U.S. Cellulosic Biomass Feedstock Supplies and Distribution

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January 10, 2008

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In 2006, the U.S. consumed approximately 100 quadrillion btus (Quads) of primary energy. Petroleum was the single largest source (40%), followed by natural gas (22%), coal (23%), and nuclear energy (8%). Renewable energies provided 7% of the total energy use with biomass energy the largest component (48%) followed by conventional hydroelectric energy (42%). Wind (4%), solar (1%), and geothermal (5%) energies comprised the remainder (DOE, 2007).

Research, development, and policy efforts are underway to substantially increase the use of renewable energy in the U.S. This paper will focus on biomass energy systems. Total biomass energy use in 2006 was 3.23 Quads and included the use of wood for residential heating (0.39 Quads), ethanol from grain (0.45 Quads), industrial power and heat (1.9 Quads mainly from black liquor and other pulp industry wastes), electricity from utilities (0.4 Quads), and other commercial uses (0.1 Quads) (DOE, 2007). As the biomass industry expands, these existing sources of biomass will continue to play a major role, but for a large scale expansion, additional biomass resources will be needed, mainly in the form of cellulosic feedstocks.

The recent Energy Bill (Energy Policy Act of 2005) defines lignocellulosic or hemicellulosic matter as that which is available on a renewable or recurring basis including (1) dedicated energy crops and trees, (2) wood and wood residues, (3) plants, (4) grasses, (5) agricultural residues, (6) fibers, (7) animal wastes and other waste materials, and (8) municipal solid waste. Several studies have indicated that the principal sources of cellulosic feedstocks will be forest residues, primary mill residues, agricultural crop residues, dedicated energy crops, and urban wood wastes. A search of the literature reveals a number of biomass resource assessments. Many are inventory studies–that is, they estimate quantities but include no economic analysis and do not estimate the prices that must be paid for the feedstocks. Many studies are limited geographically and estimate quantities at a national, multi-state, or state level. Few studies estimate county quantities–those that do tend to estimate county quantities for a single state or sub-state region. The USDA Forest Service data is the exception, providing county level quantities of forest residues and mill wastes for the entire U.S. Many of the studies are limited in scope in that they estimate quantities of forest residues or agricultural crop residues, but not both. And, the studies are conducted by numerous authors and institutions using different methodologies and assumptions. As a result, while there are numerous biomass resource assessments available, it is difficult to construct a complete, consistent, and detailed picture of the quantities of biomass resources available, the prices that will need to be paid, and the geographic distribution of the feedstocks.

To address these problems, a county level database of forest residue, primary mill residue, urban wood waste, agricultural crop residue, and dedicated energy crop supplies (quantities available at selected price levels) have been estimated for current and future time frames. This paper describes the methodology, summarizes the estimated supplies, and presents maps showing the geographic distribution of each feedstock. Supplies are presented for several price levels. The estimates presented in this paper are aggregated national quantities, however, estimates have been made at the county level for each feedstock (including numerous subclasses of feedstocks). Maps showing the county level distribution of feedstocks (by major class) are for $40/dt for the year 2010 unless otherwise noted.

All estimates of current supplies are based on the existing market, technology, and policy situation. For example, all production and collection equipment are commercially available rather than new machinery under development. Estimated costs and quantities are an approximation of the situation that would face bioenergy or bioproduct companies seeking to use biomass resources at the present time.

Estimated costs are edge-of-field costs--they estimate the cost of producing and collecting material in an appropriate form (bales, chips) and loading onto trucks or other conveyor equipment for transport to a user facility or intermediate storage area, but do not include transport costs from the collection site. Storage costs are also not included. Additionally, an explicit premium above the collection costs that may be required to entice producers to sell their biomass resources are not included. All costs are in $2006 unless otherwise noted. Quantities are in dry (0% moisture) English tons.

I. Forest Residues

Forest residues consist primarily of logging residues and other removals. Logging residues are defined as the unused portion of growing stock trees (commercial species with a diameter breast height of at least 5 inches, excluding cull trees) cut or killed by logging and left behind. Other removals are the unutilized wood volume from cut or otherwise killed growing stock, from cultural operations such as pre-commercial thinnings, or from timberland clearing (such as for urban development).

Few national level forest residue supply curves exist. The majority of studies that provide forest residue data are quantity estimates only (e.g., Perlack, 2005; Southern States Energy Board, 2006; Western Governors' Association, 2006; Encyclopedia of Southern Bioenergy Resources, 2006).
Kerstetter (2001a) estimated the availability of 3.52 million dry tons of logging residues in OR, WA, ID, and MT with collection costs ranging from \$32.40 to \$92.23/dry ton depending on the slope of the site, the size of the pieces recovered, and the distance the material is skidded to a road. The Antares group estimated the availability of 72.2 million wet tons of forest residues in the U.S. available at prices of less than \$4.00/MMBtu (Antares, 1999). Oak Ridge National Laboratory, using an somewhat updated version of a model originally developed by McQuillan (1988), estimated forest residue quantities of 44.9 million dry tons at < \$50/dt delivered (Walsh, 2000).

A. Logging Residues. This analysis uses data from the U.S. Forest Service Timber Product Output database which provides quantities of logging residues generated by tree species (measured in billion ft^3) by county for the survey year 2007. The TPO data is converted to dry tons using the species conversion factors contained in Smith, 1985. Softwood and hardwood species are grouped to provide total softwood and total hardwood logging quantities (in dry tons) for each county. An estimated 63.0 million dry tons (27.8 million dry tons softwood; 35.2 million dry tons hardwood) of logging residues were generated in the lower 48 states in 2007 (table 1).

Table 1. Logging residues type and ownership class (million dry tons)--2007

	Quantities (million dry tons)			
	National Forests	Other Public	Private	Total
Softwoods	0.95	1.71	25.14	27.81
Hardwoods	4.53	2.07	32.71	35.24
Total	1.41	3.78	57.85	63.04

Other public land includes all federal, state, county and municipal lands other than national forests. Private land includes those owned by timber companies as well as non-industrial private land.

Future year logging residue quantities are estimated using the projected timber harvests contained in the base case analysis of the most recent Resource Policy Act (RPA) Update by the Forest Service (Haynes, 2007). The RPA assessment presents historical softwood and hardwood timber harvest data (up to 2002) and projects timber harvest from forest lands for the years 2010, 2020, 2030, 2040, and 2050 for several multi-state regions. Intermediate year harvests (2015, 2025) are approximated using simple linear extrapolation. These projections and extrapolations are summarized in Appendix table 1.

Future regional multipliers are estimated for hardwood and softwood harvest based on the projected future timber harvests and 2007 roundwood removals, which are used as a proxy for timber harvest due to the lack of timber harvest data contained in the TPO database and are summarized in Appendix table 2. Since logging residues are a byproduct of timber harvest, changes in timber harvest can be used to approximate the rates of change of logging residues in future years. Estimated future multi-state regional softwood and hardwood logging residues quantities are allocated to each county within the region using an approach that more heavily weights counties displaying historical increases in logging residues (from 2002 to 2007) when the future regional quantities are increasing, and more heavily weights counties displaying historical decreases when future regional logging residues quantities are decreasing.

The estimated cost of collecting logging residues uses a model originally developed by McQuillan (1988). This model uses forest inventory data along with information on logging and chipping costs, hauling distances and costs, stocking densities, wood types, and slope and equipment operability constraints to estimate regional supply schedules (corresponding to the RPA regions) for softwood and hardwood chips for the base year of their study (1983) with projections for future years. The model includes recoverability factors which consider whether the resource is accessible (i.e., there are roads), whether it occurs in stands that are available, and how much of the resource can be retrieved (i.e., equipment limitations to gathering small pieces of wood--assumed to be 65% in this analysis). The original data in the model came from a 1976 survey of waste wood which was defined to include logging residues, rough rotten and salvable dead wood (live cull and sound dead wood), and excess sapling and small pole trees. Most of the potential wood resources can be recovered using conventional feller-bunchers and skidders. The cost of supplying wood waste chips include collection, harvesting, chipping, loading, hauling, unloading, and a return for profit and risk. McQuillan does not include stumpage prices or costs associated with gaining access to a site (e.g., temporary roads).

