Errata: *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*

Updates – May 31, 2013

The U.S. Department of Energy would like to correct formatting, tables, language, values, and figures provided in the August 11, 2011, report, *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry.* This document contains the corrected pages with the changes highlighted in yellow. Newly posted versions of the report may have corrections incorporated. Changes below are as of May 31, 2013.

Specific changes to the report are listed by page number below:

- Page xix: the last line on the first column and first line in second column, it states "Primary forest biomass (i.e., logging and fuel treatment operations and land clearing) is the single largest source of feedstock." This should be …single largest source of forest-based feedstock.
- Pages xvi–xxii: Added Glossary of Key Terms and Acronyms
- Page xxiv, Text box ES.1, 5th item: Changed "Yield improvements derived from workshop." to "Yield improvement parameters derived from workshops."
- Page xxiv, text box ES.1, second to last bullet, change to "Forestry analysis modeled independently of agricultural analysis"
- Page xxix, Fig ES.3: Reversed the legend so that blue is energy crops, orange is agricultural process residues & wastes, red is wheat, and yellow is corn stover.
- Page xxx, Fig ES.5: Added "(3% Annual Energy Crop Yield Growth Rate)" to end of title
- Page 3: Moved Footnote 3
- Page 4, Text box 1.2, under 2011 update, 4th bullet: Made 2012-2030 timeline should be a separate line
- Page 4, Text box 1.2, 6th bullet under 2011 Update: Changed language to read "Annual projections beyond 2018 based on a continuation of baseline trends (USDA projections)"
- Page 5: Changed language to "POLYSYS" to "Policy Analysis System (POLYSYS)"
- Page: Changed language to "…major crops and extends that an additional 10 years…"
- Page 8: Changed "cropland source" to "agricultural source"
- Page 8, Footnote 7: Changed reference to EIA-AEO, 2010 (not 2010c)
- Page 9: Changed language to "In total, 32 million tons of residues (primary and secondary) is currently used (Table 2.1)."
- Page 10: Changed language to "highest domestic production of corn occurred in 2009"
- Page 13: Moved footnote 14 to page 14
- Page 2: Added "per rotation" at the end of the sentence.
- Page 33: Deleted the last two paragraphs of this page. They are duplicated from the left column of the previous page (p. 32)
- Page 47: Changed 2010 to 2012
- Pages 48 and 49: Updated the feedstock categories for consistency.
- Page 61: Changed spelling to "phosphorus"

- Page 63: Removed mention of HI from previously stated, “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.”
- Page 64: Changed language to "there is strong potential, however, to realize production increases if a portion of marginal productive lands…"
- Page 65, Text Box 4.3: Changed ".56" to "0.56"
- Page 65, Text Box 4.3: Deleted last three lines. Changed language to "For purposes of estimating corn stover potential an HI of 0.5 was used."
- Page 68, Figure 4.9: Changed title to "total available supply of residues of major crops after sustainability constraints are met at various prices under baseline assumptions."
- Page 77: Changed language to reflect Table 4.5 reference.
- Page 79: Changed parentheses to "(i.e. produces bolls over a fixed period of time for a single harvest)"
- Page 79: Changed parentheses to "(i.e. produces bolls over an extended period of time with bolls maturing at different times in the growing season)"
- Page 79, Footnote 44: Added the word "on" between "report" and "six"
- Page 80: Added word "domestically" after "was crushed"
- Page 81: Added word "primarily" between "located" and "in"
- Page 81: Change language to "Washington, Texas, Georgia, New York, Oklahoma, and Michigan"
- Page 82: Changed "70" to "72"
- Page 83: Replaced the text (beginning on p. 83, 2nd paragraph, line 4) with “Medium CAFOs are AFOs that hold between 300 and 1,000 AUs and discharge manure or wastewaters through a manmade ditch or pipe to surface water. AFOs that hold less than 300 AUs are labeled small CAFOs only if designated a CAFO by a permitting authority as a significant contributor of pollutants.”
- Page 83: Fixed spelling to "phosphorus"
- Page 83. Changed end of sentence "…2030, respectively, at $45 per dry ton (Table 4.5)."
- Page 84: Changed last sentence to "The estimated amount at $40 per dry ton increases to 10.5 million dry tons per year in 2017 and continues at this level through 2030."
- Page 87, Footnote 50. Changed Wright (in press) to Wright (2012).
- Page 89: Updated sentence to read, “The optimum nitrogen rate for switchgrass managed for biomass varies (Mitchell et al., 2008; 2010), but biomass yield declines over the years if inadequate nitrogen is applied, and yield will be sustainable only with proper nitrogen application.”
- Page 89: Adjusted language to read, “…from the system and some nitrogen is recycled into the roots.”
- Page 89: Change language to "Covered storage (e.g. net wrap, tarp, or structure) is necessary to protect harvested biomass"
- Page 92: Added a 4 to read “C4.”.
- Page 103:.Changed language to "crops and found that sweet sorghum had the highest yield potential, averaging over 17 tons per acre (dry weight basis) and also performing well when intercropping with alfalfa.

- Page 108: Changed reference to “Volk et al., in press to "Volk TA, Buford M, Berguson B, Caputo J, Eaton J, Perdue J, Rials T, Riemenschneider D, Stanton B, Stanturf J. 2010. Woody feedstocks — management and regional differences. Chapter 7 Sustainable Alternative Feedstock Opportunities, Challenges and Roadmap for 6 US Regions. Soil and Water Conservation Society. pp. 99-120. (Accessed at http://www.swcs.org/documents/resources/Chapter_7__Volk__Woody_Feedstocks_6D4F290C2D22F.pdf on July 5, 2012)"
- Page 115: Changed language from 37,664 million acres to 37.66 million acres
- Page 116: 2nd para, line 8. eliminate space after hyphen in “mid-rotation”
- Page 117: Changed "phosphorous" to "phosphorus"
- Page 119: Changed language to "The total amount of permanent pasture in a given county that can convert to energy crops is limited to 50%. The remaining 50% of pastureland acreage may be intensified (thereby doubling the forage production) to maintain the pre-conversion level of forage demand within the county.”
- Page 122, Text Box 5.4, Map: Changed the legend classes from "Observed Upland Yield 10" to "Observed Upland Yield 4.5" and "Observed Lowland Yield 20" to "Observed Upland Yield 8.9"
- Page 123: Changed "phosphorous" to "phosphorus"
- Page 128, Table 5.3: Changed "phosphorous" to "phosphorus
- Page 129, Table 5.4: Changed "phosphorous" to "phosphorus
- Page 132: Changed 5.0 million to 5 million (because the number based on fig. 5.18 is actually 5.3)
- Page 132: Changed language to "About 35% of these 64 million acres are cropland and the remaining is from pasture and permanent pasture."
- Page 137: Changed language to read: "Total planted acres in 2030 at the highest price are 79 million…"
- Page 138: Deleted "...and is split almost equally between perennial grasses and woody crops."
- Pages 140–141, in all the legends: Capitalized “Woody – Cropland”.
- Page 142: Table 5.6… 2030 Price of Grain Sorghum in Baseline should be $2.89. And 2017 Baseline Scenario Price should be $3.79. (they are switched)
- Page 150, Figure 6.1: The bars on the 2022 level should be at 21 billion gallons/year
- Page 151, Figure 6.2: The bars on the 2022 level should be at 21 billion gallons/year
- Page 155, 2nd col, Environmental sustainability Section, line 18. Would add "and stabilize soils" to the sentence so it reads: "…smaller amounts of fertilizers and pesticides and stabilize soils."
- Page 162, Figure 6.6: Changed title to indicate that this is for 3% yield growth.
- Page 167, Fox et al., 2007b: Changed issue from 5 to 7
- Page 183: Changed corn starch ethanol and biodiesel box, under biodiesel, soybeans to "1.52 gallons per bushel"
- All throughout Appendix A: Changed oat to “oats,” and changed soybean to “soybeans” unless used as adjectives (e.g. soybean meal, oat straw) (In 1.3.a (p. 183), 2.a.ii.1) (p. 185), 2.a.ii.d) (p. 185), 2.a.2) (p. 185), 3a.ii (p. 185))
- Page 183: Changed citation to Wright LL, Eaton LM, Perlack RD, Stokes BJ. 2012. Woody biomass. In Comprehensive renewable energy, Volume 5 Biomass and biofuel

production, Section 5.14: Technology solutions – novel feedstocks. A Sayigd (ed.). Elsevier, Oxford, UK. pp. 263-291.

- Page 185, last line: Adjusted language to read "…east of the 100th Meridian and the Pacific Northwest."
- Page 186, USDA Agricultural Projections Box: Deleted first bullet point "Conditional scenario based"
- Page 186, Bullet 2.a.ii.1 moved to 2.a.iii (Corn then became 1, Wheat became 2, etc.) Bullet 2.a.ii.2 became 2.a.iv; 2.a.ii.c became 2.a.v
- Page 186, Footnote 3: Deleted footnote 3, replace 3 with 2 in 3.a.ii
- Page 187, Bullet 3.a.ii.1: Corn in 2012 changed to 164;
- Page 187, Bullet 3.a.ii.4: The yields for oats and barley baseline yields changed to 64 and 67 from 63 and 66

- Page 188, Bullet 5.c.v.2): Changed “industrial stocks” to “industrial uses”
- Page 189, Bullet viii.1).b): Changed “uses” to “use”
- Page 191, Bullet c.2).d): Changed language to read: Corn stover removal averages: 14.8 pounds nitrogen per dry ton; 5.1 pounds of phosphorus (P2O5) per dry ton; 27.2 pounds of potassium (K2O) per dry to
- Page 194, Bullet 9: Changed language to read: “Estimates of energy crop potential in the 2005 BTS and updated BTS assume that demands for food, feed, industrial uses, and exports continue to be met.”

Updates – August 3, 2012

The U.S. Department of Energy would like to correct formatting, tables, language, values, and figures provided in the August 11, 2011, report, *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry.* This document contains the corrected pages with the changes highlighted in yellow. Newly posted versions of the report may have corrections incorporated. Changes below are as of August 3, 2012.

Specific changes to the report are listed by page number below:

- Page xxv: Corrected language. “Primary forest biomass (i.e., logging and fuel treatment operations and land clearing) is the single largest source of feedstock.” was changed to “…single largest source of forest-based feedstock.”
- Page xviii: Updated legend. Colors changed to the following—blue is energy crops, orange is agricultural process residues & wastes, red is wheat, and yellow is corn stover.
- Page 33: Deleted duplicate text. Removed last two paragraphs that were duplicated from page 32.
- Page 65: Corrected language. Sentence was changed to "For purposes of estimating corn stover potential the suggestion is to use an HI of 0.5." Two sentences from the September 8, 2011 version were deleted.
- Page 128: Updated Table 5.3. Adjusted values, columns, and rows in the table.
- Page 129: Updated Table 5.4. Adjusted values, columns, and rows in the table.
- Page 149: Updated Figure 6.1. The bars on the 2022 level were changed to 21 billion gallons/year.
- Page 150: Updated Figure 6.2. The bars on the 2022 level were changed to 21 billion gallons/year.

Updates – August 31, 2011

The U.S. Department of Energy would like to correct formatting, values, and figures provided in the August 11, 2011, report, *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry.* This document contains the corrected pages with the changes highlighted in yellow. Newly posted versions of the report may have corrections incorporated. Changes below were made as of September 8, 2011.

Specific changes to the report are listed by page number below:

- Page vii: Corrected formatting. “Cory Christensen, Ph.D.” should maintain independent line.
- Page 27: Corrected values. “$40 per dry ton” should change to “$80 per dry ton” to be consistent with Figure 3.7 on page 28.
- Page 52: Corrected values. “55 million dry tons” should be changed to “76 million dry tons.”
- Page 134: Corrected labels in text box. In Text Box 5.6, the horizontal label in the graphs should be changed from “$40/dry ton” to “$50/dry ton Baseline;” “$50/dry ton” to “+$5/dry ton Credit;” and “$60/dry ton” to “+$10/dry ton Credit.”
- Page 194: Corrected text. “Field Residues” should be “Secondary Field Residues.”

GLOSSARY OF KEY TERMS AND ACRONYMS

Algal biofuels – Utilization of primarily microalgae to produce high quantities of biomass per unit land area. The lipids in the microalgae can be used to produce biodiesel.

Annual removals – The net volume of growing stock trees removed from the inventory during a specified year by harvesting, cultural operations (such as timber stand improvement), or land clearing.

Asexual reproduction – The naturally occurring ability of some plant species to reproduce asexually through seeds, meaning the embryos develop without a male gamete. This ensures that the seeds will produce plants identical to the mother plant.

Barrel (bbl) – A barrel of oil is 42 gallons.

Baseline scenario – Disaggregation of U.S. Department of Agriculture Projection of Major Crops to the county level, extended to 2030, with baseline assumptions of energy crops yield growth (1%) and continuation of historic tillage adoption patterns of major crops. Forestry resources are estimated using a baseline scenario consistent with the projections outlined in Chapter 3.

Billion gallons per year – BGY

Billion-Ton Study (BTS) – *Biomass as a Feedstock for Bioenergy and Bioproducts: The Feasibility of a Billion-Ton Annual Supply* (2005).

Biobased product – The term biobased product, as defined by the Farm Security and Rural Investment Act, means a product determined by the U.S. Secretary of Agriculture to be a commercial or industrial product (other than food or feed) that is composed, in whole or in significant part, of biological products or renewable domestic agricultural materials (including plant, animal, and marine materials) or forestry materials.

Biodiesel – Fuel derived from vegetable oils or animal fats. It is produced when a vegetable oil or animal fat is chemically reacted with an alcohol, typically methanol. It is mixed with petroleum-based diesel.

Bioenergy – Useful, renewable energy produced from organic matter through the conversion of the complex carbohydrates in organic matter to energy. This energy may either be used directly as a fuel, processed into liquids and gasses, or be a residual of processing and conversion.

Bioenergy Knowledge Discovery Framework (KDF) – An online resource that includes bioenergy-related research, applications, and data. Hosts *Billion-Ton Update*-related information.

Biofuels – Fuels made from biomass resources or their processing and conversion derivatives. Biofuels include ethanol, biodiesel, and methanol.

Biomass – Any organic matter that is available on a renewable or recurring basis, including agricultural crops and trees, wood and wood residues, plants (including aquatic plants), grasses, animal manure, municipal residues, and other residue materials. Biomass is generally produced in a sustainable manner from water and carbon dioxide by photosynthesis. There are three main categories of biomass: primary, secondary, and tertiary.

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

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

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

British thermal unit (Btu) – A unit of energy equal to approximately 1,055 joules. It is the amount of energy required to heat 1 pound (0.454 kilograms) of water from 39 degrees Fahrenheit to 40 degrees Fahrenheit.

C4 species – C3 and C4 are the two main photosynthetic pathways in plants. C3 plants fix carbon dioxide (CO_2) through photorespiration and require stomatal opening to acquire CO_2. C4 plants acquire CO_2 from malate and do not require open stomata; as a result, they provide higher water use efficiency and produce more biomass in hotter, drier climates. Under conditions of moderate temperatures and available soil water, C3 plants typically have an advantage in CO_2 fixation and thus overall growth.

Coarse materials – Wood residues suitable for chipping, such as slabs, edgings, and trimmings.

Commercial species – Tree species suitable for industrial wood products.

Component ration method (CRM) – Introduced by the U.S. Department of Agriculture Forest Service in 2009, CRM is a method used to estimate non-merchantable volumes from merchantable trees.

Composite integrated operations – Simultaneous production of both commercial (merchantable) wood products and thinnings. In the *Billion-Ton Update*, it is estimated as the supply of forest materials available—assuming continuation of current harvesting operations that includes 50% of logging residues and 50% of available forest thinning at each price level at the county level.

Conservation Reserve Program (CRP) – A national land set-aside program that provides farm owners or operators with an annual per acre rental payment and half the cost of establishing a permanent land cover in exchange for retiring environmentally sensitive cropland from production for 10 to 15 years. In 1996, Congress reauthorized CRP for an additional round of contracts, limiting enrollment to 36.4 million acres at any time. The 2002 Farm Act increased the enrollment limit to 39 million acres. Producers can offer land for competitive bidding based on an Environmental Benefits Index during periodic signups, or can automatically enroll more limited acreages in practices such as riparian buffers, field windbreaks, and grass strips on a continuous basis. CRP is funded through the Commodity Credit Corporation.

Construction and demolition debris (C&D) – Wood waste 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.

Conventionally sourced wood – Wood that has commercial uses other than fuel (e.g., pulpwood), but is used for energy because of market conditions. This would most likely only include smaller diameter pulpwood-sized trees.

Coppice – To regrow from a (tree) stump after harvest. This would be equivalent to a ratoon crop for sugarcane or sorghum, which would regrow from the stem after harvest.

Cotton gin trash – Residue available at a processing site, including seeds, leaves, and other material.

Cotton residue – Cotton stalks available for collection after cotton harvest.

Crop management zones (CMZ) – Spatial regions generated by the U.S. Department of Agriculture National Resource Conservation Service of similar climate and crops.

Crop residues – The portion of a crop remaining after the primary product is harvested. Crop residues include corn stover and wheat, barely, oats, and sorghum straw. Other residues are rice field residue (straw), cotton field residue, and sugarcane residues (trash-leaves, tops, and remaining stalk after primary harvest of the stalk).

Cropland – Total cropland includes five components: cropland harvested, crop failure, cultivated summer fallow, cropland used only for pasture, and idle cropland.

Cropland pasture – Land used for long-term crop rotation. However, some cropland pasture is marginal for crop uses and may remain in pasture indefinitely. This category also includes land that was used for pasture before crops reached maturity, and some land used for pasture that could have been cropped without additional improvement.

Cropland used for crops – Cropland used for crops includes cropland harvested, crop failure, and cultivated summer fallow. **Cropland harvested** includes row crops and closely sown crops; hay and silage crops; tree fruits, small fruits, berries, and tree nuts; vegetables and melons; and miscellaneous other minor crops. In recent years, farmers have double-cropped about 4% of this acreage. **Crop failure** primarily consists of the acreage on which crops failed because of weather, insects, and diseases, but includes some land not harvested due to lack of labor, low market prices, or other factors. The acreage planted to cover and soil improvement crops not intended for harvest is excluded from crop failure and is considered idle. **Cultivated summer fallow** refers to cropland in sub-humid regions of the West cultivated for one or more seasons to control weeds and accumulate moisture before small grains are planted. This practice is optional in some areas, but it is a requirement for crop production in the drier cropland areas of the West. Other types of fallow—such as cropland planted with soil improvement crops but not harvested, and cropland left idle all year—are not included in cultivated summer fallow, but they are included as idle cropland.

Cull tree – A live tree—5 inches in diameter at breast height or larger—that is non-merchantable for saw logs now or prospectively because of rot, roughness, or species. (See definitions for rotten and rough trees.)

Diameter at breast height (dbh) – The common measure of wood volume approximated by the diameter of trees measured at approximately breast height from the ground.

Energy cane – Related to sugar cane. It can be a high fiber sugar cane variety, or a hybrid between sugar cane and wild relatives of sugar cane. Energy cane is designed to give higher biomass yields than sugar cane, but have a lower sugar concentration.

Energy Independence and Security Act of 2007 (EISA) – EISA is designed to increase the production of clean renewable fuels; protect consumers; increase the efficiency of products, buildings, and vehicles; promote research on and deploy greenhouse gas capture and storage options; and improve the energy performance of the federal government.

Ethanol – Also known as ethyl alcohol or grain alcohol. It is a volatile, flammable, and colorless liquid with the chemical formula C_2H_6O. It is produced by the fermentation of sugars into ethanol. Its primary uses are for drinking and fuel. In the United States, most fuel ethanol is currently produced by fermentation of glucose from the starch in corn.

Feedstock – A product used as the basis for manufacture of another product.

Fiber products – Products derived from fibers of herbaceous and woody plant materials. Examples include pulp, composition board products, and wood chips for export.

Fine materials – Wood residues not suitable for chipping, such as planer shavings and sawdust.

Forest and Rangeland Renewable Resources Planning Act of 1974 (RPA) – Requires periodic assessments and reports the status and trends of the nation's renewable resources on all forest and rangelands.

Forest Inventory and Analysis (FIA) – 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 the *Billion-Ton Update* are summarized from more than 100,000 permanent field plots in the United States.

Forest land – Land at least 10% stocked by forest trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated. Forest land includes transition zones, such as areas between heavily forested and non-forested lands that are at least 10% stocked with forest trees and forest areas adjacent to urban and built-up lands. Also included are pinyon-juniper and chaparral areas in the West and afforested areas. The minimum area for classification of forest land is 1 acre. Roadside, streamside, and shelterbelt strips of trees must have a crown width of at least 120 feet to qualify as forest land. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if less than 120-feet wide.

Fuel Reduction Cost Simulator (FRCS) – A forest harvesting costing model utilized in the *Billion-Ton Update* to estimate the cost of harvesting small diameter trees for biomass.

Fuel Treatment Evaluator (FTE) – A strategic assessment tool capable of aiding the identification, evaluation, and prioritization of fuel treatment opportunities.

Fuelwood – Wood used for conversion to some form of energy, primarily for residential use.

Grassland pasture and range – All open land used primarily for pasture and grazing, including shrub and brush land types of pasture; grazing land with sagebrush and scattered mesquite; and all tame and native grasses, legumes, and other forage used for pasture or grazing. Due to the diversity in vegetative composition, grassland pasture and range are not always clearly distinguishable from other types of pasture and range. At one extreme, permanent grassland may merge with cropland pasture, or grassland may often be found in transitional areas with forested grazing land.

