment can involve disking, seeding, and application of nutrients and herbicides. Alternatively, perennial grasses can be established using no-till planting procedures. Costs are nearly the same, as the avoided tillage costs are replaced with the use of specialized planting equipment and application of additional herbicides, depending on the prior crop. Table 5.3 summarizes establishment and maintenance costs for switchgrass, which is used as the model perennial grass in POLYSYS. For switchgrass, establishment year costs are higher in the Southeast because of the use of Alamo seed, a lowland variety, and lime requirements. The Southern Plains also utilize Alamo, but have no lime or potassium requirements. The Northern Plains have the lowest establishment year costs because they utilize Cave-in-Rock (an upland variety with lower seed cost in the base year of analysis than Alamo) and have no lime or potassium requirements. Otherwise, production inputs for establishing switchgrass are similar across all production regions.[58]

After establishment of perennial grasses, nutrients are applied, and annual harvests are made. Harvest costs assume conventional mowing, raking, and baling operations.[59] Once established, a perennial grass stand is assumed to last 10 years before replanting is necessary. Full yield is not attained until roots are fully established, which is usually by the third growing season.

Perennial grasses can be grown on a wide variety of sites, with productivity very much determined by precipitation, temperatures, soils, and local site factors (see Text Box 5.5). As summarized in Table 5.3, productivity varies considerably with production regions. It is generally higher in the Southeast and Appalachia than the Northern or Southern Plains. Annual yields of perennial grass can range from 2 or less dry tons per acre in the western Great Plains to over 6 dry tons per acre farther east. In the Southeast and Appalachia yields can exceed 9 dry tons per acre in some locations.[60]

Like perennial grasses, woody crops are established and managed with conventional agricultural equipment. Woody crops can be planted at a variety of spacings and harvested after 6 to 12 years of growth, depending on species, region of the country, and desired characteristics. With the exception of pine, most woody crops will resprout vigorously, but current management guidelines suggest replanting with improved clones following harvest. However, there are some hardwood tree crops being bred specifically as coppiced managed crops; willow (*Salix* spp.) is the notable example.

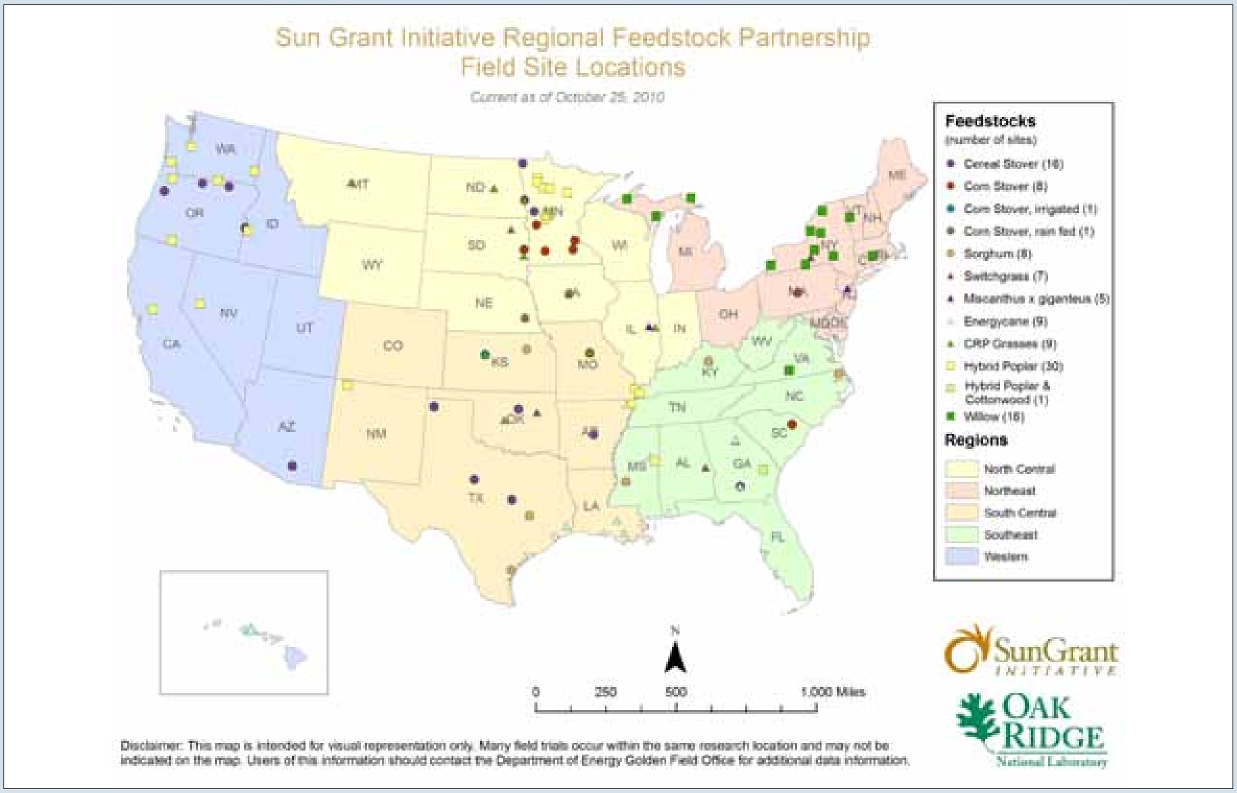
[58] For Miscanthus, establishment would be higher due to rhizome costs. However, productivity of Miscanthus is generally higher thanthat of switchgrass. So ultimately, whether switchgrass or Miscanthus is more profitable in a given area really depends more or less on the tradeoff between establishment costs and expected productivity. For energy cane, a tropical grass, establishment costs are also higher than switchgrass because of the use vegetative planting material rather than seed, but as with Miscanthus higher establishment costs are offset with higher yields at maturity.

[59] Harvesting of thicker-stemmed grasses, such as Miscanthus and energy cane, would involve more robust and/or specialized equipment.

[60] Switchgrass yields have not been demonstrated at full scale-up plots and extrapolation of demonstration plot yields to full-production scale plots is risky. However, research plots have produced yields consistent with the estimates in Table 5.5. Of course, yield alone does not determine the competiveness of energy crop production. It depends not only on crop productivity, but on how profitable the crop is in relation to existing land uses.

TEXT BOX 5.3 | THE REGIONAL FEEDSTOCK PARTNERSHIP

DOE, the Sun Grant Initiative universities, and members of USDA have established the Regional Biomass Energy Feedstock Partnership. The Partnership consists of five separate regions: Southeast, North Central, South Central, Western, and Northeast. The Partnership is addressing barriers associated with supplying a sustainable and reliable source of feedstock to a large-scale bioenergy industry. One key activity of the Partnership is to conduct field trials of energy crops to assist understanding the feedstock resource development potential. Each region is expected to have a unique contribution to the national feedstock production. A second activity is to assure existing resource supplies are assessed in a consistent manner across regions. National task teams are addressing these activities.



Although willow is most productive in the Northeast and Lake States regions, it has considerable potential to be grown farther south and west. Coppice-managed hardwoods are usually planted at much higher densities than single-rotation hardwoods and harvested on shorter rotations of 3 to 4 years. As many as seven succeeding coppice stands can be expected from the initial establishment.

Unlike perennial grasses, harvesting is a technical barrier to widespread adoption of woody crops.[61] Farmers are unlikely to have the necessary equipment to harvest tree stands. As such, woody crops are likely to be harvested as a contracted operation, even as a conventional "timber sale." The cost of harvesting woody crops is variable and is dependent on tree diameter size and planting density or spacing. A typical spatial arrangement would have narrower in-row spacing and wider between-row spacing to accommodate production (e.g., spraying and spreading equipment), as well as harvesting equipment. If managed as a single rotation, trees can be harvested with existing forestry equipment (e.g., feller-bunchers, skidders, and whole-tree chippers). The multiple stems characteristic of coppice-managed hardwoods are harvested with a standard forage harvester fitted with a specially designed cutting head for woody crops. Woody crops are generally chipped at the stump or at roadside and delivered to facilities as whole-tree chips. (Additional differences between woody and herbaceous crops are provided in Text Box 5.6)

Obtaining high productivity and survival requires specially selected planting material, good site preparation, effective weed control, and application of nutrients. If planted today, using quality cuttings and seedlings, woody crops are expected to produce 3.5 to 6.0 dry tons per acre annually, with higher yields in parts of the Northwest (6 dry tons per acre per year) and sub-tropical Florida. For willow, annual yields are likely to range from 5 to 6 dry tons per acre in the establishment rotation and slightly higher in the subsequent coppice rotations.

Energy sorghum is assumed as the model annual energy crop. Energy sorghum is only allowed on cropland, as it is a potentially erosive row crop. It is also assumed to be part of a multicrop and/or fallow rotation. Sorghum can be established in a manner similar to conventional corn, using a chisel plow and offset disk for soil preparation; however, no-till establishment is preferred. Fertilizer (nitrogen, phosphorous, and potassium) and lime (once every 3 years in regions where it is needed) are spread. Fertilizer costs are higher than for perennials. A row crop planter is used to plant sorghum seed. Weed control consists of two herbicide applications and one mechanical cultivation. Harvesting is done with a self-propelled forage harvester and high dump forage wagons to transport the chopped sorghum to the field edge.

Miscanthus and energy cane are two potentially high-yielding perennial energy crops. They, however, have higher establishment costs as they use vegetative material. Energy cane is restricted to areas without frost. Miscanthus can be grown in the Midwest. While both are thick-stemmed species (as is sorghum), Miscanthus has been harvested with forage equipment. Miscanthus can be harvested in the spring before regrowth begins. It is assumed that energy cane and Miscanthus are established in a manner similar to sugarcane, but with lower nutrient requirements. Energy cane is harvested with a forage harvester in the fall and Miscanthus is harvested with a mower-conditioner, rake, and baler in the spring. Because Miscanthus and energy cane have relatively long productive stand lives and high yields, they are potentially cost-competitive or even less costly than other perennial grasses provided establishment costs can be kept low.

High-yield scenario. As discussed at the outset, workshops were conducted to collect information on advancements needed for higher yields, the ranking of the timeliness, the likelihood of these advancements, and the projected future yields. The crop types considered in the herbaceous crops workshop were

[61] Results of studies conducted during the last two decades suggest that cost-effective harvesting requires that equipment be appropriately sized and able to cut and handle large numbers of relatively small-diameter trees. Conventional forest harvesting equipment tends to be inappropriate because it is designed for single-stemmed, stop-and-go severance of large trees. The equipment is also high-powered and expensive.

switchgrass, mixed perennial grasses, energy cane, and Miscanthus. Energy sorghum was also included, even though it is not a perennial, because it can be grown explicitly as an energy crop across a wide range of sites.

The participants discussed a wide array of limiting factors to yield improvements, as well as approaches to overcoming these barriers. While there is great potential for genetic improvement of perennials, the process of new variety breeding, selection, and trialing is relatively slow compared to annual species like corn and sorghum. Varieties of perennials are typically well adapted to a relatively narrow range of environmental conditions (e.g., climate and geography), and different varieties typically perform better in some environments than in others. Development of many varieties of each species will be required to get the best possible production performance across the breadth of available U.S. environments. Because of this geographical correlation, yield improvements were discussed within seven large resource zones across the United States that are adapted from the USDA Land Resource Regions. For switchgrass, participants estimated 2030 yield increases as high as 80% in the most productive zones and improvements as low as 5% and 10% in less productive zones.

Participants were asked for their opinions about land-use issues related to herbaceous energy crops as to how the integration of energy crops into cropping systems, germplasm improvements, and better management practices might allow for expansion of biomass production onto more marginal lands. There will be competition for land, regardless of implementation of commodity-scale energy crop production. It would be helpful to develop a better understanding of best uses for all kinds of lands, especially the vaguely defined marginal lands. While they may not be useable for row-crop production, they may be candidates for energy crop production. Land needs to be used more effectively (e.g., matching species to the environments to which adapted). Production systems need to be designed to optimize marginal lands, such as using corners in pivot-irrigated fields and rehabilitating acres idled due to crop failure, drought, poor economics, etc. Converting pasture to energy crop production introduces different productivity issues, such as soil fertility, sensitivity to rain, and slope. Since there is already competition for pastureland, there will also be a need to improve or intensify remaining pasture that is used for livestock.

Following the herbaceous workshop, a woody crops workshop was held. Woody energy crops are defined as purpose-grown plantations in which the bolewood, probably the bark, and much of the limbs and tops are used as feedstocks for energy. They can also be referred to as SRWC. SRWC are grown primarily to use the bolewood for pulpwood and, in some limited cases, for lumber. In the general sense, energy crops and SRWC are intensively-managed, fast-growing species that produce large amounts of biomass over a short period of time, usually less than 10 years. Depending on the species and the production method, the rotation length can be shortened to as little as 3 years when coppiced.

The most likely woody energy crop species to be developed for bioenergy production are poplar, southern pine, eucalyptus, and willow, but there are many other possible species, such as sycamore (*Plantanus occidentalis*) and sweetgum (*Liquidambar styraciflua*). The workshop focused on poplar, willow, and southern pine. Eucalyptus was added during the workshop.

As with the herbaceous crops workshop, participants discussed yield growth rates, identified barriers to achieving higher yields, and then some approaches to overcoming these barriers to ensure future yield increases. The barriers included the lack of improved planting stock, regeneration methods, and cultural practices; disease and pest risks; forest management practices not optimized for energy production and/or integrated with conventional forestry; uncertain landowner expectations; matching species to sites with and without restrictions; limited markets and risks; need for new types of low-impact harvesting equipment; and political and social sensitivity to the use of transgenesis. Other barriers are provided in Text Box 5.4.

Participants identified possible advances and approaches to overcoming these barriers. Some of the more important ones identified in the workshop included:

- New and improved varieties, lines, and families—molecular genetics and breeding methods for productivity, frost hardiness, and drought resistance
- Improvement in vegetative propagation and nursery production and bridging the gap between genetic breeding and application
- Germplasm development, genome sequencing, and QTL trait identification
- APHIS (Animal and Plant Health Inspection Service) permitting, gene escape controls, and sterility
- New silvicultural and stand improvement practices for weed control, nutrients, and harvesting
- Developing better yield and economic models
- Trials on coppice, multicrop, spacing, rotation length, nutrient efficiency, and carbon pools
- Monitoring and control systems for pests and diseases
- Integrated harvesting/site preparation operations, including application of precision forestry
- Developing conversion technology to use more of the biomass
- Developing business cases, how-to guidelines, and decision tools for landowners.

In POLYSYS, the high-yield scenario was implemented by using higher rates of productivity growth relative to the baseline. The effect of differing growth rates on crop productivity is summarized in Table 5.5. Under the baseline scenario, 6 dry tons per acre increase to 6.6 and 7.2 dry tons per acre by 2022 and 2030, respectively. Under the high-yield scenario, productivity growth rates of 2% to 4% increase yields from 6 dry tons per acre to 7.3 and 8.9 dry tons per acre and 8.6 and 12.2 dry tons per acre by 2022 and 2030, respectively. These projections are well within the range of estimates provided by workshop participants.

TEXT BOX 5.4 | BARRIERS TO YIELD GROWTH

As part of the environmental sustainability alternate assumption discussion, participants were asked to identify the environmental barriers, or "limiting factors," constraining yield and possible solutions. Key considerations raised by participants included:

- Implementing emerging concepts in management practices
- Minimizing nitrogen use
- Minimizing risk of new biomass crops becoming invasive or intercrossing
- Developing improved carbon sequestration and methods for indirect monitoring of carbon accumulation in soil
- Developing planned production programs
- Implementing landscape-scale management strategies
- Identifying ways to manage changes in land use for energy crop production with minimal soil carbon loss
- Conducting studies to quantify benefits of environmental services
- Leveraging ecosystem services provided by perennial crops for environmental sustainability
- Developing an integrated pest management (IPM) program for switchgrass and mixed perennial grasses
- Developing management practices and technology for harvesting perennial energy crops.

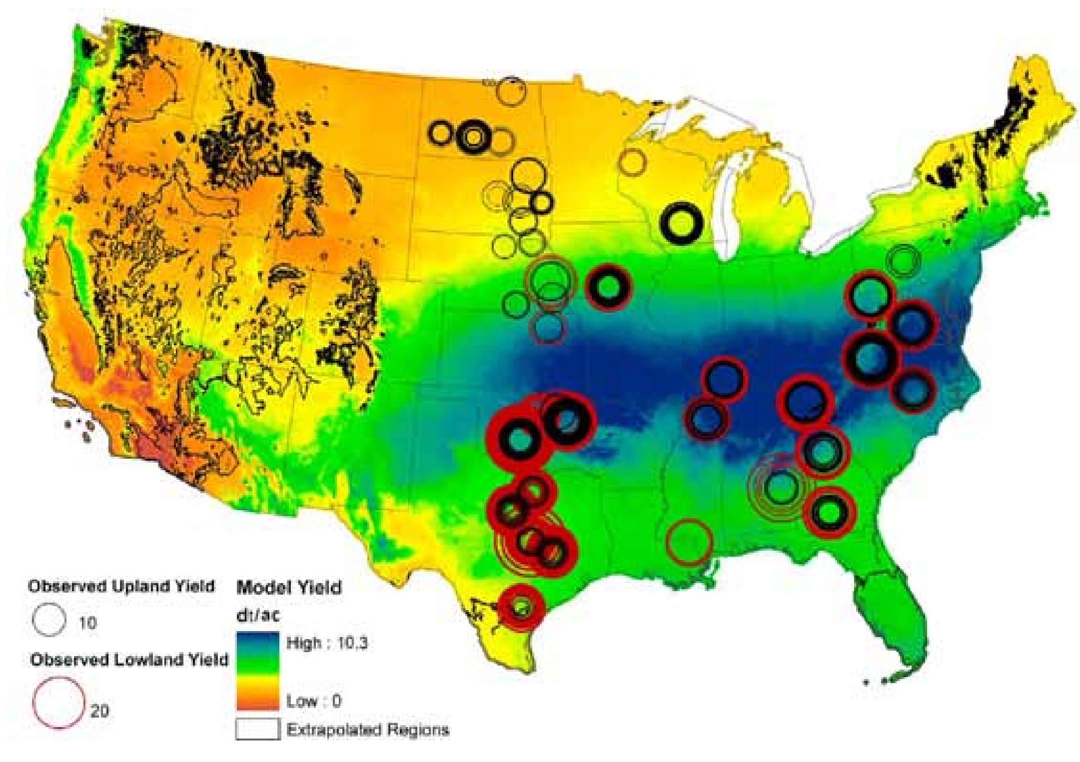
Table 5.3 Summary of Production Inputs and Costs for Perennial and Annual Grasses

Item	Units	Northeast	Appalachia	Southeast	Delta	Corn Belt	Lake States	Southern and Northern Plains
Perennial grasses								
Stand life	Years	10	10	10	10	10	10	10
Productivity	dry tons/ acre	4.0–7.5	5–9.5	3.5–9.5	3–7	4–7	3.5–5	2–6.5
Establishment								
Seed	$/lb	$10	$22	$22	$22	$10	$10	$22
Planting	lb/acre	5	5	5	5	5	5	5
Replants	percent	25	25	25	25	25	25	25
No-till drill	-	1-time	1-time	1-time	1-time	1-time	1-time	1-time
Total kill herbicide	No. applications	1-time	1-time	1-time	1-time	1-time	1-time	1-time
Pre-emergent herbicide	No. applications	1-time	1-time	1-time	1-time	1-time	1-time	1-time
Phosphorous	lbs P2O5/ acre	40	40	40	40	40	40	40
Potassium	lbs K2O/ac	80	80	80	80	80	80	0
Lime	tons/acre	1	2	2	2	1	1	0
Total establishment costs	**$/acre**	**$210**	**$340**	**$330**	**$330**	**$200**	**$200**	**$220**
Maintenance years								
Reseeding	year applied	2	2	2	2	2	2	2
Pre-emergent herbicide	No. applications	0	0	0	0	0	0	0
Nitrogen	lbs/acre	60	70	70	50	60	40	40
Phosphorous	lbs P2O5/ acre	0	0	80	0	80	0	0
Potassium	lbs K2O / acre	0	0	80	0	80	0	0
Harvest costs	**$/dry ton**	**$19.50–$21.00**	**$18.50–$19.90**	**$18.00–$20.20**	**$18.60–$20.60**	**$19.20–$20.60**	**$20.60–$21.90**	**$19.20–$22.10**
Annual Energy Crops								
Productivity	dry tons/ acre	6–8.2	6–8.7	6–9	6–9	6.7–9	n/a	6.5–9
Production costs	$/acre	$310	$330	$300	$310	$420	n/a	$230
Harvest costs	$/dry ton	$12.50	$12.10	$11.80	$11.80	$12.20	n/a	$12.10

Notes: *Discounted average costs of production for perennial grasses are $52-$80 per dry ton in the Northeast; $43-$68 per dry ton in Appalachia; $42-$91 per dry ton in the Southeast ; $54-$89 per dry ton in the Delta; $53-$71 per dry ton in the Corn Belt; $70-$94 per dry ton in the Lake States. $47-$70 in the Northern and Southern Plains. Costs assume a discount rate of 6.5% and include all variable costs exclusive of land rent. Discounted average cost of production for annual energy crops range from $38 to $59 per dry ton.*

TEXT BOX 5.5 | ESTIMATION OF SWITCHGRASS YIELD

Understanding how biomass yield varies as a function of crop management, climate, and soils is fundamental to deriving a sustainable supply of cellulosic feedstock for an emerging biofuels industry. For the herbaceous perennial switchgrass *(Panicum virgatum L.*), a database containing 1,190 observations of yield from 39 field trials conducted across the United States was compiled. Data includes site location, stand age, plot size, cultivar, crop management, biomass yield, temperature, precipitation, and information on land quality. Statistical analysis revealed the major sources of variation in yield. Frequency distributions of yield for upland and lowland ecotypes were unimodal, with mean biomass yields (± standard deviation) of 3.9 ± 1.9 and 5.6 ± 2.6 dry tons per acre for the two ecotypes, respectively. No bias was found toward higher yields associated with small plots or preferential establishment of stands on high quality lands. A parametric yield model was fit to the data and explained one-third of the observed variation in biomass yields, with an equal contribution of growing season precipitation, annual temperature, nitrogen fertilization, and ecotype. The model was used to predict yield across the continental United States. Mapped output was consistent with the natural range of switchgrass, and yields were shown to be limited by precipitation west of the Great Plains. Future studies should extend the geographic distribution of field trials and thus improve understanding of biomass production as a function of soil, climate, and crop management for promising biofuels such as switchgrass.