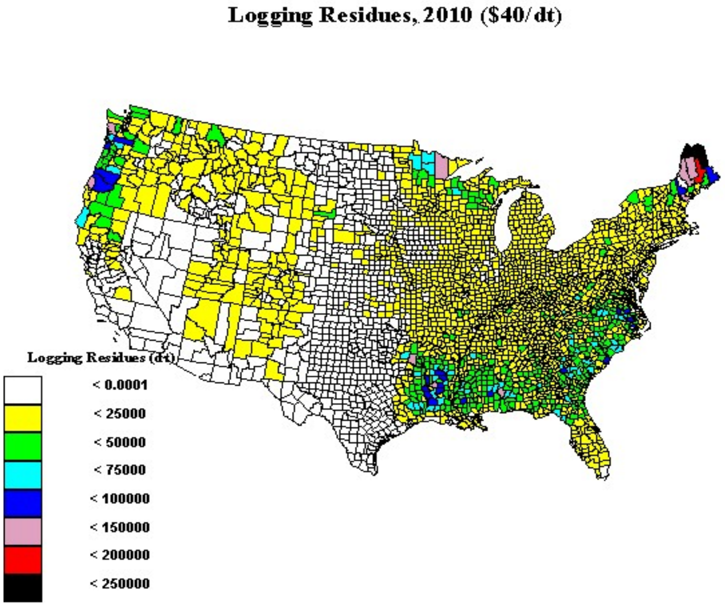
For this analysis, the inventory is updated, although the structure and distribution remain the same as in the original model–thus the revised inventory totals are allocated proportionately across the same increments. The analysis factors out the transportation component, and updates prices to $2006 using the CPI index. Using the updated model, the regional quantities of softwood and hardwood logging residues that can be collected at specified discrete costs are estimated. A cost distribution is calculated—that is, the percent of total regional logging residue quantities (by softwood and hardwood) that can be collected for each discrete collection cost is estimated. This cost distribution is then applied to all counties in the region. A key limitation of the analysis is the inability to adequately update the original model and to change some structural assumptions. Complete model documentation is no longer available to permit these changes.

The estimated logging residue supply curves for the United States for select prices for the years 2007, 2010, 2015, 2020, 2025, and 2030 are summarized in table 2. Figure 1 provides a graphical depiction of the geographic distribution of logging residues for the year 2010 and collection cost of $40/dt.

Table 2. Estimated logging residue supplies, U.S., by year

	Estimated Logging Residue Supplies (million dry tons)								
	$20/dt	**$25/dt**	**$30/dt**	**$35/dt**	**$40/dt**	**$45/dt**	**$50/dt**	**$75/dt**	**$100/dt**
2007	0.06	1.84	6.22	10.89	24.02	31.29	31.29	36.19	38.50
2010	0.065	1.81	6.41	13.23	29.37	38.70	38.70	45.02	47.89
2015	0.065	1.95	6.80	13.62	29.99	39.35	39.35	45.71	48.60
2020	0.067	2.10	7.22	14.41	31.51	41.20	41.20	47.79	50.77
2025	0.067	2.17	7.46	14.81	32.32	42.19	42.19	48.90	51.95
2030	0.068	2.25	7.70	15.22	33.12	43.17	43.17	50.01	53.13

Figure 1. Distribution of logging residues, 2010 ($40/dt)



B. Other Removals. Other removals are the unutilized wood volume from cut or otherwise killed growing stock, from cultural operations such as pre-commercial thinning, or from timberland clearing (such as for urban development). This analysis uses data from the U.S. Forest Service Timber Product Output database which provides quantities of other removals by tree species (measured in billion ft^3) by county for the survey year 2007. The TPO data is converted to dry tons using the species conversion factors contained in Smith, 1985. Softwood and hardwood species are grouped to provide total softwood and total hardwood quantities (in dry tons) for each county. An estimated 24.7 million dry tons (6.4 million dry tons softwood; 18.3 million dry tons hardwood) of other removals were generated in the lower 48 states in 2007 (table 3).

Table 3. Other removal residues generated by type and ownership class (million dry tons)--2007

	Quantities (million dry tons)			
	National Forests	Other Public	Private	Total
Softwoods	0.23	0.35	5.85	6.44
Hardwoods	0.35	1.20	16.74	18.29
Total	0.58	1.55	22.59	24.73

Other public land includes all federal, state, county and municipal lands other than national forests. Private land includes those owned by timber companies as well as non-industrial private land.

Given that a significant portion of other removals is a result of land clearing for urban development, future year quantities uses multipliers based on estimated increases in county housing units. Clearly, changes in housing are a result of numerous factors not considered in this analysis. Additionally, the distribution of housing units in future years is based on the same rate of growth as has recently occurred. It is assumed that the same counties that are currently experiencing growth (shrinking) will be those that continue to grow (shrink) in the future and at the same rate.

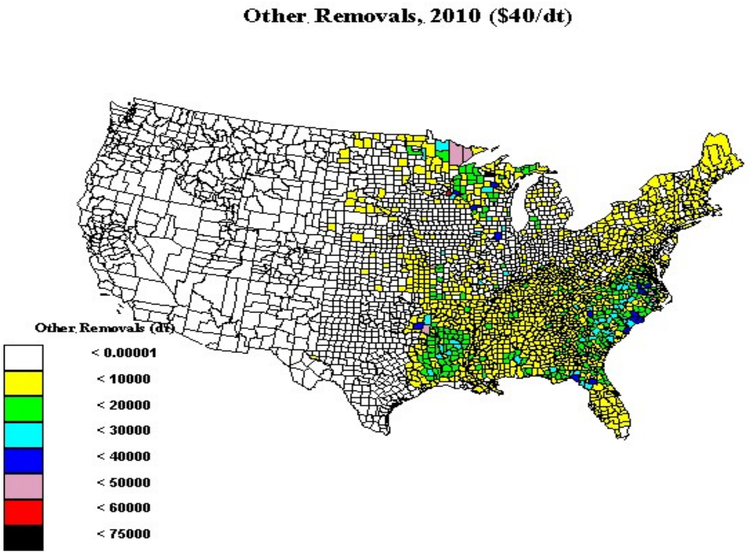
The TPO database includes harvest and thinning of trees with a dbh (diameter at breast height) of greater than 5 inches--some commercial thinning includes removal of trees that are smaller than this. Additionally, data was unavailable for AZ, CA, CO, ID, IL, IN, MT, NV, NM, ND, OR, UT, WA, and WY. Thus, the potential quantities may be higher than estimated.

Similar to logging residues, the estimated costs of harvesting and collecting the material relies on the McQuillan model, but uses the estimated costs for harvesting rough, rotten, and salvageable dead material rather than for collecting logging residues. The analysis assumes that 50 percent of the quantities generated could be available for bioenergy to account for equipment constraints and alternative uses of the merchantable quantities. The estimated supplies of other removals for the years 2007, 2010, 2015, 2020, 2025, and 2030 for select prices are shown in table 4. The geographic distribution of estimated other removal residues at $40/dt for the year 2010 is depicted in figure 2.

Table 4. Estimated other removal supplies, U.S., by year

	Estimated Other Removal Supplies (million dry tons)								
	$20/dt	**$25/dt**	**$30/dt**	**$35/dt**	**$40/dt**	**$45/dt**	**$50/dt**	**$75/dt**	**$100/dt**
2007	0.03	0.80	4.27	4.27	8.58	10.33	10.33	11.51	11.99
2010	0.03	0.82	4.35	4.35	8.72	10.47	10.47	11.66	12.14
2015	0.03	0.84	4.46	4.46	8.89	10.65	10.65	11.86	12.33
2020	0.03	0.87	4.57	4.57	9.07	10.84	10.84	12.05	12.53
2025	0.03	0.89	4.69	4.69	9.24	11.02	11.02	12.25	12.73
2030	0.03	0.92	4.81	4.81	9.43	11.22	11.22	12.46	12.94

Figure 2. Distribution of other removals, 2010 ($40/dt)