Greenhouse gases – GHG

Growing stock – A classification of timber inventory that includes live trees of commercial species meeting specified standards of quality or vigor. Cull trees are excluded. When associated with volume, this classification only includes trees 5 inches in diamete at breast height and larger.

Harvest index (HI) – For traditional crops, the ratio of residue to grain.

High-yield scenario – A set of scenarios that follow similar forecast assumptions as the baseline scenario with three exceptions: energy crop yield growth varies due to higher research and development (five cases: 1%, 2%, 3%, and 4%); traditional crop yield growth is higher; and shifts from conventional tillage production to no-till and reduced tillage occurs faster. There is no high-yield scenario for forestry resources.

Idle cropland – Land in cover and soil improvement crops, and cropland on which no crops were planted. Some cropland is idle each year for various physical and economic reasons. Acreage diverted from crops to soil-conserving uses (if not eligible for and used as cropland pasture) under federal farm programs is included in this component. Cropland enrolled in the Federal Conservation Reserve Program is included in idle cropland.

Industrial wood – All commercial roundwood products except for fuelwood.

Live cull – A classification that includes live cull trees. When associated with volume, it is the net volume in live cull trees that are 5 inches in diameter at breast height and larger.

Logging residues – The unused portions of growing-stock and non-growing-stock trees that have been cut or killed by logging and left in the woods.

Mill residues – Bark and woody materials that are generated in primary wood-using mills when roundwood products are converted to other products. Examples are slabs, edgings, trimmings, sawdust, shavings, veneer cores and clippings, and pulp screenings. Includes bark residues and wood residues (both coarse and fine materials), but excludes logging residues. May include both primary and secondary mills.

Municipal solid waste (MSW) – Wastes (garbage) collected from municipalities consisting mainly of yard trimmings and paper products.

Non-forest land – Land that has never supported forests, and lands formerly forested where use of timber management is precluded by development for other uses. (*Note*: Includes area used for crops, improved pasture, residential areas, city parks, improved roads of any width and adjoining clearings, powerline clearings of any width, and 1- to 4.5-acre areas of water classified by the Census Bureau as land. If intermingled in forest areas, unimproved roads and nonforest strips must be more than 120-feet wide, and clearings, etc., must be more than 1 acre in area to qualify as non-forest land.)

Nonindustrial private – An ownership class of private lands where the owner does not operate wood-using processing plants.

Other forest land – Forest land other than timberland, as well as reserved forest land. It includes available forest land, which is incapable of annually producing 20 cubic feet per acre of industrial wood under natural conditions because of adverse site conditions such as sterile soils, dry climate, poor drainage, high elevation, steepness, or rockiness.

Other removals and residues – Unutilized wood volume from cut or otherwise killed growing stock, from cultural operations such as precommercial thinnings, or from timberland clearing for other uses (i.e., cropland, pastureland, roads, and urban settlement). Does not include volume removed from inventory through reclassification of timberland to productive reserved forest land.

Other wood sources – Sources of roundwood products that are not growing stock. These include salvable dead, rough and rotten trees, trees of noncommercial species, trees less than 5 inches in diameter at breast height, tops, and roundwood harvested from non-forest land (for example, fence rows).

Perennial – A crop that lives for more than two years. Well-established perennial crops have a good root system and provide cover that reduces erosion potential. They generally have reduced fertilizer and herbicide requirements compared to annual crops.

Poletimber trees – Live trees at least 5 inches in diameter at breast height, but smaller than sawtimber trees.

Policy Analysis System (POLYSYS) – An agricultural policy modeling system of U.S. agriculture, including both crops and livestock. It is based at the University of Tennessee Institute of Agriculture, Agricultural Policy Analysis Center: http://www.agpolicy.org/polysys.html.

Primary agricultural resources – Primary agricultural resources include energy feedstocks (annual energy crops, coppice and non-coppice woody crops, perennial grasses), crop residues (barely straw, corn stover, oat straw, sorghum stubble, wheat straw), and conventional crops (barley, corn, cotton, hay, oats, rice, sorghum, soybeans, wheat). The projections included for this category of feedstocks are two baseline scenarios (one with no energy crops—e.g., feedstock price of zero—and another including energy crops) and four high-yield scenarios with estimated biomass prices ranging between $40 and $80 at $5 increments.

Primary wood-using mill – A mill that converts roundwood products into other wood products. Common examples are sawmills that convert saw logs into lumber and pulp mills that convert pulpwood roundwood into wood pulp.

Pulpwood – Roundwood, whole-tree chips, or wood residues that are used for the production of wood pulp (also referred to as conventional wood within the database).

Renewable Fuel Standard (RFS) – The RFS was established by the Energy Policy Act of 2005. It required 7.5 billion gallons of renewable-based fuel (which was primarily ethanol) to be blended into gasoline by 2012. This original RFS (referred to sometimes as RFS1) was expanded upon by the Energy Independence Security Act of 2007 to include diesel in addition to gasoline, as well as to increase the volume of renewable fuel to be blended into fossil-based fuel to 9 billion and ultimately 36 billion gallons by 2022 (RFS2). Lifecycle greenhouse gas requirements (less than fossil fuels they replace) for renewable fuels were established.

Renewable Portfolio Standard (RPS) – A standard or regulation that requires electricity utilities and other retail electricity suppliers to obtain a certain percent of their electricity from certified renewable sources.

Revised Universal Soil Loss Equation (RUSLE2) – A computer program that estimates erosion and sediment delivery for conservation planning in crop production.

Rotten tree – A live tree of commercial species that does not contain a saw log now or prospectively primarily because of rot (that is, when rot accounts for more than 50% of the total cull volume).

Rough tree – (a) A live tree of commercial species that does not contain a saw log now or prospectively primarily because of roughness (that is, when sound cull—due to such factors as poor form, splits, or cracks—accounts for more than 50% of the total cull volume); or (b) a live tree of non-commercial species.

Roundwood products – Logs and other round timber generated from harvesting trees for industrial or consumer use.

Salvable dead tree – A downed or standing dead tree that is considered currently or potentially merchantable by regional standards.

Saplings – Live trees 1.0–4.9 inches in diameter at breast height.

Secondary wood-processing mills – Mills that use primary wood products in the manufacture of finished wood products, such as cabinets, moldings, and furniture.

Soil Conditioning Index (SCI) – An index indicating the impact of crop management activities on soil organic matter.

Sound dead – The net volume in salvable dead trees.

Stand density index (SDI) – A measure of stocking of trees per unit area based on the number of trees per unit area and the average of diameter at breast height in the area. It is usually well correlated with the stand volume.

Starch – A carbohydrate consisting of many glucose units. It is the most common carbohydrate in the human diet.

Stumpage value – The sale value of the products that can be obtained from a stand of trees. This is the value of the wood products at a processing or end-use facility minus transport and harvest costs and a profit for the harvester.

Sugarcane trash – Tops and branches of sugarcane plants left on the field available for collection.

Thinnings (other forest land treatment thinnings) – Thinnings can come from operations to reduce fuel load (i.e., removal of small trees to reduce the fire danger) and from composite integrated operations on forest land (activities to harvest merchantable commercial wood and low-quality wood for bioenergy applications simultaneously). Thinnings can also come from pre-commercial operations and from other forest land to improve forest health.

Timber Product Output (TPO) Database Retrieval System – Developed in support of the 1997 Resources Planning Act Assessment, this system acts as an interface to a standard set of consistently coded TPO data for each state and county in the country. This set of national TPO data consists of 11 data variables that describe for each county the roundwood products harvested, the logging residues left behind, the timber otherwise removed, and the wood and bark residues generated by its primary wood-using mills.

Timberland – Forest land that is producing or is capable of producing crops of industrial wood, and that is not withdrawn from timber utilization by statute or administrative regulation. Areas qualifying as timberland are capable of producing more than 20 cubic feet per acre per year of industrial wood in natural stands. Currently inaccessible and inoperable areas are included.

Urban wood wastes – These come from municipal solid waste (MSW) and construction and demolition debris. In the MSW portion, there is a wood component in containers, packaging and discarded durable goods (e.g., furniture), and yard and tree trimmings.

Wheat dust – The portion of wheat left after processing, known as dust and chaff.

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 improvement parameters derived from workshops
- 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 modeled independently of agricultural analysis
- 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 forest-based 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.

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

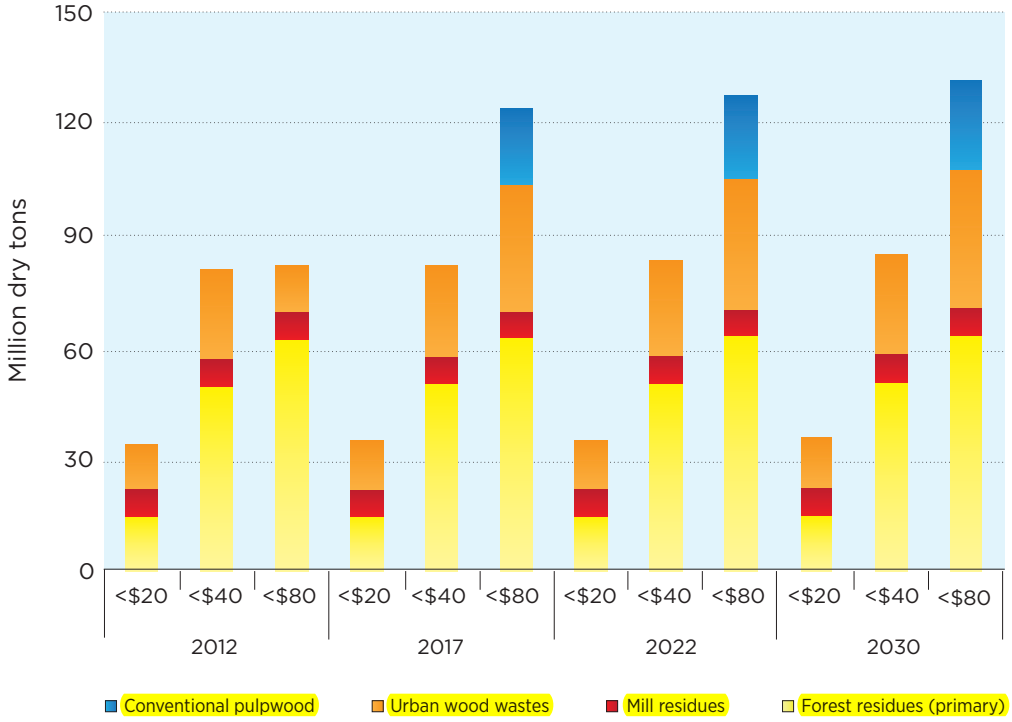


Figure ES.2 Estimated agricultural biomass under baseline assumptions

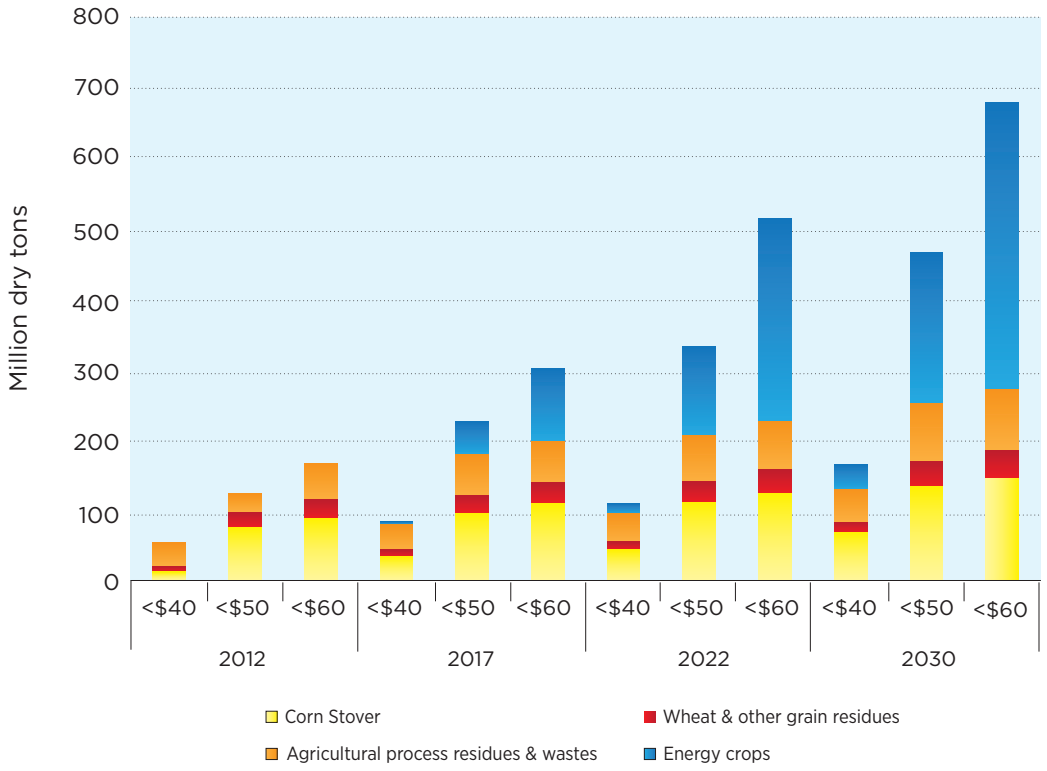


Figure ES.3 Estimated forest and agricultural biomass availability at $60 per dry ton or less under high-yield assumptions

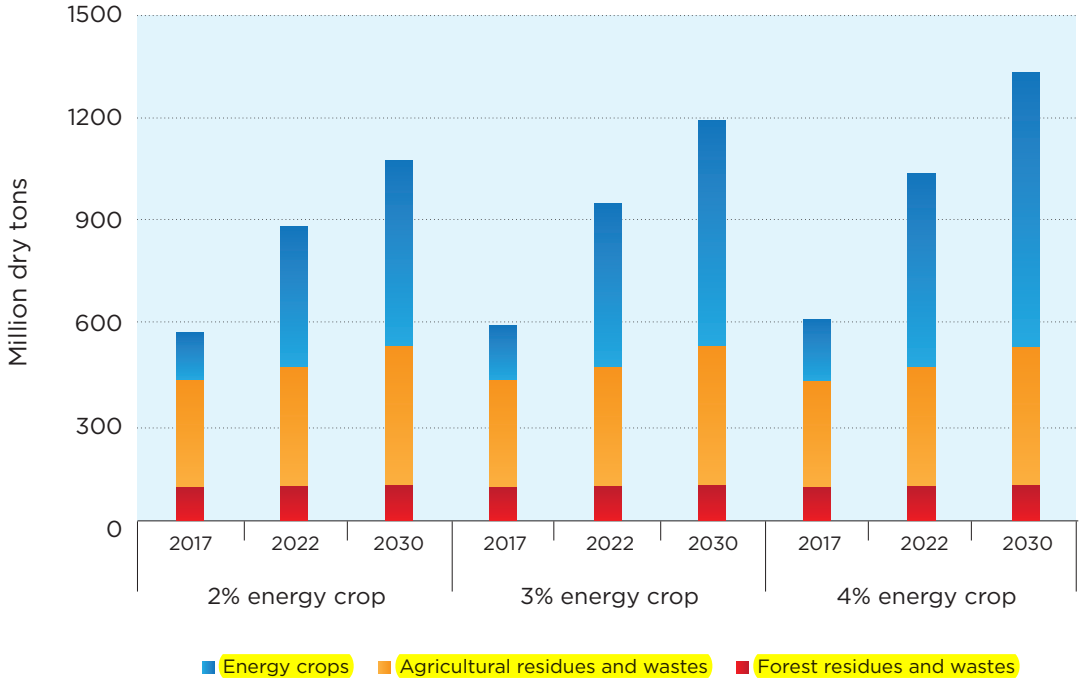


Figure ES.4 Summary of currently used and potential resources at $60 per dry ton or less identified under baseline assumptions

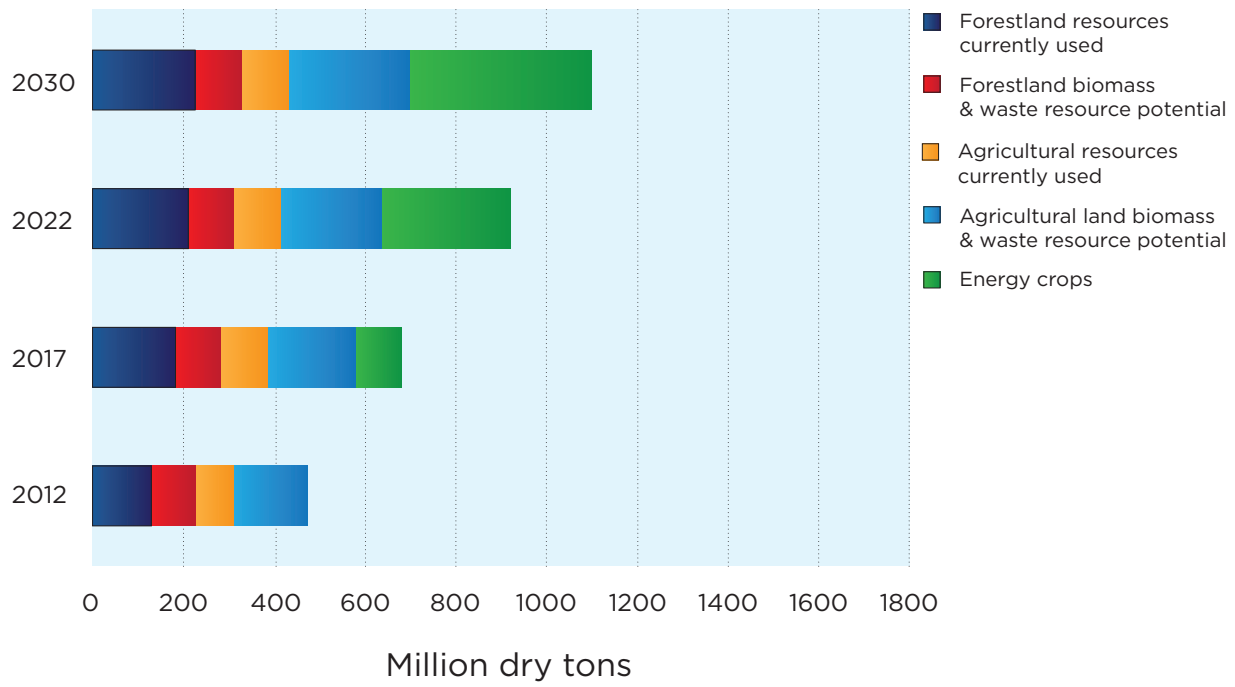
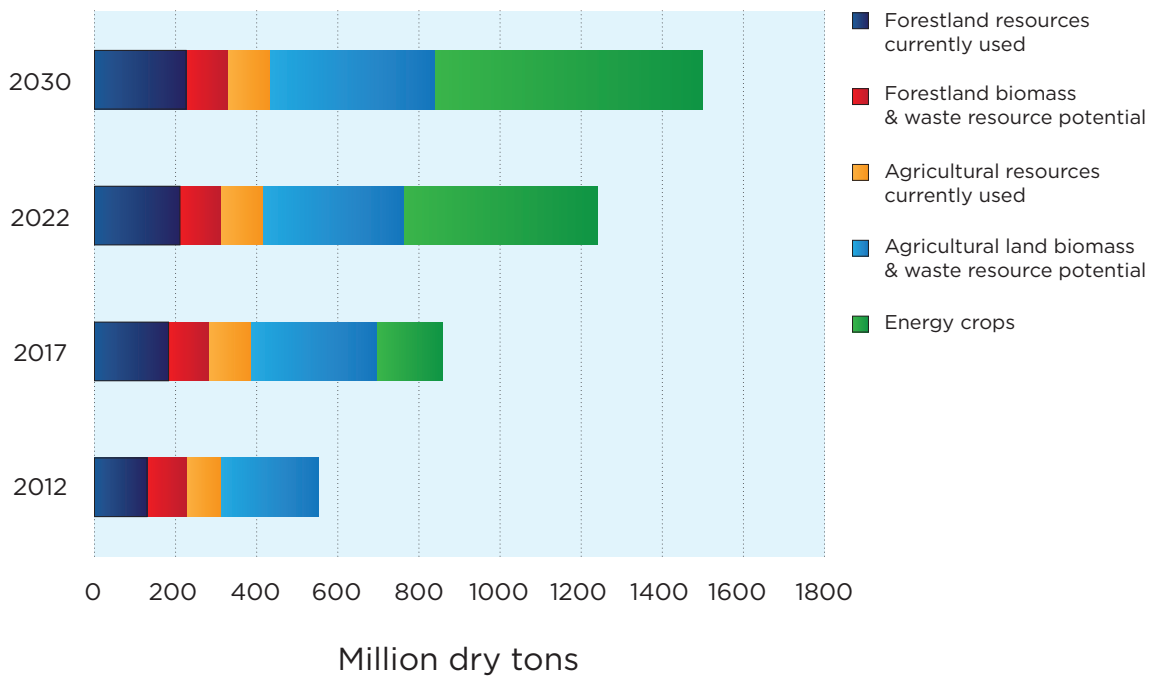


Figure ES.5 Summary of currently used and potential resources at $60 per dry ton or less identified under high-yield assumptions (3% annual energy crop yield growth rate)



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.