Sources: *Wullschleger et al., 2010; Jager et al., 2010*

Table 5.4 Summary of Production Inputs and Costs for Woody Crops

Item	Units	Poplar	Pine	Eucalyptus	Willow (coppiced)
Rotation	Years	8	8	8	4[a] (5 harvests)
Spacing	sq. ft.	60	60	60	7.5
	trees/acre	726	726	726	5800
Productivity	dry tons/acre-year	3.5–6.0	5.0–5.5	6.0	5.1
Growing range	Region	Northeast, Lake States, Northwest, Midwest, Plains	Southeast	Sub-tropics	Northeast and Lake States
Establishment - year 1					
Cuttings	$/tree	$0.10	$0.06	$0.10	$0.12
Planting	$/tree	$0.09	$0.09	$0.09	$0.02
Replants	percent	5	5	5	0
Moldboard plow	-	1-time	1-time	1-time	1-time
Disk	-	1-time	1-time	1-time	1-time
Cultivate	-	2-times	2-times	2-times	2-times
Total kill herbicide	No. applications	1-time	1-time	1-time	1-time
	lbs a.i./acre	1.5	1.5	1.5	1.5
Pre-emergent herbicide	No. applications	1-time	1-time	1-time	1-time
	lbs a.i./acre	1.5	1.5	1.5	1.5
Phosphorous	lbs/acre	0	40	0	0
Establishment costs	$/acre	$310	$280	$310	$1120
Maintenance years					
Cultivate – year 2	-	2-times	2-times	2-times	1-time
Cultivate – year 3		1-time	1-time	1-time	None
Pre-emergent herbicide – year 2	No. applications	1	1	1	1
	lbs a.i./acre	1.5	1.5	1.5	1.5
Lime – year 3	tons/acre	90	90	90	100
	year applied	-	year 3	year 3	-
Nitrogen – year 4 and 6	lbs/acre	90	90	90	100
	year applied	4 and 6	2,4, and 6	4 and 6	4
	-	-	-	-	-
Phosphorous – year 3	lbs/acre	20	40	15	-
	year applied	3	3	3	-
Potassium – year 3	lbs/acre	35	40	25	-
	year applied	3	3	3	-
Maintenance costs – year 2	$/acre	$60	$100	$100	$30
Maintenance costs – year 3–8	$/acre	$220	$200	$200	$100[b]
Harvest costs	**$/dry ton**	**$20**	**$20**	**$20**	**$15**

Notes: *Productivity for coppiced managed systems is expected to be about 15% higher after first coppice. "a.i." is active ingredient. Discounted average costs of production for poplar, pine, and willow are $43-$47, $43-$46, and $38-$45 per dry ton, respectively. Costs assume a discount rate of 6.5% and include all variable costs exclusive of land rent.*

Table 5.5 Yield Growth Between the Baseline and High-Yield Scenarios

Crop	2012 Yield	2017	2022	2030	2017	2022	2030
		Baseline 1% annual growth			High-yield 2%–4% annual growth		
		Dry tons/acre/year			Dry tons/acre/year		
Low end of yield range	2	2.1	2.2	2.4	2.2 – 2.4	2.4 – 3.0	2.9 – 4.1
	3	3.2	3.3	3.6	3.3 – 3.6	3.7 – 4.4	4.3 – 6.1
	4	4.2	4.4	4.8	4.4 – 4.9	4.9 – 5.9	5.7 – 8.1
	5	5.3	5.5	6.0	5.5 – 6.1	6.1 – 7.4	7.1 – 10.1
	6	6.3	6.6	7.2	6.6 – 7.3	7.3 – 8.9	8.6 – 12.2
Middle of yield range	7	7.4	7.7	8.4	7.7 – 8.5	8.5 – 10.4	10.0 – 14.2
	8	8.4	8.8	9.6	8.8 – 9.7	9.8 – 11.8	11.4 – 16.2
High end of yield range	9	9.5	9.9	10.8	9.9 – 10.9	11.0 – 13.3	12.9 – 18.2
	10	10.5	11.0	12.0	11.0 – 12.2	12.2 – 14.8	14.3 – 20.3
	11	11.6	12.2	13.2	12.1 – 13.4	13.4 – 16.3	15.7 – 22.3
	12	12.6	13.3	14.4	13.2 – 14.6	14.6 – 17.8	17.1– 24.3

Notes: *The yields shown for 2017–2030 for the baseline and high-yield scenarios reflect the standing yield of the energy crop before losses. It is the yield for the energy crop planted in that particular year. For example, if the 2009–2012 yield for a particular crop is 5 dry tons per acre, the yield for that crop would be 5.5 dry tons per acre if planted in 2022 under the baseline and 6.1 to 7.4 dry tons per acre under the high-yield scenario.*

5.3 Results

Two scenarios are considered—a baseline and high yield. The baseline and high-yield scenarios differ by assumed productivity growth over time. For the baseline, it is assumed that regional productivity increases by 1% annually, starting in year 2014, for all subsequent plantings (Table 5.5). Crop productivity growth is due to learning or experience in planting energy crops and limited gains that can be had through breeding and selection of better varieties. Under high-yield scenarios, projected increase in crop productivity over time is modeled at 2% to 4% annually. These gains are due not only to experience in planting energy crops, but to more aggressive implementation of breeding and selection programs. One could expect that there might be some regional variation in productivity growth especially if research were targeted to a specific variety or clone. However, there was no clear basis to differentiate regional productivity growth in this study.

A number of simplifying assumptions are made to implement energy crop simulations in POLYSYS. These are summarized below:

- For all energy crops, the earliest year planting can start is 2014. This is a somewhat arbitrary decision that reflects the current availability of seeds, seedlings, and cuttings for planting. Delaying the introduction of energy crops to later years (e.g., 2015) would simply delay the deployment time path.
- It is assumed that once land is planted to an energy crop, it remains in that energy crop through the end of the simulation period (2030). That is, the model does not allow the shifting of land in and out of energy crops.[62]
- For the baseline and high-yield scenarios, crop productivity is determined by the year in which the crop is planted. For example, a crop planted in 2022 in a particular county would realize a yield of 4.4 dry tons per acre if the 2014 yield for that county was 4 dry tons per acre under the baseline (Table 5.5) and 4.9 to 5.9 dry tons per acre under the high-yield scenario.
- It is assumed that the geographic range where energy crop production can occur is limited to areas where production is under rain-fed conditions, without the use of supplemental irrigation.
- Perennial grasses and woody crops can be planted on cropland, cropland currently used as pasture, and permanent pasture. Conversion of pastureland is restricted to counties east of the 100th Meridian. Energy sorghum, the annual energy crop simulated in the model, is restricted to cropland and is assumed to be part of a 4-year multicrop and/or fallow rotation.
- Energy crop productivity is assumed the same for cropland and pastureland.[63]
- Perennial grasses are assumed to have a stand life of 10 years before replanting is required; woody crops are managed on an 8-year rotation, and coppiced woody crops are managed on a 4-year rotation with a total stand life of 20 years. These assumptions are made for the convenience of modeling only. Rotation ages for woody crops will be different depending on species, spacing, and management.
- The collection of corn stover, wheat straw, and other grain residue is included when estimating energy crop potential because the energy crops must compete for land, and these additional income streams affect the profitability of residue producing crops.

[62] This assumption was made to facilitate model programming. However, the authors consider this to be a reasonable assumption because it is likely a grower will have a long-term commitment or contract to supply biomass.

[63] An exhaustive analysis of switchgrass productivity data showed that there was no significant relationship between productivity and land capability class for either lowland or upland ecotypes that are analyzed together or separately (Wullschleger et al., 2010). The authors conclude that this could be due to the planting of switchgrass field trials, mainly during the 1990s, on "marginal lands" as a common expectation at the time was that less-than-prime agricultural lands would be used for woody and herbaceous energy crop production. It is likely that with additional plantings of energy crops on cropland, results may show relatively higher yields on cropland than pastureland. In this update, this would imply that the croplands used are too low and conservative.

5.3.1 Baseline Estimates of Energy Crop Potential

Potential supplies of energy crops at alternative farmgate prices of $40 to $60 per dry ton are summarized in Figure 5.16. At the lowest farmgate price ($40 per dry ton), energy crop production reaches nearly 4 million dry tons by 2017, increases to 14 million dry tons by 2022, and by 2030, reaches 34 million dry tons. There is very little woody crop production at this price and 4.2 million dry tons of energy sorghum by 2030. At $50 per dry ton, total energy crop production is 210 million dry tons by 2030, with 129 million dry tons of perennial grasses, almost 14 million dry tons of energy sorghum, and 67 million dry tons of woody crops. Woody crops account for about one-third of 2030 total energy crop production at the $50 and $60 farmgate prices. At the highest price, the model estimates a potential supply of 255 million dry tons of perennial grasses, 126 million dry tons of woody crops, and 19 million dry tons of energy sorghum.

Supply curves for selected years—2017, 2022, and 2030—are shown in Figure 5.17. As previously explained, future supplies increase over time due to the assumed productivity growth (energy crops becoming more competitive) and woody crops coming into production. At the $60 simulated price, total energy crop production reaches nearly 282 million dry tons by 2022 and 400 million dry tons by 2030. Total energy crop production would exceed 500 million dry tons as simulated prices approach $80 per dry ton.

The planted acres associated with the simulated energy crop production are displayed in Figure 5.18 by price and year for major energy crop type. At the lowest price, about 5.0 million acres of energy crops are planted mostly on cropland by 2030. Planted acreage increases significantly at the higher simulated prices. At $50 per dry ton total planted acreage approaches 20 million acres by 2022 and 32 million acres by 2030. Sixty-four million acres are planted to energy crops by 2030 at the highest simulated price. About 35% of these 64 million acres are cropland and the remaining cropland is used as pasture and permanent pasture.

Energy crop production is summarized in the state maps shown in Figure 5.19 at simulated farmgate prices of $40, $50, and $60 per dry ton. These maps also show agricultural crop residues because their collection is assumed with the energy crops. What stands out is the dominance of the Great Plains in perennial grass and woody crops in the South and to a lesser extent in the North. The Corn Belt is very much the dominant area in the production of crop residues. The key reasons for the dominance of perennial grass production in the Plains is due to the availability of cropland and pastureland (see Text Box 5.2) and the relatively low profitability of current land uses.

Figure 5.16 Potential production of energy crops at various years and farmgate prices in baseline scenario

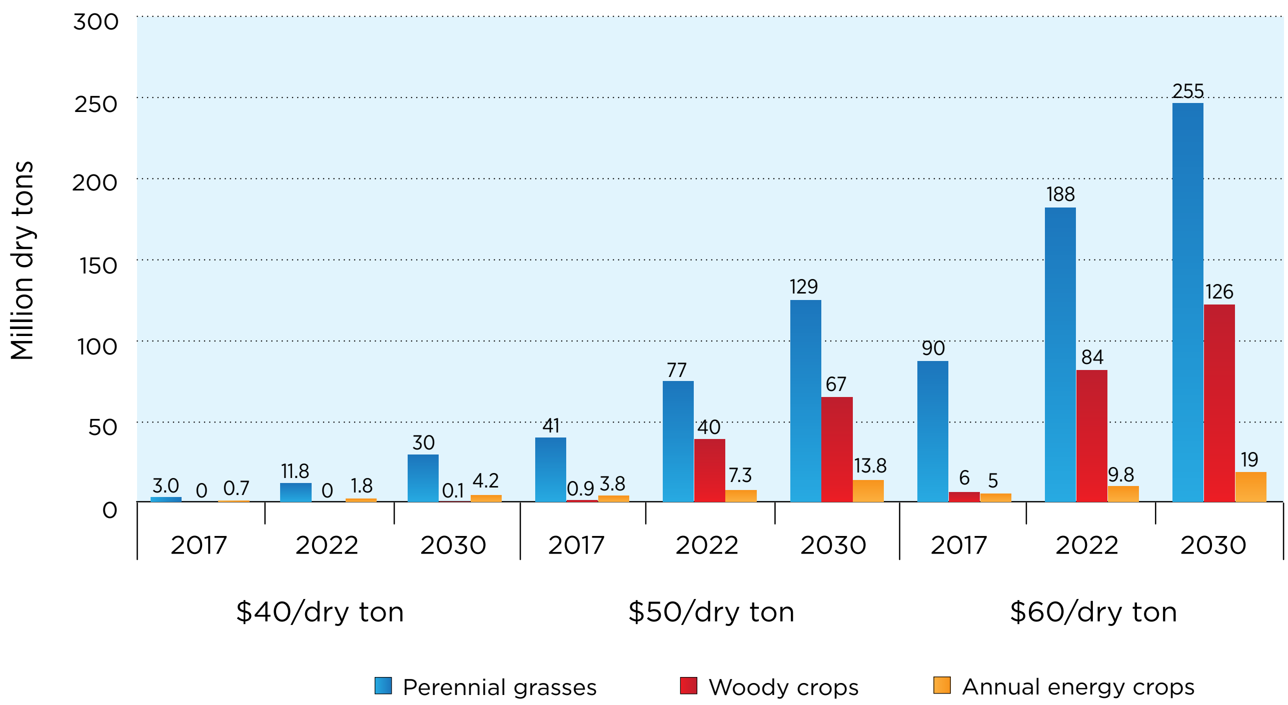


Figure 5.17 Supply curves for all energy crops at selected years in baseline scenario

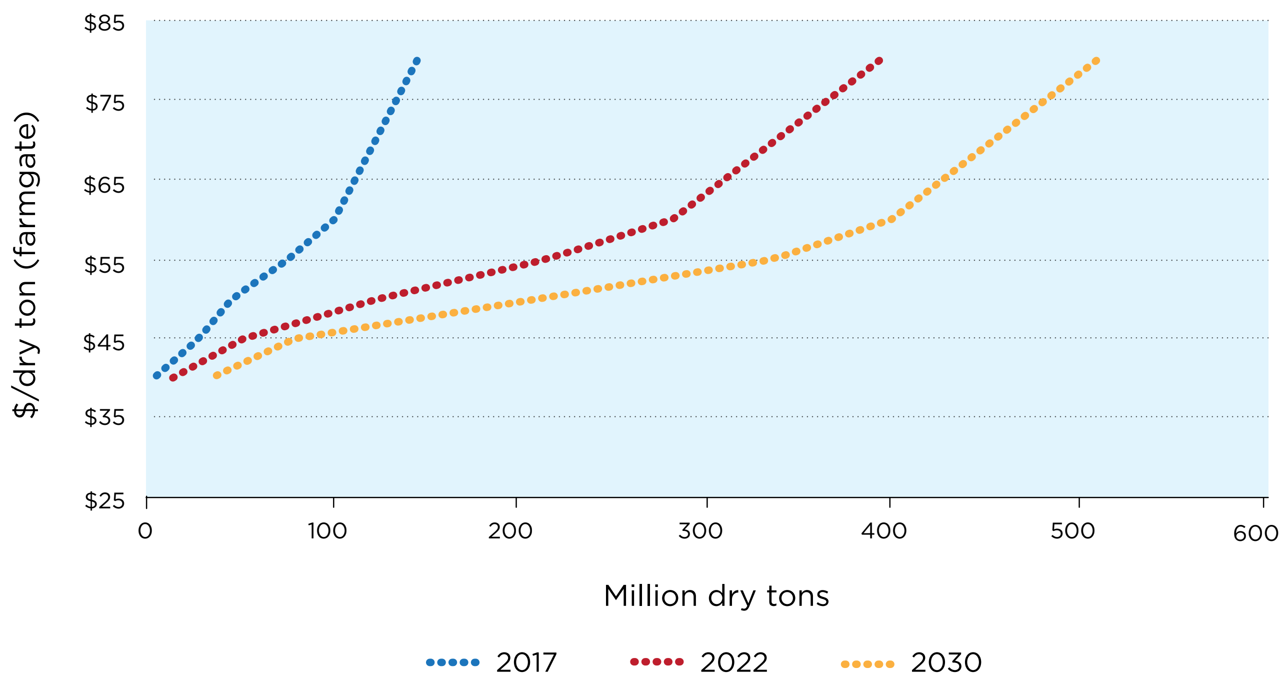


Figure 5.18 Planted acres in perennial grasses, woody crops, and annual energy crops for selected years and prices in baseline scenario