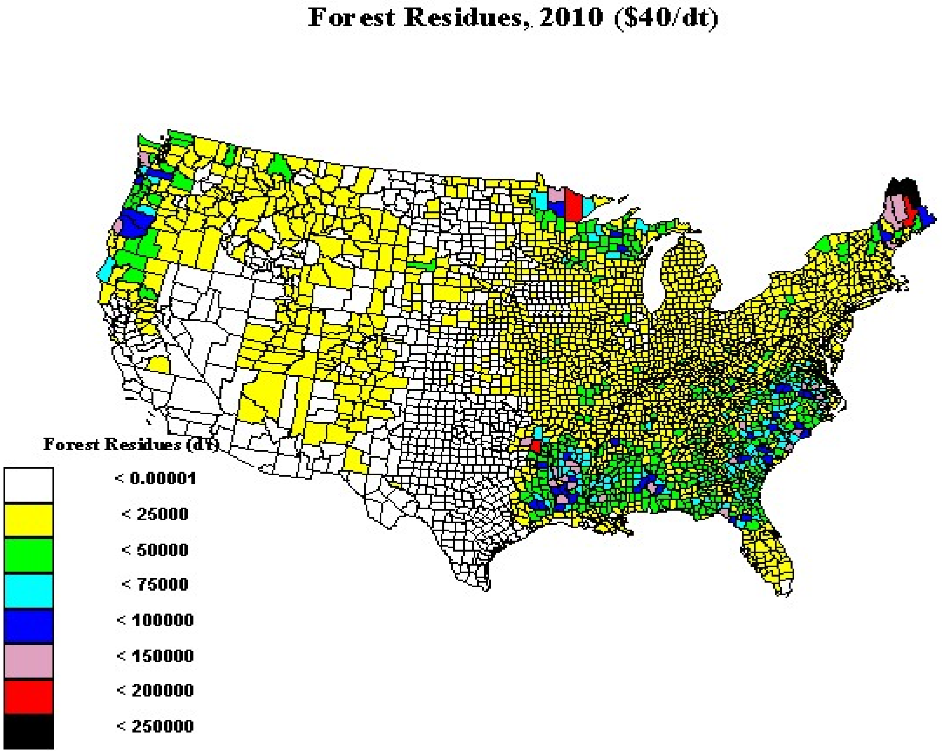


C. Total forest residues. The estimated quantities of total forest residues (combined logging residues and other removals) are presented in table 5 for the years 2007, 2010, 2015, 2020, 2025, and 2030 and geographically depicted in figure 3 for the year 2010 and collection cost of $40/dt.

Table 5. Estimated total forest residue supplies, U.S., by year

	Estimated Total Forest Residue Supplies (million dry tons)								
	$20/dt	$25/dt	$30/dt	$35/dt	$40/dt	$45/dt	$50/dt	$75/dt	$100/dt
2007	0.09	2.63	10.49	15.16	32.61	41.62	41.62	47.71	50.49
2010	0.09	2.63	10.76	17.59	38.08	49.17	49.17	56.68	60.03
2015	0.09	2.79	11.26	18.08	38.87	50.00	50.00	57.56	60.93
2020	0.09	2.96	11.80	19.00	40.58	52.04	52.04	59.84	63.31
2025	0.10	3.07	12.15	19.50	41.56	53.21	53.21	61.15	64.68
2030	0.10	3.17	12.51	30.02	42.55	54.39	54.39	62.47	66.07

Figure 3. Distribution of forest residues, 2010 ($40/dt)



D. Other Potential Forest Biomass Materials. The forest residue supply curves estimated in this analysis are limited to logging residues and other removals. Other potential sources of forest materials include fuelwood, fuel treatment removals to maintain healthy forests and limit catastrophic forest fires, and changes in the management of pine plantations.

In the United States, wood is currently used to produce energy, primarily for residential heat purposes, but also for industrial heat, steam, and electricity. The USDA Forest Service reports that fuelwood use declined from 3.11 billion cubic feet in 1986 to 2.36 billion cubic foot (about 35.4 million dry tons at an assumed average wood density of 30 dry lb/cu. ft.) in 2000, but is projected to increase steadily to about 3.46 billion cubic feet (about 51.9 million dry tons) by 2050 (Haynes, 2003). Hardwood species are the principal source of fuelwood and the South is the largest user followed by the Northeast.

Between 100 and 200 million acres of U.S. forest lands are estimated to be at high risk for catastrophic wildfires due to overcrowded conditions and the build-up of diseased and dead materials. The removal of this material offers a potentially new source of forest materials. The Healthy Forests Initiative and the Healthy Forests Restoration Act of 2003 (P.L.108-148) include provisions to remove and utilize excess woody biomass material to produce a full range of wood fiber products and bioenergy and bioproducts. The quantities that need to be removed could be substantial with estimates ranging from 124 to 445 million dry tons in the Western states alone (Rummer, 2003; Skog, 2005; Ince, 2006). Excessive fuel loading also occurs in forests in the Eastern U.S.

Between 1994 and 2003, pulpwood demand in the Southern U.S. (the major pulp producing region) declined from 130.8 to 121 million green tons while the supply of pulpwood increased due to increased acreage and greater management intensity of pine plantations (Leightley, 2006). The USDA Forest Service projects that total U.S. pulpwood demand will continue to decline over the next decade, but will begin to rebound after 2020 and increase by 25 percent by 2050 (Haynes, 2003). The belief that the industry will rebound in the southern U.S. is not shared by all however, and some forestry researchers suggest that pine plantation owners might alter the way they manage their stands in order to meet other fiber markets or supply material for emerging bioenergy markets. Data regarding the potential quantities and price of this material are not available. However, there are around 30 million acres of pine plantations in the south (Siry, 2002; Conner and Hartsell, 2002).

II. Primary Mill Residues

Primary mills are those that convert roundwood products (i.e., logs) into other wood products and include sawmills that produce lumber, pulp mills, veneer mills, etc. In the process of converting trees into wood products, waste residues are generated consisting of bark, fine wood residues, and coarse wood residues which are used in a variety of ways. According to the USDA Forest Service for 2007 (Timber Product Output Database, http://www.fia.fs.fed.us), 88.7 million dry tons of primary mill residues were produced, but only 1.3 million tons were not used either as fuel (mostly in low efficiency boilers), for fiber uses, or for other uses (table 6).

Table 6. Primary mill residues quantities and uses—2007 (million dry tons)

	Total Generated	Used as Fiber	Used as Fuel	Used as Other	Not Used
Bark	24.8	0.2	18.6	5.6	0.4
Coarse	25.0	6.1	13.8	4.7	0.4
Fines	36.9	29.2	4.3	3.0	0.5
TOTAL	88.7	35.4	36.7	13.3	1.3

Total quantities may not equal the sum of individual quantities due to rounding.

Most studies that provide primary mill residue data are quantity only and are based either on data from the TPO database for previous or current years and extensions of the TPO data to future years (e.g., Perlack, 2005; Southern States Energy Board, 2006; Western Governors' Association, 2006; Encyclopedia of Southern Bioenergy Resources, 2006). A few local studies are available and are based on surveys of local producers (e.g., Buehlmann, 2001). Few studies attempt to estimate supply curves (i.e., quantities available as a function of price) for mill residues either for current or future time frames. The Antares group estimated a total quantity of 111 million wet tons of wood wastes (includes mill residues and urban wood wastes) available at prices of less than $4.00/MMBtu but did not separate the feedstock sources in their report (Antares, 1999). Walsh, 2000 estimated state forest residue supply curves and summed the state data to obtain total U.S. forest residue quantities at several prices (e.g., 23.7, 34.8, and 44.9 million dry tons available at delivered prices of $30/dt, $40/dt, and $50/dt respectively). Given the extensive use of primary mill residues, most studies assume the only quantities available for bioenergy are those not already used.

This study differs from other studies in that it assumes that residues currently used to produce other products are still potentially available for bioenergy if a sufficiently high price is paid to attract the feedstock away from its existing use. The overall approach is to approximate that price.

The analysis uses the U.S. Forest Service Timber Product Output database quantities of primary mill residues. The database classifies mill residues as bark, coarse wood residues suitable for chipping (i.e., slabs, edgings, veneer cores, etc.), and fine wood residues not suitable for chipping due to their small particle size and the large proportion of fibers that are cut or broken

(i.e., sawdust, veneer clippings, etc.) and provides existing uses of residues. End use categories include fuel, fiber uses, and other uses (e.g., mulch and bedding). Bark is primarily used as a hog fuel and increasingly for mulch. Fine wood residues are used mostly to produce particleboard and for bedding. Coarse residues are used to produce a variety of products including pulp for paper and cardboard, and engineered wood products such as fiberboard, oriented strandboard, medium density fiberboard, etc.
The TPO data is supplemented with information from individual state reports which provide additional information regarding end uses and delineate residue sources between hardwood and softwood materials. The same proportion of state residue uses is then applied to each county in the state.

National data for mill residues does not specify whether the residues are from softwood or hardwood tree species, but the data for logging residues distinguishes between the two and thus the percent of hardwood and softwood tree species harvested in each county can be estimated. This percent is applied to the mill residues to provide a breakdown of mill residue of softwood and hardwood percents. Future mill residue quantities are estimated using the logging residue multipliers for softwoods and hardwoods (Appendix tables 1 and 2). The regional multiplier is applied to each county and state within the region.