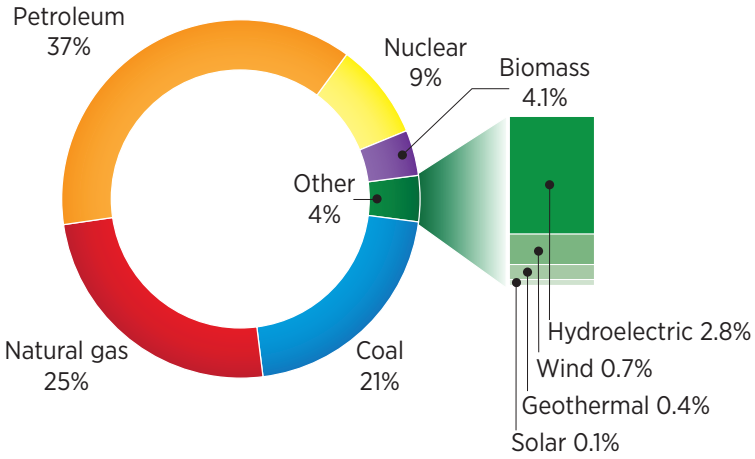
In this update, two scenarios are evaluated. First, there is the baseline scenario that essentially assumes a continuation of the USDA 10-year forecast for the major crops and extends that an additional 10 years to 2030. Second, the update provides an opportunity to further evaluate and refine changes 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 Policy Analysis System (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).

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, an agricultural 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, 2010) 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 tons of residues (primary and secondary) is 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 of corn 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.

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.

[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.

[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.

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 per rotation. 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

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 2012 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.

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, industrial uses, and exports continue to be met**

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 Residues	4.4	12	12	12	12	12
Integrated 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 Residues, Unused Primary	1.3	1.3	1.3	1.3	1.3	1.3
Mill Residues, 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 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 phosphorus 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.

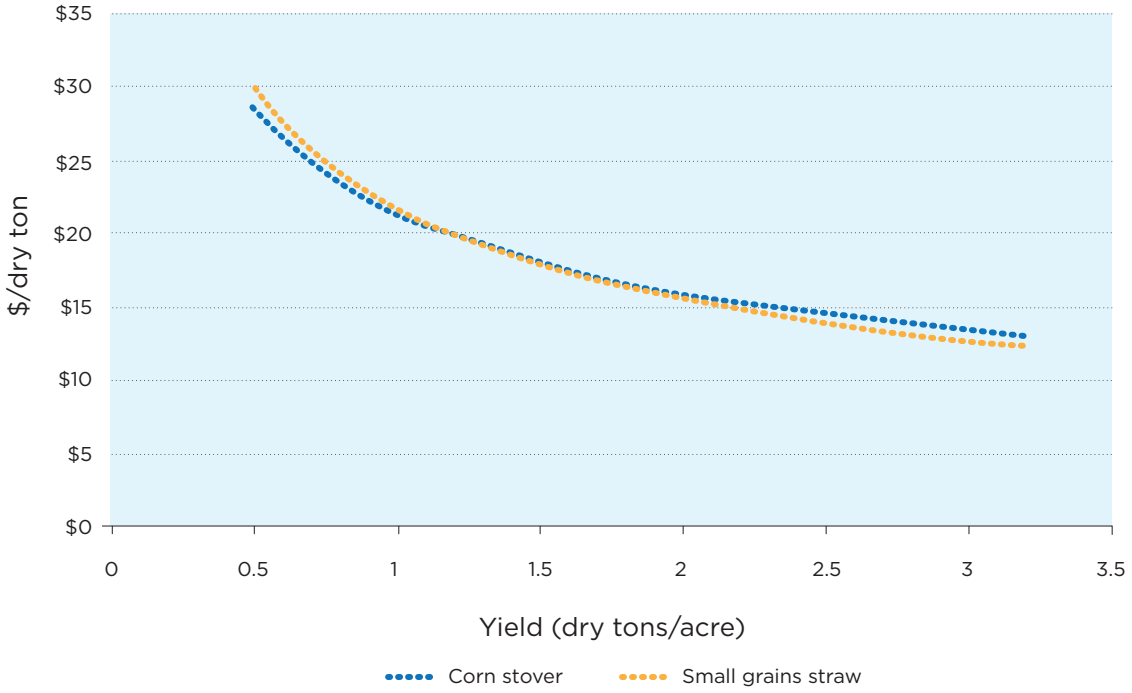
Most corn produced in the United States is grown in rotation with soybeans. As corn stover decomposes in the field, nutrients become available. Phosphorus and potassium are not generally lost and are utilized by all crops. For nitrogen, there is a question as to whether it becomes available during the 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 4.7 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 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]

Participant discussion and opinions relative to HI were

[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.

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 production 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 0.56 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).*

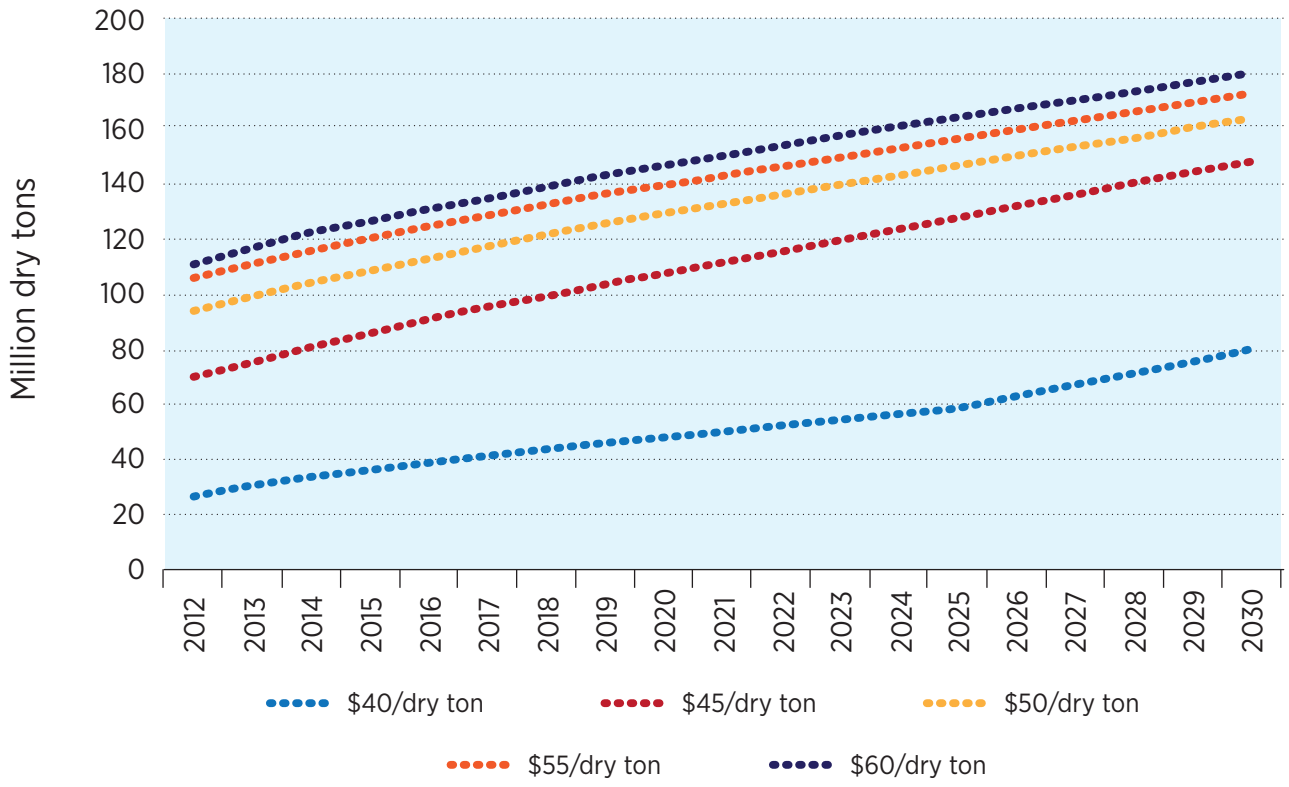
There are some seemingly contradictory statements in the literature about the effect of plant density on HI. Tollenaar et al. (1994) state that harvest index decreases when plant density increases above a certain critical threshold. Dobermann et al. (2002) examined corn under three different plant densities (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.] For purposes of estimating corn stover potential, an HI of 0.5 was used.

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 residues of major cropos after sustainability constraints are met at various prices under baseline assumptions



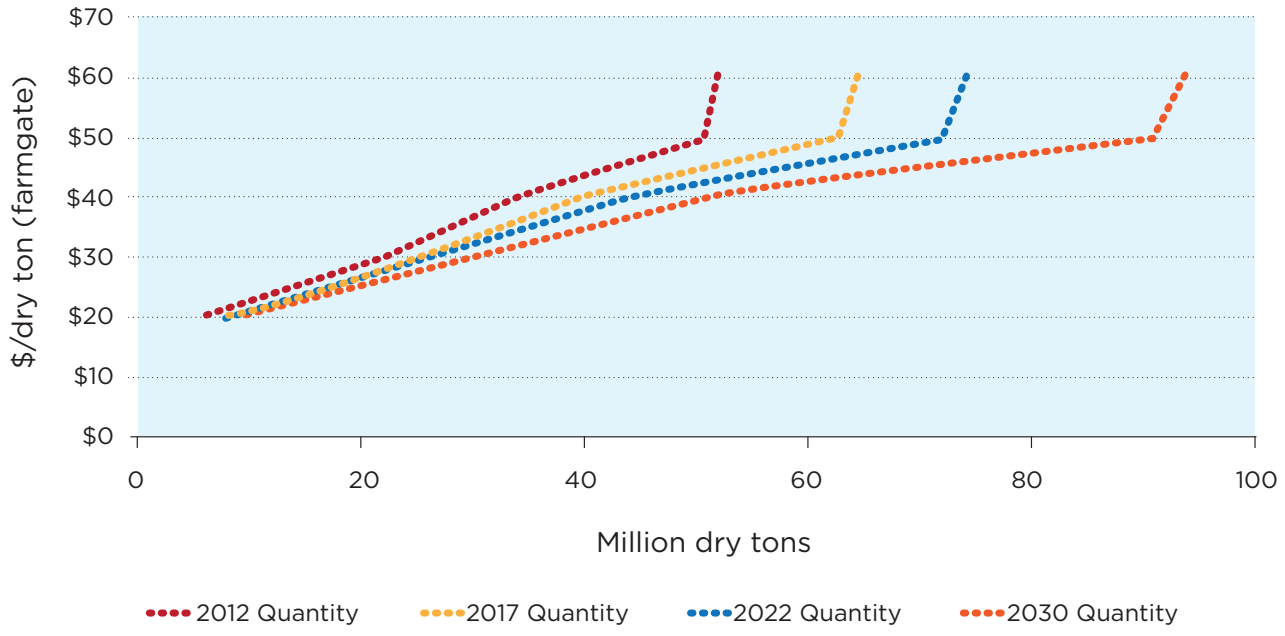
[40] This assumes a conversion rate of 85 gallons per dry ton and about 20% of the total feedstock unavailable due to losses in hauling, storing and handling, and/or some of the feedstock being stranded.

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 4.5). 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 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.

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 (i.e., produces bolls over a fixed period of time for a single harvest) (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 (i.e., produces bolls over an extended period of time with bolls maturing at different times in the growing 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 on 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

Feedstock	<$20 per dry ton				<$30 per dry ton				<$40 per dry ton			
	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 domestically, 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 primarily in Washington, Texas, Georgia, New York, Oklahoma, 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.

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 72 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 manure or wastewaters through a manmade ditch or pipe to surface water. AFOs that hold less than 300 AUs are labeled small CAFOs only if designated a CAFO by a permitting authority as a significant contributor of pollutants.

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, phosphorus, 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, at $45 per dry ton (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 at $40 per dry ton 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.

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 (2012).

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 yield declines over the 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 into the roots. 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 (e.g., net wrap, tarp, or structure) 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

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 C4 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).

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 17 tons per acre (dry weight basis) and also performing well when intercropping with alfalfa. 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,

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. 2010) (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

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 37.66 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 phosphorus 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 phosphorus (at 200-pound nitrogen per acre and 25-pound phosphorus 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 (Fox et al., 2007a).

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.

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.

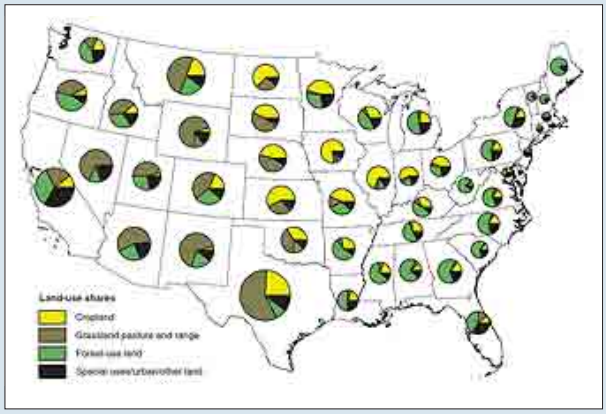
The availability of pasture (permanent pasture and cropland pasture) for conversion to perennial grasses and woody crops is constrained to counties east of the 100th Meridian (for reference, this parallel runs through Dodge City, Kansas). Counties east of the 100th Meridian are assumed to have sufficient 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:

- The total amount of permanent pasture in a given county that can convert to energy crops is limited to 50%. The remaining 50% of pastureland acreage may be intensified (thereby doubling the forage production) to maintain the pre-conversion level of forage demand within the county.
- 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 5.4). 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.

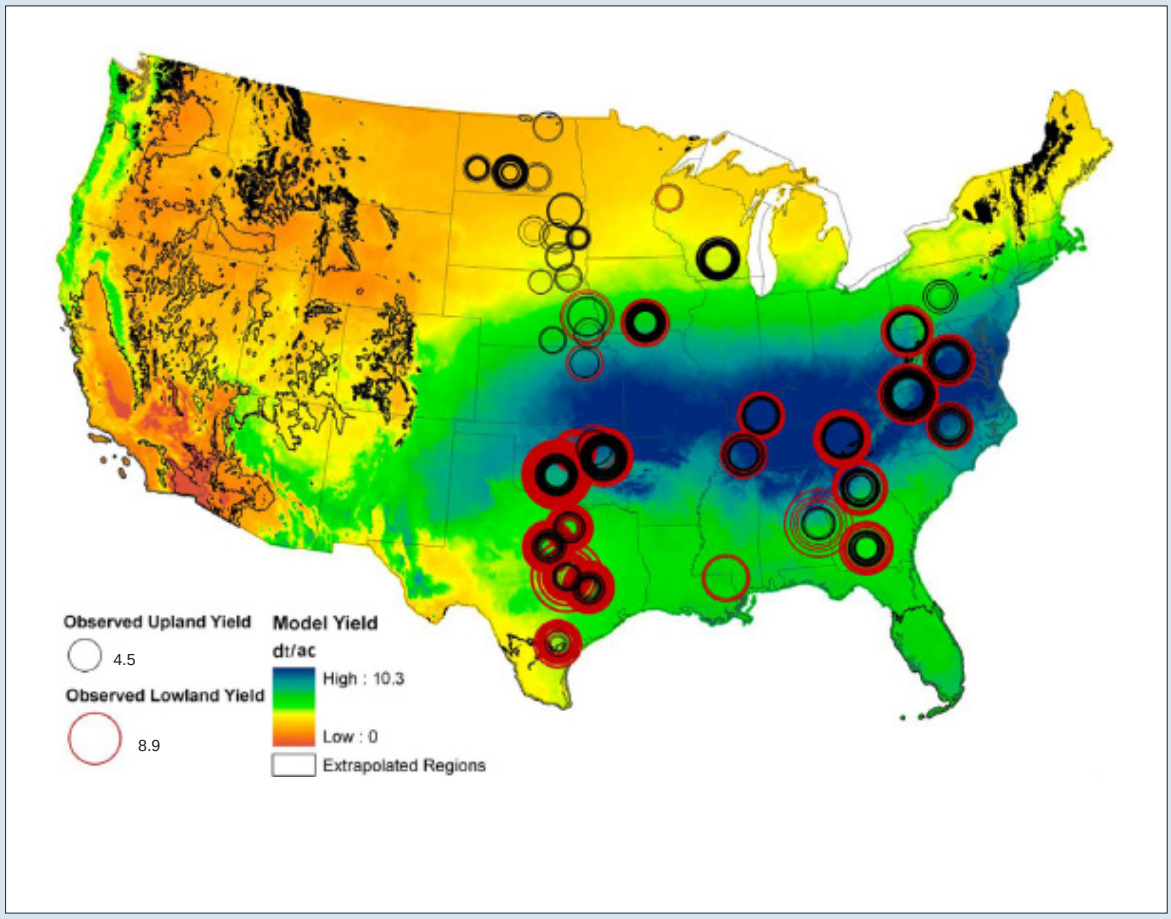
[58] For Miscanthus, establishment would be higher due to rhizome costs. However, productivity of Miscanthus is generally higher than that of switchgrass. So ultimately, whether switchgrass or Miscanthus is more profitable in a given area really depends more or less on the tradeoff between establishment 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 5.4 | 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*

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 5.5)

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, phosphorus, 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.

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	$22/10[a]
Planting	lb/acre	5	5	5	5	5	5	5
Replants	percent	25	25	25	25	25	25	25
No-till drill	-	1-time	1-time	1-time	1-time	1-time	1-time	1-time
Total kill herbicide	No. applications	1-time	1-time	1-time	1-time	1-time	1-time	1-time
Pre-emergent herbicide	No. applications	1-time	1-time	1-time	1-time	1-time	1-time	1-time
Phosphorus	lbs P2O5/ acre	40	40	40	40	40	40	40
Potassium	lbs K2O/ac	80	80	80	80	80	80	0
Lime	tons/acre	1	2	2	1	1	1	0
Total establishment costs	**$/acre**	**$250**	**$340**	**$340**	**$300**	**$230**	**$230**	**$170/230[a]**
Maintenance years								
Reseeding	year applied	2	2	2	2	2	2	2
Pre-emergent herbicide	No. applications	0	0	0	0	0	0	0
Nitrogen[b]	lbs/acre	52-98	65-124	46-124	39-91	52-91	46-65	26-84
Phosphorus	lbs P_2O_5/acre	40	40	40	40	40	40	40
Potassium	lbs K_2O /acre	80	80	80	80	80	80	0
Harvest costs	**$/dry ton**	**$15.80-$18.80**	**$14.60-$16.90**	**$14.20-$18.60**	**$15.00-$20.40**	**$15.60-$18.40**	**$17.60-$19.70**	**$15.70-$28.40**
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	$290	$280	$280	$270	$280	n/a	$200
Harvest costs	$/dry ton	$9.50-$13.00	$8.60-$12.50	$8.20-$12.20	$8.10-$12.20	$8.40-$11.30	n/a	$8.30-$11.60

[a] First number for Southern Plains, second number for Northern Plains

[b] 13 lb/dry ton of yield

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; and $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.*

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 (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 (PNW), Midwest, Plains	Southeast	Sub-tropics	Northeast and Lake States
Establishment - year 1					
Cuttings	$/tree	$0.12	$0.10	$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	1.68
Phosphorus	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	1, 0 in PNW	1	1	0
	year applied	year 3	year 3	year 3	-
Nitrogen –	lbs/acre	90	90	90	100
	year applied	4,6	2,4,6	4,6	2,5,9,13,17
	-	-	-	-	-
Phosphorus –	lbs P_2O_5/acre	15-40	40	15	-
	year applied	1	1,3	1	-
Potassium –	lb K_2O lbs/acre	15-50	40	25	-
	year applied	1	1,3	1	-
Maintenance costs – year 2	$/acre	$60	$100	$100	$30
Maintenance costs – year 3–8	$/acre	$170–$220	$200	$200	$100[a]
Maintenance costs – total over years 3 and 4	$/acre	-	-	-	100
Harvest costs	**$/dry ton**	**$18.80–20.20**	**$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.*

[a] *Maintenance costs for years 3 and 4*

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 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 is from 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.