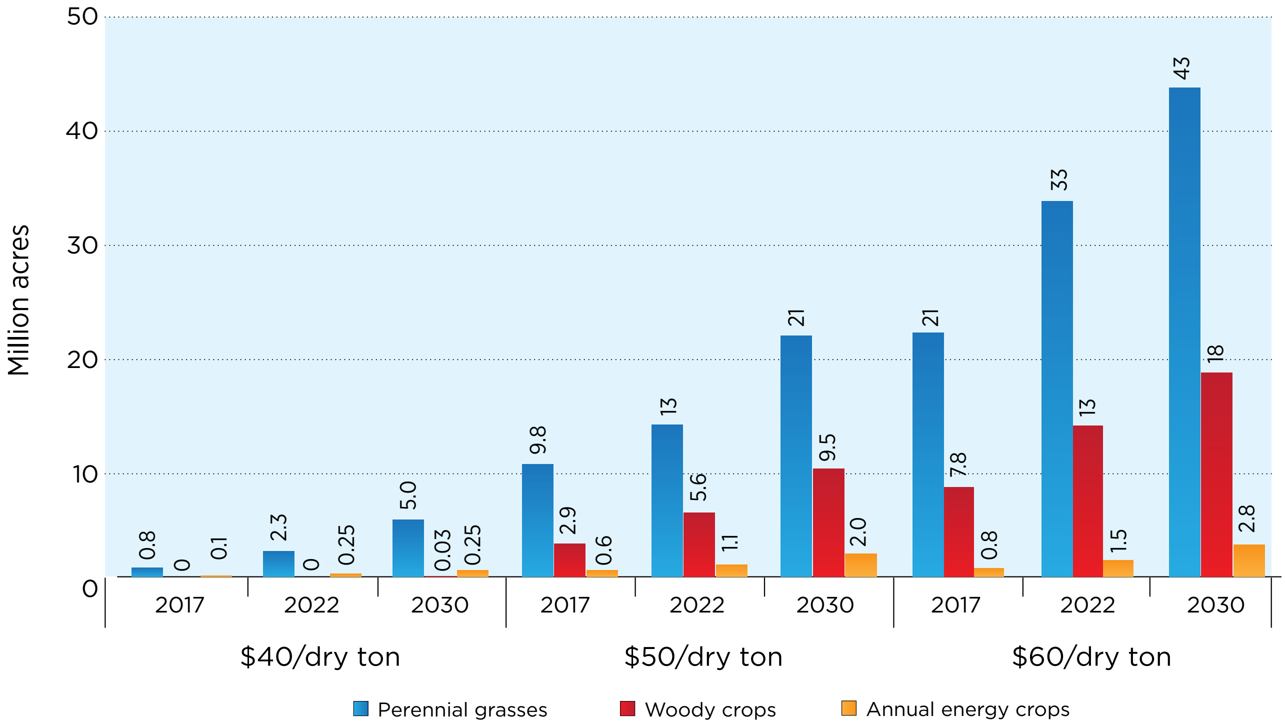
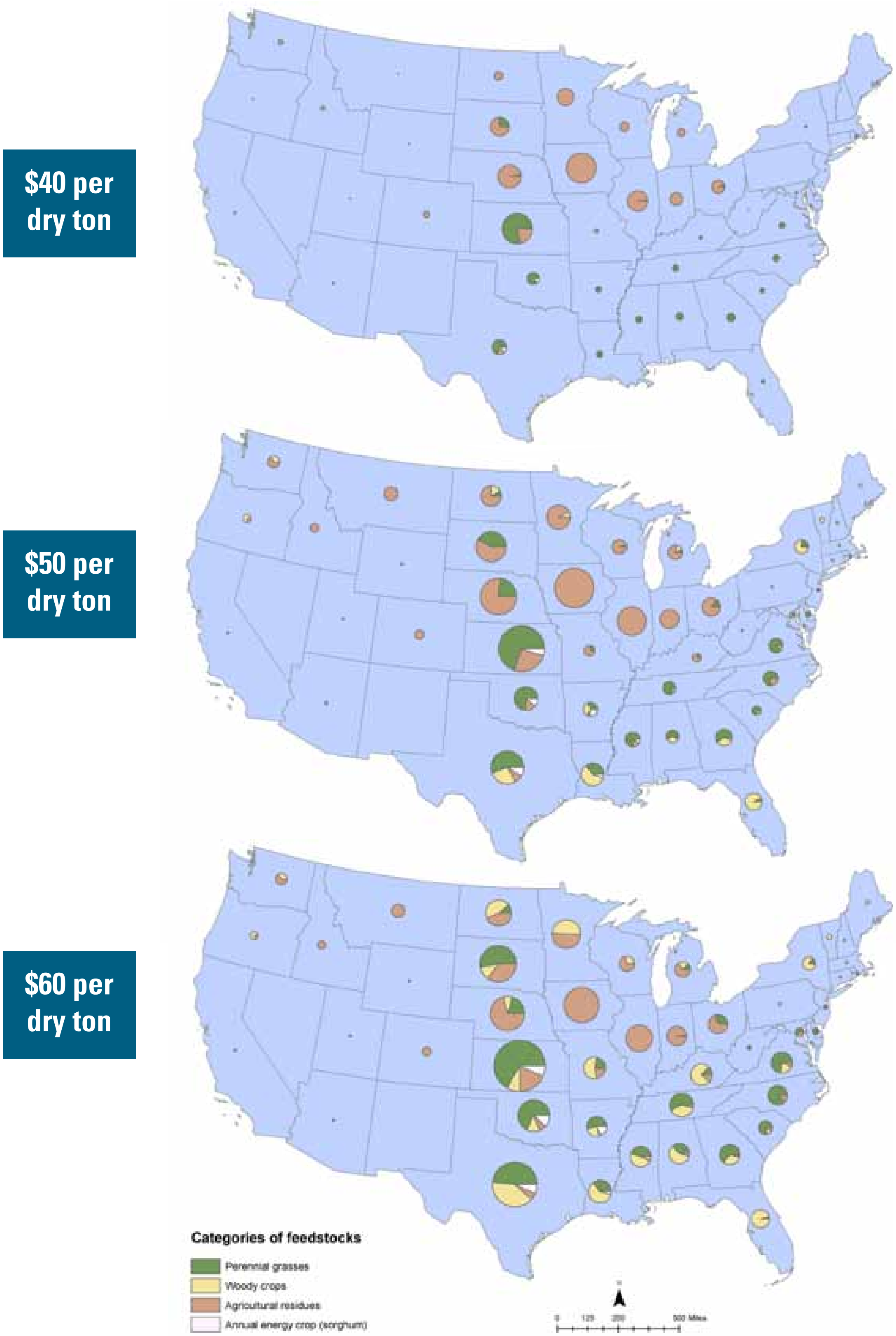


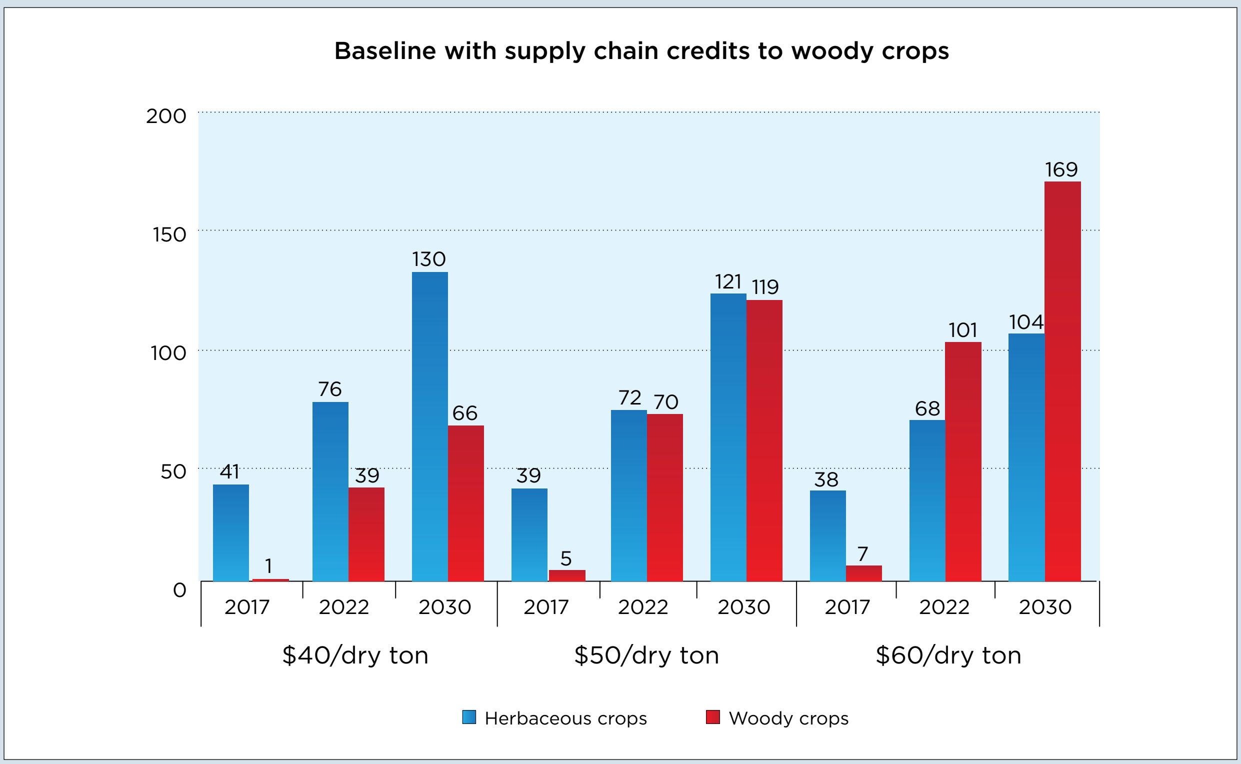
Figure 5.19 Estimated state shares of energy crops and agricultural residues supplies at farmgate prices of $40, $50, and $60 per dry ton in 2030



TEXT BOX 5.6 | COMPETITIVENESS OF WOODY AND HERBACEOUS CROPS WHEN SUPPLY CHAIN ADVANTAGES ARE CONSIDERED

In addition to competing for land with conventional energy crops, energy crops also compete with each other. Farmgate analysis can distort the relative competiveness of energy crops when there are differences in feedstock logistics and supply chains. For example, woody crops have potentially less complex supply chains. In its simplest form, a woody crop can be harvested, chipped, and transported directly to the conversion facility. Further, woody crops can be stored on the stump, increasing volume, until needed at the conversion facility. Perennial grasses, annual energy crops, and crop residues have limited harvest and/or collection seasons and require storage between seasons. These herbaceous feedstocks also require more handling operations.

The figure below summarizes the effect of a credit given to woody crops to account for their potential supply chain advantages. The results show the baseline scenario at a farmgate price of $50 per dry ton and the same baseline with a $5 and $10 per dry ton credit given to woody crops. There were modest decreases in herbaceous crops and large increases in woody crops as the credit increased. Under the baseline at $50 per dry ton, woody crops are about one-third of total energy crop production in 2030. This percentage increases to 50%, with a $5 per dry ton credit and 65%, with a $10 per dry ton credit. Of course, this is a very simplistic comparison and a more thorough analysis of the entire feedstock supply and conversion chain is required. But the results do show that differences in assumed costs and assumptions among energy crops can have significant results in terms of the energy crop mix.



5.3.2 High-Yield Estimates of Energy Crop Potential

There are numerous opportunities for making technical improvements in crop establishment and harvesting methods that could serve to lower production costs. Cost reduction could also come from having machinery that is more efficient in handling biomass. Further, as farmers become more familiar with growing biomass, they should also become more efficient producers.

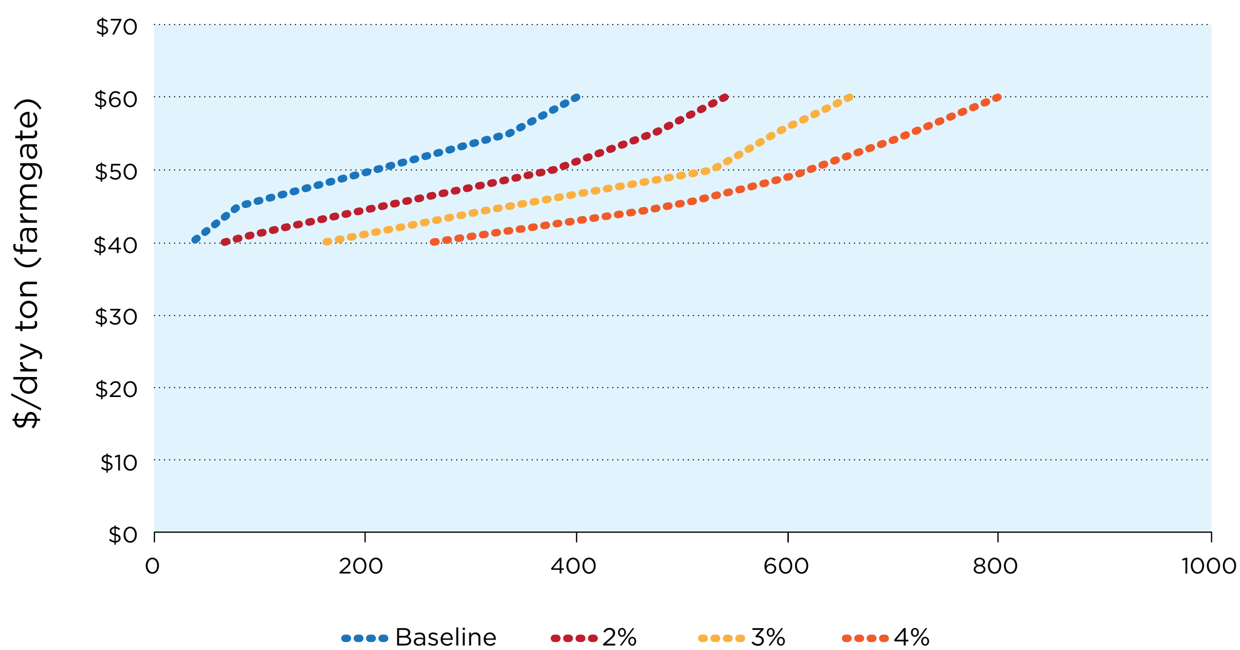
Learning-by-doing, as well as some improvements in machinery and fuel use, could lower energy crop production costs. However, the major opportunity for lowering production costs lies in increasing crop productivity. In the 2005 *BTS*, average annual crop yields of 5 and 8 dry tons per acre were assumed under the moderate and high-yield scenarios. In this update, high-yield is modeled as an annual increase in yield of 2%, 3%, and 4%. As shown in Table 5.5, an annual yield of 5 dry tons per acre attainable today increases to 7.1 dry tons per acre in 2030 under a 2% annual growth rate and over 10.1 dry tons per acre at 4% growth for a crop planted in 2030.

Results of the energy crop simulation at a 2% to 4% annual yield growth are shown in Figure 5.20; the baseline supply is also shown. The effect of assuming higher yield growth over time is that the supply curves shift outward. Under baseline assumptions, energy crop supply reaches nearly 400 million dry tons in 2030, at a $60 per dry ton simulated price. Under the 2% to 4% higher annual crop yield growth rates, supplies increase to 540 and 799 million dry tons, respectively.

Figure 5.20 shows there is a wide production range of about 400 million dry tons between the baseline and the 4% yield growth curve for all simulated prices, with the exception of the lowest simulated price ($40). Meeting the feedstock source requirements for a fixed demand for biofuels under the RFS could potentially be met with energy crops at minimum farmgate prices ranging from mid- to high-40s, under higher yield growth to mid- to high-50s, under baseline yield growth.

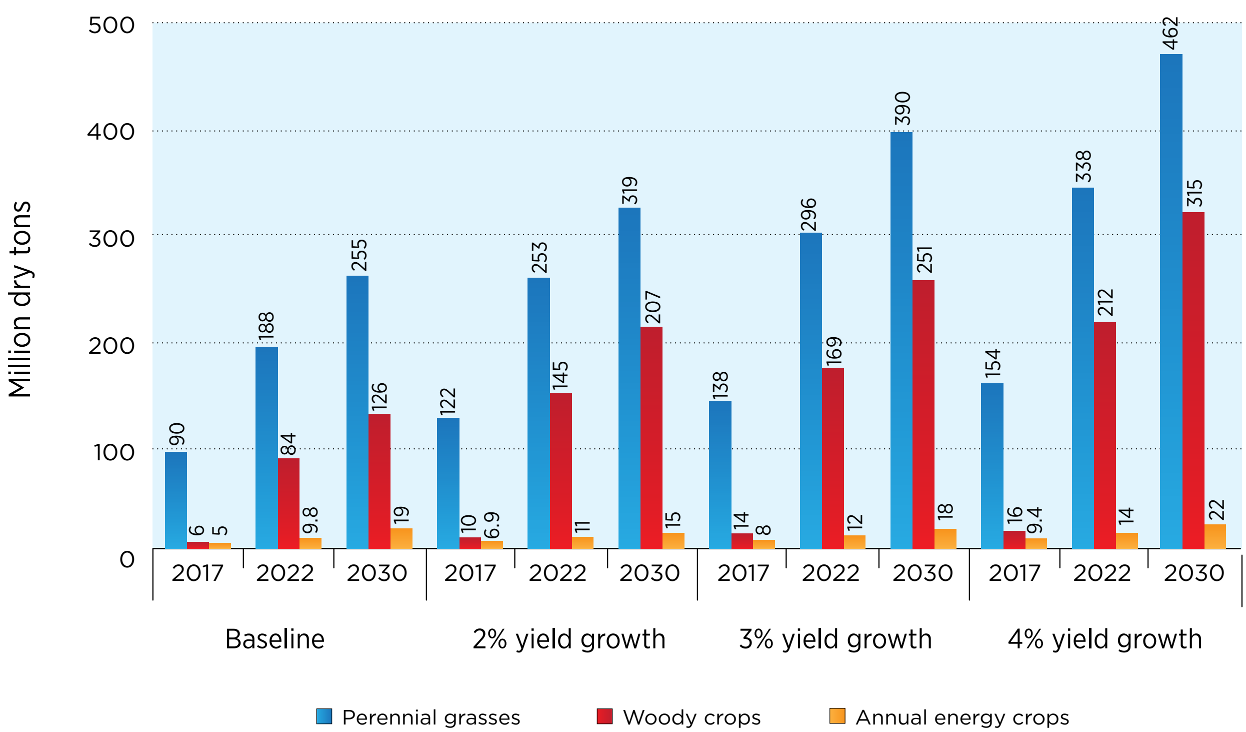
The relative quantities of the three major types of energy crops at a $60 per dry ton simulated price for selected years in the high-yield scenario are

Figure 5.20 Year 2030 energy crop production under baseline and 2% to 4% annual growth in energy crop yield



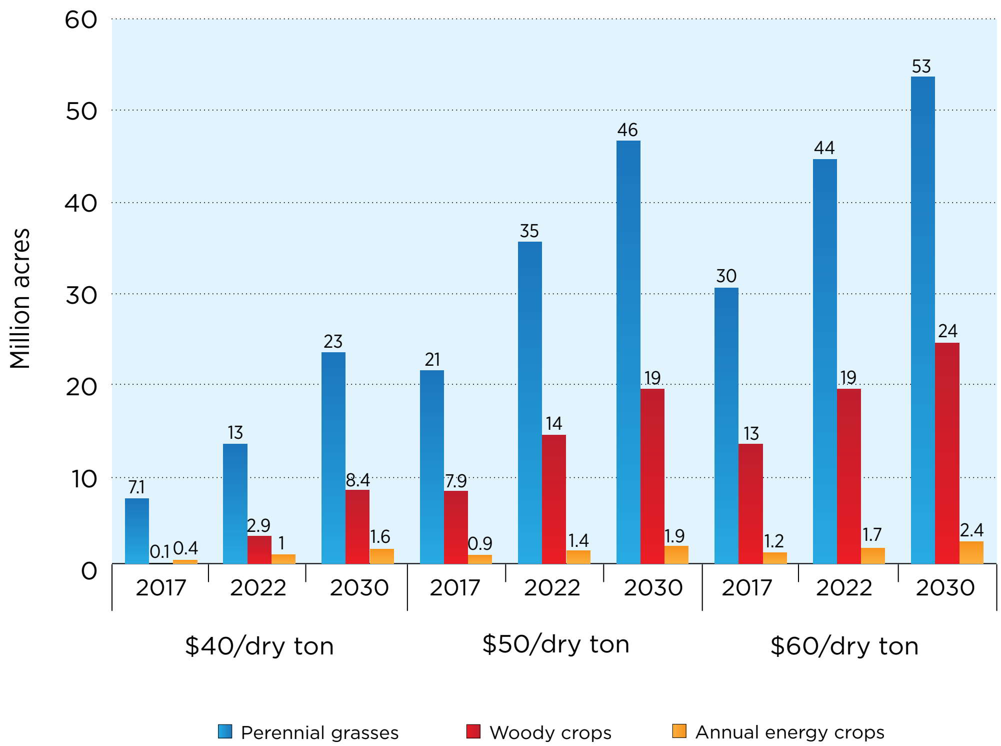
summarized in Figure 5.21. Relative to the baseline, total energy crop production in 2030 increases by 140 million dry tons at the 2% yield growth, 258 million dry tons at 3%, and about 400 million dry tons at 4%. Under the high-yield scenario across all assumed growth rates, perennial grasses account for slightly less than 60% of total energy crops in 2030, woody crop slightly less than 40%, and annual energy crops about 3% of the total. In 2022 and earlier, woody crops are proportionately less owing to assumed rotation lengths or cutting cycles.[64] Planted acres for the high-yield scenario under the 4% annual yield growth scenario are summarized in Figure 5.22. Total planted acres in 2030 are at the highest price 79 million with 53, 24, and 2.4 million in perennial grasses, woody crops, and annual energy crops, respectively. At the lowest simulated price, planted acres are much less, totaling about 32 million.