For all mill residues generated, additional processing and disposal costs are estimated. Processing costs involve the cost of chipping large pieces of wood and miscellaneous handling costs such as scooping materials up, loading vans, etc. The costs of using equipment are estimated using AAEA (2000) recommended methodology. The analysis also assumes that 10 percent of the residues will be too fine (i.e., a powder) to be useful and will be disposed of. The disposal cost is based on the state median tipping fee at Construction and Demolition landfills (Chartwell, 2006).

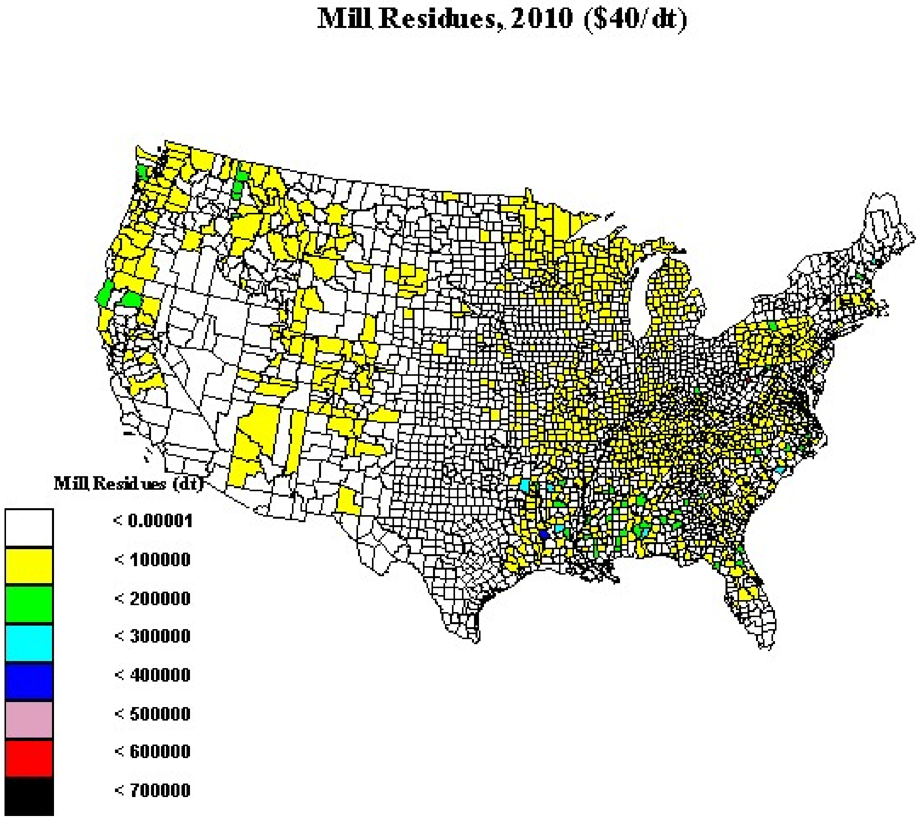
For mill residues that are currently used to produce other products, a minimum price needed to attract the residues away from their existing uses is estimated and added to the processing and disposal costs. These costs are estimated in a very simple manner and assume that for fiber uses, 35 percent of the market price of the product is for the raw wood used in their production. For other uses, it is assumed that 65 percent of the market price is the raw wood value.

Table 7 presents the estimated primary mill residue quantities potentially available for bioenergy and bioproduct uses. Figure 4 graphically illustrates the distribution of primary mill residues at $40/dt in 2010.

Table 7. Estimated total primary mill residue supplies, U.S., by year

Primary Mill Residue Quantities (million dry tons)									
	$20/dt	$25/dt	$30/dt	$35/dt	$40/dt	$45/dt	$50/dt	$75/dt	$100/dt
2007	0.43	4.93	6.03	19.34	20.14	41.46	42.38	50.31	51.04
2010	0.55	5.70	7.29	21.91	22.80	46.03	47.37	56.29	57.33
2015	0.56	5.93	7.51	22.88	23.77	48.00	49.34	58.55	59.61
2020	0.58	6.16	7.74	23.85	24.73	49.97	51.31	60.82	61.88
2025	0.59	6.34	7.93	24.58	25.47	51.46	52.82	62.55	63.61
2030	0.60	6.52	8.12	25.31	26.20	52.96	54.31	64.28	65.35

Figure 4. Distribution of primary mill residues, 2010 ($40/dt)



In addition to primary mill wood residues, other mill wastes are generated. Secondary mills are those that convert primary mill products into consumer products such as furniture, cabinets, etc. Few studies have attempted to estimate potential secondary mill residue supplies due to the paucity of data and methodological issues (Buggeln, 2002). Rooney (1998) estimated that 12.5 million dry tons of secondary mill wood residues are generated, but that only 1.2 million dry tons could be available for bioenergy after correcting for assumed recoverability factors, percent of residues contaminated, etc.

Black liquor is a by-product of the kraft pulping process used in the paper and pulp industry. Most of this material is currently used by paper mills for the production of heat, steam, and electricity and constitutes the largest component of existing bioenergy production. As of July 2006, 3,442 thousand megawatts of net electricity generation came from wood, black liquor, and other wood waste with 2,497 thousand megawatts from industrial firms (the paper industry) and the remaining from electric utilities and independent power producers (DOE, 2006).

III. Urban Wood Wastes

Urban wood waste is a catchall term for wood contained in municipal solid waste such as packaging (containers, crates, pallets), durables (furniture) and yard trimmings; residential and non-residential construction wastes; residential and non-residential demolition wastes; and renovation and remodeling wastes. Some analysts also include wood wastes from the maintenance of municipal parks, utility line and right-of-way maintenance, urban land clearing, residues from commercial nurseries and landscapers, etc. Urban residues produced as a result of storm events are also sometimes included in the description. Most studies, however, limit the analysis to municipal solid waste (MSW) including yard trimmings, and to construction, renovation, and demolition (C&D) wastes.

The majority of studies estimate the quantities available either locally, regionally, or nationally. Examples of local/regional studies include the Triangle J study in North Carolina (Buehlmann, 2001) and the Northeast Waste Management Officials Association study (NEWMOA, 2005). National assessments include the MSW and C&D Characterization studies conducted by Franklin and Associates for the Environmental Protection Agency (EPA, 2000; Franklin and Associates, 1998); the landfill surveys from Virginia Polytech University (Araman, 1997; Bush, 1997); *BioCycle* magazine's biannual State of the Garbage Survey; and various studies by McKeever and colleagues (e.g., McKeever, 2003; Falk and McKeever, 2004). The studies show considerable variation with respect to the estimated quantities of urban wood wastes generated and available. EPA (2006) estimated that in 2005, 245.7 million tons of municipal solid waste was generated and wood and yard trimmings represented 5.7% and 13.1% of the total (by weight), respectively. Falk and McKeever (2004) estimated that 12 million metric tons of durable and packaging wood waste, and 14.8 million metric tons of wood yard trimmings were generated in 2002. *BioCycle* magazine estimated total MSW quantities of 388 million tons in 2004 but didn't provide an estimate of the percent that is wood.

Even less data is available regarding construction and demolition wastes. According to an EPA study (Franklin and Associates, 1998), an estimated 135.5 million tons of total C&D waste was generated in 1996. Falk and McKeever (2004) estimated that 10.5 million metric tons of construction/renovation wood waste and 25.2 million metric tons of demolition wood waste were generated in 2002, and that 7.8 and 8.7 million metric tons of construction and demolition wood wastes, respectively, could be available for bioenergy.

Few studies attempt to estimate urban wood waste prices. The Antares Group (1999) estimated that 10.1 million wet tons of yard trim, 6.8 million wet tons of other MSW wood wastes, 6.2 million wet tons of construction wood waste, and 7.9 million wet tons of demolition wood wastes could be available at delivered prices of less than $4.00/MMBtu. Wiltsee (1998) surveyed waste generation rates in 30 U.S. metropolitan areas and extrapolated the data to the remainder of the U.S. He estimated that up to 60 million tons of wood wastes could be available at prices of less than $0/ton, based on tipping fees. Walsh (2000) estimated that 36.8 million dry tons of urban wood wastes (combined MSW, construction/ demolition, and yard trimmings) could be available at a delivered price of $30/dt.

This study estimates county level supplies for MSW, yard trim, construction, demolition, and renovation wood wastes. The approach involves first estimating current and future quantities of urban wood wastes by type and then estimating the cost of the wastes.

A. Current Quantities of Urban Wood Wastes.

1. Municipal Solid Waste. Most ordinary household waste (garbage or trash) is classified as municipal solid waste (MSW) and is disposed of in MSW landfills. The wood component of MSW includes durable wood materials (e.g., cabinets, furniture), packaging materials (e.g., pallets, crates), some yard trimmings, and some construction, renovation, and demolition materials (mainly from home do-it-yourself projects) (EPA, 2000). Local data regarding the quantities of urban wood waste discarded in MSW is not readily available for most locations, requiring that the quantities of wood MSW be estimated.