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. 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 at the highest price are 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

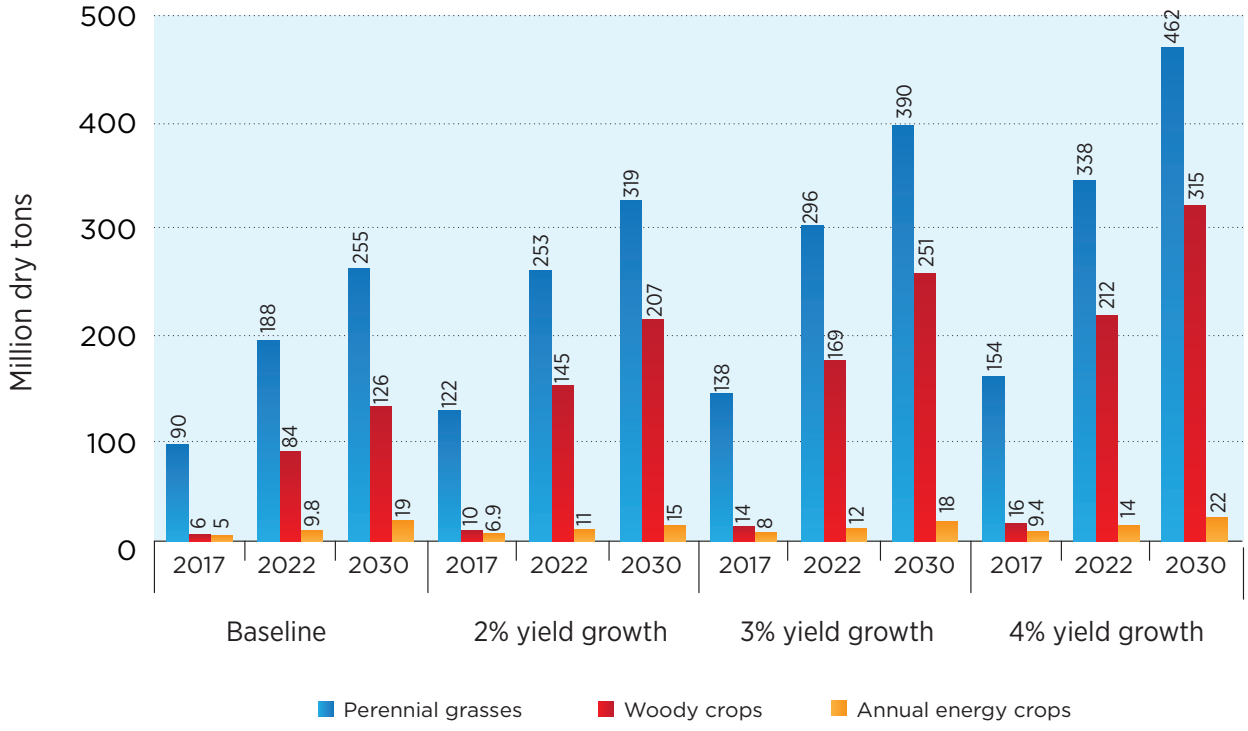


Figure 5.23 Land-use change under baseline assumptions for 2017, 2022, and 2030 at farmgate prices of $40, $50, and $60 per dry ton

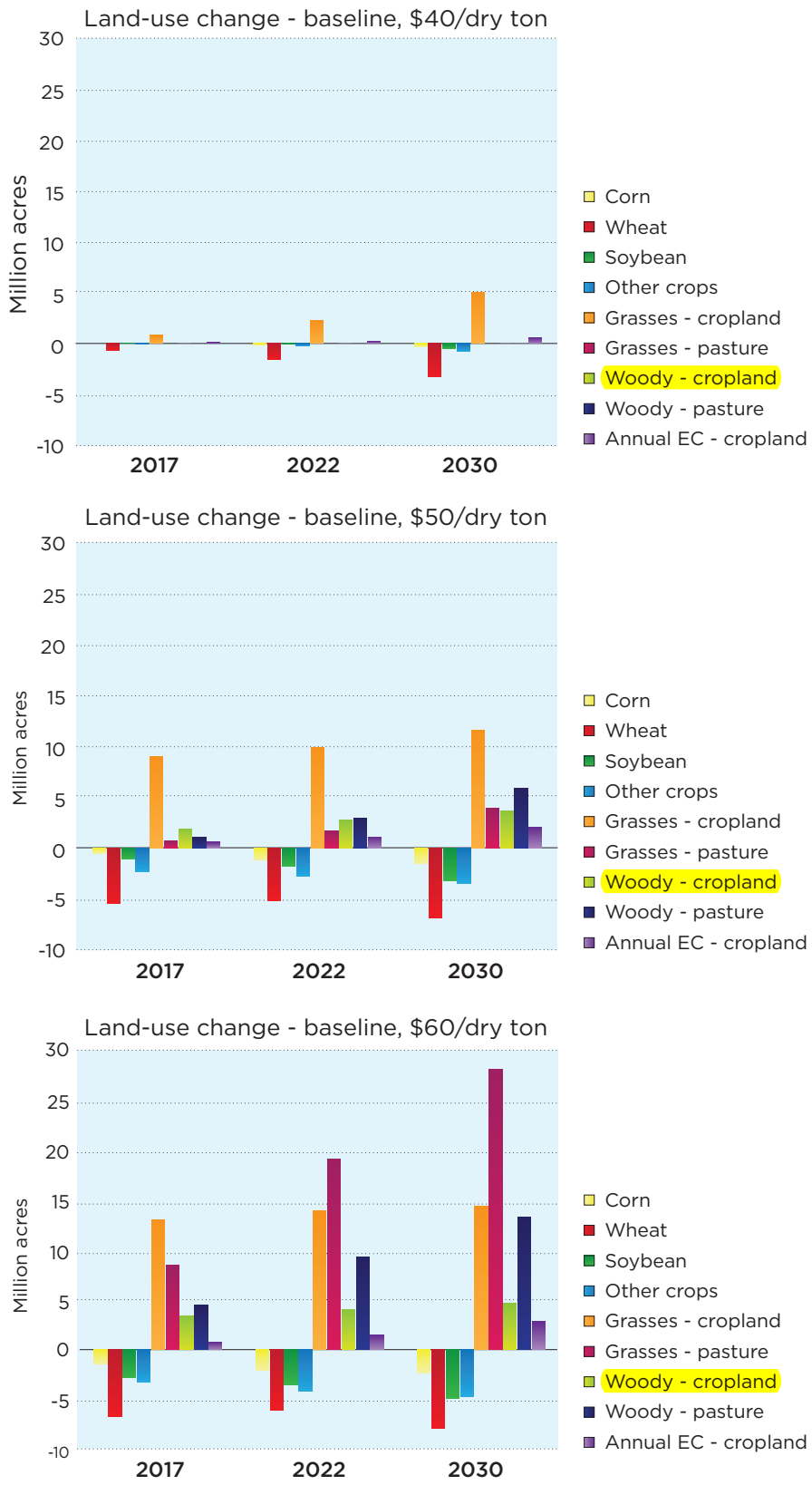


Figure 5.24 Land-use change under high-yield (3%) assumptions for 2017, 2022, and 2030 at farmgate prices of $40, $50, and $60 per dry ton

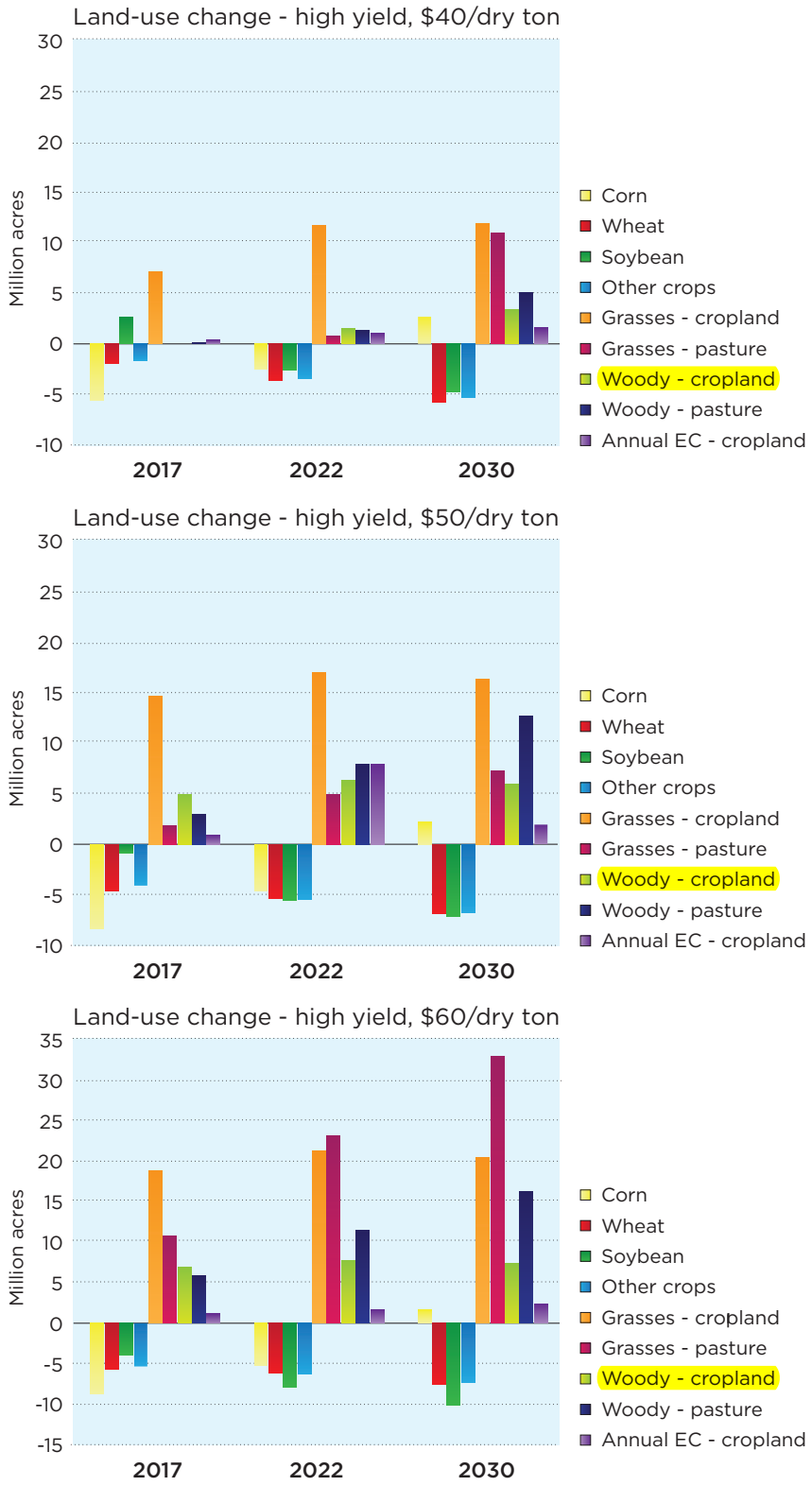


Table 5.6 Summary Comparison of USDA Projections for Major Crops with Baseline Projections for Biomass Resources Derived from Cropland and Pastureland, at $50 per Dry Ton Farmgate Price

Crop	USDA Baseline Forecast[1]				Baseline scenario		
	2012[1]	2017[1]	2022[2]	2030[2]	2017	2022	2030
Crop prices ($/bu)							
Corn	3.70	3.75	3.60	3.43	3.79	3.71	3.57
Grain Sorghum	3.30	3.35	3.20	2.89	3.79	3.71	3.57
Oat	2.35	2.35	2.28	2.11	2.37	2.39	2.32
Barley	3.90	3.95	3.79	3.36	4.27	4.39	3.89
Wheat	5.35	5.45	5.43	5.32	6.15	6.20	6.35
Soybean	8.70	8.75	8.42	7.92	8.95	8.72	8.44
Cotton ($/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

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

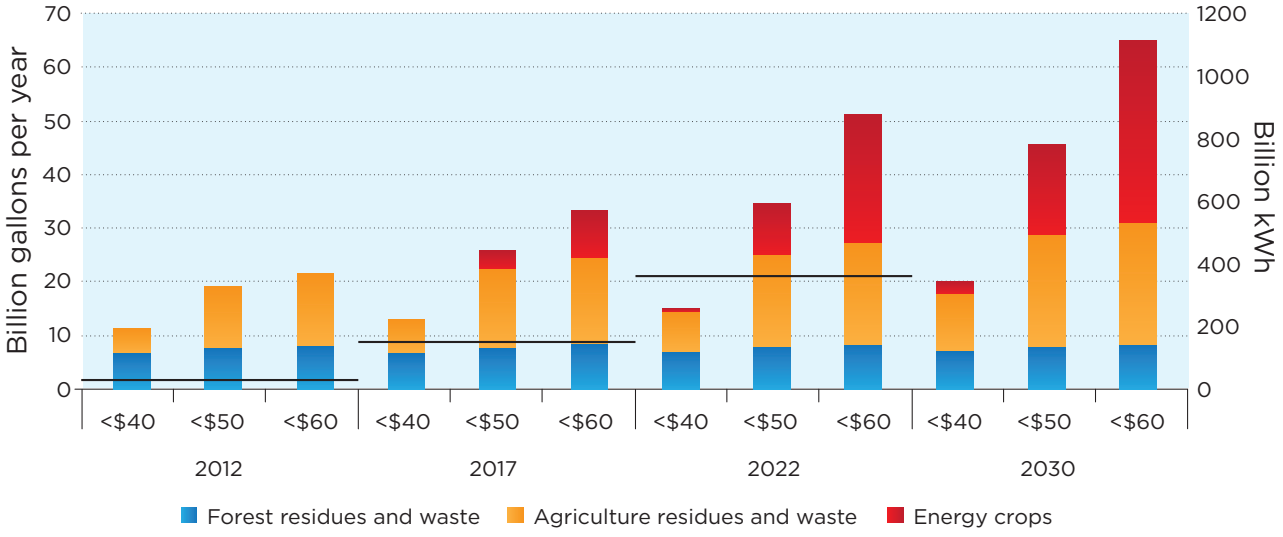
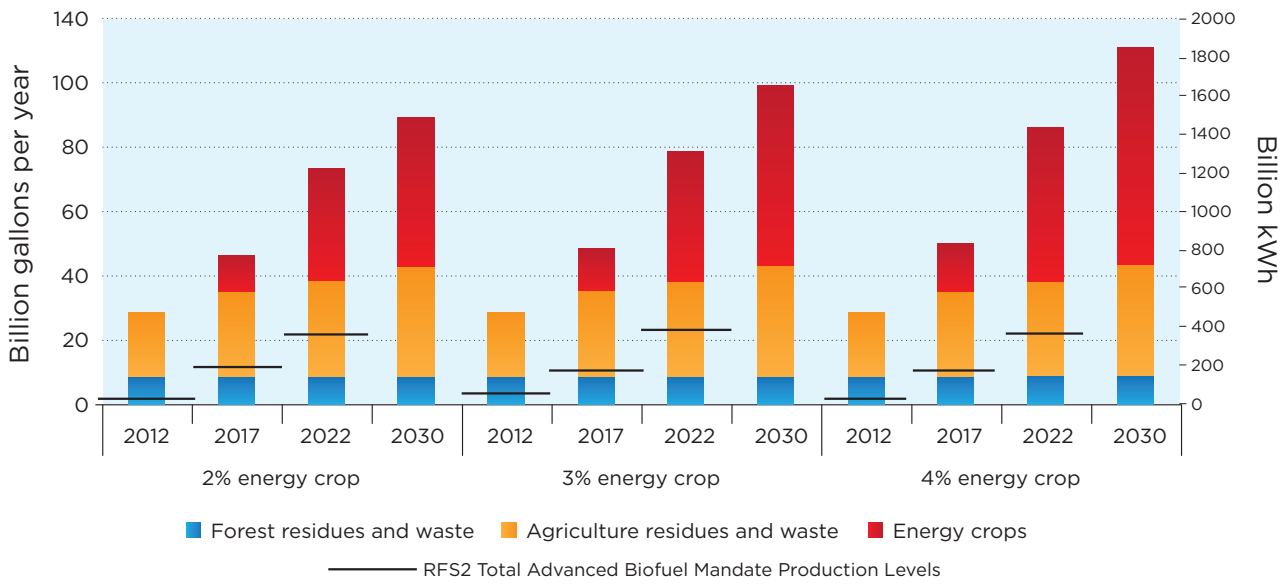


Table 6.2 Summary of Available Forest and Agriculture Biomass at $60 per Dry Ton under High-Yield Assumptions

	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*

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[69] 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 and stabilize soils. 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

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

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

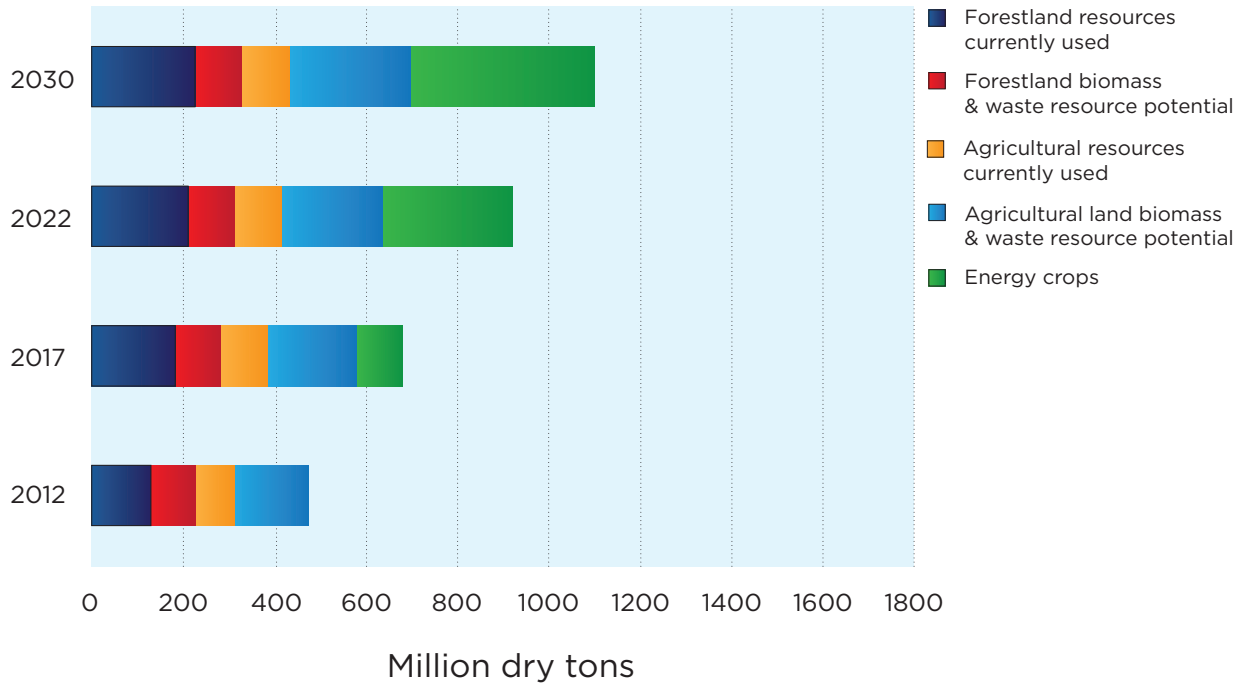
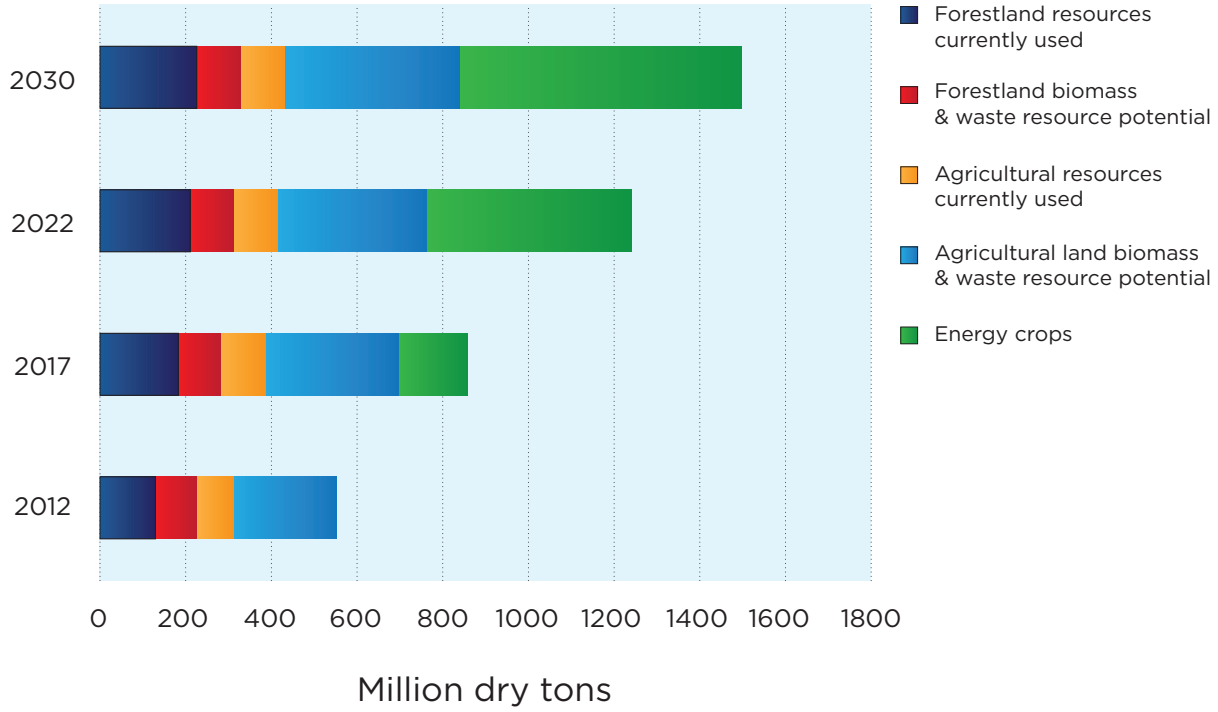


Figure 6.6 Summary of currently used and potential resources at $60 per dry ton or less identified under high-yield assumptions (3% annual energy crop yield growth rate)



EPA. 2008. Municipal Solid Waste in the United States: 2007 Facts and Figures. (5306P) EPA530-R-08-010. U.S. Environmental Protection Agency, Office of Solid Waste. November.

EPA. 2010. Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis. EPA-420-R-10-006. U.S. Environmental Protection Agency, Assessment and Standards Division, Office of Transportation and Air Quality. February.

Ercoli L, Mariotti M, Masoni A, Bonari E. 1999. Effect of irrigation and nitrogen fertilization on biomass yield and efficiency of energy use in crop production of Miscanthus. Field Crops Research 63(1):3–11.

Eriksson G. 1991. Challenges for forest geneticists. Silva Fennica 25(14):257–269.

Evans AM, Perschel RT. 2009. An assessment of biomass harvesting guidelines. Forest Guild, Santa Fe, NM.