Figure 5.21 Perennial grasses, woody crops, and annual energy crops production for selected years in baseline and high-yield scenarios



[64] Additionally, because the costs to establish woody crops are relatively lower, high-yield growth scenarios may have a disproportionate effect on net returns of woody crops relative to herbaceous crops.

Figure 5.22 Planted acres in perennial grasses, woody crops, and annual energy crops for selected years and prices in high yield scenario with 4% annual energy crop yield growth



5.3.3 Land-Use Change and Economic Impacts

In this section, the estimated changes to land use from the collection of crop residues and the growing of energy crops are summarized. Associated changes in planted acres, crop prices, livestock production, inventories, and prices, and net returns to agriculture are also described. Potential economic impacts are within a range that is typical of normal market forces at lower simulated prices. At higher simulated prices and/or assumptions about yield growth, estimated changes in acres and crop prices are somewhat greater, but reasonable given the extent of land-use change.

Land-use change. The growing of energy crops and, to a lesser extent, the collection of crop residues changes the allocation of land among conventional crops. Under baseline conditions, energy crop production ranges from nearly 4 million dry tons in 2017 at a $40 per dry ton farmgate price to 400 million dry tons in 2030 at the highest simulated farmgate price ($60 per dry ton). The same farmgate price range makes 41 million dry tons (2017 at $40 per dry ton) to 180 million dry tons (2030 at $60 per dry ton) of corn stover, wheat straw, and other crops that are profitable to collect.

The land-use changes among conventional and energy crops under the baseline scenario are reported in Figure 5.23 for three farmgate prices and for years 2017, 2022, and 2030. There are a few clear observations. First, the acres displaced by energy crops increase over time as energy crops deploy. At the lowest simulated price, land-use change is limited to cropland. Wheat declines by 3.2 million acres over the baseline forecast by 2030, followed by soybeans at 0.5 million acres and corn at 0.3 million acres. Land planted in the five other major crops declines by about 0.8 million acres in total, with cotton (almost 0.4 million acres) and grain sorghum (almost 0.4 million acres) being the largest. Higher simulated farmgate prices move energy crops onto pasture. This result is clearly seen at the highest simulated price ($60 per dry ton) in Figure 5.23. By 2022, it is estimated that energy crops could displace 28 million acres of cropland used as pasture and permanent pasture. As energy crops deploy, this quantity of displaced pasture increases to more than 41 million acres by 2030 and is split almost equally between perennial grasses and woody crops. The amount of cropland displaced increases proportionately, with higher simulated prices and through time.

Figure 5.24 shows results of a simulation in which the rate of growth in energy crop yields were increased from 1% to 3% annually beginning in 2014 and in subsequent plantings. Results are as expected, with changes in crop acres much greater than under the baseline. In this simulation, higher yields move energy crops onto pasture at the lowest simulated price—slightly more than 16 million acres by 2030. However, at the higher simulated prices there are significantly more energy crops planted on pasture than under the baseline. At the highest simulated price, there are about 49 million acres of energy crops planted on pastureland, in addition to 30 million acres of cropland. This is a significant land-use change requiring pasture intensification to make up for lost forage. As recognized by participants in the high-yield workshops, understanding the competition for pastureland and seeking ways to improve pasture productivity are relevant avenues for research for this degree of land-use change.

Economic impacts. Changes in crop prices, planted acres, and crop net returns are summarized in Table 5.6 for the baseline scenario. The results shown for the baseline scenario assume a $50 per dry ton farmgate price for biomass feedstocks. Relative to the USDA projections, simulated results show a loss of crop acres to energy crops and higher crop prices for all major crops. For producers, the higher crop prices more than compensate for the loss in crop acres. This is reflected in higher net crop returns relative to the baseline as shown in Table 5.6. For consumers, however, these higher crop prices are one of the factors that affect food and feed prices. The same set of results is shown in Table 5.7 for the high-yield scenario, in which energy crop yields increase at an annual rate of 4%. Crop acres are generally somewhat lower than the baseline scenario results (Table 5.6), with most crop prices and net crop returns somewhat higher. The price of corn is lower due to the excess grain produced under this high-yield scenario.

Comparing the simulated results to the USDA projections shows only minor changes in total livestock production, beef cattle farm prices, and inventories of cattle. The key assumption is that increased forage productivity compensates for losses because of the presence of energy crops on pastureland.

Total net crop returns increase significantly under the baseline scenario where crop residues are collected and energy crops produced. Total net returns from livestock production decline by a relatively small amount. Overall, total net returns to agriculture increase by about $9.5 billion by 2030. Under the high-yield scenario, total net returns to agriculture are nearly $27 billion higher by 2030.

Figure 5.23 Land-use change under baseline assumptions for 2017, 2022, and 2030 at farmgate prices of $40, $50, and $60 per dry ton

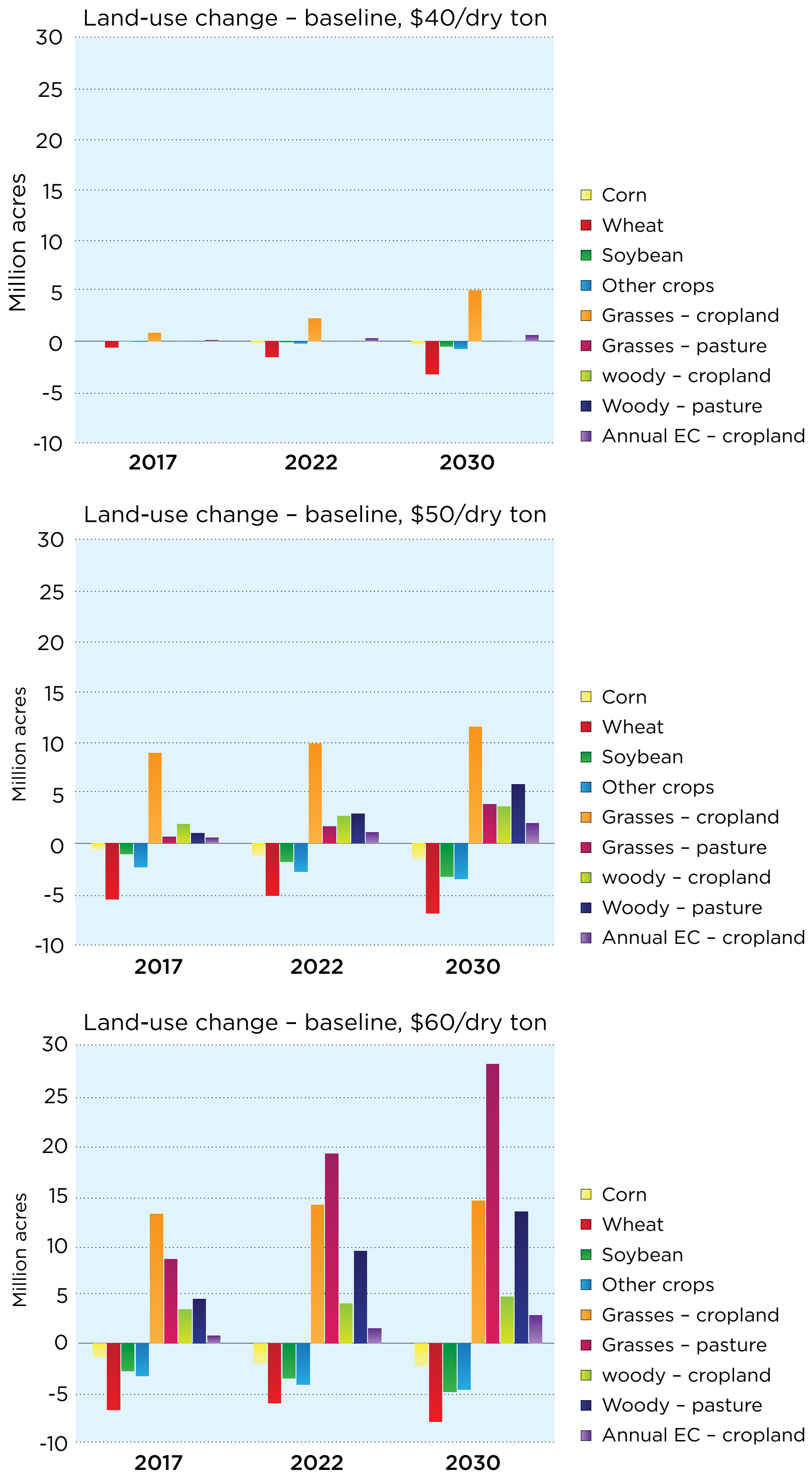


Figure 5.24 Land-use change under high-yield (3%) assumptions for 2017, 2022, and 2030 at farmgate prices of $40, $50, and $60 per dry ton

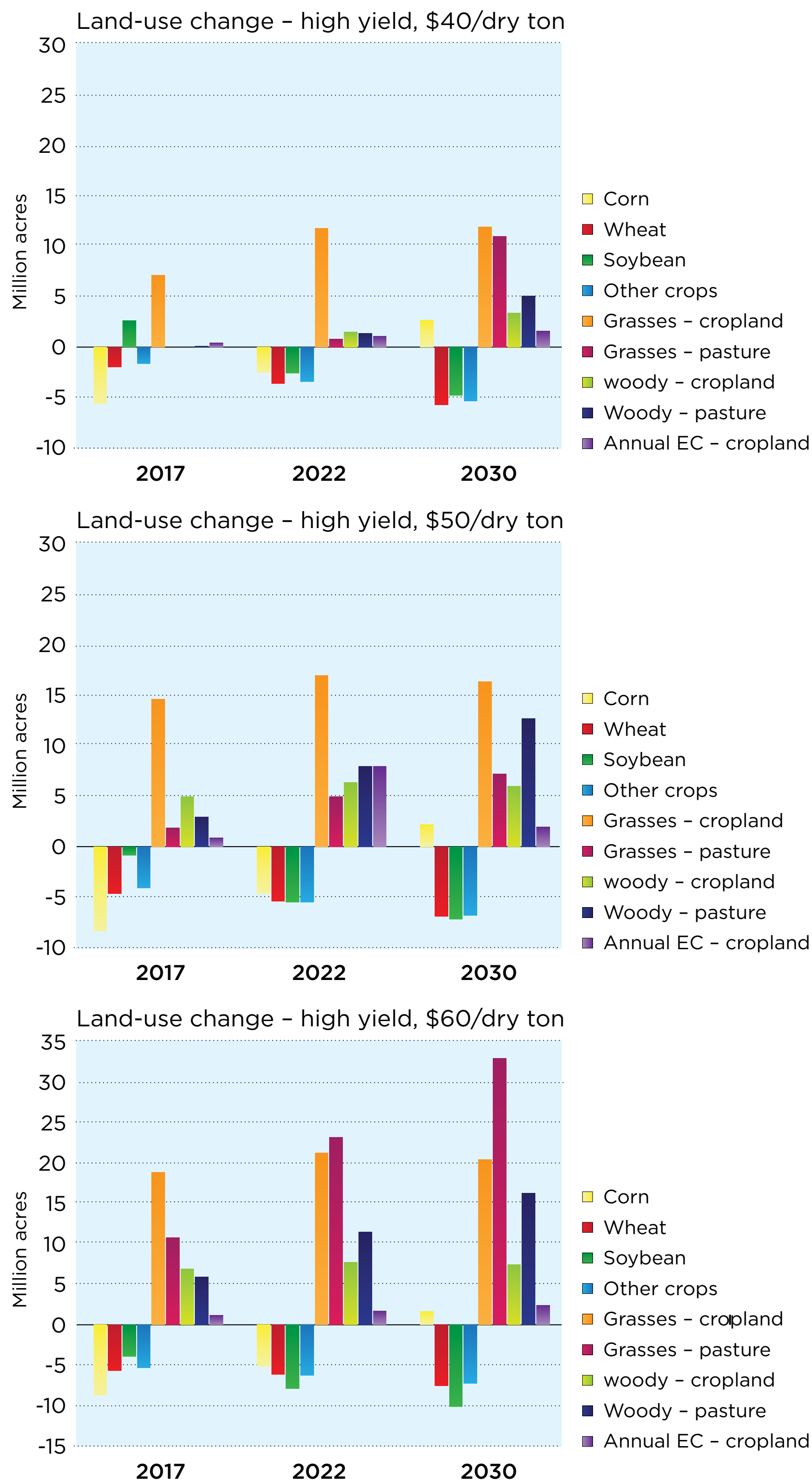


Table 5.6 Summary Comparison of USDA Projections for Major Crops with Baseline Projections for Biomass Resources Derived from Cropland and Pastureland, at $50 per Dry Ton Farmgate Price

Crop	USDA Baseline Forecast[1]				Baseline scenario		
	2012[1]	2017[1]	2022[2]	2030[2]	2017	2022	2030
Crop prices ($/bu)							
Corn	3.70	3.75	3.60	3.43	3.79	3.71	3.57
Grain Sorghum	3.30	3.35	3.20	3.79	2.89	3.71	3.57
Oat	2.35	2.35	2.28	2.11	2.37	2.39	2.32
Barley	3.90	3.95	3.79	3.36	4.27	4.39	3.89
Wheat	5.35	5.45	5.43	5.32	6.15	6.20	6.35
Soybean	8.70	8.75	8.42	7.92	8.95	8.72	8.44
Cotton ($/lb)	0.61	0.63	0.63	0.63	0.67	0.68	0.68
Rice ($/cwt)	10.60	11.78	12.20	12.46	13.31	13.76	13.80
Crop acres (millions)							
Corn	90	90.5	89.35	87.69	89.9	88.1	86.2
Grain Sorghum	7.5	7.4	7.24	7.05	6.8	6.2	5.7
Oat	3.4	3.4	3.4	3.34	3.3	3.3	3.1
Barley	4.0	4.0	3.97	3.85	3.8	4.0	3.9
Wheat	60.5	59.5	59.73	61.06	54.0	54.6	54.2
Soybean	71.5	71.0	70.2	68.0	69.9	68.4	64.7
Cotton	9.7	10.2	10.47	10.81	9.0	9.2	9.1
Rice	3.0	3.1	3.1	3.1	2.8	2.8	2.8
Crop net returns (millions)							
Corn	25,441	28,383	27,430	26,564	29,153	29,182	29,074
Grain Sorghum	446	433	351	205	593	519	459
Oat	73	75	61	33	77	72	51
Barley	463	499	461	337	563	614	507
Wheat	6,213	6,706	6,619	6,347	7,923	8,013	8,252
Soybean	17,801	18,931	18,480	17,494	19,373	19,153	18,643
Cotton	1,370	1,475	1,400	1,222	1,498	1,451	1,365
Rice	1,092	1,523	1,628	1,702	1,794	1,927	1,979
Livestock							
Total production (million lbs)	**25,763**	**27,395**	**27,972**	**27,970**	**27,497**	**28,059**	**28,066**
Price ($/cwt)	104	106	105	105	106	105	105
Inventory (1000 head)	93,241	96,847	102,410	110,766	96,834	102,362	110,669
Total crop net returns (millions)	**49,593**	**54,424**	**52,203**	**49,603**	**59,183**	**59,081**	**59,569**
Total Livestock net returns (millions)	**115,413**	**124,240**	**127,914**	**123,479**	**124,069**	**127,645**	**123,004**
Total agriculture net returns (millions)	**165,006**	**178,664**	**180,117**	**173,082**	**183,252**	**186,726**	**182,573**

[1] Source: USDA -OLE/WAOB, 2009

[2] Extended baseline

Table 5.7 Summary Comparison of USDA Projections for Major Crops with High-Yield Projections for Biomass Resources from Cropland and Pastureland, at $50 per Dry Ton Farmgate Price

Crop	USDA Projections[1]				High-Yield scenario		
	2012[1]	2017[1]	2022[2]	2030[2]	2017	2022	2030
Crop prices ($/bu)							
Corn	3.70	3.75	3.60	3.43	2.87	3.04	3.01
Grain Sorghum	3.30	3.35	3.20	2.89	2.87	3.04	3.01
Oat	2.35	2.35	2.28	2.11	1.88	2.09	2.50
Barley	3.90	3.95	3.79	3.36	4.05	4.39	4.26
Wheat	5.35	5.45	5.43	5.32	5.62	6.16	6.80
Soybean	8.70	8.75	8.42	7.92	8.75	9.50	9.77
Cotton ($/lb)	0.61	0.63	0.63	0.63	0.67	0.70	0.72
Rice ($/cwt)	10.60	11.78	12.20	12.46	13.69	14.03	15.69
Crop acres (millions)							
Corn	90.0	90.5	89.4	87.7	82.1	84.7	89.9
Grain Sorghum	7.5	7.4	7.2	7.1	5.0	4.3	4.2
Oat	3.4	3.4	3.4	3.3	3.3	3.0	2.7
Barley	4.0	4.0	4.0	3.9	3.9	3.8	3.6
Wheat	60.5	59.5	59.7	61.1	54.9	54.4	54.2
Soybean	71.5	71.0	70.2	68.0	70.2	64.7	60.8
Cotton	9.7	10.2	10.5	10.8	9.1	8.8	8.3
Rice	3.0	3.1	3.1	3.1	2.7	2.7	2.6
Crop net returns (millions)							
Corn	25,441	28,383	27,430	26,564	21,045	28,764	35,765
Grain Sorghum	446	433	351	205	184	144	71
Oat	73	75	61	33	29	35	46
Barley	463	499	461	337	518	588	491
Wheat	6,213	6,706	6,619	6,347	6,968	7,796	8,693
Soybean	17,801	18,931	18,480	17,494	19,053	20,535	20,332
Cotton	1,370	1,475	1,400	1,222	1,718	1,889	1,611
Rice	1,092	1,523	1,628	1,702	1,874	1,961	2,182
Livestock							
Total production (million lbs)	**25,763**	**27,395**	**27,972**	**27,970**	**27,462**	**28,044**	**28,002**
Price ($/cwt)	104	106	105	105	104	104	105
Inventory (1000 head)	93,241	96,847	102,410	110,766	97,471	102,698	110,877
Total crop net returns (millions)	**49,593**	**54,424**	**52,203**	**49,603**	**52,396**	**65,335**	**77,896**
Total Livestock net returns (millions)	**115,413**	**124,240**	**127,914**	**123,479**	**124,415**	**127,333**	**121,944**
Total agriculture net returns (millions)	**165,006**	**178,664**	**180,117**	**173,082**	**176,811**	**192,668**	**199,813**

Note: *High-yield scenario is 3% yield increase annually.*

[1] Source: USDA -OLE/WAOB, 2009

[2] Extended baseline

5.4 Total Potential Supply of Biomass Energy Crops

Table 5.8 shows the estimated supplies of energy crops at three simulated prices. Over the $20 per dry ton price range, estimated supplies vary from a low of about 34 million dry tons in 2030 to 400 million dry tons at the highest simulated price. Results are also shown for high-yield scenarios. Estimated supplies increase from 69 to 540 million dry tons for $40 to $60 per dry ton, assuming energy crop productivity increases 2% annually. The high-yield scenario at the 3% and 4% annual change in crop productivity increases potential supply to 658 and nearly 799 million dry tons by 2030, respectively.

5.5 Summary

Results were reported for three major classes of energy crops—perennial grasses, woody crops, and annual energy crops. Each of these crop classes must compete for land with existing uses and with each other. The existing uses are crops on cropland and forage on pastureland. Energy crops must offer higher net returns to displace crops on cropland. For pastureland, energy crop returns must be greater than the rental value of the pastureland plus additional intensification costs to make up for lost forage. In assessing the relative profitability of energy crops, the most important data relate to crop yield. In this assessment, annual energy crop yields assumed vary considerably across the United States, ranging from 2 to 9.5 dry tons per acre for perennial grasses, 3.5 to 6 dry tons per acre for woody crops, and 6 to 9 dry tons per acre for annual energy crops. These baseline yields for perennial grasses and woody crops are well within observed test plot yields. However, these estimates are based on rather limited field trial data even for species that have had relatively more attention, such as switchgrass. Additional field trial data are clearly needed to develop more precise spatial estimates of yield and how these yields might vary according to land use (cropland or pastureland) within a county. Further, additional field trial data are lacking for more regionally specific species, such as energy cane, as well as annual energy crops.