State MSW wood quantities are estimated using the State of the Garbage surveys (BioCycle, 2006) as the source for state MSW generation, EPA (2000, 2006) and Araman (1997) as sources of national and regional data on the percent of MSW that is wood which is then applied to the states in each region to estimate state MSW wood quantities. State quantities are allocated to counties based on population (Census Bureau, 2005). These sources were also used to identify quantities of wood wastes that are recycled into other products (such as mulch, compost, bedding, fuel, etc.). Assuming average moisture of 20%, an estimated 17.2 million dry tons of durable and packaging wood materials were generated in MSW in 2005.

Yard trimmings are assumed to be 25% wood (NEOS, 1994) with an assumed moisture content of 35%. An estimated 8.22 million dry tons of wood were generated as MSW yard trim in 2005.

2. Residential Construction. The quantities of residential construction wood waste generated are estimated as a function of the numbers of housing units by type (single family, multi-family), size (square feet), and waste generation factors. County housing permit data is from the U.S. Census Bureau (2000, 2004). Square footage data (regional averages) are from the National Association for Home Builders (2000) (Appendix tables 3 and 4). Data from case studies in Franklin and Associates (1998) are used to construct simple regression curves to estimate the quantities of construction waste generated as a function of square footage for single family residences. For multi-family residences, waste generation factors of 4.05 and 3.73 lb/ft^2 for units less than and greater than 1000 ft^2 respectively are used (Franklin and Associates, 1998). The estimated percent of construction waste that is wood differs by study, ranging from a low of 25 percent (ICF, 1995) to a high of 42.4 percent (Franklin and Associates, 1998). This study uses data from Bush, 1997 who surveyed C&D landfills regarding the quantities of wood that were discarded. The study provides regional (rather than national) estimates of wood quantities for four multi-state regions and estimates a national average wood composition of 37.8 percent which is intermediate to the other two studies. Assuming 20% moisture, an estimated 1.91 million dry tons of residential wood waste was generated in 2005.

3. Non-Residential Construction. Non-residential construction includes wharehouses, hotels/motels, office buildings, commercial buildings, schools, churches, hospitals, farm buildings, and other miscellaneous types of structures (e.g., public safety, entertainment, etc.). Little data is available regarding the amount of wood waste that is generated by these activities, although expected quantities tend to be small due to the fact that many of these types of structures use concrete, brick, and steel in much larger proportions that wood. The total square footage of non-residential construction is estimated by dividing the state non-residential construction expenditures by the national average expenditure per square foot (estimated as the total construction expenditures divided by total square feet and equal to \$160.77/ft^2) (Department of Commerce, 2000; Census Bureau, 2001; DOE 1999). The pounds of waste generated/ft^2 are assumed to be 4.1 (www.oikos.com) and the percent of waste that is wood is assumed to be 21.5 % (Franklin and Associates, 1998). Estimated state quantities of non-residential construction wood are allocated to the counties based on the percent of the state population accounted for by each county. Assuming a moisture content of 20%, an estimated 0.88 million dry tons of non-residential wood waste were generated in 2005.

4. Residential Renovation. Residential renovation wood wastes are generated from remodeling, home additions, and maintenance of homes. Renovation wastes are intermediate to construction and demolition wastes in that they contain new wood used to build or renovate structures as well as removal of existing materials similar to demolition wastes. This study makes no attempt to separate the two. Estimated quantities are based on the number of regional renovation jobs by type (e.g., bathroom, kitchen, bedroom, other indoor remodels; fencing/walls; patio/terrace/deck; and shed/detached garages) (U.S. Census Bureau, 2000). Waste generation factors by job type (i.e., tons of waste/job) are used to estimate total residential renovation waste which is assumed to be 45% wood (Franklin and Associates, 1998). Quantities are allocated to the states as a function of the percent of total regional expenditures accounted for by the state and further allocated to counties based on the percent of the total state population accounted for by each county. Assuming a moisture content of 20%, an estimated 14.7 million dry tons of renovation wood waste were generated in 2005.

5. Residential and Non-Residential Demolition. Regional residential and non-residential demolition waste is estimated as a function of the total number of C&D landfills and the average quantity of waste received by landfill (Bush, 1997). Regional C&D wastes are allocated to the states as a function of the percent of the region’s housing units accounted for by each state. It is assumed that 15% of C&D waste is residential demolition waste (Franklin & Associates, 1998). The percent of residential demolition waste that is wood varies by region (Bush, 1997). It is assumed that 35% of the total C&D waste is non-residential demolition waste and that 20% of this waste is wood (Franklin & Associates, 1998). State quantities are allocated to counties based on the percent of the state population that is accounted for by the county. Assuming 20% moisture, an estimated 2.31 and 2.86 million dry tons of residential and non-residential wood wastes respectively, were generated in 2005.

B. Future Quantities of Urban Wood Wastes.

Quantities of urban wood are estimated for the years 2010, 2015, 2020, and 2025. Future quantities of wood wastes that are generated are estimated as a function of projected changes in population growth (MSW--durables and packaging), projected increases in future housing units (MSW-yard trim, construction, and demolition), and projected changes in middle-aged population (renovation wastes).

Projected growth in state populations (U.S. Census Bureau, 2005) is allocated to the counties based on the percent of population growth that occurred between 2000 and 2004 for each county. Thus counties whose population is increasing rapidly are weighted more heavily than those in which population is growing more slowly. Projected future quantities of yard trim, construction, and demolition wood wastes are based on projected changes in housing units which were constructed from projected number of state households. The projected state housing units were allocated to each county within the state based on the rate of growth in housing units for the years 2000 to 2005. Thus counties with the greatest increase in housing growth are weighted more heavily than counties with slower growth (U.S. Census Bureau, 2000, 2004). Projected future renovation wastes are estimated as a function of the population age structure (U.S. Census Bureau, 2000, 2005). The rationale for this is that younger and older aged people tend to build new homes (either a first home or a retirement home) while middle age persons tend to remodel existing homes. The projected changes in population and housing statistics are used to construct county multipliers for future years which are applied to current quantities of urban wastes to project future quantities by waste type.

C. Estimated Costs of Urban Wood Wastes.

Wood waste supply curves are based on the estimated minimum prices that must be paid for wood that is recovered but not used and for wood that is recovered and used to produce wood-based products. The minimum price is estimated in a multi-step manner that includes (1) sorting and processing costs for wood, (2) the value of non-wood materials recovered during sorting of mixed wastes, (3) net tip fees, (4) the value of recovered wood not used to produce other products, (5) the profits from recycled wood-derived products, and (6) the quantities of recovered wood wastes used to produce wood-derived products. The same framework and approach is used to estimate C&D and MSW wood wastes supply curves—only the specific assumptions differ for each wood waste source and use.

1. Sorting and Processing Costs. For co-mingled (mixed) wastes, wastes are first sorted with the recovered wood further processed to produce a more uniform sized clean chip, while source-separated wastes only undergo size reduction processing. Mixed waste sorting is assumed to be performed manually. For all facilities, costs include capital investment costs for land, buildings and construction based on facility size; costs associated with owning and operating machinery and equipment used to sort and process wastes; labor costs; and miscellaneous other unaccounted for costs such as utilities, etc. Equipment costs include depreciation; maintenance and repair costs; taxes, housing, and insurance costs; and fuel costs and are estimated using American Agricultural Economic Association methodology for machinery costs (AAEA, 2000). The configuration of the facilities, and equipment cost and performance parameters, are compiled from limited descriptions found in a number of studies resulting in highly stylized waste recovery facilities. Data sources include Dubanowitz, 2000; USGS, 2000; Goldstein, 2004; BioCycle, 2000; Oshins, 2005; Florida DEP, 2000; Badger, 2002; and BLS, 2007.

2. Value of Other Materials Recovered. While sorting wastes, additional materials can be recovered such as plastic, paper and cardboard, glass, and metals (steel, aluminum, etc.) from MSW and paper and cardboard, gypsum (drywall), metal, plastic, and concrete from C&D waste. These materials can be sold and generate a revenue stream for the waste recovery facility. The quantities recovered depend on the composition of the MSW and C&D waste streams as well as the technology employed to sort and recover the materials. Additionally, the value of the materials can vary substantially depending on the quality of the recovered materials. Data sources for this information include EPA, 2006; Kelly, 2006; CIWMB, 2002, Howard, 2002, USGS, 2007 and Global Recycling Network, 2007.