Falk RH, McKeever DB. 2004. Recovering wood for reuse and recycling: a United States perspective. Proceedings of Management of Recovered Wood Recycling, Bio-energy and Other Options, April 22–24, 2004. C Gallis (ed.). European COST E31 Conference. University Studio Press, Thessaloniki, Greece. pp. 29–40.

FAO. 2007. State of the world's forests 2007. Food and Agriculture Organization of the United Nations, Rome, Italy. 144 pp. (Accessed at http://www.fao.org/docrep/009/a0773e/a0773e00.htm on March 21, 2011.)

FAPRI. 2010. FAPRI 2010 U.S. and world agricultural outlook. Report 10-FSR 1. Food and Agricultural Policy Research Institute, Iowa State University, Ames, IA.

Farage PK, Blowers D, Long SP, Baker NR. 2006. Low growth temperatures modify the efficiency of light use by photosystem II for CO_2 assimilation in leaves of two chilling-tolerant C4 species *Cyperus longus* L. and *Miscanthus x giganteus*. Plant Cell & Environment 29(4):720–728.

Farnham D. 2001. Corn planting guide, PM 1885. Iowa State University, University Extension, Ames, IA.

Fehrs J. 1999. Secondary Mill Residues and Urban Wood Waste Quantities in the United States. Prepared for the Northeast Regional Biomass Program, CONEG Policy Research Center, Inc. Washington, DC. December.

Fight RD, Hartsough BR, Noordijk P. 2006. Users guide for FRCS: Fuel Reduction Cost Simulator software. General Technical Report PNW–GTR–668. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR. 23 pp.

Fixen PE. 2007. Potential biofuels influence on nutrient use and removal in the US. Better Crops 91(2):12-14.

Foereid B, de Neergaard A, Høgh-Jensen H. 2004. Turnover of organic matter in a Miscanthus field: effect of time in *Miscanthus* cultivation and inorganic nitrogen supply. Soil Biology and Biochemistry 36(7):1075–1085.

Follett RF, Varvel GE, Kimble J, Vogel KP. 2009. No-till corn after bromegrass: effect on soil C and soil aggregates. Agronomy Journal 101(2):261–268.

Fox TR, Allen HL, Albaugh TJ, Rubilar R, Carlson CA. 2007a. Tree nutrition and forest fertilization of pine plantations in the Southern United States. Southern Journal of Applied Forestry 31(1):5–11.

Fox TR, Jokela EJ, Allen HL. 2007b. The development of pine plantation silviculture in the Southern United States. Journal of Forestry 105(7):337–347.

Fransen S. 2009. Agronomics of Switchgrass for Biofuel in the West. In Proceedings of the 2009 Western Alfalfa & Forage Conference, December 2009. Reno, NV. 9 pp.

Will RE, Markewitz D, Hendrick RL, Meason DF, Crocker TR, Borders BE. 2006. Nitrogen and phosphorus dynamics for 13-year-old loblolly pine stands receiving complete competition control and annual N fertilizer. Forest Ecology and Management 227(1–2):155–68.

Wortmann CS, Liska AJ, Ferguson RB, Lyon DJ, Klein RN, Dweikat I. 2010. Dryland performance of sweet sorghum and grain crops for biofuel in Nebraska. Agronomy Journal 102(1):319–326.

Wright LL. 2007. Historical perspective on how and why switchgrass was selected as a "model" high-potential energy crop. ORNL/TM-2007/109. Oak Ridge National Laboratory, Oak Ridge, TN. July. 45 pp.

Wright LL, Eaton LM, Perlack RD, Stokes BJ. 2012. Woody biomass. In Comprehensive renewable energy, Volume 5 Biomass and biofuel production, Section 5.14: Technology solutions – novel feedstocks. A Sayigd (ed). Elsevier, Oxford, UK. pp. 263–291.

Wu S, Lu YC, McMurtrey JE, Weesies G, Devine TE, Foster GR. 2004. Soil conservation benefits of large biomass soybean (LBS) for increasing crop residue cover. Journal of Sustainable Agriculture 24(1):107–128.

Wu X, Zhao R, Bean SR, Seib PA, McLaren JS, Madl RL, Tuinstra MR, Lenz MC, Wang D. 2007. Factors impacting ethanol production from grain sorghum in the dry-grind process. Cereal Chemistry 84(2):130–136.

Wullschleger SD, Davis EB, Borsuk ME, Gunderson CA, Lynd LR. 2010. An empirical model of biomass production in switchgrass: database description and determinants of yield. Agronomy Journal 102(4):1158–1168.

Zalesny Jr. RS, Riemenschneider DE, Hall RB. 2005. Early rooting of dormant hardwood cuttings of *Populus*: analysis of quantitative genetics and genotype × environment interactions. Canadian Journal of Forest Research 35(4):918–929.

Zalesny Jr. RS, Hall RB, Zalesny JA, McMahon BG, Berguson WE, Stanosz GR. 2009. Biomass and genotype × environment interactions of *Populus* energy crops in the Midwestern United States. BioEnergy Research 2(2):106–122.

Zalesny Jr. RS, Zalesny JA. 2009. Selecting *Populus* with different adventitious root types for environmental benefits, fiber, and energy. Chapter 18. In Adventitious Root Formation of Forest Trees and Horticultural Plants – From Genes to Applications. K Niemi, C Scagel (eds.). Research Signpost, Kerala, India. pp. 359–384.

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 and 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)

iii. Yield projections for eight major agricultural crops (major crops are corn, sorghum,2 barley, oats, wheat, rice, cotton, and soybeans) 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)

1) Corn 2012 baseline yield (average for United States) is 163 bushels per acre increasing to 201 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, oats, 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

iv. Residue to grain ratios are 1:1 for corn and sorghum, 1:2 for oats, 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 soybeans

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 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

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[2], barley, oats, wheat, rice, upland cotton, and soybeans 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

USDA AGRICULTURAL PROJECTIONS

- 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
- Biodiesel at 1 billion GPY by 2012

[2] Sorghum grown for energy is treated as an energy crop and assumptions are included under those for annual energy crops.

counties 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 164 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, oats, 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.

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 uses, 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) Use 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

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, oats, 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 (P_2O_5) per dry ton; 27.2 pounds of potassium (K_2O) 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

GLOSSARY OF KEY TERMS AND ACRONYMS

Algal biofuels – Utilization of primarily microalgae to produce high quantities of biomass per unit land area. The lipids in the microalgae can be used to produce biodiesel.

Annual removals – The net volume of growing stock trees removed from the inventory during a specified year by harvesting, cultural operations (such as timber stand improvement), or land clearing.

Asexual reproduction – The naturally occurring ability of some plant species to reproduce asexually through seeds, meaning the embryos develop without a male gamete. This ensures that the seeds will produce plants identical to the mother plant.

Barrel (bbl) – A barrel of oil is 42 gallons.

Baseline scenario – Disaggregation of U.S. Department of Agriculture Projection of Major Crops to the county level, extended to 2030, with baseline assumptions of energy crops yield growth (1%) and continuation of historic tillage adoption patterns of major crops. Forestry resources are estimated using a baseline scenario consistent with the projections outlined in Chapter 3.

Billion gallons per year – BGY

Billion-Ton Study (BTS) – *Biomass as a Feedstock for Bioenergy and Bioproducts: The Feasibility of a Billion-Ton Annual Supply* (2005).

Biobased product – The term biobased product, as defined by the Farm Security and Rural Investment Act, means a product determined by the U.S. Secretary of Agriculture to be a commercial or industrial product (other than food or feed) that is composed, in whole or in significant part, of biological products or renewable domestic agricultural materials (including plant, animal, and marine materials) or forestry materials.

Biodiesel – Fuel derived from vegetable oils or animal fats. It is produced when a vegetable oil or animal fat is chemically reacted with an alcohol, typically methanol. It is mixed with petroleum-based diesel.

Bioenergy – Useful, renewable energy produced from organic matter through the conversion of the complex carbohydrates in organic matter to energy. This energy may either be used directly as a fuel, processed into liquids and gasses, or be a residual of processing and conversion.

Bioenergy Knowledge Discovery Framework (KDF) – An online resource that includes bioenergy-related research, applications, and data. Hosts *Billion-Ton Update*-related information.

Biofuels – Fuels made from biomass resources or their processing and conversion derivatives. Biofuels include ethanol, biodiesel, and methanol.

Biomass – Any organic matter that is available on a renewable or recurring basis, including agricultural crops and trees, wood and wood residues, plants (including aquatic plants), grasses, animal manure, municipal residues, and other residue materials. Biomass is generally produced in a sustainable manner from water and carbon dioxide by photosynthesis. There are three main categories of biomass: primary, secondary, and tertiary.

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

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

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

British thermal unit (Btu) – A unit of energy equal to approximately 1,055 joules. It is the amount of energy required to heat 1 pound (0.454 kilograms) of water from 39 degrees Fahrenheit to 40 degrees Fahrenheit.

C4 species – C3 and C4 are the two main photosynthetic pathways in plants. C3 plants fix carbon dioxide (CO_2) through photorespiration and require stomatal opening to acquire CO_2. C4 plants acquire CO_2 from malate and do not require open stomata; as a result, they provide higher water use efficiency and produce more biomass in hotter, drier climates. Under conditions of moderate temperatures and available soil water, C3 plants typically have an advantage in CO_2 fixation and thus overall growth.

Coarse materials – Wood residues suitable for chipping, such as slabs, edgings, and trimmings.

Commercial species – Tree species suitable for industrial wood products.

Component ration method (CRM) – Introduced by the U.S. Department of Agriculture Forest Service in 2009, CRM is a method used to estimate non-merchantable volumes from merchantable trees.

Composite integrated operations – Simultaneous production of both commercial (merchantable) wood products and thinnings. In the *Billion-Ton Update*, it is estimated as the supply of forest materials available—assuming continuation of current harvesting operations that includes 50% of logging residues and 50% of available forest thinning at each price level at the county level.

Conservation Reserve Program (CRP) – A national land set-aside program that provides farm owners or operators with an annual per acre rental payment and half the cost of establishing a permanent land cover in exchange for retiring environmentally sensitive cropland from production for 10 to 15 years. In 1996, Congress reauthorized CRP for an additional round of contracts, limiting enrollment to 36.4 million acres at any time. The 2002 Farm Act increased the enrollment limit to 39 million acres. Producers can offer land for competitive bidding based on an Environmental Benefits Index during periodic signups, or can automatically enroll more limited acreages in practices such as riparian buffers, field windbreaks, and grass strips on a continuous basis. CRP is funded through the Commodity Credit Corporation.

Construction and demolition debris (C&D) – Wood waste 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.

Conventionally sourced wood – Wood that has commercial uses other than fuel (e.g., pulpwood), but is used for energy because of market conditions. This would most likely only include smaller diameter pulpwood-sized trees.

Coppice – To regrow from a (tree) stump after harvest. This would be equivalent to a ratoon crop for sugarcane or sorghum, which would regrow from the stem after harvest.

Cotton gin trash – Residue available at a processing site, including seeds, leaves, and other material.

Cotton residue – Cotton stalks available for collection after cotton harvest.

Crop management zones (CMZ) – Spatial regions generated by the U.S. Department of Agriculture National Resource Conservation Service of similar climate and crops.

Crop residues – The portion of a crop remaining after the primary product is harvested. Crop residues include corn stover and wheat, barely, oats, and sorghum straw. Other residues are rice field residue (straw), cotton field residue, and sugarcane residues (trash-leaves, tops, and remaining stalk after primary harvest of the stalk).

Cropland – Total cropland includes five components: cropland harvested, crop failure, cultivated summer fallow, cropland used only for pasture, and idle cropland.

Cropland pasture – Land used for long-term crop rotation. However, some cropland pasture is marginal for crop uses and may remain in pasture indefinitely. This category also includes land that was used for pasture before crops reached maturity, and some land used for pasture that could have been cropped without additional improvement.

Cropland used for crops – Cropland used for crops includes cropland harvested, crop failure, and cultivated summer fallow. **Cropland harvested** includes row crops and closely sown crops; hay and silage crops; tree fruits, small fruits, berries, and tree nuts; vegetables and melons; and miscellaneous other minor crops. In recent years, farmers have double-cropped about 4% of this acreage. **Crop failure** primarily consists of the acreage on which crops failed because of weather, insects, and diseases, but includes some land not harvested due to lack of labor, low market prices, or other factors. The acreage planted to cover and soil improvement crops not intended for harvest is excluded from crop failure and is considered idle. **Cultivated summer fallow** refers to cropland in sub-humid regions of the West cultivated for one or more seasons to control weeds and accumulate moisture before small grains are planted. This practice is optional in some areas, but it is a requirement for crop production in the drier cropland areas of the West. Other types of fallow—such as cropland planted with soil improvement crops but not harvested, and cropland left idle all year—are not included in cultivated summer fallow, but they are included as idle cropland.

Cull tree – A live tree—5 inches in diameter at breast height or larger—that is non-merchantable for saw logs now or prospectively because of rot, roughness, or species. (See definitions for rotten and rough trees.)

Diameter at breast height (dbh) – The common measure of wood volume approximated by the diameter of trees measured at approximately breast height from the ground.

Energy cane – Related to sugar cane. It can be a high fiber sugar cane variety, or a hybrid between sugar cane and wild relatives of sugar cane. Energy cane is designed to give higher biomass yields than sugar cane, but have a lower sugar concentration.

Energy Independence and Security Act of 2007 (EISA) – EISA is designed to increase the production of clean renewable fuels; protect consumers; increase the efficiency of products, buildings, and vehicles; promote research on and deploy greenhouse gas capture and storage options; and improve the energy performance of the federal government.

Ethanol – Also known as ethyl alcohol or grain alcohol. It is a volatile, flammable, and colorless liquid with the chemical formula C_2H_6O. It is produced by the fermentation of sugars into ethanol. Its primary uses are for drinking and fuel. In the United States, most fuel ethanol is currently produced by fermentation of glucose from the starch in corn.

Feedstock – A product used as the basis for manufacture of another product.

Fiber products – Products derived from fibers of herbaceous and woody plant materials. Examples include pulp, composition board products, and wood chips for export.

Fine materials – Wood residues not suitable for chipping, such as planer shavings and sawdust.

Forest and Rangeland Renewable Resources Planning Act of 1974 (RPA) – Requires periodic assessments and reports the status and trends of the nation's renewable resources on all forest and rangelands.

Forest Inventory and Analysis (FIA) – 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 the *Billion-Ton Update* are summarized from more than 100,000 permanent field plots in the United States.

Forest land – Land at least 10% stocked by forest trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated. Forest land includes transition zones, such as areas between heavily forested and non-forested lands that are at least 10% stocked with forest trees and forest areas adjacent to urban and built-up lands. Also included are pinyon-juniper and chaparral areas in the West and afforested areas. The minimum area for classification of forest land is 1 acre. Roadside, streamside, and shelterbelt strips of trees must have a crown width of at least 120 feet to qualify as forest land. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if less than 120-feet wide.

Fuel Reduction Cost Simulator (FRCS) – A forest harvesting costing model utilized in the *Billion-Ton Update* to estimate the cost of harvesting small diameter trees for biomass.

Fuel Treatment Evaluator (FTE) – A strategic assessment tool capable of aiding the identification, evaluation, and prioritization of fuel treatment opportunities.

Fuelwood – Wood used for conversion to some form of energy, primarily for residential use.

Grassland pasture and range – All open land used primarily for pasture and grazing, including shrub and brush land types of pasture; grazing land with sagebrush and scattered mesquite; and all tame and native grasses, legumes, and other forage used for pasture or grazing. Due to the diversity in vegetative composition, grassland pasture and range are not always clearly distinguishable from other types of pasture and range. At one extreme, permanent grassland may merge with cropland pasture, or grassland may often be found in transitional areas with forested grazing land.

Greenhouse gases – GHG

Growing stock – A classification of timber inventory that includes live trees of commercial species meeting specified standards of quality or vigor. Cull trees are excluded. When associated with volume, this classification only includes trees 5 inches in diamete at breast height and larger.

Harvest index (HI) – For traditional crops, the ratio of residue to grain.

High-yield scenario – A set of scenarios that follow similar forecast assumptions as the baseline scenario with three exceptions: energy crop yield growth varies due to higher research and development (five cases: 1%, 2%, 3%, and 4%); traditional crop yield growth is higher; and shifts from conventional tillage production to no-till and reduced tillage occurs faster. There is no high-yield scenario for forestry resources.

Idle cropland – Land in cover and soil improvement crops, and cropland on which no crops were planted. Some cropland is idle each year for various physical and economic reasons. Acreage diverted from crops to soil-conserving uses (if not eligible for and used as cropland pasture) under federal farm programs is included in this component. Cropland enrolled in the Federal Conservation Reserve Program is included in idle cropland.

Industrial wood – All commercial roundwood products except for fuelwood.

Live cull – A classification that includes live cull trees. When associated with volume, it is the net volume in live cull trees that are 5 inches in diameter at breast height and larger.

Logging residues – The unused portions of growing-stock and non-growing-stock trees that have been cut or killed by logging and left in the woods.

Mill residues – Bark and woody materials that are generated in primary wood-using mills when roundwood products are converted to other products. Examples are slabs, edgings, trimmings, sawdust, shavings, veneer cores and clippings, and pulp screenings. Includes bark residues and wood residues (both coarse and fine materials), but excludes logging residues. May include both primary and secondary mills.

Municipal solid waste (MSW) – Wastes (garbage) collected from municipalities consisting mainly of yard trimmings and paper products.

Non-forest land – Land that has never supported forests, and lands formerly forested where use of timber management is precluded by development for other uses. (*Note*: Includes area used for crops, improved pasture, residential areas, city parks, improved roads of any width and adjoining clearings, powerline clearings of any width, and 1- to 4.5-acre areas of water classified by the Census Bureau as land. If intermingled in forest areas, unimproved roads and nonforest strips must be more than 120-feet wide, and clearings, etc., must be more than 1 acre in area to qualify as non-forest land.)

Nonindustrial private – An ownership class of private lands where the owner does not operate wood-using processing plants.

Other forest land – Forest land other than timberland, as well as reserved forest land. It includes available forest land, which is incapable of annually producing 20 cubic feet per acre of industrial wood under natural conditions because of adverse site conditions such as sterile soils, dry climate, poor drainage, high elevation, steepness, or rockiness.

Other removals and residues – Unutilized wood volume from cut or otherwise killed growing stock, from cultural operations such as precommercial thinnings, or from timberland clearing for other uses (i.e., cropland, pastureland, roads, and urban settlement). Does not include volume removed from inventory through reclassification of timberland to productive reserved forest land.

Other wood sources – Sources of roundwood products that are not growing stock. These include salvable dead, rough and rotten trees, trees of noncommercial species, trees less than 5 inches in diameter at breast height, tops, and roundwood harvested from non-forest land (for example, fence rows).

Perennial – A crop that lives for more than two years. Well-established perennial crops have a good root system and provide cover that reduces erosion potential. They generally have reduced fertilizer and herbicide requirements compared to annual crops.

Poletimber trees – Live trees at least 5 inches in diameter at breast height, but smaller than sawtimber trees.

Policy Analysis System (POLYSYS) – An agricultural policy modeling system of U.S. agriculture, including both crops and livestock. It is based at the University of Tennessee Institute of Agriculture, Agricultural Policy Analysis Center: http://www.agpolicy.org/polysys.html.

Primary agricultural resources – Primary agricultural resources include energy feedstocks (annual energy crops, coppice and non-coppice woody crops, perennial grasses), crop residues (barely straw, corn stover, oat straw, sorghum stubble, wheat straw), and conventional crops (barley, corn, cotton, hay, oats, rice, sorghum, soybeans, wheat). The projections included for this category of feedstocks are two baseline scenarios (one with no energy crops—e.g., feedstock price of zero—and another including energy crops) and four high-yield scenarios with estimated biomass prices ranging between $40 and $80 at $5 increments.

Primary wood-using mill – A mill that converts roundwood products into other wood products. Common examples are sawmills that convert saw logs into lumber and pulp mills that convert pulpwood roundwood into wood pulp.

Pulpwood – Roundwood, whole-tree chips, or wood residues that are used for the production of wood pulp (also referred to as conventional wood within the database).

Renewable Fuel Standard (RFS) – The RFS was established by the Energy Policy Act of 2005. It required 7.5 billion gallons of renewable-based fuel (which was primarily ethanol) to be blended into gasoline by 2012. This original RFS (referred to sometimes as RFS1) was expanded upon by the Energy Independence Security Act of 2007 to include diesel in addition to gasoline, as well as to increase the volume of renewable fuel to be blended into fossil-based fuel to 9 billion and ultimately 36 billion gallons by 2022 (RFS2). Lifecycle greenhouse gas requirements (less than fossil fuels they replace) for renewable fuels were established.

Renewable Portfolio Standard (RPS) – A standard or regulation that requires electricity utilities and other retail electricity suppliers to obtain a certain percent of their electricity from certified renewable sources.

Revised Universal Soil Loss Equation (RUSLE2) – A computer program that estimates erosion and sediment delivery for conservation planning in crop production.

Rotten tree – A live tree of commercial species that does not contain a saw log now or prospectively primarily because of rot (that is, when rot accounts for more than 50% of the total cull volume).

Rough tree – (a) A live tree of commercial species that does not contain a saw log now or prospectively primarily because of roughness (that is, when sound cull—due to such factors as poor form, splits, or cracks—accounts for more than 50% of the total cull volume); or (b) a live tree of non-commercial species.

Roundwood products – Logs and other round timber generated from harvesting trees for industrial or consumer use.

Salvable dead tree – A downed or standing dead tree that is considered currently or potentially merchantable by regional standards.