In addition to the yield data, the estimation of potential energy crop supplies identified several needs; these are summarized next:

- The modeling of energy crops assume all pastureland is currently used by the livestock sector and lost forage from displaced pastureland must be made up. In POLYSYS, lost forage is made up through pasture intensification, which is assumed possible where there is sufficient rainfall or in counties east of the 100th meridian and the Pacific Northwest. Additional research is needed on the implications of pasture displacement by energy crops, as well as to determine the intensity of current pastureland use and whether in fact all pastureland is currently used as forage.
- The analysis assumes energy crops become available for planting in 2014. This decision assumes two to three years are required for energy crop planting material to become available for large-scale deployment. Additional study is needed to understand more fully the requirements for commercial scale-up.
- At the highest simulated prices reported in the study ($60 per dry ton), about 60 million acres of cropland and pastureland could potentially convert to energy crops under the baseline scenario and up to 80 million acres under the high-yield scenario. This is a considerable amount of land use change requiring the annual establishment of many millions of acres. Although these levels of annual acre changes are within what has been seen for the major commodity crops, there is a need to understand more fully potential economic and environmental impacts associated with potential land use changes of this magnitude.

- The analysis assumes energy crops are grown under rain-fed conditions without any supplemental irrigation. This assumption overlooks potential opportunities to use wastewater and processing water especially in western areas of the United States where growing of energy crops without supplemental water is limited. There is a need to evaluate this potential.
- Potential energy crop supplies were estimated at the farmgate. This assumption makes for a clear point of comparison with the existing land uses (i.e., comparing energy crop net returns with conventional commodity crops). However, the energy crops have different supply chains and stopping the analysis at the farmgate can bias results to those energy crops requiring additional processing and storage.

Table 5.8 Summary of Baseline and High-Yield Scenario Availability of Energy Crops

	<$40 per dry ton			<$50 per dry ton			<$60 per dry ton		
Feedstock	2017	2022	2030	2017	2022	2030	2017	2022	2030
Baseline scenario					*(Million dry tons)*				
Perennial grasses	3.0	12	30	41	77	129	90	188	255
Woody crops	0.0	0.0	0.1	0.9	40	67	5.7	84	126
Annual energy crops	0.7	1.8	4.2	3.8	7.3	14	5.0	10	19
Total	**3.7**	**14**	**34**	**46**	**124**	**210**	**101**	**282**	**400**
High-Yield (2% annual growth)									
Perennial grasses	11	43	57	67	152	239	122	253	319
Woody crops	0.0	0.1	4.2	1.9	78	127	10	145	207
Annual energy crops	1.6	4.1	7.4	5.5	8.7	12	6.9	11	15
Total	**13**	**47**	**69**	**75**	**239**	**378**	**139**	**409**	**540**
High-Yield (3% annual growth)									
Perennial grasses	24	71	107	85	213	329	138	296	390
Woody crops	0.0	1.5	43	9.3	101	186	14	168	251
Annual energy crops	2.4	6.6	11	6.2	10	14	8.0	12	18
Total	**26**	**79**	**162**	**101**	**324**	**520**	**160**	**476**	**658**
High-Yield (4% annual growth)									
Perennial grasses	35	100	202	106	270	406	154	338	462
Woody crops	0.1	5.3	45	12	118	199	16	212	315
Annual energy crops	3.4	9.0	14	6.8	11	18	9.4	14	22
Total	**39**	**114**	**261**	**124**	**399**	**622**	**180**	**564**	**799**

Note: *Totals may not add up due to rounding.*

6 SUMMARY

As noted at the outset, a major limitation of the 2005 *BTS* is that the identified biomass is not restricted by cost, and some of the potential would likely be too expensive relative to other renewable feedstocks under current and prospective technological changes. This update attempts to estimate biomass supplies (costs and quantities) of feedstocks identified in the 2005 *BTS*. For the major primary resources, estimates are made at a county level and summarized in this report as national totals. For some resources, such as processing residues and wastes, only state-level estimates can be developed.[65]

The 2005 *BTS* combined resources that are currently used for energy production with unused and prospective resources because they all counted toward the billion-ton goal. In this update, a clearer distinction is made between currently used resources (e.g., corn grain, soybeans, pulping liquors, mill residues, and fuelwood) and unused and prospective resources available for additional energy (such as feedstock needed to meet the EISA RFS targets of 16 BGY of cellulosic biofuels and 4 BGY of other advanced biofuels by 2022).

This updated resource assessment treats environmental sustainability much more comprehensively and rigorously than the approach taken in the 2005 *BTS*. For primary crop residues, sustainability is explicitly modeled, accounting for soil erosion and carbon. The sustainability of forest residue harvests, which is defined as maintaining sufficient amounts of residue onsite to maintain soil productivity and prevent erosion, was accounted for at the individual forest plot level. For energy crops, costs generally assume application of BMPs. Land-use change associated with the growing of energy crops is evaluated at a county level using the POLYSYS modeling framework. The POLYSYS model allocates land to the most profitable activities and tracks changes in crop prices for the eight major crops (corn, grain sorghum, oats, barley, wheat, soybeans, cotton, and rice); production quantities for food, feed, and industrial uses; exports; and crop and livestock income. When energy crops displace cropland (i.e., any of the eight major crops), cropland used as pasture, or permanent pasture, it implies that they are more profitable. Generally, energy crops are planted on the more marginal cropland and pastureland.

As discussed in previous chapters, the POLYSYS model is anchored to the USDA projections. As such, POLYSYS simulation results are conditioned by the accuracy of the baseline forecast. POLYSYS results also depend on a host of county-level databases developed by a number of sources, such as NASS (National Agricultural Statistics Service) and the Census of Agriculture, as well as databases that relate to energy crop yields, hay and pasture acres, and productivity. Although an attempt was made to use the best available data, there is still a great deal of uncertainty that cannot be overcome without a concerted effort to develop new data; for example, research underway by the Regional Feedstock Partnership, or through the development of new data sources (e.g., use of remotely sensed data). Finally, the POLYSYS model is deterministic and thus does not allow one to provide confidence intervals around model output. Results are thus presented as point estimates and should be interpreted with all the appropriate caveats related to data uncertainty. The remainder of this chapter summarizes the resource assessment for the baseline and high-yield scenarios.

[65] A separate database containing the disaggregated biomass supplies by county and state is available through the Bioenergy Knowledge Discovery Framework (http://bioenergykdf.net/) with other data for users to capture, visualize, and analyze information on the complete bioenergy supply chain and the infrastructure needed to support that chain (ORNL, 2010).

6.1 Baseline Estimates

Under baseline assumptions, the current combined resources from forests and agricultural lands range from about 138 to nearly 258 million dry tons at forest roadside or farmgate prices from $40 to $60 per dry ton (Table 6.1). The combined forest and agricultural resource supply increases to 187 to 602 million dry tons by 2022 over the $40 to $60 per dry ton price range and to 243 to 767 million dry tons by 2030 at the same prices. The forest resources are estimated with and without the inclusion of resources from federally owned land. This consideration affects the total by about 5 to 7 million dry tons.

The estimated quantities in Table 6.1 only show supplies available at forest roadside or farmgate prices of $40 to $60 per dry ton.[66] Additional resources are available at higher prices. Further, Table 6.1 only shows biomass resources that are currently unused and do not include resources now used for energy. These currently unused resources are potentially available for conversion into biofuels and biopower.

Figure 6.1 summarizes the estimated baseline resources for each major biomass source—forest residues and wood wastes, agricultural residues and wastes, and energy crops. The results of this update find that there are potentially sufficient biomass feedstocks to meet EISA and RFS mandates, provided that viable, efficient conversion and transport systems are available.[67] For 2022, under baseline assumptions, a combination of forest and agricultural residues and energy crops could meet 20 BGY of cellulosic and advanced biofuels at a forest roadside or farmgate price of $50 per dry ton or less. This assumes a conversion rate of 85 gallons per dry ton (U.S. Department of Energy, 2011). At higher simulated prices, significantly more feedstock is available for conversion into biofuel. The secondary axis in Figure 6.1 shows the conversion of these resources into biopower. The year 2022 supply at a simulated price of $60 per dry ton equates to potentially 590 billion kWh of electricity assuming a heat rate of about 13,000 Btu per kWh. By 2030, sufficient feedstock is available to generate potentially 750 billion kWh. As summarized next, changes in the baseline crop yield assumptions can dramatically increase the resource potential.

6.2 High-Yield Estimates

The high-yield scenario increases the proportion of corn in reduced and no-till cultivation and increases corn yields to about double the current rate of annual increase. For energy crops, the high-yield scenario increases the annual rate of crop productivity growth from 1% to 2%, 3%, and 4% annually. No high-yield scenario is evaluated for forest resources, except for the woody crops. Forest residues come from existing timberlands, and there is no obvious way to increase volumes other than reducing fractions left behind to meet environmental sustainability, which is not recommended.

Table 6.2 summarizes the estimated (unused) quantities of forestland, agricultural land, and energy crop resources at an assumed price of $60 per dry ton. Results are presented for three assumptions about annual energy crop yield growth: 2%, 3%, and 4%. The agricultural residues estimate assumes higher proportions of reduced and no-till cultivation, as well as higher corn grain yields. The forest residue and waste estimates total about 100 million dry tons by year 2022, only slightly higher than the 2012 estimates. The agricultural residues and wastes total 244 million

[66] Inclusion of the currently used biomass resources identified in Chapter 2 would increase the year 2030 total quantity to nearly 1.1 billion dry tons (an amount that approaches what was found in the 2005 *BTS* under the high-yield scenario).

[67] Table 6.1 and 6.2 quantities account for losses in collection or harvesting and handling to the farmgate or forest roadside. They do not account for additional losses that may occur in storage, transportation, and handling to conversion facilities. The estimates in Figure 6.1 and 6.2 reflect additional losses of 20%. These additional losses could be lower depending on the specifics of feedstock supply chain, length of storage, handling, and other factors.

dry tons currently, which include about 51 million dry tons of secondary residues and wastes (the amount as in the baseline scenario). In 2022, the total agricultural resources approach 350 million dry tons due to higher corn yields and additional acres in no-till and exceed 400 million dry tons by 2030. By 2022, the energy crops are the largest potential source of biomass feedstock. As shown in Table 6.2, potential energy crop supplies vary considerably depending on what is assumed about productivity. At a 2% annual growth rate, energy crops total 139, 409, and 540 million dry tons per year in 2017, 2022, and 2030, respectively. Potential energy crop supplies at the 3% productivity growth rate increase to 476 and 658 million dry tons in years 2022 and 2030, respectively, and for the 4% annual yield increase to 564 million dry tons in 2022 and 799 million dry tons in 2030. In total, potential supplies at a forest roadside or farmgate price of $60 per dry ton range from 856 to 1009 million dry tons by 2022 and from about 1047 to 1304 million dry tons by 2030, depending on what is assumed about energy crop productivity (2% to 4% annual increase over 2014 yields).

This feedstock potential under the high-yield assumptions at a $60 per dry ton price offers enough feedstock to produce up to nearly 70 BGY of biofuels by 2022 and substantially more by 2030 (Figure 6.2). Alternatively, biomass resources are large enough to potentially produce almost a trillion kWh by 2022 with much higher quantities by 2030.

Table 6.1 Summary of Available Forest and Agriculture Biomass at Selected Prices and Years under Baseline Assumptions (in Millions)

	<$40 per dry ton				<$50 per dry ton				<$60 per dry ton			
Feedstock	2012	2017	2022	2030	2012	2017	2022	2030	2012	2017	2022	2030
	Million dry tons											
Forest resources												
Primary forest residues – all land	48	49	44	50	51	51	52	52	57	58	58	59
Primary forest residues without federal land	44	44	45	45	46	46	47	47	50	51	51	52
Forest processing residues and wastes	31	32	32	34	40	41	42	43	40	41	42	44
Total forest & wood wastes resources	**79**	**81**	**82**	**83**	**91**	**92**	**93**	**95**	**97**	**98**	**100**	**102**
Total without federal land	74	76	77	79	85	87	88	90	90	92	93	95
Agricultural resources												
Crop residues (major crops)	27	41	52	80	94	117	136	164	111	135	154	180
Agriculture processing residues and wastes	31	36	40	46	50	56	65	82	51	58	67	84
Total agricultural residues & wastes	**59**	**77**	**92**	**126**	**143**	**174**	**201**	**245**	**162**	**192**	**221**	**265**
Energy crops[1]												
Perennial grasses	-	3.0	12	30	-	41	77	129	-	90	188	252
Woody crops	-	0.0	0.0	0.1	-	0.9	40	67	-	5.9	84	126
Annual energy crops	-	0.7	1.8	4.2	-	3.8	7.3	14	-	5.0	10	19
Total energy crops	**-**	**3.7**	**14**	**34**	**-**	**46**	**124**	**210**	**-**	**101**	**282**	**400**
Total with all land	**138**	**161**	**187**	**243**	**234**	**311**	**418**	**551**	**258**	**392**	**602**	**767**
Total without federal land	134	157	182	238	229	306	413	545	252	385	595	760

Note: *The total forest supply is 239 to 251 million dry tons at the highest price to roadside.*

Figure 6.1 Summary of potential bioenergy supply from forest and agriculture residues and wastes and energy crops at selected prices and years under baseline assumptions

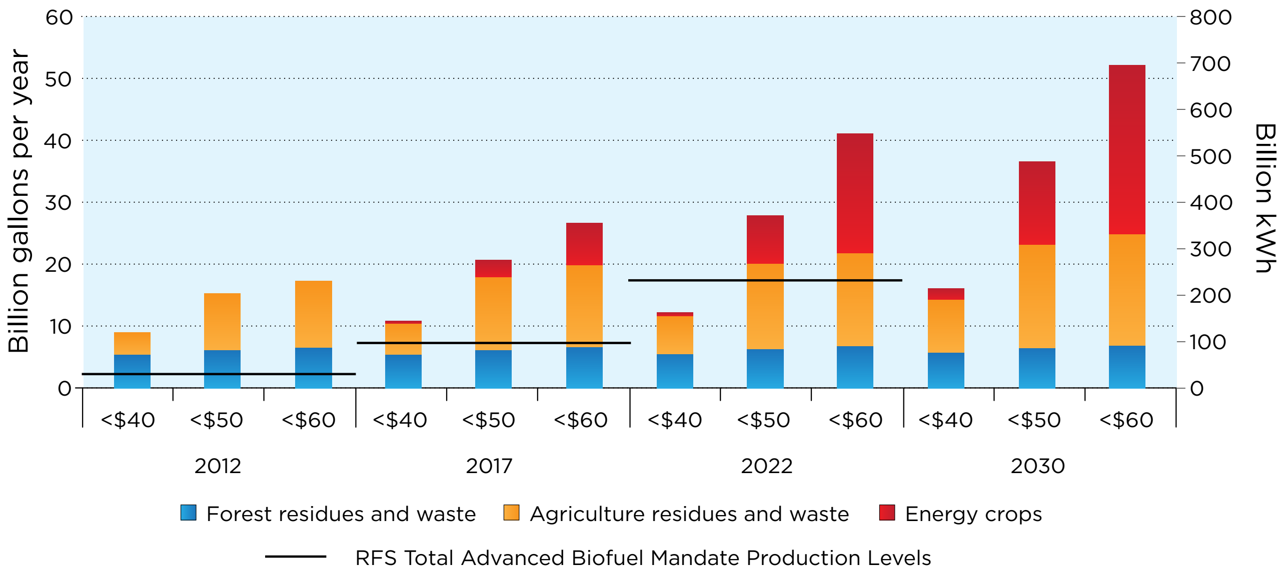
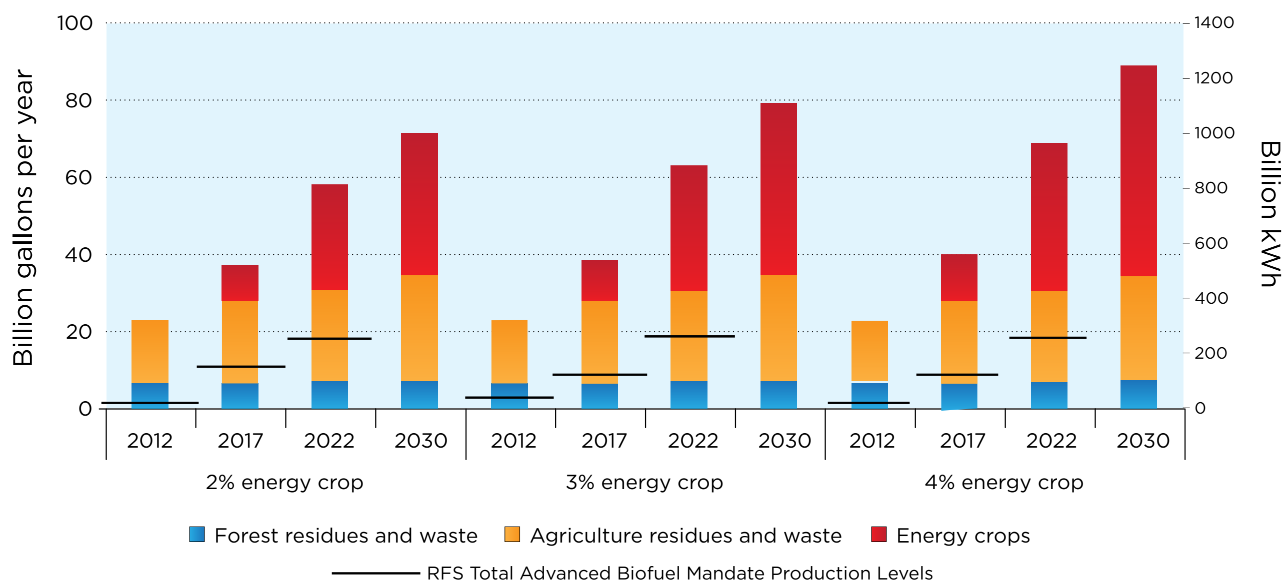


Table 6.2 Summary of Available Forest and Agriculture Biomass at $60 per Dry Ton under High-Yield Assumptions

	2% energy crop				3% energy crop				4% energy crop			
Feedstock	2012	2017	2022	2030	2012	2017	2022	2030	2012	2017	2022	2030
	Million dry tons											
Total forest & wood wastes resources	97	98	100	102	97	98	100	102	97	98	100	102
Total agricultural residues & wastes	244	310	347	405	244	310	346	404	244	307	346	403
Total energy crops	-	139	409	540	-	160	476	658	-	180	564	799
Total	**340**	**548**	**856**	**1,047**	**340**	**568**	**922**	**1,164**	**340**	**586**	**1,009**	**1,304**

Note: *totals may not add up due to rounding.*

Figure 6.2 Summary of potential bioenergy supply from available forest and agriculture biomass at $60 per dry ton under high-yield assumptions



6.3 Report Implications and Further Discussion

6.3.1 Other Assessments

National. Since the publication of the 2005 *BTS*, there has been a proliferation of biomass assessments at various spatial scales, from the state-level to the global level. For example, a Forest Service website lists 30 states with some type of woody biomass assessment and three major regional studies (U.S. Forest Service, 2011b). Many states also have an agricultural biomass resource assessment and some include forest resources. Some assessments go into great detail. As an example, in a study completed for the State of Washington by Oneil and Lippke (2009), field surveys of forest residues on federal, state, and private lands were conducted to develop a model for logging residues as a function of harvest volume.

A recent economic biomass assessment estimates that about 700–1000 million dry tons of agricultural biomass will be available in 2030 at a price up to about $130 per dry ton under various costs, land, and yield scenarios (Khanna et al., 2011). The biomass availability estimates are similar to the *BTS* update; however, at higher prices and a different mixture of feedstocks. The timeline is 2007–2030 for this report whereas the update timeline is 2012–2030. At a comparable $60 per dry ton with the transport costs removed, the report estimates range from about 450 to 780 million dry tons. The study does not include wood, nor does it include any currently used biomass. This will compare to about 250–1300 million dry tons in the update at $60 per dry ton over the range of scenarios and up to 2030.