3. Net Tip Fees. Materials discarded at landfills are charged a fee, called a tipping fee, which varies substantially by state and individual landfills. This analysis assumes the median state tip fee (range from $21 to $98/ton in 2006 for MSW; $18/ton to $120/ton for C&D) for recovery facilities accepting co-mingled (mixed) wastes (Chartwell, 2006). Dedicated wood processing facilities (source separated facilities) frequently charge a lower tip fee than mixed waste facilities/landfills to encourage separation at the generation site and disposal at the wood processing facility. These fees are unknown and are assumed to be 75% of the co-mingled fees in this analysis. This fee serves as a source of revenue for the recovery facility, however, not all material received can be recovered, and some material is assumed to still require landfilling. The costs paid to landfill this material are subtracted from the received tip fee to estimate a net tip fee.

4. Estimated Price of Recovered Wood Not Used for Other Products. The value of the recovered wood that is not used to produce other products is estimated as the sum of the net tip fee and the value of the other recovered products minus the sort/process costs.

5. Estimated Profit of Products Made from Recovered Wood. The profitability of existing uses of recovered wood wastes is estimated as the sum of the cost of the wood used as a raw input and the cost of converting the wood to the final product. These costs are estimated in a simple way as the sorting/processing cost divided by a conversion efficiency factor (i.e., product produced per dry ton of wood used). The cost of converting the wood into other products is estimated simply as the sorting/processing cost for wood times a conversion cost multiplier. The profit is estimated as the price the product can be sold at, minus the production cost. In some cases, the profitability is negative. In these cases, the absolute value of the difference is used. Negative values seem counterintuitive with respect to profit maximization, and in those cases, the product would probably not be produced. However, many mixed waste facilities are municipal facilities and production of some products may occur even if unprofitable by the methodology and assumptions used in this analysis because the municipality is trying to save landfill space and may also use the product (such as mulch) negating the need to purchase the product. It should also be recognized however, that the methodology is simple and the data crude. Thus the estimated costs are only rough approximations. Data is compiled from numerous sources including *Biocycle* (2000).

6. Estimated Quantities of Recovered Wood Used to Make Wood-Derived Products. The quantities of recovered wood by waste type$_i$ used to make wood-derived products$_j$ such as mulch, compost, etc., are a function of recovery (recycling) rates and the percent of recovered wood used for each product. Data is derived from several sources including EPA, 2006; Bush, 1997; Araman, 1997; Franklin & Associates, 1998; NEOS Corporation, 1998; and Rooney, 1998. Recovery rates and percent uses of recovered wood are national averages and are applied to each state, and subsequently allocated to each county in the state. Thus, each county assumes the same recovery and use rates as the national average.

D. Urban Wood Waste Supplies.

Using the above methodology, minimum prices are calculated for wood wastes recovered from mixed waste facilities and for source separated facilities. The analysis assumes that all demolition and renovation wastes are collected and processed as mixed wastes throughout the time period of the analysis. It is also assumed that most (80 percent) durable and packaging MSW waste is collected as mixed waste and that this percent remains unchanged during the time period of the analysis. A greater percent of construction and yard trim waste is assumed to be collected as source separated materials than for other urban waste categories, and the quantities of source separated wastes are assumed to increase slightly over time. Yard trim is frequently collected separately and taken directly to processing facilities as a result of municipal collection of spring pruning and fall leaf pickup, and private disposal by landscapers and tree removal companies. Additionally, some states are beginning to require that at least some construction waste (i.e., mostly from construction of housing developments rather than single homes) be source separated. It seems reasonable to assume that the percent of yard trim and construction wastes collected as mixed wastes are lower than for the other waste categories, and that the percent of mixed collection will decline over time. However, it should be noted that no data was found to support the percents used in the analysis. Table 8 summarizes the estimated urban wood waste supplies by waste type for the year 2005 and table 9 presents the estimated combined urban waste quantities for the years 2010, 2015, 2020, and 2025 for select prices.

Table 8. Estimated supplies of urban wood wastes by category, 2005 (million dry tons)

	Wood Waste Supplies (million dry tons)					
	$20/dt	$30/dt	$40/dt	$50/dt	$75/dt	$100/dt
MSW	2.71	10.14	16.45	16.56	16.76	16.93
MSW-Yard Trim	1.98	3.24	3.37	4.13	6.08	6.10
Residential Construction	1.51	1.63	1.74	1.76	1.81	1.81
Non-Residential Construction	0.235	0.259	0.287	0.339	0.751	0.766
Residential Demolition	0.039	1.23	1.85	1.85	1.89	2.12
Non-Residential Demolition	1.68	2.29	2.29	2.29	2.43	2.62
Residential Renovation	11.75	11.75	11.75	11.86	13.25	13.35
Total Urban Wood	19.91	30.55	37.73	38.78	42.97	43.69

Totals don't sum due to rounding

Table 9. Estimated supplies of urban wood wastes (million dry tons)

	Urban Wood Waste Quantities (million dry tons)								
	$20/dt	$25/dt	$30/dt	$35/dt	$40/dt	$45/dt	$50/dt	$75/dt	$100/dt
2005	19.91	22.06	30.55	36.69	37.73	38.10	38.78	42.97	43.69
2010	20.88	23.13	32.10	38.58	39.69	40.06	40.79	45.17	45.92
2015	22.07	24.50	34.01	40.85	42.03	42.43	43.22	47.63	48.41
2020	22.33	24.87	34.90	42.09	43.34	43.75	44.57	49.09	49.90
2025	24.78	27.51	38.15	45.72	47.04	47.48	48.39	53.06	53.91

E. Contamination.

The above analysis does not take into account, the quality of the wood due to the lack of data regarding the extent and type of contamination of urban wood wastes. Much of the wood is likely to be highly contaminated. It is either painted or stained, pressure treated or treated with chemicals (such as copper chromate arsenate (CCA) for decking materials) (E&A Environmental, 1997). Construction and furniture manufacture increasingly involves the use of engineered wood products (relative to solid wood) which contain binders and adhesives (Fridley, 2002). Wood-plastic components are increasingly being used for fences and decks (Winandy, 2004). The sources of wood likely to be the least contaminated are yard trimmings, construction wood, the packaging component of MSW, and the detached shed/garage component of residential renovation. Assuming 50% of construction wood, 75% of the garage/shed component of renovation wastes, the packaging component of MSW, and yard trim wastes significantly reduces the quantities of urban residues that might be available (table 10).

Table 10. Estimated supplies of uncontaminated urban wood wastes (million dry tons)

	Uncontaminated Urban Wood Waste Quantities (million dry tons)								
	$20/dt	$25/dt	$30/dt	$35/dt	$40/dt	$45/dt	$50/dt	$75/dt	$100/dt
2010	5.92	7.23	12.14	15.74	16.45	16.74	17.36	19.91	20.06
2015	6.53	7.98	13.23	17.03	17.79	18.11	18.82	21.53	21.69
2020	6.59	8.09	13.62	17.62	18.42	18.74	19.46	22.07	22.23
2025	7.19	8.84	14.73	18.95	19.80	20.14	20.93	23.49	23.66

IV. Agricultural Crop Residues

Agricultural crop residues (the non-grain, above ground component of crops) are complementary products to the production of grain and oilseed crops, and the same factors that drive the production of these crops drives the quantities of crop residues produced. All of the major grain and oilseed crops can be potential suppliers of agricultural residues, but most analyses, including this one, focus on corn stover and wheat straw due to the large quantities produced and their wide distribution across the U.S.

Few other studies exist. Gallagher (2003a,b) estimated that in the eleven largest corn producing states, 98.9 million tons of corn stover could be available for bioenergy use at an estimated harvest cost (including fertilizer replacement costs) of approximately $12.50/dt. Kerstetter (2001a,b) estimates the availability of 15.4 million tons of wheat straw in WA, OR, ID, and MT with 9.5 million dt available at delivered costs of less than $50/dt to pre-identified sites. Examples of other local studies include Graf and Kochler (2000), Johnson and Baugsund (1990), and Mann and Bryan (2001). Examples of studies that estimate crop residue supplies for crops other than, or in addition to, corn and wheat straw include Fife, 1999 (rice straw in California); Rooney, 1998 (cotton gin and other small grains); and Perlack, 2005 (other small grains—quantities only).

The quantities of agricultural crop residues than can be sustainably removed is directly influenced by a number of factors including grain yield, crop rotation, field management practices (e.g., type and timing of tillage and other management practices), climate, and physical characteristics of the soil (soil type, erodibility index, topography, etc.). The methodology to estimate agricultural crop residue supplies involves estimating the quantities of residues produced, the quantities that must remain on the field to maintain soil quality characteristics and long-term productivity, and the cost of collecting/harvesting available residues.