Saplings – Live trees 1.0–4.9 inches in diameter at breast height.

Secondary wood-processing mills – Mills that use primary wood products in the manufacture of finished wood products, such as cabinets, moldings, and furniture.

Soil Conditioning Index (SCI) – An index indicating the impact of crop management activities on soil organic matter.

Sound dead – The net volume in salvable dead trees.

Stand density index (SDI) – A measure of stocking of trees per unit area based on the number of trees per unit area and the average of diameter at breast height in the area. It is usually well correlated with the stand volume.

Starch – A carbohydrate consisting of many glucose units. It is the most common carbohydrate in the human diet.

Stumpage value – The sale value of the products that can be obtained from a stand of trees. This is the value of the wood products at a processing or end-use facility minus transport and harvest costs and a profit for the harvester.

Sugarcane trash – Tops and branches of sugarcane plants left on the field available for collection.

Thinnings (other forest land treatment thinnings) – Thinnings can come from operations to reduce fuel load (i.e., removal of small trees to reduce the fire danger) and from composite integrated operations on forest land (activities to harvest merchantable commercial wood and low-quality wood for bioenergy applications simultaneously). Thinnings can also come from pre-commercial operations and from other forest land to improve forest health.

Timber Product Output (TPO) Database Retrieval System – Developed in support of the 1997 Resources Planning Act Assessment, this system acts as an interface to a standard set of consistently coded TPO data for each state and county in the country. This set of national TPO data consists of 11 data variables that describe for each county the roundwood products harvested, the logging residues left behind, the timber otherwise removed, and the wood and bark residues generated by its primary wood-using mills.

Timberland – Forest land that is producing or is capable of producing crops of industrial wood, and that is not withdrawn from timber utilization by statute or administrative regulation. Areas qualifying as timberland are capable of producing more than 20 cubic feet per acre per year of industrial wood in natural stands. Currently inaccessible and inoperable areas are included.

Urban wood wastes – These come from municipal solid waste (MSW) and construction and demolition debris. In the MSW portion, there is a wood component in containers, packaging and discarded durable goods (e.g., furniture), and yard and tree trimmings.

Wheat dust – The portion of wheat left after processing, known as dust and chaff.

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 improvement parameters derived from workshops
- 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 modeled independently of agricultural analysis
- 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 forest-based 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.

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

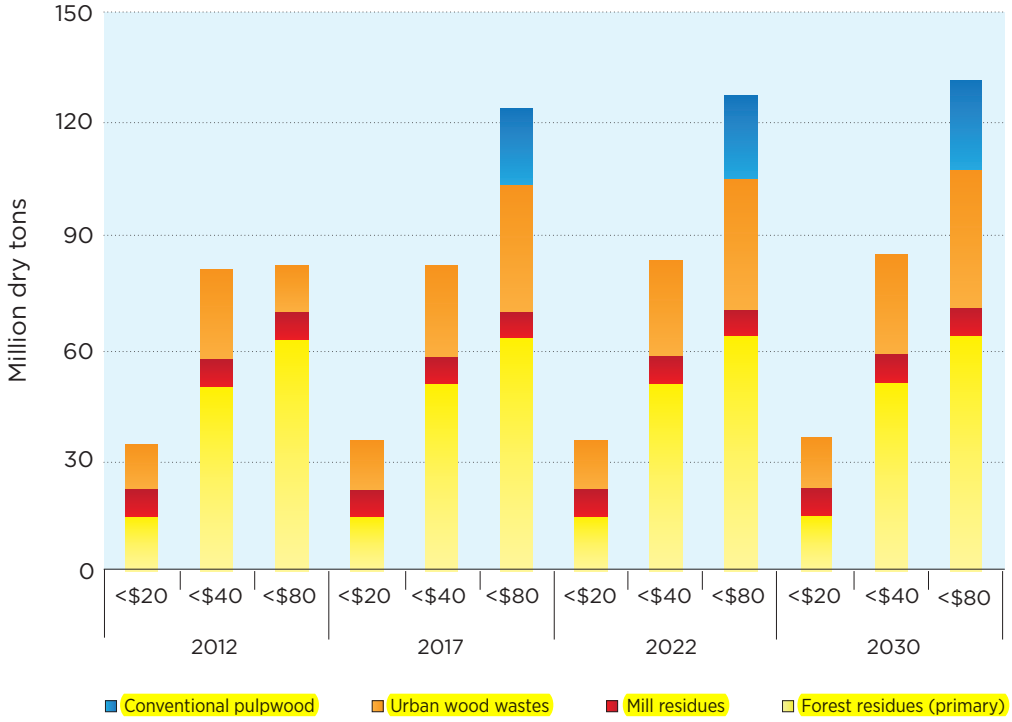


Figure ES.2 Estimated agricultural biomass under baseline assumptions

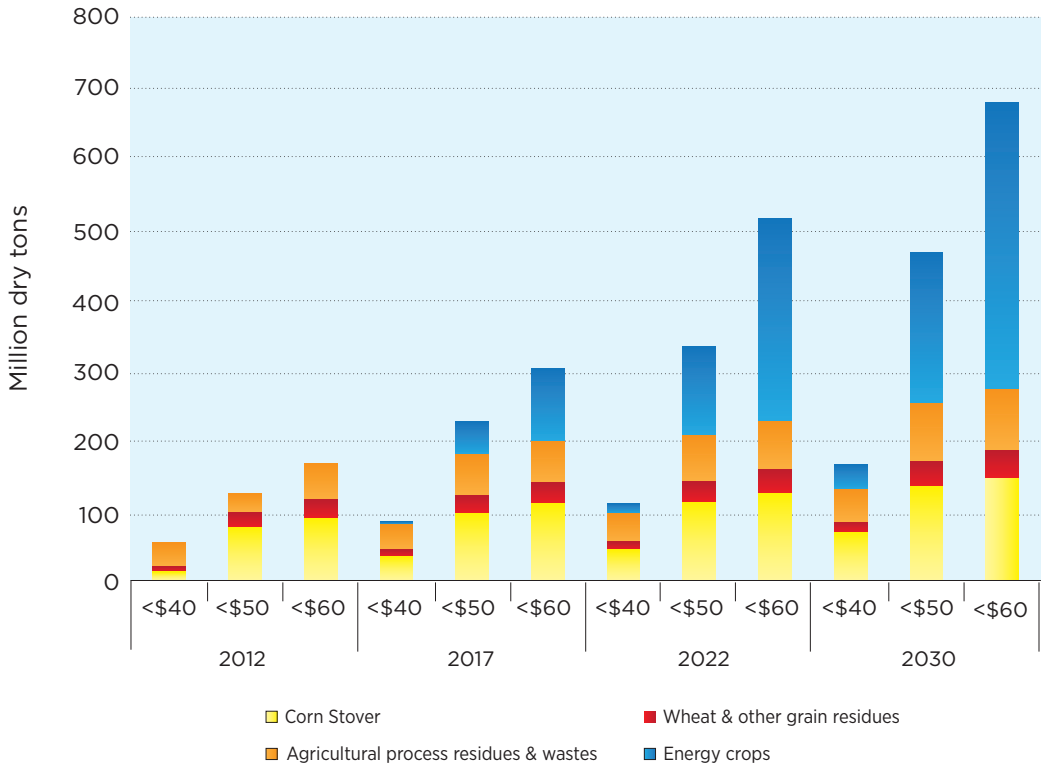


Figure ES.3 Estimated forest and agricultural biomass availability at $60 per dry ton or less under high-yield assumptions

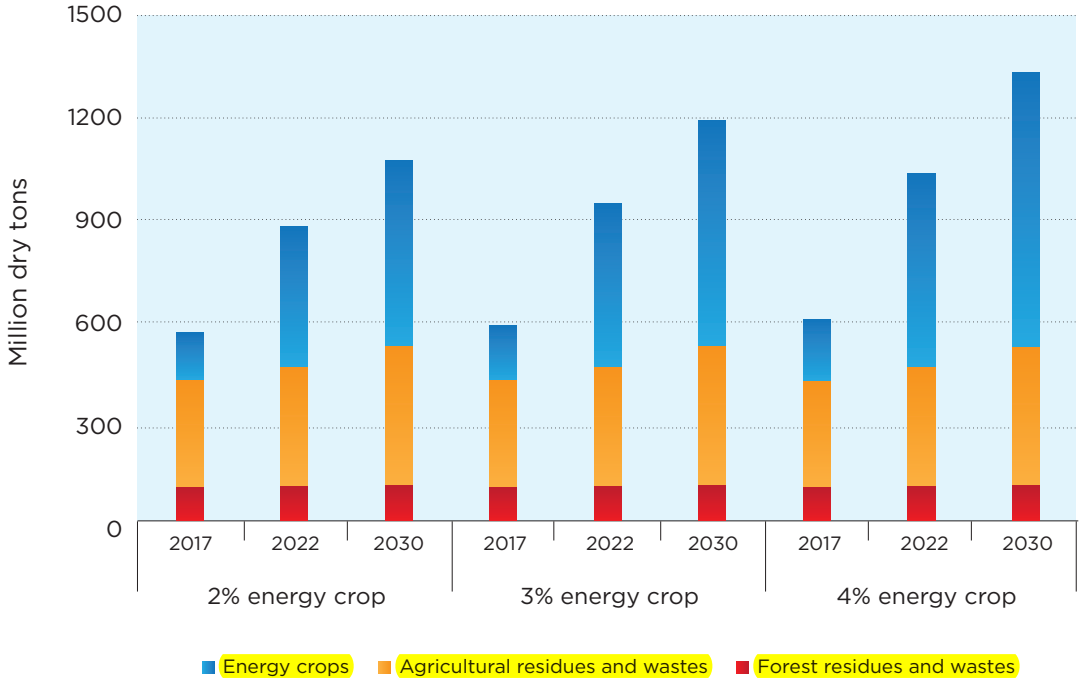


Figure ES.4 Summary of currently used and potential resources at $60 per dry ton or less identified under baseline assumptions

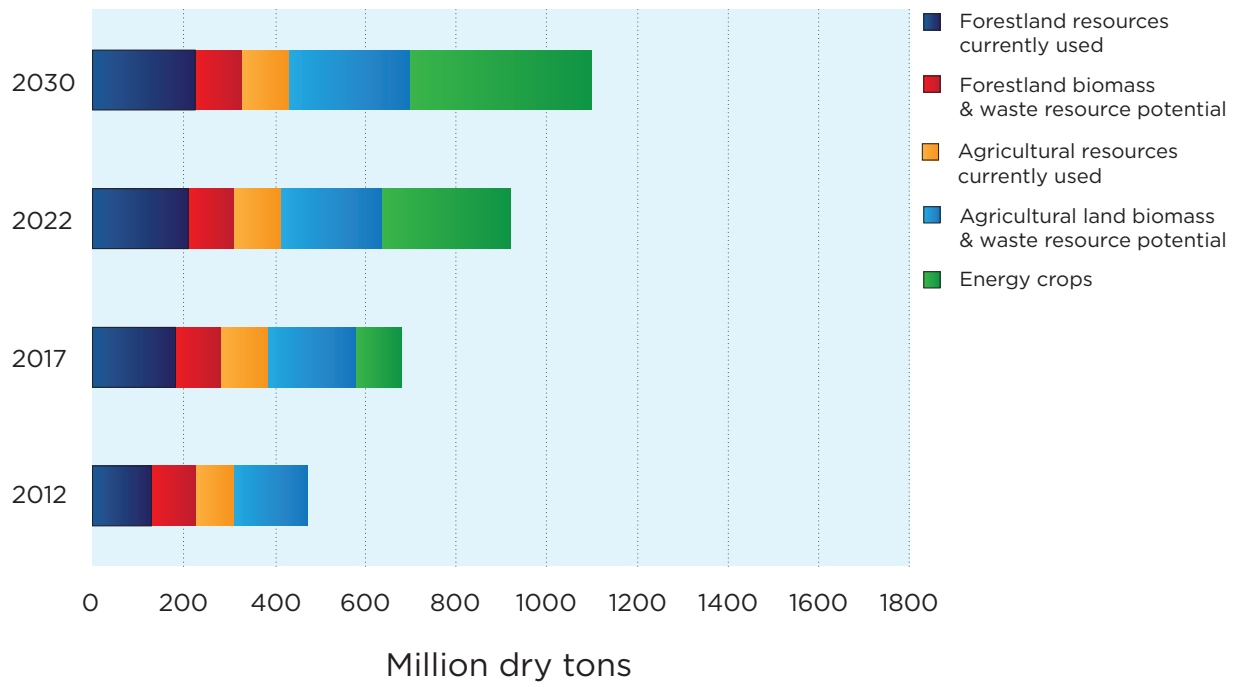
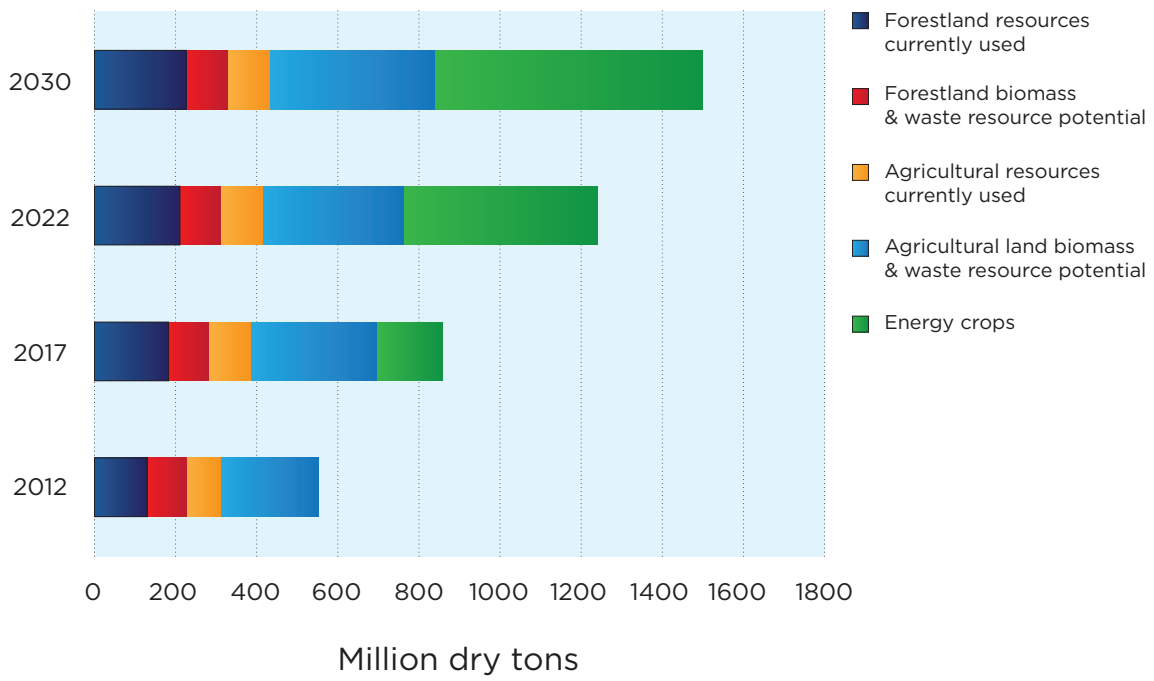


Figure ES.5 Summary of currently used and potential resources at $60 per dry ton or less identified under high-yield assumptions (3% annual energy crop yield growth rate)



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.

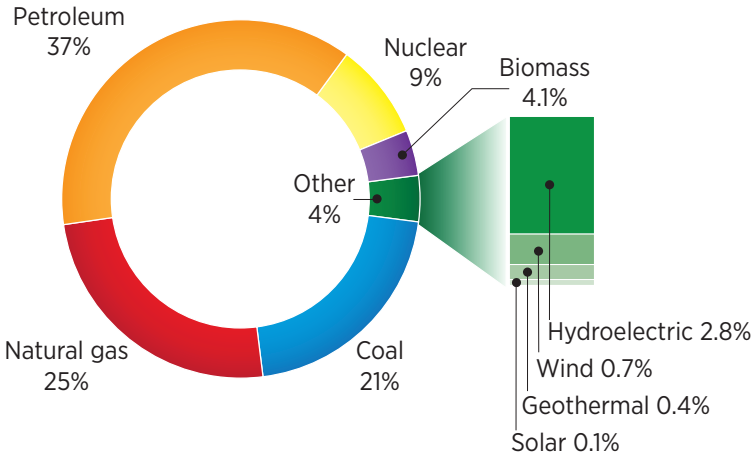
In this update, two scenarios are evaluated. First, there is the baseline scenario that essentially assumes a continuation of the USDA 10-year forecast for the major crops and extends that an additional 10 years to 2030. Second, the update provides an opportunity to further evaluate and refine changes 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 Policy Analysis System (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).

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, an agricultural 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, 2010) 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 tons of residues (primary and secondary) is 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 of corn 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.

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.

[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.

[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.

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 per rotation. 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

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 2012 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.

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, industrial uses, and exports continue to be met**

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 Residues	4.4	12	12	12	12	12
Integrated 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 Residues, Unused Primary	1.3	1.3	1.3	1.3	1.3	1.3
Mill Residues, 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 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 phosphorus 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.

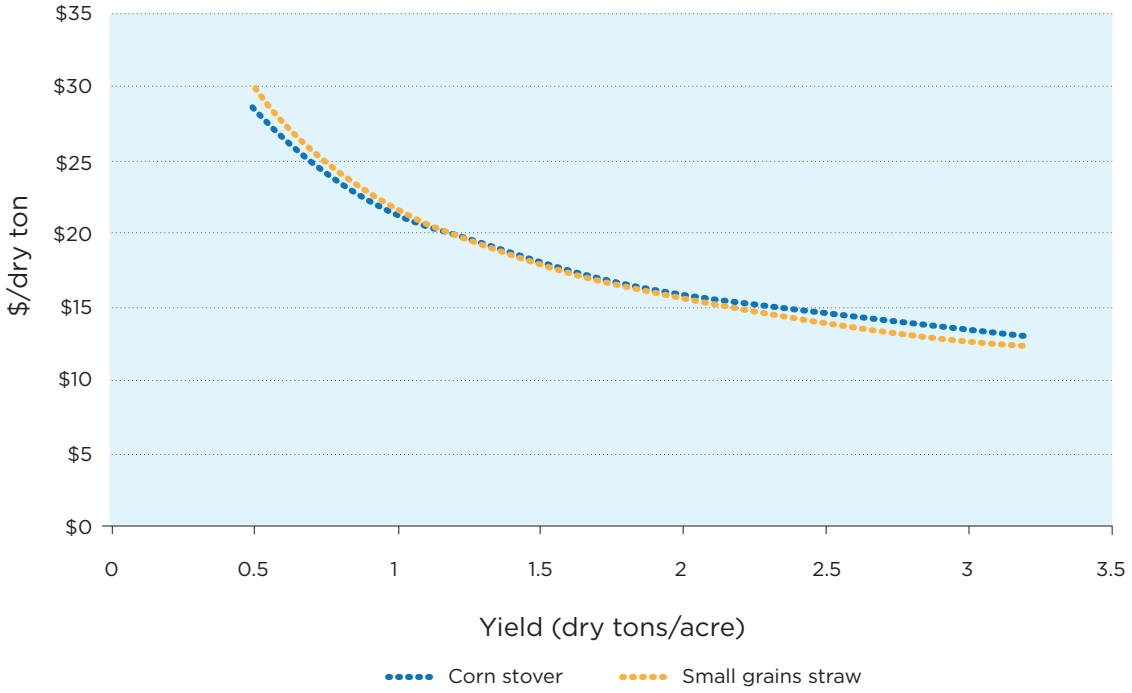
Most corn produced in the United States is grown in rotation with soybeans. As corn stover decomposes in the field, nutrients become available. Phosphorus and potassium are not generally lost and are utilized by all crops. For nitrogen, there is a question as to whether it becomes available during the 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 4.7 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 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]

Participant discussion and opinions relative to HI were

[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.