Parker et al. (2011) use a spatially specific supply model to assess the potential for large-scale biofuels production in the United States. The report includes the same feedstocks as in the update, except it includes more than just wood from MSW and has less optimistic energy crop assumptions. The analysis includes an assessment developed by the authors for 2018 and another assessment using the updated *BTS* baseline assessment data for 2022. For the developed assessment, a low-, baseline-, and high-yield scenario result in about 317, 533, and 797 million dry tons, respectively, at a maximum roadside cost of $200 per dry ton. However, for the baseline scenario, a majority of the MSW and agricultural and forestry residues become available at less than $70 per dry ton, and energy crops are available at costs between $80 and $120 per dry ton. The model is then used to determine the amount of biofuels volumes available using the *BTS* update data, where the biorefineries would be distributed to meet the RFS.

An analysis of the biomass demand for meeting both a theoretical 25% RFS and a 25% RES (renewable electricity standard) by 2025 estimates a need for 1,302 million green tons from agricultural and forestry residues, urban wood wastes, and energy crops (EIA, 2007a). Sample et al. (2010) compare the estimated demand to a Department of Energy supply estimate of 491 million dry tons (approximately 715 million green tons). The available supply is based on several assumptions, including a high energy cost of $5 per million Btu. The limited amount of available biomass is projected to result in a significant shortfall that will be made up from using roundwood (i.e., wood from the bole of trees rather than limbs, tops, and other wastes). The updated *BTS* estimates approximately 980–1440 total dry tons available in 2025 at a price of $60 per dry ton, which may not result in such a large shortfall if the market supports that price. However, these estimates include "currently used" biomass and no differentiation as to what biomass is available to meet a specific target or use.

Table 6.3 Estimate of U.S. Cellulosic Biomass by 2020 (NAS, 2009)

Feedstock	Millions of dry tons
Corn stover	112
Wheat and grass straw	18
Hay	18
Dedicated energy crops	164
Woody	124
Animal manure	12
MSW	100
Total	**548**

The National Academy of Sciences (NAS, 2009) completed an assessment of biomass for energy and reports that approximately 550 million dry tons per year of cellulosic biomass can be produced by 2020 without any major impact on food production or the environment (see Table 6.3). The estimate does not include corn for ethanol and oil crops for biodiesel. The Academy estimates compare very well to the updated *BTS* for the baseline when the currently used biomass is removed.

International. The Biomass Energy Europe organization invests considerable efforts in standardizing biomass assessments (Rettenmaier, 2010). A comparison of over 150 studies in the European Union concludes that nearly all of the assessments are technical and economic potential studies as compared to the theoretically maximum. The studies are resource based and include land-use competition for biomass with other uses. The deviations in estimated total potentials among these studies are substantial, with differences up to five fold. The authors attribute the large deviations to varying methods, data, and assumptions with the latter being the most significant source of differences, especially the assumptions regarding land availability for energy crops. The updated *BTS* uses the POLYSYS model to handle this specific issue, but as explained below, assumptions are very important. Scenarios are used to better present and compare underlying assumptions in the update.

Bauen et al. (2009) estimate that biomass can theoretically provide between one-quarter and one-third of the global primary energy supply by 2030 (see Table 6.4), even when factoring in land use and raw material competition. The current estimate is that biomass supplies about 50 exajoules of primary energy (heating value) (calculated[68] to be about 3.2 billion dry tons). This is mostly conventional biomass that is used for heating and cooking in developing countries. An optimistic estimate of the technical potential of sustainable biomass by 2050 is between 200 and 500 exajoules per year (roughly 12–31 billion dry tons).

[68] Assumes 63 million dry tons per exajoule, which is based on an average of 15 million Btu/dry ton.

There are many biomass assessments at different spatial and technical levels. The updated *BTS* provides a national-to-county-level economic biomass availability analysis for all agricultural and forest lands. The results from the update roughly align with other assessments, but the underlying assumptions vary and must be addressed in any comparison.

Table 6.4 Estimate of Global Biomass Potential by 2030 (Bauen et al., 2009)

Region	Energy crops (M acres)	Dry tons (Billion)
Europe	62-222	0.4-1.5
USA 2005 *BTS*	74	1.1
USA 2011*BTS*	63	1.4
Latin America	299	1.5
China & India	212	1.7
Australia	-	<4M

Notes: *Timeframes are 2017–2030. 2011 BTS added at $60/ton for 2030 with 2% scenario. Conversion to dry tons based on 63 million tons per exajoule.*

6.3.2 Significance of Underlying Assumptions

Scenarios. This update report evaluates two scenarios—baseline and high-yield. The baseline scenario assumes a continuation of the USDA 10-year baseline forecast for the major food and forage crops plus a 10-year extension to 2030. The USDA projections are based on specific assumptions about macroeconomic conditions, policy, weather, and international developments, with no domestic or external shocks to global agricultural markets (USDA-OCE/WAOB, 2010). It is a USDA long-term scenario for the agricultural sector based on a continuation of current policies and programs. Changes in any of the key fundamental assumptions underlying the baseline, such as economic growth, population, trade projections, or biofuels policy, will affect the projections. It is intended as a reference or business-as-usual case.

Over the 20-year simulation period, the average annual corn yield increase is slightly more than 1%. The baseline scenario, as implemented in this update, assumes a mix of tillage with a trend toward no-till and reduced tillage cultivation over the simulation period (see Table 4.4). Corn yield and tillage are two of the key determinants of stover availability, the largest single source of currently available biomass residue. Energy crop yields in the baseline scenario assume an annual increase of 1% that reflects learning or experience in planting energy crops and limited gains attained through breeding and selection of better varieties and clones.

In contrast, the high-yield scenario assumes higher corn yields and a much larger fraction of crop acres in reduced and no-till cultivation. The projected increase in corn yield averages almost 2% annually over the 20-year simulation period. The energy crop productivity increases are modeled at three levels—2%, 3%, and 4% annually. These gains are due not only to experience in planting energy crops, but also to more aggressive implementation of breeding and selection programs. Only a baseline scenario is assumed for forest biomass, as these residues are contingent on the demand for pulpwood and sawlogs with future projections based on RPA projections of timber harvests.

As discussed, the baseline scenario and underlying assumptions used in this resource assessment are generally conservative and essentially reflect a continuation of current trends with respect to commodity crop yields, planted acres, and current and projected demand for pulpwood and sawlogs. The high-yield scenario examines alternative assumptions about yield growth and the mix of tillage. In combination with market price, yield is the key determinant of resource availability, and tillage affects how much crop residue can be sustainably removed.

Yield. Annual energy crop yields assumed for the baseline scenario vary considerably, ranging from 2 to 9.5 dry tons per acre for perennial grasses, 3.5 to 6 dry tons per acre for woody crops, and 6 to 9 dry tons per acre for annual energy crops (Tables 5.3 and 5.4). These baseline yields for perennial grasses and woody crops are well within observed test plot yields (See Section 5.1) and for specific crops (e.g., switchgrass).[69] The baseline results for 2030 at a $60 per dry ton farmgate price (1% annual yield growth for plantings after year 2014) show a national average perennial grass harvested yield of 6 dry tons per acre, slightly less for woody crops, and 6.8 dry tons per acre for the annual energy crop. Results for the high-yield scenario in 2030—assuming the same farmgate price and a 3% annual yield growth—have perennial grass harvested yields increasing to a national average of 7.7 dry tons per acre, the same for woody crops, and 8.5 dry tons per acre for the annual energy crop. These yields are a national average based on harvested acres of energy crops in 2030.

Tillage. A number of key modeling assumptions involve tillage. The baseline assumes a combination of conventional, reduced, and no-till cultivation (see Table 4.4). Over the simulation period, a small fraction of corn acres shift into reduced and no-till. These tillage changes are relatively restrained, as about one-third of corn acres will still be in conventional tillage by 2030 and will be restricted from residue collection. Under the high-yield scenario, a much larger fraction of acres are assumed to shift from conventional tillage to no-till. The tillage proportions assumed in the high-yield scenario recognize that some corn acres will never shift from conventional tillage owing to farmers' resistance to change; the potential for disease and weed control problems; and soil wetness issues in some situations. By comparison, the high-yield scenario in the 2005 *BTS* assumed 100% no-till.

Management practices and input costs. No attempt was made to conduct sensitivity analysis on management practices and input costs as the intent is to understand the resource potential, which is largely driven by yield and, in the case of crop residues, by tillage restrictions in addition to crop yield. For example, a reduction in crop residue collection costs owing to technology improvement will tend to shift supply curves down, thus making residue collection more profitable at lower farmgate prices. However, this modeled reduction in costs will not substantially change the reported quantities at the higher simulated prices.

Time of implementation. Throughout this report, currently used and unused resources, such as crop and forest residues, are reported for 2012 and for selected years through 2030. For energy crops, simulation modeling of these prospective resources is assumed to begin in 2014 with initial results reported in 2017. The 2017 results do not include woody crops because of the 4- and 8-year cutting cycles or rotation lengths. As noted in Chapter 5, year 2014 is perhaps the earliest time when seeds and other planting materials will be readily available, assuming it will take 3 years to scale-up nursery operations. Results of model simulations show delays in the 2014 start date will shift estimated supply curves in time.

Energy crop demand for resources. Perennial grasses and woody crops generally require less fertilizer, pesticides, and fossil fuel than the commodity crops they displace—with the exception of the annual energy crops, which require about the same level of inputs. However, perennial grasses and woody crops are more intensive than pasture, requiring more fertilizer and pesticides, especially during crop establishment.

Modeling of land-use change. Land-use change is principally affected by the presence of simulated markets (and prices) for energy crops. To be sure, some land-use change is associated with crop residue collection, but this amount is much less than the displacement of commodity cropland and pastureland

[69] For example, average annual yields for switchgrass ranged from about 4 to 10 dry tons per acre, with most locations having an average between 5.5 and 8 dry tons per acre (McLaughlin and Kszos, 2005; BRDI, 2008). For woody crops, annual yields have been generally 5 dry tons per acre in most locations with the exception of the Pacific Northwest and subtropics (eucalyptus) where they have been higher.

by energy crops. Land-use change is modeled by POLYSYS, which allocates land to competing crops based on net returns. If model results show a given commodity crop in a particular county displaced by an energy crop, then the energy crop is more profitable. In the case of pasture, energy crop returns must be greater than the rental value of the pastureland plus additional 'intensification' costs to make up for lost forage. A key assumption in this analysis is that for every acre of pasture converted to energy crops, an additional acre of pasture is intensified to make up for lost forage. Because sufficient rainfall is needed, the analysis limits the conversion of pastureland to energy crops to counties situated east of the 100th Meridian and in the Pacific Northwest.

POLYSYS modeling includes 250 million acres planted to the eight major crops, 61 million acres of land in hay production, and 140 million acres of cropland pasture and non-irrigated, permanent pasture. This land base is assumed constant throughout the modeling period. The analysis does not account for any competition and potential losses (or gains) of land to other major land uses, such as the conversion of pastureland to urban uses and the conversion of forestland to cropland. The analysis does not include land currently enrolled in the CRP[70] or land that might become available as contracts expire. This update (as well as the USDA projections) assumes that there are approximately 32 million acres currently enrolled in the CRP throughout the simulation period. The analysis does not consider any scenarios where high biomass prices provide strong financial incentives for growers to withdraw from the CRP, give up annual rental payments, and convert land into energy crop production. Further, the analysis does not consider any policy changes to the CRP that will allow the harvesting of energy crops. Finally, the CRP is designed to reduce soil erosion and provide other benefits (e.g., create wildlife habitat, reduce sedimentation, improve water quality, prevent excess crop production, and provide a stable source of income for farmers). Removing land from the CRP has the potential to reduce wildlife habitat and increase the delivery of sediment, nutrients, and pesticides to water bodies (BRDI, 2008). Although it is recognized that the conversion of some CRP land to energy crops can occur without any adverse environmental impacts, especially if sensitive areas are removed from consideration, the analysis of the CRP for either energy crop production or crop and forage production is not considered in this update.

Environmental sustainability. The primary crop residues, on both cropland and forestlands, explicitly consider resource sustainability with potential collection quantities that are only available after all restrictions are satisfied. This includes meeting soil erosion restrictions due to water and wind and maintaining soil carbon levels for crop residue removal. The forest residue analysis removes steep, wet, and roadless sites and restricts residue removal based on slope considerations. These slope restrictions consider erosion, soil nutrients, biodiversity, soil-organic carbon, and LTSP. For energy crops, sustainability is assumed practiced as implemented through BMPs, and crop budgets reflect these considerations. Displacement of commodity crops by perennial grasses and woody crops should improve environmental sustainability because they require smaller amounts of fertilizers and pesticides. Once established, perennial grasses and woody crops require little maintenance. These crops can provide more habitat diversity and depending on how planted provide riparian buffers and offer opportunities to capture runoff of nutrients. For annual energy crops, planting is assumed limited to non-erosive cropland, considered part of a multi-crop rotation, and grown using BMPs so as not to impose any additional impacts to local and regional ecosystems.

Roundwood markets. In Section 3.1.2 there is a discussion of an underlying assumption that unmerchantable biomass components of forest stands are uneconomic, unless they are removed during the harvest of commercial roundwood. The analysis includes an upper biomass availability level that is associated with the roundwood harvest level for each state. The restriction is only an approximation due to the fact that wood is transferred among states to processing facilities and is based on 2006 data and the 2005 RPA projections, which are subject to change

[70] USDA Conservation Reserve Program, Status— April 30, 2011. http://www.fsa.usda.gov/Internet/FSA_File/april2011onepager.pdf

under different economic conditions. The assumption removes a significant amount of biomass from the assessment—about 7 million dry tons annually for the United States. More importantly, almost half the states lose 50% or more of the potential thinning biomass because of this restriction.

6.3.3 Factors Affecting Potential Product Estimates

Gross versus net tonnage. The estimated dry tons are those that are available at the farmgate or forest roadside. Each type of feedstock has certain physical properties and harvest/recovery characteristics that influence the standing volumes versus how much biomass is available at roadside, and more importantly, at the biorefinery. In the report, the estimates of potentially available biomass account for losses incurred during collection or harvesting and in the moving of the biomass to the field edge or forest roadside.

The update does not consider feedstock logistics and supply chain issues as comprehensively as desired, and not at all beyond the farmgate and roadside. One potential loss is from handling and storage. Such losses are specific to the feedstock, the feedstock condition and form, the type of handling system, and storage conditions. In cases where storage induces loss, the actual availability for conversion into energy is less than the presented estimates.

Although the potential biomass amounts are estimated at the county level, the assessment does not take into account the many factors such as feedstock density, markets, feedstock preference, incentives, and economics that can change availability.

Feedstock characteristics. The update, as described, includes no preference toward a specific feedstock or particular conversion process for energy production potential. For example, corn stover includes stalks and cobs, and forest residues include limbs, bark, and solid wood of different compositions that may or may not work well at a particular facility. The physical and chemical characteristics of feedstocks vary widely and greatly impact conversion yield, but also, and more importantly, these characteristics impact how much of the estimated biomass potential is actually available at the throat of the conversion facility because of specifications at the biorefinery. A report sponsored by the Western Governors' Association (Parker et al., 2011) is an example of a source for such an analysis. The analysis includes updated *BTS* biomass resource supply potential and estimates fuel price through various conversion pathways. This particular study represents the usefulness of resource potential estimates for one of multiple approaches to estimate the feedstock supply and cost characteristics of additional bioenergy.

There are ongoing efforts to develop feedstock logistic systems that can handle a wider variation of feedstock types that meet tighter quality specifications. In the future, biorefineries may require feedstocks of consistent quality, particle size, and moisture content. It is likely that more uniform feedstocks will have greater market potential (Hess et al., 2009). The effect on biomass potential still needs additional study. Some resources may become stranded as the cost to improve quality may outweigh value, or conversely, the improvement process can make more biomass of a specified quality available.

Markets. As previously discussed, the POLYSYS model allocates land to competing uses based on net returns with any changes in land use affecting the supplies of both crop residues and energy crops. The model assumes that farmers will grow energy crops if they can produce a net return or profit equal to or greater than the profit made by producing one of the eight commodity crops or forage. Energy crops also compete for land with each other and for land where crop residue collection is profitable. Simulation results show much higher net crop returns relative to the baseline forecast and only a slight decline in net returns to livestock production.

In the absence of significant markets for bioenergy feedstocks, it is difficult to project what farmers will require as a minimum profit to grow energy crops. A study by Jensen et al. (2005) attempts to address this question by assessing farmers' views and interest in producing switchgrass, profits that would be required to induce farmers to grow switchgrass, and the amount of land and types of crops that farmers might be willing to convert to switchgrass production. Survey results vary considerably, especially between farmers with a knowledge of and interest in growing switchgrass and those not interested. Jensen et al. (2005) reports an average net return per acre among those interested in growing switchgrass of $102 per acre and $330 per acre for those not interested. The results presented in this analysis show profits from about $100 to $140 per acre (inclusive of land rents) at annual yields per acre of 7 to 8 dry tons per acre. These yields are currently attained in Genera Energy's switchgrass plantings in eastern Tennessee (Genera Energy, 2011).

6.3.4 Innovations in Management and Technology

Use of water-limited lands. A significant underlying assumption within the update that restricts biomass availability is that energy crops on land that would require irrigation are excluded. Water scarcity and the depletion of aquifers are already looming issues in agriculture. There is concern that adding large acreages of irrigated energy crops would not be sustainable, especially with competition for increased commodity crop production. Therefore, much of the western United States is excluded in the analysis of energy crop potential. However, the assumption is an oversimplification because there are both barriers and opportunities to expanding sustainable production of energy crops beyond rain-fed land. The assumption is not meant to imply that such land will not become accessible for biomass production under innovative approaches and technologies.

A National Research Council report (NRC, 2008) concludes that increased agricultural production for biofuels will probably not alter the national aggregate use of water in the next 10–15 years. However, the report indicates that growing crops for biofuel production is likely to have significant regional and local impacts, and there is a need to encourage the growth of new technologies, best agricultural practices, and the development of traditional and cellulosic crops that require less water and fertilizer and are optimized for fuel production. There is ongoing and expanding research to grow traditional crops with less water and to develop new cultivars and crop varieties for the more arid lands. Dryland farming and other agronomic approaches, such as integrated rotations, are being considered for energy crops (e.g., the use of winter grass cover crops). Also, it appears that some crops, such as switchgrass, could be grown under very limited irrigation. Finally, as discussed in Chapter 5, new approaches to irrigation using saline or waste water from municipal to industrial sources, including mine and oil production, are being explored.

Use crop rotations and multiple crops. The discussion and analysis in Chapter 4 on the agricultural crop wastes retention modeling points out the important role of crop rotation and the use of cover crops and fallowing for production and sustainability. For energy crops in Chapter 5, the focus is on agronomical and silvicultural practices, such as double or multiple cropping to increase productivity and other practices to ensure sustainability. A good example is the use of sweet sorghum as a complementary crop to energy cane. The concept is to double or triple (number of rows) drill sweet sorghum on conventional sugarcane rows and harvest with the same sugarcane harvester earlier than the cane (McCutchen and Avant, 2008). However, the analyses in the update focus primarily on yield and tillage and not an incorporation of crop rotation and multiple cropping. Another example is to optimize the rotation length (time between harvests) and the number of rotations between re-establishing woody crops, especially for coppice crops. The update uses one set of assumptions, even though other forms of rotation might provide significant increases in potential biomass. One form of rotation not included in this report is intercropping, which is the planting of grasses between the rows of trees early in the rotation. This report serves to establish a baseline from which alternative land management scenarios can be examined that could potentially increase biomass production and accessibility, as well as enhance environmental quality.

Input levels of production. An attractive feature of cellulosic and advanced biomass feedstocks is that they provide higher levels of biomass with relatively fewer inputs than traditional bioenergy feedstocks (e.g. corn grain). The update addresses the importance of corn and energy crop yield through two scenarios, but does not include further analysis on reduced input production scenarios. In Chapter 5, the sensitivity of yields to input adjustments is addressed according to trials of individual dedicated energy crops. However, for the update, only one set of input levels is assumed for the projections. This approach does not undermine the need to consider resource potential in light of the applications of varied levels of inputs. Developing energy crops that efficiently utilize nutrients and water remains a priority in providing appropriate yields that maintain farm profitability and affordable feedstocks for conversion. As stated earlier in the report, ongoing efforts to increase yields or maintain yields with fewer inputs focus on genetic techniques (e.g., breeding, biotechnology, and bioengineering) and agronomic and silvicultural practices.