A. Crop Residues Produced

The quantities of corn stover and wheat straw that are produced are estimated by multiplying the grain yield by a residue-to-grain ratio (harvest index). This analysis assumes corn and wheat grain weights of 56 and 60 lb/bu respectively (the weight of the grain at 15.5% moisture and 13.5% moisture respectively) and residue ratios of 1:1 for corn, 1.7:1 for winter wheat and 1.3:1 for spring wheat (Heid, 1984; Larson, 1997 a, b; Brown, 2003). County level average (for the years 2000-2005) corn and wheat grain yields are obtained from the U.S. Department of Agriculture, National Agricultural Statistics Service (NASS). These yields are used to estimate the average (dt/ac) quantities of corn and wheat residues that are produced in each county of the U.S. where corn and wheat production occurs.

B. Available Crop Residues

Crop residues play a crucial role in limiting soil erosion and maintaining the health and productivity of soils (e.g., maintaining soil organic matter). The quantities of crop residues that can potentially be available for bioenergy uses must account for the quantities that must be left on the field to maintain soil characteristics taking into consideration tillage practices, crop rotations, field topography, and soil type. This study includes soil erosion and organic matter constraints, but does not include other potential soil quality indicators such as moisture, microbial activity, etc.

1. Soil erosion. This study uses the soil erosion analysis of Nelson (2002, 2003) who estimated the quantities of corn stover, winter wheat straw, and spring wheat straw that can be removed by soil type, topography, tillage practice (conventional, reduced till, and no-till) and crop rotation while controlling for wind and rain erosion at or below the tolerable soil loss level, T (the maximum rate of soil erosion that will not lead to prolonged soil deterioration and/or loss of productivity). Quantities that must remain to control for water and wind erosion are estimated using RUSLE (Revised Universal Soil Loss Equation) (Renard, 1996) and the Wind Erosion Equation (WEQ) (Skidmore 1970, 1979, 1988). Water erosion dominates in the eastern two-thirds of the U.S. with wind erosion being more prominent in the western U.S. Erosion needs are estimated for ***all*** cropland soil types where corn and wheat are produced (USDA-NRCS, 1995). Three tillage scenarios (conventional, reduced, and no-till) are analyzed for each crop rotation on each soil type. The percent of tillage practices currently used are obtained from CTIC (2000, 2004). This analysis assumes that corn is produced in a corn-soybean rotation while wheat is produced in a continuous wheat rotation.

2. Soil carbon. Soil carbon levels are an important indicator of soil quality as it affects soil processes such as cation exchange, aggregate stability, water holding capacity, and soil microbial activity. This analysis includes ***crude*** estimates of the quantities of residues that must remain on the field to maintain soil organic matter levels. These quantities are based loosely on the Soil Conditioning Index (SCI) developed by the USDA Natural Resource Conservation Service (Lightle, 1997, 1999) and are not as detailed or as rigorous as are the estimated quantities that must remain to control soil erosion. The SCI considers the amount of organic material returned to the soil and the effects of the tillage and planting on organic matter decomposition, and under the assumed conditions, qualitatively determines whether soil organic matter increases, decreases, or remains constant. It is predicated on the assumption that the amount of biomass which must be returned to the soil to maintain equilibrium is inversely proportional to the rate of decay.

C. Residue Collection Costs.

This analysis assumes that corn stover and wheat straw are collected as large round bales (5' x 6' diameter) although other collection methods are possible. Round baling is widely used in existing haying operations throughout the U.S. and the equipment is available. Collection operations include mowing, raking, and baling the crop residue; moving the bales to the edge of the field (staging); and stacking the bales at field’s edge for storage. Equipment cost estimates use recommended methods and agricultural equipment parameters and engineering performance standards (AAEA, 2000; ASAE, 2001) and include repairs, fuel/lube/oil, depreciation and interest, labor, taxes, housing, and insurance. Input costs are obtained from USDA (NASS, 2003 a,b) and from the Hotline Farm Equipment Guide (Heartland, 2004). Input costs (i.e., machine prices, labor, fuel, etc.) vary by region in the U.S. and regional costs are used in the analysis. Different collection practices (combinations of windrowing, mowing, raking and baling operations) and equipment configurations (use of a crop processor or not) are assumed depending on removable quantity level.

The decomposition of the crop residues provides nutrients (nitrogen, phosphorus, and potassium) that must be replaced. The estimated value of replacement nutrients vary substantially among studies (e.g., Atchinson, 2004; Gallagher, 2003; Schechinger, 2004; Sheehan, 2002) depending on the assumed nutrient costs, quantities of nutrients per dry ton of residue, and quantities of nutrients that must be replaced. This analysis assumes 2/3 replacement and uses regional fertilizer prices providing estimated nutrient replacements costs of $8.78 to $10.35/dt corn stover removed and $3.99 to $4.68/dt of wheat straw removed.

D. Crop Residue Model.

Corn stover and wheat straw supplies are estimated using a dynamic agricultural policy simulation model of the U.S. agricultural sector (POLYSYS) that includes national demand, regional supply, livestock, and aggregate income modules (de la Torre Ugarte, 2000; Ray, 1976; Huang, 1988). POLYSYS is anchored to published baseline projections for all model variables (USDA, 2006; FAPRI, 2006), and estimates deviations from the baseline. Commodities endogenously considered in POLYSYS are corn, grain sorghum, oats, barley, wheat, soybeans, cotton, and rice, and beef, pork, lamb and mutton, broilers, turkeys, eggs, and milk. Commodities considered exogenously include alfalfa, other hay, and edible oils and oilseed meals. The model simulates changes in planted and harvested acres, yields, production, exports, variable costs, market demand by use, farm price, cash receipts, government payments, and net realized income.

The crop supply module is composed of 305 independent linear programming (LP) models, each of which represents the land allocation decision in a specific geographic region with relatively homogeneous production characteristics (Agricultural Statistical Districts--ASDs). The crop supply module first determines the acres in each ASD which are available to shift production and then allocates available acres among competing crops based on maximizing returns above costs. Enterprise budgets are used in each region to determine production costs for each crop. The crop demand module utilizes estimated demand elasticities and price flexibilities and estimates prices for the eight major crops and demand utilization for each crop by use (food, feed, industrial, export, and stock carryover). Commodity demand is a function of price, cross-price shifters, and non-price shifter variables. The livestock module is an econometric model that interacts with the demand and supply modules to estimate production quantities and market prices. The primary link between the livestock and crop sectors is through feed demand.

POLYSYS includes all of the acres identified by USDA as cropland in the contiguous 48 states (431.4 million acres) and planted to the eight major crops, alfalfa and other hay crops; idled; planted to pasture; and enrolled in the Conservation Reserve Program. The 2 percent of cropland acres used for fruits, vegetables, and other minor crops are not included.

Several modifications were made to POLYSYS to enable its use to estimate crop residue supplies. These include extending the baseline to 2025. Traditional crop yields are assumed to increase over time (Appendix table 5). POLYSYS had previously been modified to include dedicated energy crops (switchgrass, hybrid poplar, and willow). For this analysis, the switchgrass module was updated and revised and the potential to collect corn stover and wheat straw was added. The grain/residue ratios, collection costs, and quantities that must remain on the field, as estimated by the methodologies described above, are incorporated into POLYSYS. Thus, as the corn and wheat acres of production change, POLYSYS estimates the quantities of stover and straw that can be available. The profitability of corn and wheat acres is based on the combined grain and residue profits. The analysis assumes the use of conservation tillage practices increase over time (table 11) and improvements in collection technology will reduce costs to 75% of current costs (table 12).

Table 11. Assumed tillage practices for corn and wheat production

Year	Conventional Till	Reduced Till	No-Till
2005 to 2010	60	20	20
2011 to 2015	55	20	25
2016 to 2020	40	20	40
2021 to 2025	25	20	55

Table 12. Assumed changes in corn stover and wheat straw collection costs

Year	Percent of Baseline Cost
2005 to 2010	100 percent
2011 to 2015	95 percent
2016 to 2020	85 percent
2021 to 2025	75 percent

E. Corn Stover and Wheat Straw Supplies.

The estimated corn stover and wheat straw supplies for the years 2005, 2010, 2015, 2020, and 2025 are summarized in tables 13 and 14 for select prices. The estimated quantities assume that collection occurs on all acres of corn and wheat production and thus represents an upper bound. The distribution of corn stover and wheat straw production at $40/dt for the year 2010 is shown in figures 5 and 6. The ASD quantities are allocated to counties using a static county level model that contains the same cost and availability assumptions as are incorporated into POLYSYS.