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 production 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 0.56 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).*

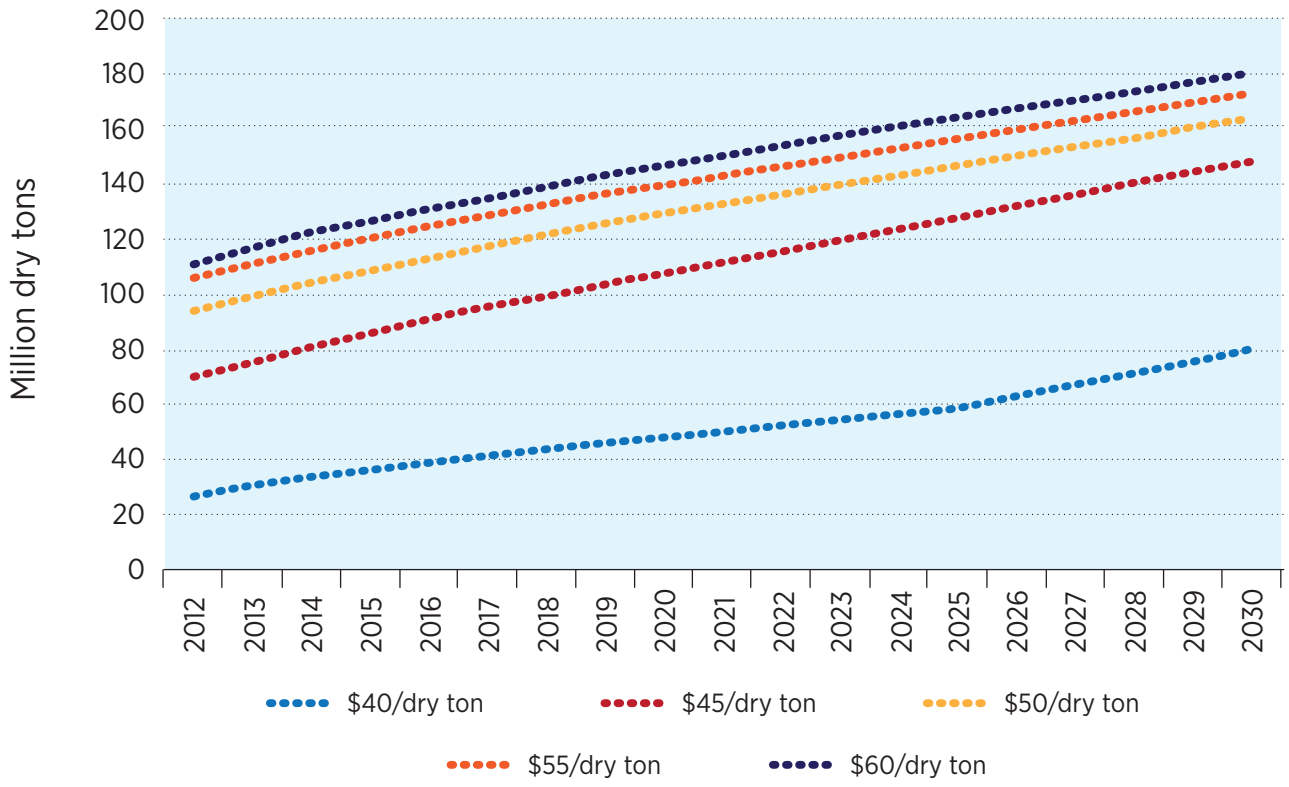
There are some seemingly contradictory statements in the literature about the effect of plant density on HI. Tollenaar et al. (1994) state that harvest index decreases when plant density increases above a certain critical threshold. Dobermann et al. (2002) examined corn under three different plant densities (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.] For purposes of estimating corn stover potential, an HI of 0.5 was used.

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 residues of major cropos after sustainability constraints are met at various prices under baseline assumptions



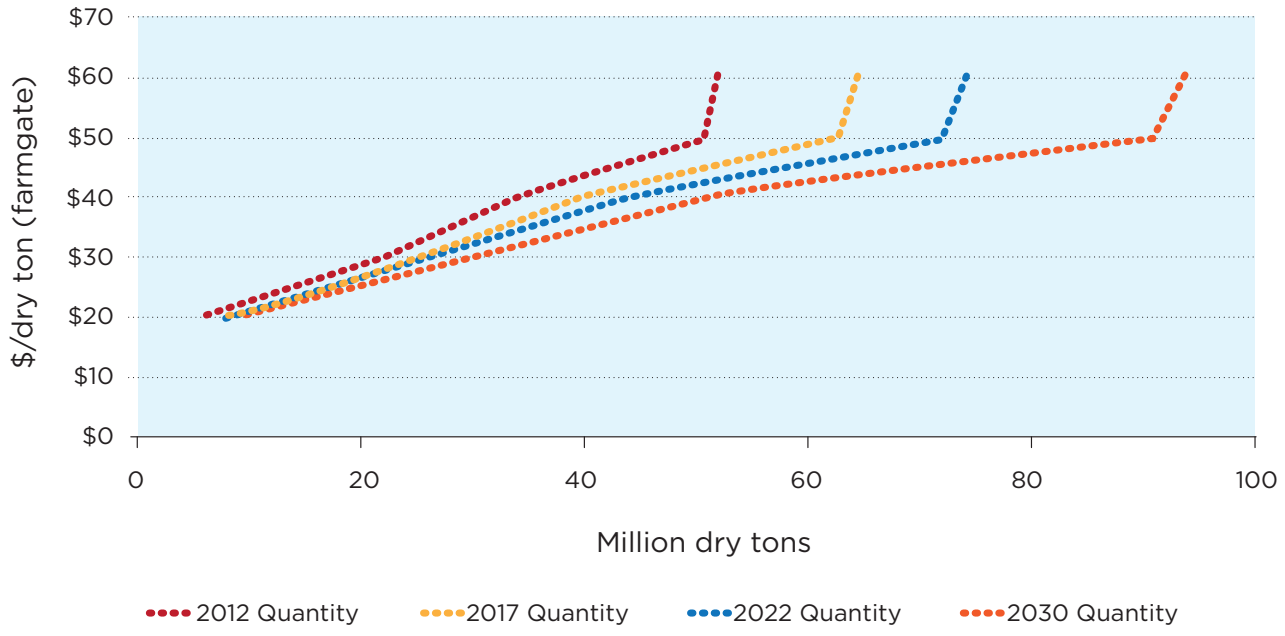
[40] This assumes a conversion rate of 85 gallons per dry ton and about 20% of the total feedstock unavailable due to losses in hauling, storing and handling, and/or some of the feedstock being stranded.

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 4.5). 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 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.

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 (i.e., produces bolls over a fixed period of time for a single harvest) (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 (i.e., produces bolls over an extended period of time with bolls maturing at different times in the growing 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 on 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

Feedstock	<$20 per dry ton				<$30 per dry ton				<$40 per dry ton			
	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 domestically, 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 primarily in Washington, Texas, Georgia, New York, Oklahoma, 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.

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 72 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 manure or wastewaters through a manmade ditch or pipe to surface water. AFOs that hold less than 300 AUs are labeled small CAFOs only if designated a CAFO by a permitting authority as a significant contributor of pollutants.

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, phosphorus, 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, at $45 per dry ton (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 at $40 per dry ton 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.

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 (2012).

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 yield declines over the 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 into the roots. 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 (e.g., net wrap, tarp, or structure) 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

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 C4 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).

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 17 tons per acre (dry weight basis) and also performing well when intercropping with alfalfa. 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,

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. 2010) (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

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 37.66 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 phosphorus 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 phosphorus (at 200-pound nitrogen per acre and 25-pound phosphorus 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 (Fox et al., 2007a).

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.

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.

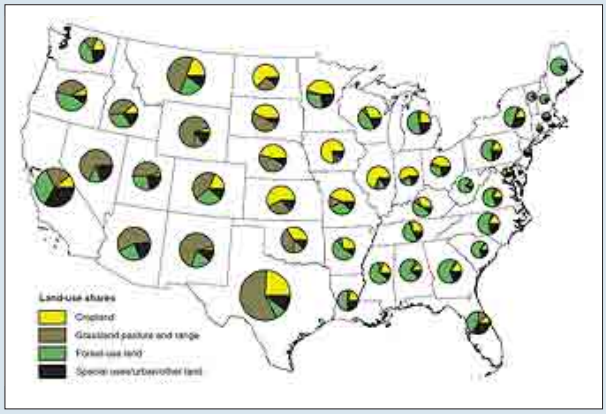
The availability of pasture (permanent pasture and cropland pasture) for conversion to perennial grasses and woody crops is constrained to counties east of the 100th Meridian (for reference, this parallel runs through Dodge City, Kansas). Counties east of the 100th Meridian are assumed to have sufficient 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:

- The total amount of permanent pasture in a given county that can convert to energy crops is limited to 50%. The remaining 50% of pastureland acreage may be intensified (thereby doubling the forage production) to maintain the pre-conversion level of forage demand within the county.
- 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 5.4). 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.

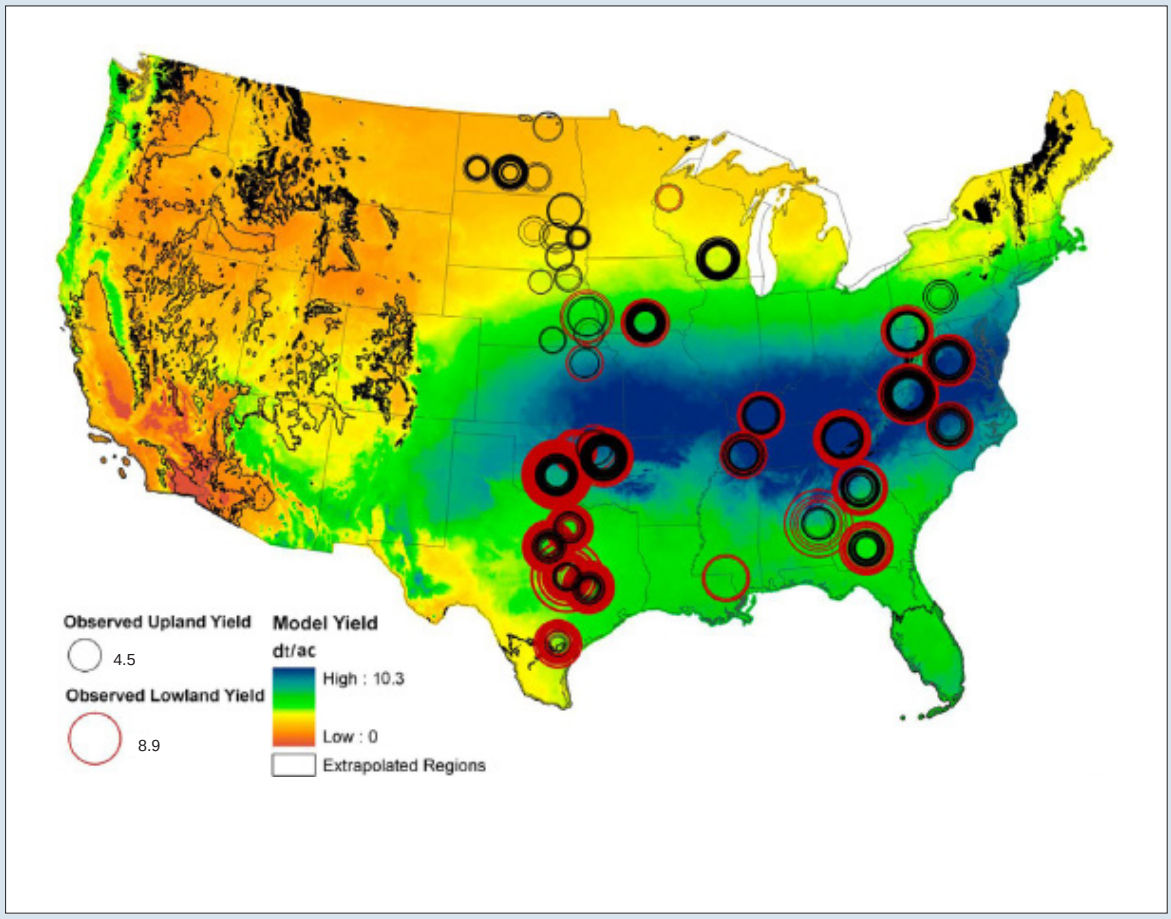
[58] For Miscanthus, establishment would be higher due to rhizome costs. However, productivity of Miscanthus is generally higher than that of switchgrass. So ultimately, whether switchgrass or Miscanthus is more profitable in a given area really depends more or less on the tradeoff between establishment 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 5.4 | 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*

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 5.5)

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, phosphorus, 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.

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	$22/10[a]
Planting	lb/acre	5	5	5	5	5	5	5
Replants	percent	25	25	25	25	25	25	25
No-till drill	-	1-time	1-time	1-time	1-time	1-time	1-time	1-time
Total kill herbicide	No. applications	1-time	1-time	1-time	1-time	1-time	1-time	1-time
Pre-emergent herbicide	No. applications	1-time	1-time	1-time	1-time	1-time	1-time	1-time
Phosphorus	lbs P2O5/ acre	40	40	40	40	40	40	40
Potassium	lbs K2O/ac	80	80	80	80	80	80	0
Lime	tons/acre	1	2	2	1	1	1	0
Total establishment costs	**$/acre**	**$250**	**$340**	**$340**	**$300**	**$230**	**$230**	**$170/230[a]**
Maintenance years								
Reseeding	year applied	2	2	2	2	2	2	2
Pre-emergent herbicide	No. applications	0	0	0	0	0	0	0
Nitrogen[b]	lbs/acre	52-98	65-124	46-124	39-91	52-91	46-65	26-84
Phosphorus	lbs P_2O_5/acre	40	40	40	40	40	40	40
Potassium	lbs K_2O /acre	80	80	80	80	80	80	0
Harvest costs	**$/dry ton**	**$15.80-$18.80**	**$14.60-$16.90**	**$14.20-$18.60**	**$15.00-$20.40**	**$15.60-$18.40**	**$17.60-$19.70**	**$15.70-$28.40**
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	$290	$280	$280	$270	$280	n/a	$200
Harvest costs	$/dry ton	$9.50-$13.00	$8.60-$12.50	$8.20-$12.20	$8.10-$12.20	$8.40-$11.30	n/a	$8.30-$11.60

[a] First number for Southern Plains, second number for Northern Plains

[b] 13 lb/dry ton of yield

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; and $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.*

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 (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 (PNW), Midwest, Plains	Southeast	Sub-tropics	Northeast and Lake States
Establishment - year 1					
Cuttings	$/tree	$0.12	$0.10	$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	1.68
Phosphorus	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	1, 0 in PNW	1	1	0
	year applied	year 3	year 3	year 3	-
Nitrogen –	lbs/acre	90	90	90	100
	year applied	4,6	2,4,6	4,6	2,5,9,13,17
	-	-	-	-	-
Phosphorus –	lbs P_2O_5/acre	15-40	40	15	-
	year applied	1	1,3	1	-
Potassium –	lb K_2O lbs/acre	15-50	40	25	-
	year applied	1	1,3	1	-
Maintenance costs – year 2	$/acre	$60	$100	$100	$30
Maintenance costs – year 3–8	$/acre	$170–$220	$200	$200	$100[a]
Maintenance costs – total over years 3 and 4	$/acre	-	-	-	100
Harvest costs	**$/dry ton**	**$18.80–20.20**	**$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.*

[a] *Maintenance costs for years 3 and 4*

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 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 is from 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.

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. 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 at the highest price are 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

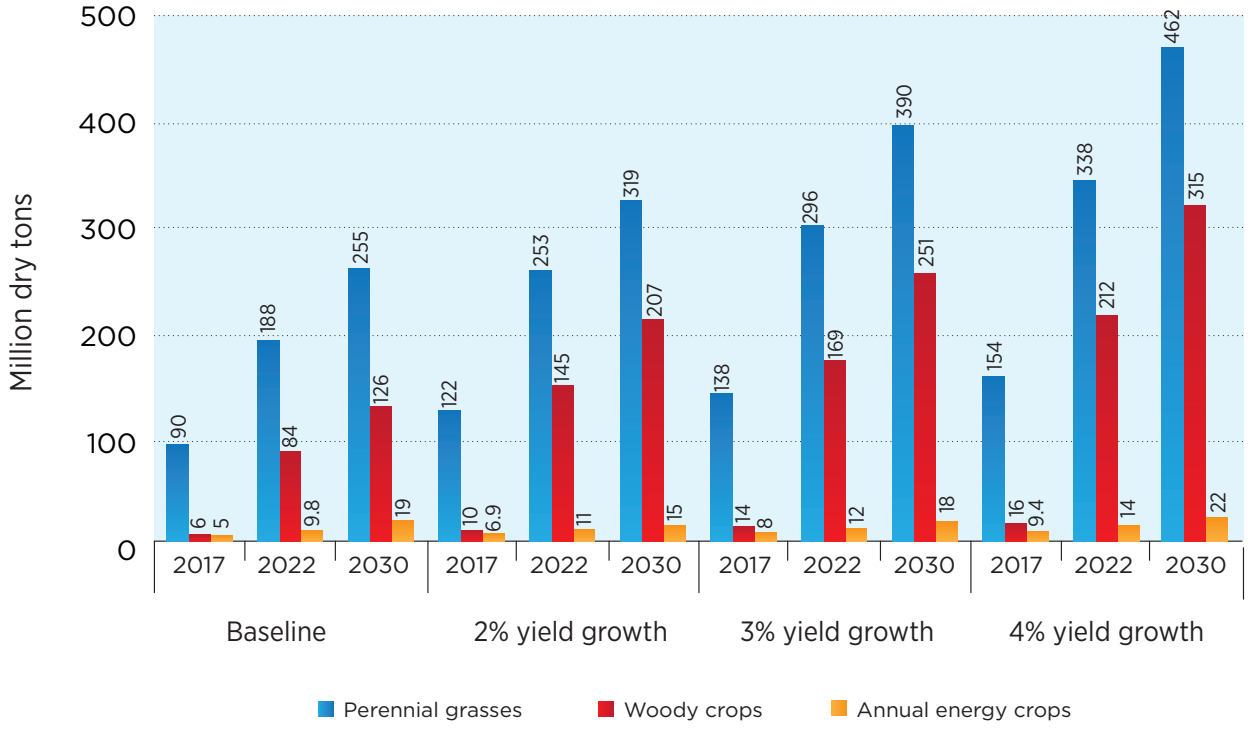


Figure 5.23 Land-use change under baseline assumptions for 2017, 2022, and 2030 at farmgate prices of $40, $50, and $60 per dry ton

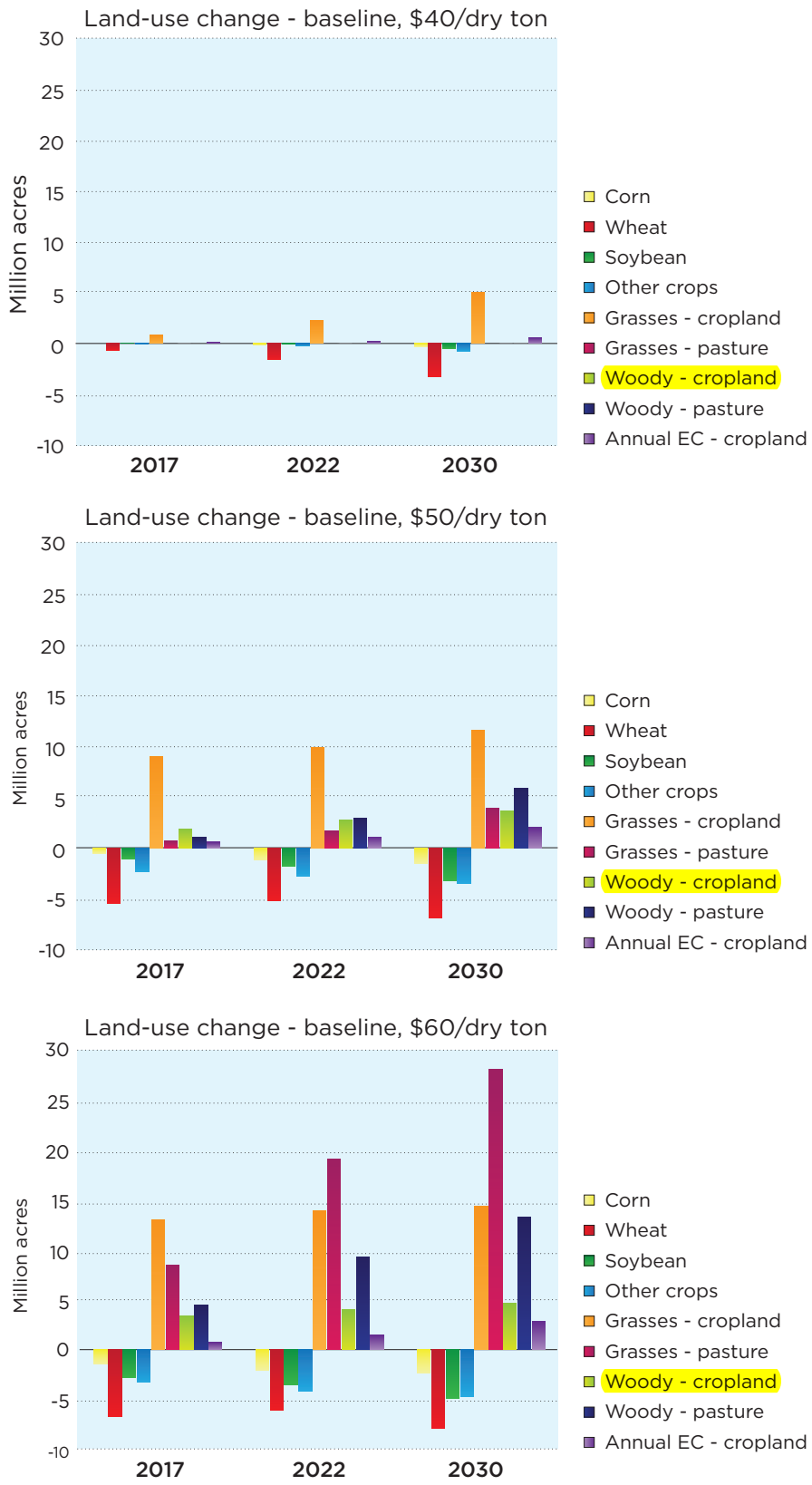


Figure 5.24 Land-use change under high-yield (3%) assumptions for 2017, 2022, and 2030 at farmgate prices of $40, $50, and $60 per dry ton