Improved systems. The availability and cost of the biomass production, recovery and harvest, and preprocessing is predicated mostly on current technologies, except for the yield scenarios that include future increases in on-farm production. The literature generally does not fully address biomass feedstocks from the industrial perspective—the optimization of current production systems for biomass or the development of new and innovative feedstock systems. Much of the current research and development is conducted at laboratories and bench-scale, or at the most, small pilots. This approach has significant effects on biomass potential, which could change greatly with different assumptions of system productivity and costs. Current systems are mostly adapted from current crop, forage, and forest systems. Although the estimates used in the report are relevant and constitute very likely system functions and costs in the near term, the long-term impact of new machine development and optimization of systems may positively impact the results. Analysis to integrate the flow of materials through the system to optimize the recovery efficiency and access life-cycle performance is beyond the scope of the report. In general, as such systems are further developed and implemented on larger scales, the availability of biomass at different prices will change.

For example, DOE is developing an advanced uniform-format design that will make an evolutionary progression from present-day, conventional-logistic systems to high-volume, bulk-handling systems that provide a uniform, specified raw material in a commodity-type market much like grain systems (Hess et al., 2009). DOE has also supported the design and demonstration of a comprehensive system to handle the harvesting, collection, preprocessing, transport, and storage of sufficient volumes of sustainably produced feedstocks.

6.3.5 Data, Research, and Technology Needs

A major approach for the update is to overcome some of the shortcomings in the 2005 *BTS* that required the development of better datasets, models, and analytical approaches. Although significant effort did go into the process, and there are many improvements in the update, there are still some additional needs that were identified. The needs that support future enhancement of the data and assumptions presented in this report are:

- Additional availability and costs data and databases are needed to improve the quality of the analysis for:
  - Many, if not all, of the agricultural processing residues and wastes
  - Secondary mill wastes from wood processing
  - Urban wood waste data, including tipping fees
  - Biomass portions of the FIA database
  - Land-use databases, especially those for pasture and marginal lands
- Better quantification of future potential yields and geographic variation
- Improved information on system integration, such as production, harvesting, and conversion efficiency loss of biomass
- Better modeling of the conventionally sourced wood supply curve to account for additional future wood resource demand
- Understanding and modeling of the long-term effects of wood biomass removal under a range of soil, climate, and management schemes
- Understanding of the impacts of climate change
- Development and integration of biological and economic models for sustainability
- Increases attributed to the available biomass from residuals and wood wastes through management and technology
- Better understanding of stover yields and harvest index with changes in grain yields from breeding and biotechnology
- Improvement of system data on equipment efficiency and cost data for current and evolving systems
- Understanding factors that limit the availability of land-for-crop expansion, which include competition for agriculture crops versus livestock production
- Increased understanding of potential pasture intensification and its role in making additional forage available
- Improved understanding of the potential for specialized harvesting equipment to handle various energy crop feedstocks (e.g., thick-stemmed grasses) more efficiently than commercial hay equipment
- Improved understanding of the potential for specialized logging equipment to more efficiently harvest forest residues and energy crops
- Understanding of landowner response to energy crop market opportunities.

6.3.6 Opportunities for Further Analysis

Modeling output that supports the production forecasts within this report is available online for public access. The Bioenergy KDF (ORNL, 2010) is an online, infrastructure-utilizing, Web 2.0 technology that contains county- and state-level forecasts and online mapping services. For example, a user may define the feedstock, year, and price of interest for direct data download, online map projection, and map export. Additionally, a number of custom datasets are available for immediate access that align with figures and tables from the Executive Summary of this report. These datasets summarize the spatial distribution of potential feedstocks across the two scenarios and multiple feedstock sources. An additional feature of the Bioenergy KDF is the ability to submit and access spatially referenced data and models from peer reviewed articles related to bioenergy.

6.4 Conclusions

This updated resource assessment for the conterminous United States identifies sufficient biomass feedstock to meet near-term and potentially long-term bioenergy goals, depending on different cost and productivity scenarios. The assessment finds significant biomass resources across the United States with the exception of some areas of the arid west. These resources are shown for 2030 in Figure 6.3 as state-level shares of major categories of feedstocks and in Figure 6.4 as total potential resources by county. Under high-yield assumptions, ambitious goals may be feasible. The assessment takes into consideration environmental sustainability and identifies likely costs to access these resources. There are, of course, limitations to exploiting these prospective supplies. One limitation of the assessment is that it was conducted using a forest roadside and farmgate perspective. Reported costs do not represent the total cost or the actual available tonnage to a biorefinery. There are additional costs to preprocess, handle, and transport the biomass, and there may be storage costs for specific feedstocks. Such losses are specific to the feedstock, the feedstock condition and form, the type of handling system, and storage conditions. For example, switchgrass can lose 2% to 25% depending on the type of storage (Turhollow et al., 2009). The reported estimates do include losses to roadside, but do not include losses due to continued handling, additional processing, storage, material degradation, and quality separation. In effect, for instance, more than one billion tons from estimates in the report would be required to have a billion tons ready to process at a biorefinery. The amount would be dependent on many variables in the continued supply chain and final conversion technology. In addition, the biomass is in varied form and may not be directly comparable at a biorefinery in either cost or conversion efficiency. Determining such values is outside the scope of the report.

Although the assessment was conducted at a county level for the major primary feedstocks, the assessment does not account for landscape-type issues, such as feedstock density and nearness to demand, or conversion facilities that may have economic implications or other incentives that would change availability, or even preference, among feedstocks. These considerations would likely reduce the size of the resource potential as well. There are other efforts underway to better understand feedstock density issues, to optimize facility location and logistic systems. This report provides information complementary to the underlying feedstock availability at a range of prices.

There are also limitations on available data, especially at the county level, for many of the feedstocks that do not have any historical prices. When there is price data, it may not represent optimal production systems or technology. Furthermore, many assumptions are used in making the estimates. An effort was made to use the best information and to maintain a conservative approach as appropriate.

Overall, results of this update are consistent with the 2005 *BTS* in terms of the magnitude of the resource potential, assuming a farmgate or forest roadside feedstock price of $60 per dry ton. These findings for 2030 are summarized in Figures 6.5 and 6.6 for the baseline and high-yield scenarios—assuming high corn yield, high no-till, and energy crop productivity increasing by 3% annually. The forest residue potential is determined to be somewhat less as measured by the unused resources and by properly accounting for pulpwood and sawlog markets that provide the demand and the residue. The crop residue potential is determined to be somewhat less owing to the consideration of soil carbon in crop residue removal and not counting any residue produced on land that is conventionally tilled. The energy crop potential is estimated to be much greater because of higher planted acreage—a result of the spatially explicit land use change modeling that was used.

This report has several enhancements over the original report. Just as the 2005 *BTS* did over the last 5 years, hopefully this update will provide a foundation for further analysis by others and resolution of issues and concerns. It has limitations that can be better addressed as the data and outputs become available through the KDF. Through the development of the report, challenges and opportunities are identified that may suggest needed investments in research and analysis capabilities.

Figure 6.3 State-level shares of all potentially available resources at $60 per dry ton or less in 2030, under baseline assumptions

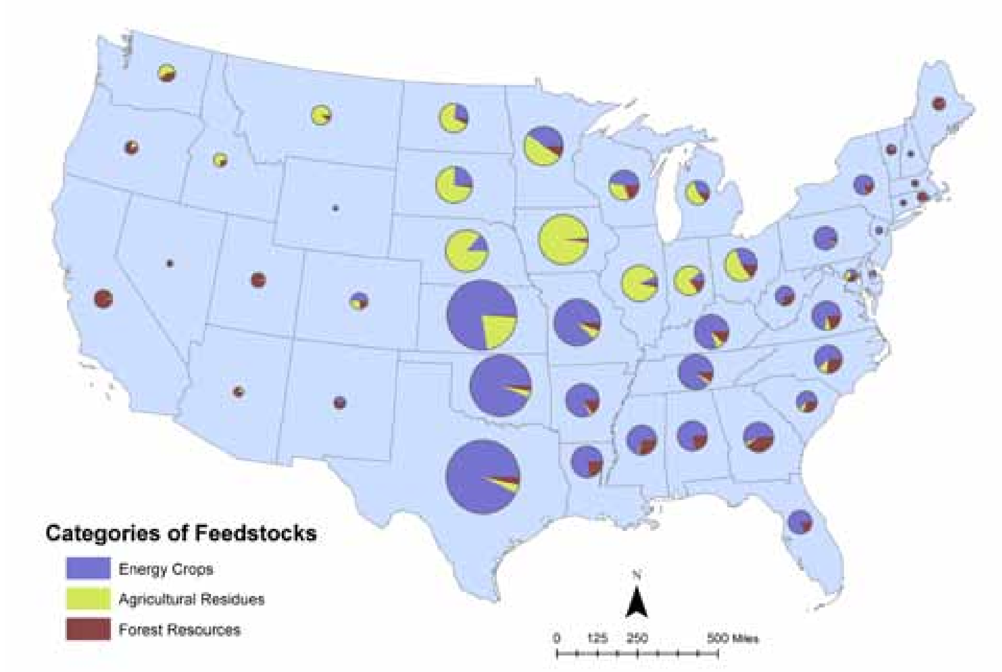


Figure 6.4 Potential county-level resources at $60 per dry ton or less in 2030, under baseline assumptions

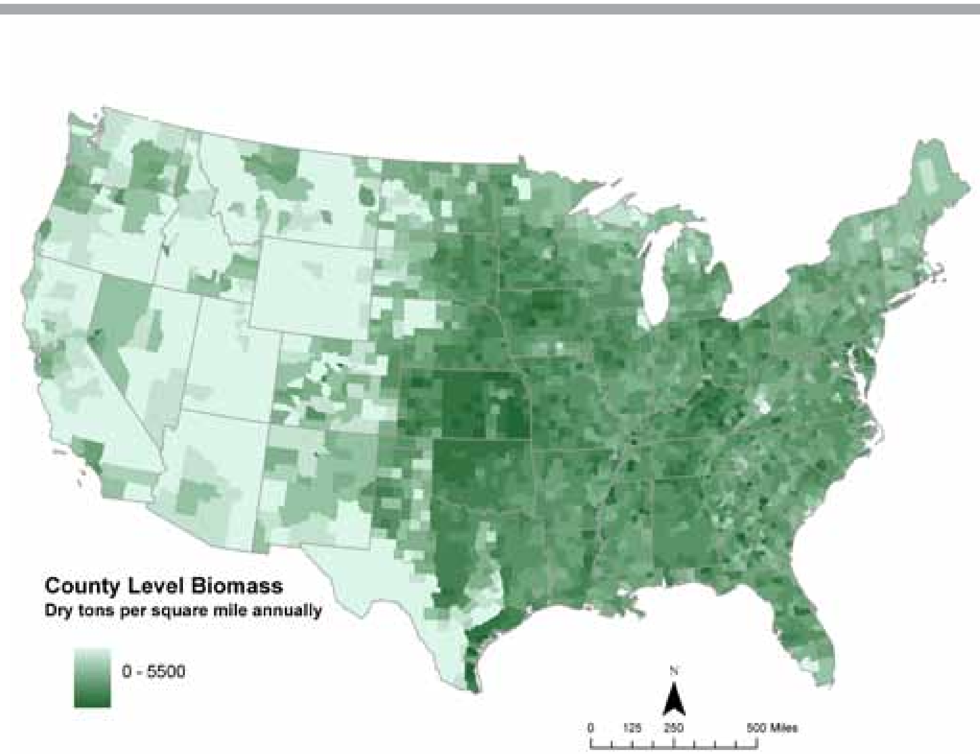


Figure 6.5 Summary of currently used and potential resources at $60 per dry ton or less identified under baseline assumptions

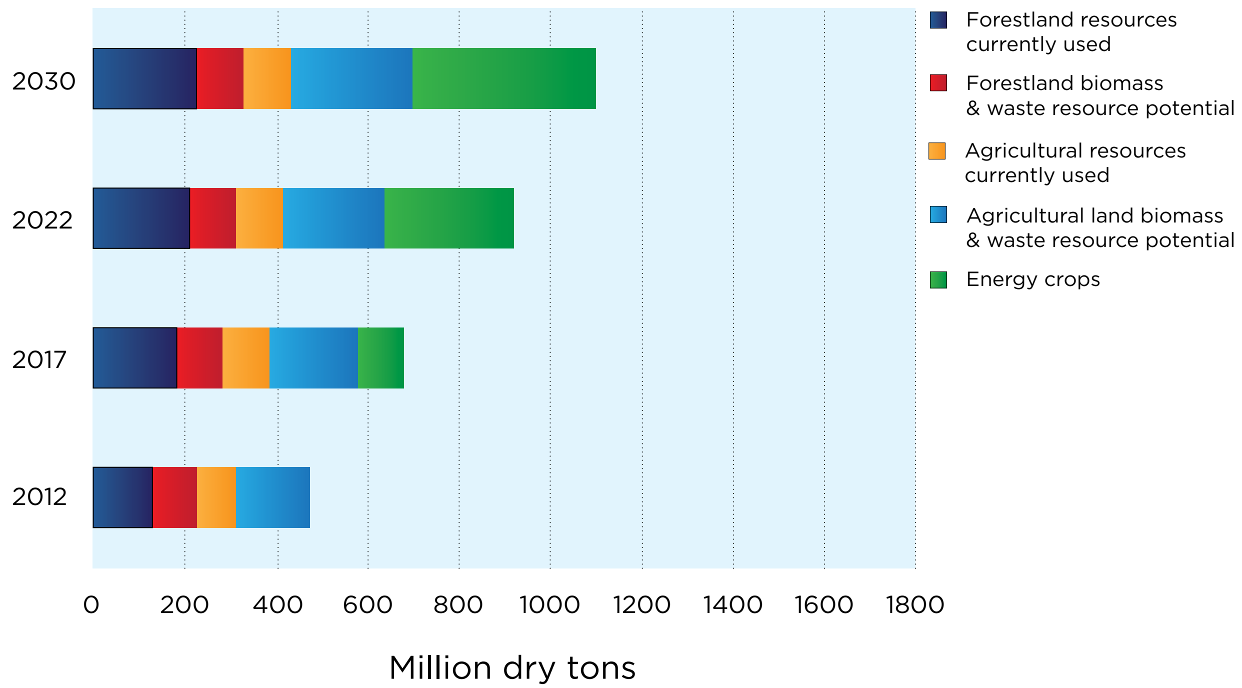
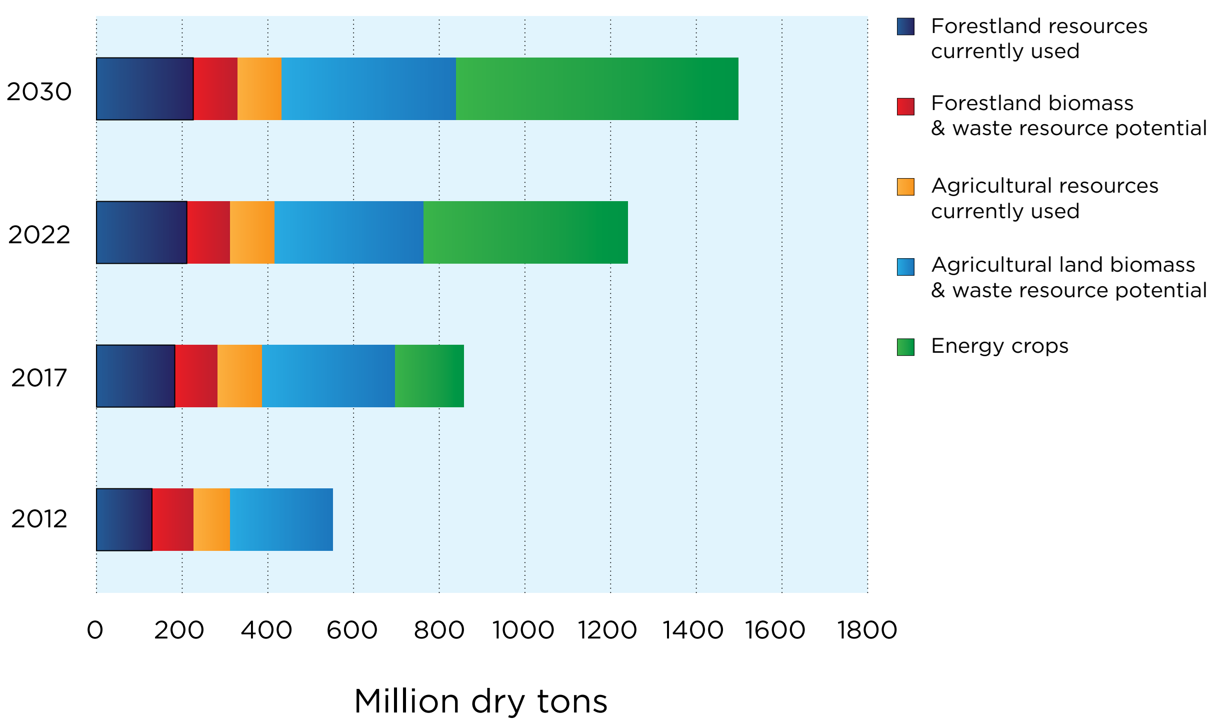


Figure 6.6 Summary of currently used and potential resources at $60 per dry ton or less identified under high-yield assumptions



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APPENDICES

Appendix A: Feedstocks

1. Currently used (Discussed in Chapter 2)

a. Agriculture

i. Grain crops (primarily corn) for ethanol up to 15 BGY RFS)

1) Corn

2) Sorghum

3) Barley

4) Other grains

ii. Other crops (sugarcane, sugar beets, etc.)

iii. Oil crops (primarily soybeans for biodiesel up to 1 BGY RFS)

1) Soybeans

2) Other crops (canola, sunflower, rapeseed, etc.)

iv. Municipal solid wastes (biomass, landfill gas, biosolids)

b. Forestry

i. Fuelwood

ii. Mill residues

iii. Pulping liquors

iv. Urban wood wastes and construction & demolition wastes

2. Forest biomass and waste resources (Discussed in Chapter 3)

a. Logging residues (timberland—see definitions in Appendix B)

b. Other removal residues (timberland and other forestland)

c. Thinnings (timberland)

d. Thinnings (other forestlands)

e. Composite (portions of logging residues and thinnings)

f. Conventional pulpwood diverted to bioenergy

g. Unused mill residues (primary and secondary processing mills)

h. Urban wood wastes and construction & demolition wastes

3. Agriculture biomass and waste resources (Discussed in Chapter 4)

a. Crop residues includes corn stover (stalk, leaves, and cobs), sorghum stubble, and straw from small grains (wheat, oat, and barley)

b. Crop processing residues

c. Waste oil and greases

d. Animal manures

e. MSW (e.g., food waste and textiles)

Corn Starch Ethanol and Biodiesel

- Used EISA Mandates
- Corn and other crops ethanol
  - ~12 BGY 2012–2014
  - 15 BGY 2015–2030
  - 2.8 gallons per bushel of corn
  - 56 pounds per bushel at 15.5% moisture content
  - ~69% ethanol
  - ~31% distillers grains
- Biodiesel
  - 1 BGY 2012–2030
  - Soybeans (43%)
    - 1.52 gallon per bushel
    - 60 pounds per bushel at 10% moisture content
  - Other (57%)
    - Fats
    - Vegetable oils

4. Energy crops (Discussed in Chapter 5)

a. Perennial grasses (e.g., switchgrass, miscanthus, etc.)

b. Woody crops (poplar, willow, southern pine, eucalyptus)

c. Annual energy crops (high-yield sorghum)

5. Algae not included

Appendix B: General Assumptions[1]

1. Land base

a. Conterminous United States; excludes Alaska, Hawaii, and U.S. territories

b. EISA compliance

i. Agriculture lands meet established criteria. Federal forestlands are shown optionally (excluded under EISA)

c. Forest resources

i. FIA land definitions

1) Forestland – greater than or equal to 1 acre and has 10% live tree stocking

2) Timberland – capable of producing more than 20 cubic feet per acre per year

3) Other forestland – other than timberland or reserved forestland and incapable of producing 20 cubic feet per acre per year

4) Reserved forest lands excluded – set aside by statute or regulation

ii. Inventoried roadless areas excluded

iii. No or little road building (over 0.5 miles from road excluded)

iv. Areas with slopes greater than 80% (slightly less than 40 degrees) excluded

v. Selected wet-area stand types excluded

vi. Federal lands (except reserve and roadless) included separately

d. Agriculture resources

i. Perennial grasses and woody crops can be established on cropland, cropland used as pasture, and permanent pasture.

ii. Annual energy crops (e.g., energy sorghum) restricted to cropland with low erosion potential and assumed part of a multicrop rotation

iii. Energy crops are not planted on land requiring supplemental irrigation

iv No forestland conversion

v. USDA baseline acres apportioned to counties using a four-year average of crop acres from NASS; county cropland pasture and permanent pasture acres derived from the 2007 Census of Agriculture

vi. Pasture conversion to perennial grasses and woody crops limited to counties east of the 100th Meridian, except for the Pacific Northwest

1 Presented in brevity – please use main document for more detail explanation.

2. Yields and recovery

a. Baseline scenario for agriculture

i. Anchored to *USDA Baseline Agricultural Projections* for agricultural land

ii. Production of traditional crops allocated to counties based on 4-year trailing average of NASS surveys (2006–2009)

1) Yield projections for eight major agricultural crops (major crops are corn, sorghum,[2] barley, oat, wheat, rice, cotton, and soybean) based on USDA Agricultural Projections to 2019 for 2010–2019 and "straight-line" extension of the last 3 years of the forecast through 2030. Baseline yields apportioned to counties based on a 4-year average of NASS data (excluding hay, which is from 2007 USDA Agricultural Census)

a) Corn 2012 baseline yield (average for United States) is 163 bushels per acre increasing to 201 bushels per acre by 2030

b) Wheat 2012 baseline yield (average for United States) is 44 bushels per acre increasing to 50 bushels per acre by 2030

c) Soybean 2012 baseline yield (average for United States) is 44 bushels per acre increasing to 52 bushels per acre by 2030

d) Sorghum, oat, and barley baseline yield (average for United States) is 64, 64, and 67 bushels per acre, increasing to 74, 72, and 79 bushels per acre by 2030, respectively

2) Residue to grain ratios are 1:1 for corn and sorghum, 1:2 for oat, 1:1.5 for barley, and 1:1.7 and 1:1.3 for winter and spring wheat, respectively (implemented as a weighted average of winter and spring wheat acres). No residue collection is assumed for soybean

3) Tillage includes conventional, reduced, and no-till. Residue collection is not allowed on conventionally tilled acres. Separate residue retention coefficients estimated for reduced tillage and no-till. No-till allows for removal of more residue than reduced tillage

b. Baseline for forestry

i. Residues are based on inventory and not yield data.