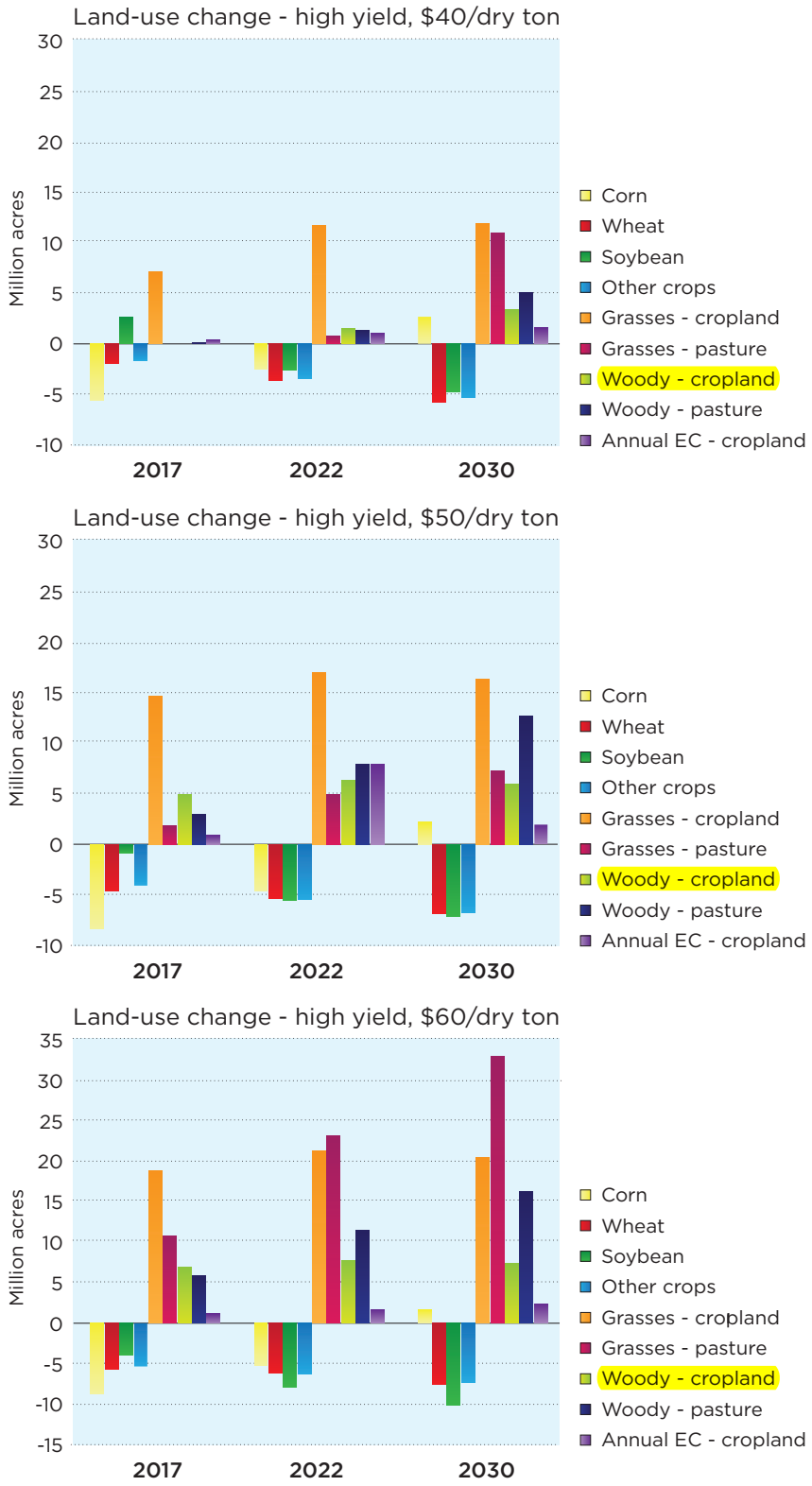


Table 5.6 Summary Comparison of USDA Projections for Major Crops with Baseline Projections for Biomass Resources Derived from Cropland and Pastureland, at $50 per Dry Ton Farmgate Price

Crop	USDA Baseline Forecast[1]				Baseline scenario		
	2012[1]	2017[1]	2022[2]	2030[2]	2017	2022	2030
Crop prices ($/bu)							
Corn	3.70	3.75	3.60	3.43	3.79	3.71	3.57
Grain Sorghum	3.30	3.35	3.20	2.89	3.79	3.71	3.57
Oat	2.35	2.35	2.28	2.11	2.37	2.39	2.32
Barley	3.90	3.95	3.79	3.36	4.27	4.39	3.89
Wheat	5.35	5.45	5.43	5.32	6.15	6.20	6.35
Soybean	8.70	8.75	8.42	7.92	8.95	8.72	8.44
Cotton ($/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

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

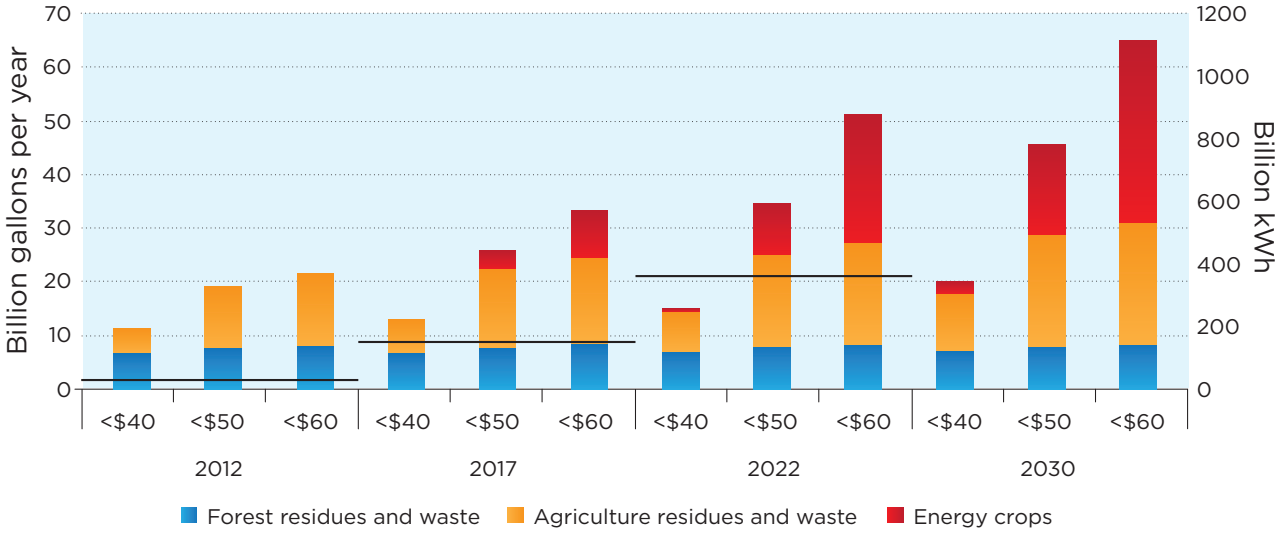
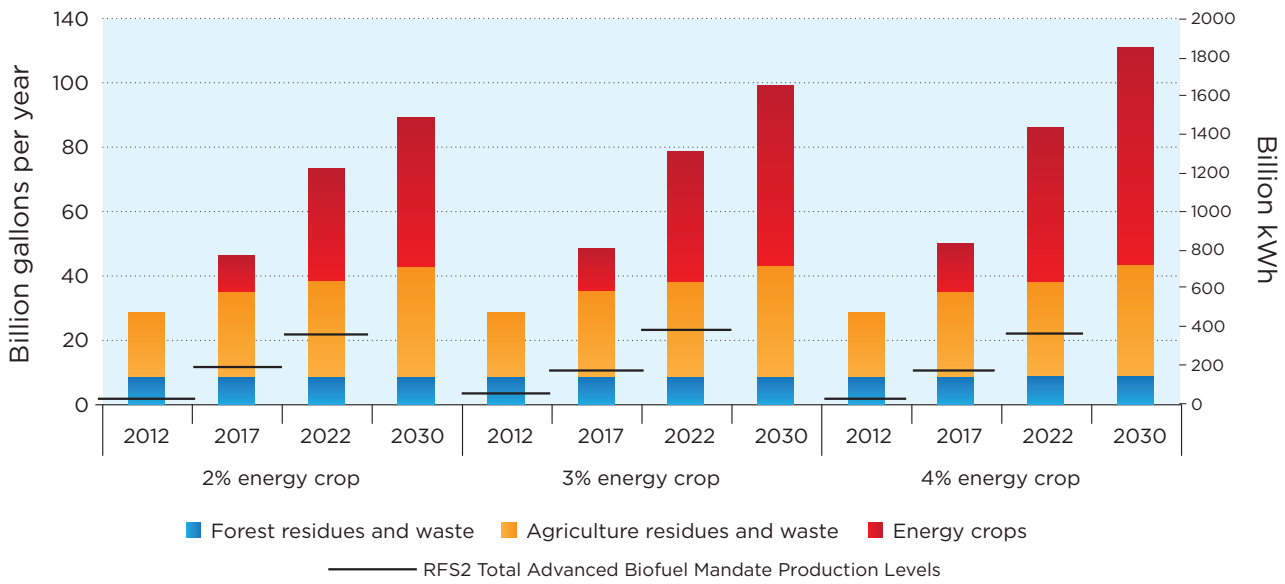


Table 6.2 Summary of Available Forest and Agriculture Biomass at $60 per Dry Ton under High-Yield Assumptions

	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*

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[69] 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 and stabilize soils. 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

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

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

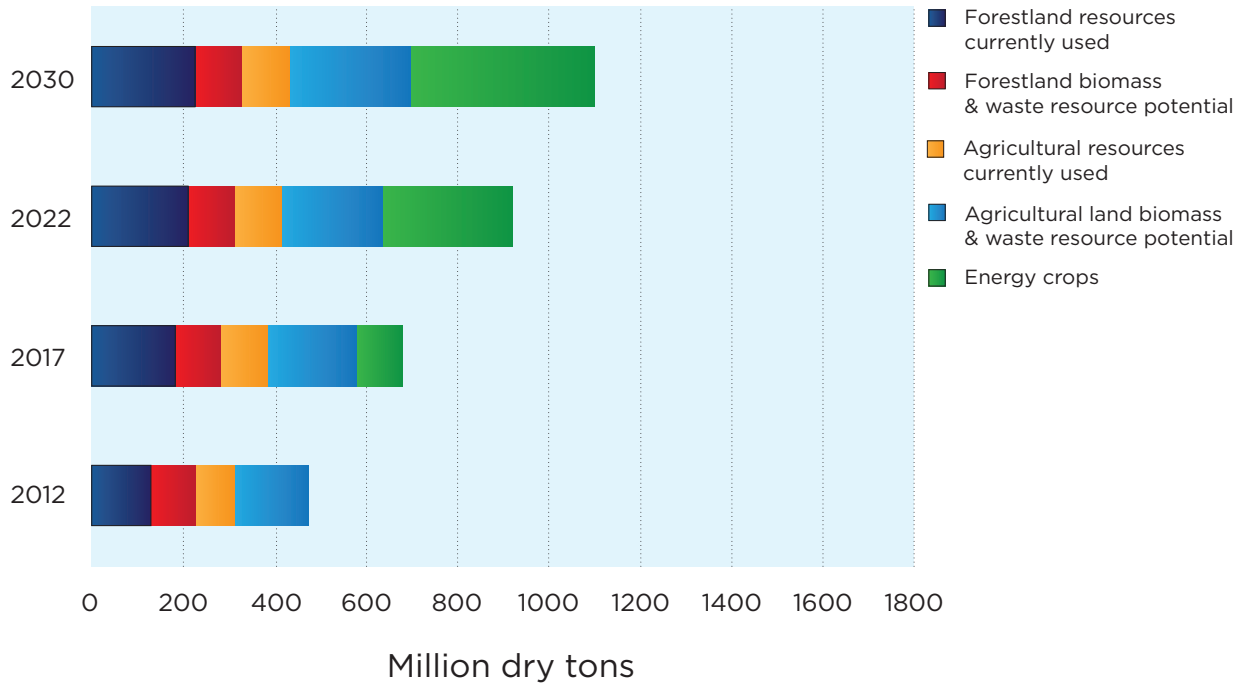
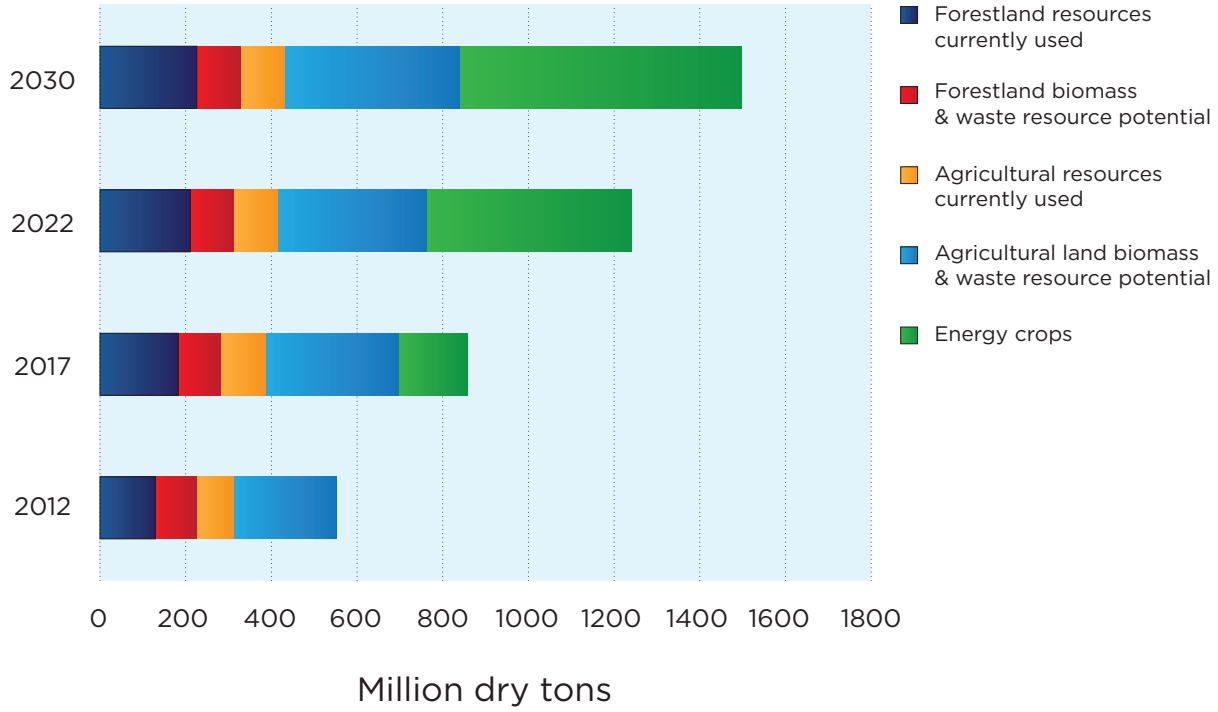


Figure 6.6 Summary of currently used and potential resources at $60 per dry ton or less identified under high-yield assumptions (3% annual energy crop yield growth rate)



EPA. 2008. Municipal Solid Waste in the United States: 2007 Facts and Figures. (5306P) EPA530-R-08-010. U.S. Environmental Protection Agency, Office of Solid Waste. November.

EPA. 2010. Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis. EPA-420-R-10-006. U.S. Environmental Protection Agency, Assessment and Standards Division, Office of Transportation and Air Quality. February.

Ercoli L, Mariotti M, Masoni A, Bonari E. 1999. Effect of irrigation and nitrogen fertilization on biomass yield and efficiency of energy use in crop production of Miscanthus. Field Crops Research 63(1):3–11.

Eriksson G. 1991. Challenges for forest geneticists. Silva Fennica 25(14):257–269.

Evans AM, Perschel RT. 2009. An assessment of biomass harvesting guidelines. Forest Guild, Santa Fe, NM.

Falk RH, McKeever DB. 2004. Recovering wood for reuse and recycling: a United States perspective. Proceedings of Management of Recovered Wood Recycling, Bio-energy and Other Options, April 22–24, 2004. C Gallis (ed.). European COST E31 Conference. University Studio Press, Thessaloniki, Greece. pp. 29–40.

FAO. 2007. State of the world's forests 2007. Food and Agriculture Organization of the United Nations, Rome, Italy. 144 pp. (Accessed at http://www.fao.org/docrep/009/a0773e/a0773e00.htm on March 21, 2011.)

FAPRI. 2010. FAPRI 2010 U.S. and world agricultural outlook. Report 10-FSR 1. Food and Agricultural Policy Research Institute, Iowa State University, Ames, IA.

Farage PK, Blowers D, Long SP, Baker NR. 2006. Low growth temperatures modify the efficiency of light use by photosystem II for CO_2 assimilation in leaves of two chilling-tolerant C4 species *Cyperus longus* L. and *Miscanthus x giganteus*. Plant Cell & Environment 29(4):720–728.

Farnham D. 2001. Corn planting guide, PM 1885. Iowa State University, University Extension, Ames, IA.

Fehrs J. 1999. Secondary Mill Residues and Urban Wood Waste Quantities in the United States. Prepared for the Northeast Regional Biomass Program, CONEG Policy Research Center, Inc. Washington, DC. December.

Fight RD, Hartsough BR, Noordijk P. 2006. Users guide for FRCS: Fuel Reduction Cost Simulator software. General Technical Report PNW–GTR–668. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR. 23 pp.

Fixen PE. 2007. Potential biofuels influence on nutrient use and removal in the US. Better Crops 91(2):12-14.

Foereid B, de Neergaard A, Høgh-Jensen H. 2004. Turnover of organic matter in a Miscanthus field: effect of time in *Miscanthus* cultivation and inorganic nitrogen supply. Soil Biology and Biochemistry 36(7):1075–1085.

Follett RF, Varvel GE, Kimble J, Vogel KP. 2009. No-till corn after bromegrass: effect on soil C and soil aggregates. Agronomy Journal 101(2):261–268.

Fox TR, Allen HL, Albaugh TJ, Rubilar R, Carlson CA. 2007a. Tree nutrition and forest fertilization of pine plantations in the Southern United States. Southern Journal of Applied Forestry 31(1):5–11.

Fox TR, Jokela EJ, Allen HL. 2007b. The development of pine plantation silviculture in the Southern United States. Journal of Forestry 105(7):337–347.

Fransen S. 2009. Agronomics of Switchgrass for Biofuel in the West. In Proceedings of the 2009 Western Alfalfa & Forage Conference, December 2009. Reno, NV. 9 pp.

Will RE, Markewitz D, Hendrick RL, Meason DF, Crocker TR, Borders BE. 2006. Nitrogen and phosphorus dynamics for 13-year-old loblolly pine stands receiving complete competition control and annual N fertilizer. Forest Ecology and Management 227(1–2):155–68.

Wortmann CS, Liska AJ, Ferguson RB, Lyon DJ, Klein RN, Dweikat I. 2010. Dryland performance of sweet sorghum and grain crops for biofuel in Nebraska. Agronomy Journal 102(1):319–326.

Wright LL. 2007. Historical perspective on how and why switchgrass was selected as a "model" high-potential energy crop. ORNL/TM-2007/109. Oak Ridge National Laboratory, Oak Ridge, TN. July. 45 pp.

Wright LL, Eaton LM, Perlack RD, Stokes BJ. 2012. Woody biomass. In Comprehensive renewable energy, Volume 5 Biomass and biofuel production, Section 5.14: Technology solutions – novel feedstocks. A Sayigd (ed). Elsevier, Oxford, UK. pp. 263–291.

Wu S, Lu YC, McMurtrey JE, Weesies G, Devine TE, Foster GR. 2004. Soil conservation benefits of large biomass soybean (LBS) for increasing crop residue cover. Journal of Sustainable Agriculture 24(1):107–128.

Wu X, Zhao R, Bean SR, Seib PA, McLaren JS, Madl RL, Tuinstra MR, Lenz MC, Wang D. 2007. Factors impacting ethanol production from grain sorghum in the dry-grind process. Cereal Chemistry 84(2):130–136.

Wullschleger SD, Davis EB, Borsuk ME, Gunderson CA, Lynd LR. 2010. An empirical model of biomass production in switchgrass: database description and determinants of yield. Agronomy Journal 102(4):1158–1168.

Zalesny Jr. RS, Riemenschneider DE, Hall RB. 2005. Early rooting of dormant hardwood cuttings of *Populus*: analysis of quantitative genetics and genotype × environment interactions. Canadian Journal of Forest Research 35(4):918–929.

Zalesny Jr. RS, Hall RB, Zalesny JA, McMahon BG, Berguson WE, Stanosz GR. 2009. Biomass and genotype × environment interactions of *Populus* energy crops in the Midwestern United States. BioEnergy Research 2(2):106–122.

Zalesny Jr. RS, Zalesny JA. 2009. Selecting *Populus* with different adventitious root types for environmental benefits, fiber, and energy. Chapter 18. In Adventitious Root Formation of Forest Trees and Horticultural Plants – From Genes to Applications. K Niemi, C Scagel (eds.). Research Signpost, Kerala, India. pp. 359–384.

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 and 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)

iii. Yield projections for eight major agricultural crops (major crops are corn, sorghum,2 barley, oats, wheat, rice, cotton, and soybeans) 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)

1) Corn 2012 baseline yield (average for United States) is 163 bushels per acre increasing to 201 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, oats, 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

iv. Residue to grain ratios are 1:1 for corn and sorghum, 1:2 for oats, 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 soybeans

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 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

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[2], barley, oats, wheat, rice, upland cotton, and soybeans 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

USDA AGRICULTURAL PROJECTIONS

- 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
- Biodiesel at 1 billion GPY by 2012

[2] Sorghum grown for energy is treated as an energy crop and assumptions are included under those for annual energy crops.

counties 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 164 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, oats, 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.

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 uses, 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) Use 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

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, oats, 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 (P_2O_5) per dry ton; 27.2 pounds of potassium (K_2O) 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