1) Current logging and other removal residues from USDA Forest Service TPO data updated in 2007
2) Future logging residues derived using USDA Forest Service RPA (Resource Planning Act) projections of timber harvests to 2030
3) Thinnings derived from USDA Forest Service database downloaded on February 3, 2010

USDA AGRICULTURAL PROJECTIONS

- Conditional scenario based
- Specific assumptions
  - Macroeconomy
  - Agriculture and trade policies
  - Weather
  - International developments
- No domestic or external shocks to global markets
- Normal weather
- Current law through projections (e.g., Farm Bill, EISA, Energy Improvement and Extension Act)
- Biofuels tax credits—ethanol $0.45, biodiesel $1.00, and $0.54 ethanol import tariff
- Starch biofuel at 15 billion GPY by 2015

3. High-yield scenario

a. Agriculture

i. Used *USDA Agricultural Projections* as basis for agricultural crops

ii. Yield projections for eight major agricultural crops (major crops are corn, grain sorghum[3], barley, oat, wheat, rice, upland cotton, and soybean were based on *USDA Agricultural Projections to 2019* for 2010–2019 and "straight-line" extension of the last 3 years of the forecast through 2030. Yields apportioned to counties

[2] Sorghum grown for energy is treated as an energy crop and assumptions are included under those for annual energy crops.

[3] Sorghum grown for energy is treated as an energy crop and assumptions are included under those for other energy crops.

based on a 4-year average of NASS data (excluding hay, which is from 2007 USDA Agricultural Census)

1) Corn 2012 baseline yield (average for United States) is 163 bushels per acre increasing to 265 bushels per acre by 2030

2) Wheat 2012 baseline yield (average for United States) is 44 bushels per acre increasing to 50 bushels per acre by 2030

3) Soybean 2012 baseline yield (average for United States) is 44 bushels per acre increasing to 52 bushels per acre by 2030

4) Sorghum, oat, and barley baseline yield (average for United States) is 64, 63, and 66 bushels per acre increasing to 74, 72, and 79 bushels per acre by 2030, respectively.

iii. Average annual increases in yield for agricultural crops for 2010-2030 are

1) Corn – 1.95%

2) Other major crops – same as baseline (see *2. a. ii. 1) b)–d)* on previous page)

iv. Residue to grain ratios – same as baseline (see *2. a. ii. 2)* on previous page)

v. Tillage includes conventional, reduced, and no-till. Residue collection is not allowed on conventionally tilled acres. Separate residue retention coefficients estimated for reduced tillage and no-till. No-till allows for the most residue removal. High-yield assumes conversion of 80–85% of conventionally tilled acres to no-till by 2030

vi. Forestry – no high-yield scenario is assumed

4. Forest residues

a Sustainability

i. Retention of biomass

1) 30% retention of biomass by tonnage on slopes less than or equal to 40%

2) 40% retention of biomass by tonnage on slopes greater than 40% less than or equal to 80%

3) No removal of biomass on slopes greater than 80%

4) Biomass specifically retained not defined—assumed any combination of small trees, limbs and tops of merchantable, harvested trees, dead standing trees, cull trees, portions culled from trees, etc.

ii. No or little road building—used “distance from road” FIA variable to exclude plots

1) Excluded biomass greater than 0.5 mile for ground-based system

2) Excluded biomass greater than 1300 feet for cable-based system

iii. Excluded areas with slope greater than 80%

iv. Used cable system on slope greater than 40% instead of ground-based system

v. Assume BMPs, regulation, and certification (as applicable) compliance and costs are reflected in cost curves

vi. Thinnings and pulpwood volumes capped based on pulpwood and sawlog markets

1) Annual harvest in county cannot exceed annual growth (i.e., 2006 harvest levels in 2007 RPA)

2) Integrated logging of pulpwood and sawtimber harvest cannot exceed pulpwood/sawtimber market 2006 levels in 2007 RPA

b. Biomass

i. Small trees

1) 1–5 inches dbh (diameter breast height) in the East

2) 1–7 inches dbh in the West

ii. Tree components – limbs, tops, and cull components of merchantable, harvested trees

iii. Dead standing trees

iv. Cull trees or components – do not meet commercial specifications because of size or quality

c. Conversion factor – 30 dry pounds per cubic foot and 50% moisture content

5. Energy crops

a Grown on either cropland, cropland used as pasture, or permanent pastureland—not on forestland

b. Energy crops grown on pasture assume lost forage made up through the intensification of other pastureland

c. POLYSYS modeling framework

i. Assesses economic competitiveness with commodity crops (3,110 counties)

ii. Estimates land-use change (county by county) for cropland, hay land, cropland used as pasture, and permanent pastureland

iii. Prices vary parametrically in $5 increments to estimate supply

iv. Uses upper limits of 250, 61, 23, and 117 million acres in cropland, hay land, cropland in pasture, and permanent pasture, respectively

v. Allocates land based on

1) Maximization of expected returns above variable costs for all commodity crops (e.g., corn, wheat, and soybeans) and energy crops (perennial grasses, woody crops, and energy sorghum)

2) Subject to meeting demands for food, feed, industrial stocks, and exports

3) Excludes forestland

4) Excludes Conservation Reserve Program (CRP) land

5) Energy crops displace conventional crops and pasture if more profitable, but conventional crop demand is still met on other land

6) Only 10% of cropland can convert to energy crops each year. The total amount of cropland in any given county that can convert to energy crops (perennial grasses, woody crops, and energy sorghum) is limited to 25%

7) Conversion of pastureland to energy crops is limited to counties east of the 100th meridian for sustainability except for the Pacific Northwest

a) Intensifying pasture needed to replace lost forage

b) Only 5% of permanent pasture can convert in given year. The total amount of permanent pasture in a given county that can convert to energy crops is limited to 50% (i.e., assumed doubling of forage through intensification)

c) Only 20% of cropland pasture can convert to energy crops each year. The total amount of cropland pasture in a given county that can convert to energy crops is limited to 50% (same assumption as permanent pasture)

vi. Eight-year rotation for non-coppice woody crops, 20-year rotation and 4-year cutting cycle for coppice woody crops, 10-year stand life for perennial grasses

vii. Costs include seed (or plantings), fertilizer, herbicide, insecticide, machinery services, custom operations, fuel and lube, repairs, handling, labor, and technical services

1) Broad production regions

2) Perennial grasses are species-specific by region

3) Intensifying cropland currently used as pasture costs $50 per acre the first year and an additional $10 per acre in subsequent years

4) For permanent pasture, first-year costs are $100 per acre and $15 per acre in following years.

5) Energy crops must overcome the additional costs in *3)* and *4)* plus the pasture rental rate to come into production

viii. Systems

1) Perennial grasses

a) Planted, managed, and harvested like a hay crop
b) Uses no-till establishment
c) Annual harvests with reduced yields in first and second years, maturity reached in third year
d) Conventional mowing, raking, and baling
e) Ten years before replanting
f) Productivity is a function of precipitation, temperature, soils, and local site factors
g) No irrigation

2) Woody crops

a) Can be either single-rotation or coppice
b) Established and managed with conventional agriculture equipment
c) Harvested using conventional forestry equipment for single-stem and specialized equipment for coppice (multiple stems at the stump)
d) Up to seven stands regrown by coppice before re-establishment

3) Energy sorghum

a) Annual crop
b) Only on non-erosive cropland
c) Part of multicrop and/or fallow rotation

4) Miscanthus

a) Higher yields are offset by higher establishment costs due to the fact that they use vegetative planting material, which results in similar production costs to modeled perennial grasses (e.g., switchgrass)

ix) Yields

1) Species and regional specific

2) Perennial grasses baseline yield

a) See Table 5.3
b) Baseline perennial grass yields (dry tons per acre): 3.0–9.9 dry tons per acre in 2014; 3.6–12.0 dry tons per acre in 2030

3) Woody crops baseline yield

a) See table 5.4

b) Baseline woody crop yields (dry tons per acre): 3.5–6.0 dry tons per acre in 2014; 4.2–7.2 dry tons per acre in 2030

4) Energy sorghum (8–11 dry tons per acre)

5) High yield – used three growth rates: 2%, 3%, and 4% annually

d) Herbaceous biomass (crop residues, perennial grasses, and annual energy crops) include 10% biomass losses at the field edge. Woody crops assume a 5% loss at the field edge

6. Costs and production

a. All costs to farmgate or roadside (excludes handling and loading, transportation, and storage)

b. Forest

i. Includes chipping (i.e., preprocessing) for forest residues, thinnings, and conventionally sourced wood

ii. Systems

1) Logging residues are integrated harvest (i.e. biomass removed with merchantable products and as trees to roadside)

2) Thinnings

a) Thinned if stand density index (SDI) greater than 30% of maximum SDI for reference stand type to a SDI of 30% of maximum

b) Integrated harvest (i.e., multiple products)

c) Uneven-aged prescription (some trees removed from all diameter classes as needed to meet target SDI)

3) Pulpwood harvest

a) Harvest only pulpwood diameter classes; do not harvest other merchantable product diameter classes

b) All of tree is considered to be biomass (i.e., no other product recovered from tree)

4) Ground-based logging is whole tree to roadside (no processing at stump, i.e., no cut-to-length system)

5) Cable system limited to 1300 feet from road access

iii. Stumpage costs are regional 2007 averages (data were 2006–2008)

iv. Chipping costs average $13 per dry ton across states because of labor and fuel cost difference

v. Harvest costs (felling and transport to roadside) estimated using Fuel Reduction Cost Simulator (FRCS) model

vi. Supply curves

1) Logging residues and thinnings

a) Includes stumpage costs

b) Includes chipping costs for logging residues and thinnings

c) Includes harvest (felling/extraction) costs for the small, dead, and cull (non-merchantable) trees portion of thinning)

d) Minimum supply curve stumpage is $0 to $4 per dry ton (plus other applicable costs)

i) Stumpage is $0 per dry ton for federal lands

ii) Stumpage is $4 per dry ton for private lands

e) Maximum of supply curve stumpage is up to 90% of 2007 pulpwood stumpage price

2) Pulpwood

a) Includes stumpage, harvest, and chipping costs

b) Same minimum and maximum stumpage as above

c) Only 20% of 2006 county harvest can shift from pulpwood to bioenergy use because of uncertainty in economic parameters and potential increases in supply

3) Other removal residues

a) Only 50% of the TPO levels recoverable (based on expert opinion)

b) Assumed one-third available at $20 per dry ton and the remaining amount available at $30 per dry ton

4) Thinnings from other forestlands
   a) All costs borne by the biomass as no merchantable trees recovered
   b) An assumption was one-half available at $60 per dry ton and other half at $70 per dry ton
5) Unused mill residues – $20 per dry ton, an assumed price based on past and projected costs
6) Urban wood
   a) Recoverable amounts based on Forest Products Laboratory report (McKeever 1998, 2004)
   b) Cost based on Walsh (2006): Of the identified, recoverable wood, 75% can be acquired at cost of $20 per dry ton; 85% at $30 per dry ton; 90% at $40 per dry ton; and all at $60 per dry ton

c. Agriculture

i. Residues (corn stover, wheat straw, barley and oat straw, sorghum stubble)
1) Production
   a) POLYSYS used to estimated corn, wheat, sorghum, oat, barley residues
      i) Depends on crop yield and harvest index
      ii) Crop yield/harvest index discussed under scenario
   b) Cotton and rice residues estimated separately from other data
   c) No soybean residue
   d) Retention of biomass
      i) No removals from conventionally tilled acres, only on reduced-tillage and no-till
      ii) Depends on tolerable soil loss as indicated by NRCS
      iii) Retention coefficients estimated from RUSLE2 and WEPS
      iv) Technical (physical) removal depends on the collection equipment complement – moderate removal ~35%, moderately high removal ~50%, high removal ~80%
      v) Incorporates rotation into retention
      vi) Calculates county averages retention to prevent erosion from wind and rain, and carbon loss for each rotation, tillage combination, and crop management zone
2) Grower payment
   a) Value of removed nutrients from trailing average of regional fertilizer prices (2006–2009 prices)
   b) Includes additional payment of $1 per dry ton for the organic matter value of the residues and a $10 per dry ton grower return
   c) Nutrient requirements discounted according to county-level rotation
   d) Corn stover removal averages: 14.8 pounds nitrogen per dry ton; 5.1 pounds of phosphorus per dry ton; 27.2 pounds of potassium per dry ton
   e) Average is $26 per dry ton for corn stover and $25 per dry ton for wheat straw
3) Collection, storage, and handling costs
   a) Assumed raking and large rectangular baling
   b) Costs vary according to residue tonnage per acre

ii. Secondary processing wastes
1) Production
   a) Calculated from available data of primary crops or animal units, and residue/byproduct coefficients and harvest index.
   b) Sugarcane coefficient is 0.14 ratio for bagasse and 0.0375 for field trash
   c) Cotton gin trash is a function of the type of picker

   d) Excluded soybean exports in hulls (58% processed in the United States)
   e) Rice hulls are 20% of rice production and exclude hulls in exports
   f) Rice residue harvest index is 0.5 with moisture content of 13.5%
   g) 1% of wheat is dust and chaff
2) Costs are specific to feedstock
   a) Wheat dust, cotton gin trash and rice hulls
      i) Zero value (no grower payment)
      ii) Collection and handling cost of $10 per dry ton for half and $20 per dry ton for half
   b) Rice and cotton field residue
      i) Zero value (no grower payment)
      ii) Collection and handling costs calculated like stover and straw, i.e., rake and large rectangle baling
   c) Sugarcane
      i) Field residue calculated like stover and straw (e.g., rake and large rectangular baling)
      ii) Bagasse assumed used and unavailable
   d) Manure costs include fertilizer replacement and $15 per dry ton for handling
   e) Animal fats and waste oils priced at market
   f) Soybean hulls priced at market
   g) Rice hulls priced at market
   h) Rice field residues calculated like stover and straw
   i) Wheat dust and chaff available at assumed prices
   j) Orchard and vineyard prunings costs available at assumed prices
   k) Other wastes
   l) Trap and sewage greases
   m) Yellow grease
   n) Municipal solid waste (food waste, textiles, etc.)

Appendix C: Major differences between 2005 *BTS* and updated *BTS*

1. **Separation of "used" and "potential" feedstocks. In the 2005 *BTS*, feedstocks currently used for energy production or could be shifted from another market to energy production were counted in the biomass potential. In the update, the currently used biomass is clearly delineated from the potential**
2. **EIA Annual Energy Outlook was used more extensively to project future quantities of currently used biomass**
3. **The updated *BTS* covers the present through 2030 period instead of the 2025–2050 focus of the 2005 *BTS***
4. **Additional agricultural environmental sustainability requirements in updated *BTS***

   a. Cost assumptions include compliance with statutes, regulations, and BMPs

   b. Assumed the use of acceptable management practices

   c. Explicitly modeled crop residue retention, tillage, and crop rotation to provide erosion protection and maintenance of soil organic carbon

   d. Modeled nutrient replacement, crop rotation, and reduced tillage practices to ensure long-term site productivity.
5. **Additional forestry environmental sustainability requirements in updated *BTS***

   a. Cost assumptions include compliance with statutes, regulations, and BMPs

   b. Assumed the use of acceptable management practices

   c. Little to no road building

   d. Restricted operations above 80% ground slope

Text Box C.1 | 2005 *Billion-Ton Study*

- National estimates – no spatial information
- No cost analyses
- Environmental sustainability addressed from national perspective
- No explicit land use change modeling
- 2005 USDA agricultural baseline and 2000 forestry RPA/TPO
- Long-term time horizon (2025–2050)
- Estimates of current availability
- Long-term projections involving changes in crop productivity, crop tillage, residue collection efficiency, and land use change.

2011 *Update to the Billion-Ton*

- County-level analysis with aggregation to state, regional, and national levels
- County supply curves for major primary feedstocks
- Environmental sustainability modeled for residue removal
- 2009 USDA agricultural baseline and 2007 forestry RPA/TPO
- 2012–2030 timeline
- Land use change modeled for energy crops
- Annual projections based on a continuation of baseline trends (USDA Agricultural Projections – baseline forecast)
- Annual projections based on changes in crop productivity, tillage, and land use.

6. **Used gradient retention of biomass based on ground slope. Additional energy crop sustainability requirements in updated *BTS***
   a. Cost assumptions include compliance with statutes, regulations, and BMPs
   b. Assumed the use of acceptable management practices
   c. No conversion of forest lands
7. **Energy crop potential is modeled at a county-level using an agricultural policy simulation model (POLYSYS)**
8. **High-yield scenario for agricultural resources assumes changes in corn yield, changes in tillage, and several scenario growth rates for energy crop yields**
9. **Estimates of energy crop potential in the 2005 *BTS* and updated *BTS* assume that demands for food, feed, and exports continue to be met**

Appendix D: Data Sources

Appendix Table D.1. Data Sources

Feedstock	Sources and Notes
Forests	-
Fuelwood	EIA, AEO, 2010
Mill residues	USFS TPO, 2007
Pulp liquors	EIA, REA, 2007
Logging residues	USFS TPO, 2007
Thinnings (timberland)	USFS Inventory, 2010—further analysis/assumptions
Thinnings (other forestland)	USFS Inventory, 2010—further analysis/assumptions
Other removals	USFS TPO, 2007
Urban wood	EPA, 2007; McKeever, 1998 and 2004
Conventional (pulpwood)	2005 RPA; USFS Inventory, 2010—further analysis/assumptions
Agriculture	-
Corn starch ethanol	EISA
Biodiesel	EISA
Field residues	USDA Agricultural Projections

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