Table 13. Estimated corn stover supply (million dry tons)

Year	$20/dt	$30/dt	$40/dt	$50/dt	$60/dt	$75/dt	$100/dt
2005	0	0	30.77	49.17	53.73	55.72	56.70
2010	0	0.38	76.11	89.80	99.64	103.43	105.88
2015	0	0.77	98.62	118.31	121.86	121.65	119.12
2020	0	112.35	151.80	156.62	157.29	154.85	150.45
2025	0.37	176.89	192.56	193.64	191.78	188.00	184.64

Table 14. Estimated wheat straw supply (million dry tons)

Year	$20/dt	$30/dt	$40/dt	$50/dt	$60/dt	$75/dt	$100/dt
2005	0	0.40	2.07	3.22	3.48	3.64	3.81
2010	0	0.49	1.60	5.20	5.49	5.76	6.13
2015	0	0.52	3.48	6.61	7.24	7.38	7.66
2020	0.12	2.51	9.95	10.64	11.03	11.32	11.36
2025	0.25	13.55	15.24	15.08	15.49	16.62	16.87

Figure 5. Corn stover distribution, 2010, ($40/dt)

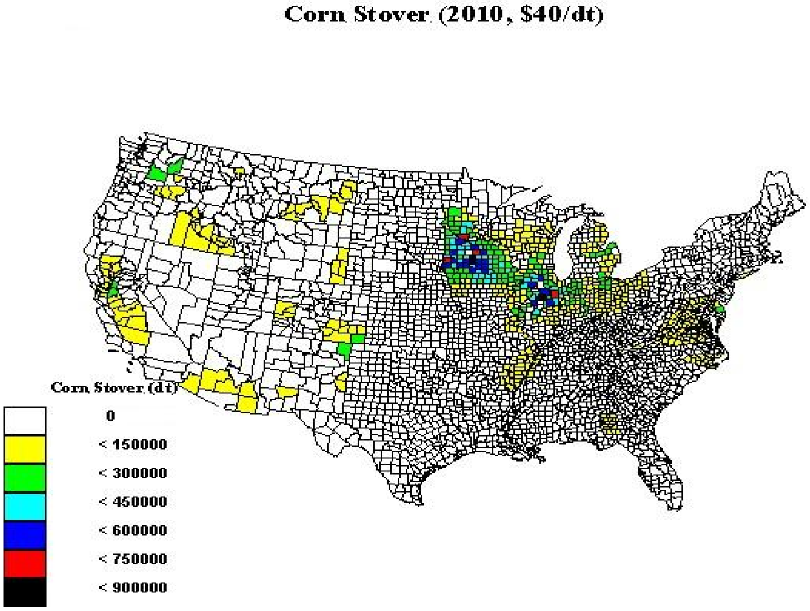
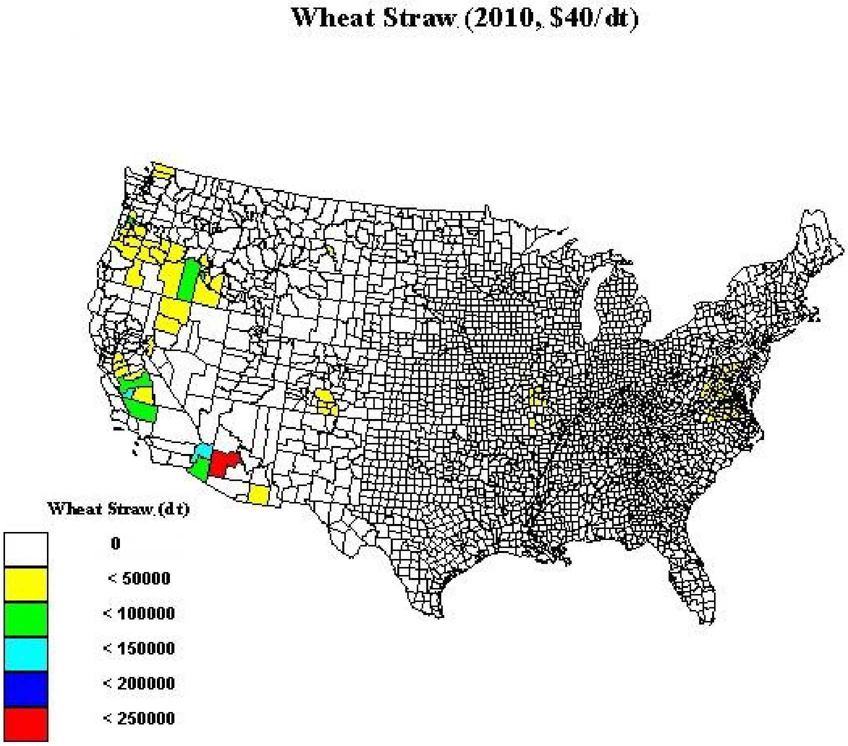


Figure 6. Wheat straw distribution, 2010, ($40/dt)



F. Other Crop Residues.

This analysis considers only corn stover and wheat straw. Other crop residues could potentially be available, but are limited supplies relative to corn stover and wheat straw, and many are highly dispersed geographically (rice straw and sugar cane bagasse are exceptions). Table 15 presents the estimated quantities of barley, oat, rye, rice, and sorghum straws produced in 2005. Quantities that must remain to maintain soil quality have not been accounted for.

Table 15. Small grain straw production (million dry tons), 2005

	Harvested Acres (2005) (millions)	Yield (2005)	Quantities of Straw Produced (million dry tons)
Barley	3.27	64.8 bu/ac	7.63
Oats	1.82	63.0 bu/ac	2.57
Rye	0.28	27.0 bu/ac	0.32
Rice	3.36	6,636 lb/ac	15.60
Sorghum	5.74	68.5 bu/ac	10.81

Estimated straw production is based on harvested grain acres and yields for 2005 (USDA, National Agricultural Statistical Service, www.usda.gov/nass). Barley straw production assumes a straw-to-barley grain ratio of 1.5:1 and a barley grain weight of 48 lbs/bu; Oat straw production assumes a straw-to-oat grain ratio of 1.4:1 and an oat grain weight of 32 lbs/bu; Rye straw production assumes a straw-to-rye grain ratio of 1.5:1 and a rye grain weight of 56 lbs/bu. Rice straw production assumes a straw-to-rice grain ratio of 1.5:1. Sorghum straw production assumes a straw-to-sorghum grain ratio of 1:1 and a sorghum grain weight of 55 lbs/bu (Brown, 2003; Heid, 1984; and Larson, 1997a, 1997b). **Estimated quantities do not account for quantities that must remain on the field to maintain soil quality.**

V. Dedicated Energy Crops

Crops grown specifically for energy uses (i.e., dedicated energy crops) are expected to become a major biomass resource as a biobased industry develops. Numerous herbaceous (grasses) and woody crops can be developed for bioenergy and bioproduct uses and a number of researchers are exploring several options. At present, dedicated energy crops are not being commercially produced—their potential must be estimated using models. De La Torre Ugarte (2003) and Walsh (2003) examined the potential supply and economic impacts of three dedicated energy crops (switchgrass, hybrid poplar, and willow) using a dynamic model of the U.S. agricultural sector (POLYSYS) that had been modified to include these crops. Unlike other models that have been modified to include energy crops (ASM and its forestry version FASOM) (Adams 1994; McCarl, 1993), POLYSYS provides annual estimates of changes in land use, adoption of new technologies, and changes in economic conditions; captures the adjustments that must be made in the agricultural sector to accommodate a new technology and/or policies that encourage adoption of the technologies; and reflects the challenges presented by the annual and decentralized nature of agricultural decision making. Additionally, POLYSYS contains significantly more production regions permitting a more detailed look at the potential for bioenergy crop production.

This analysis also uses POLYSYS (described above under crop residues), but updates crop management and yield assumptions relative to the earlier analysis, and limits the analysis to switchgrass only (i.e., no hybrid poplar or willow). Additional differences relative to those for crop residues include the use of a net present value approach to account for the multi-year characteristics of bioenergy crops. A real discount rate of 6.0 percent is used. To avoid corner solutions, POLYSYS contains embedded flexibility constraints that limit the acres that a given crop can lose or gain each year. To accommodate the addition of bioenergy crops, these allocation rules are modified so that the extent to which acres can be increased or decreased relative to the baseline is a function of whether the net present value (NPV) returns of traditional crops are positive, negative, or a mixture for three years. Also, acres that can be lost or gained for each crop are limited to 20 percent of its baseline acres. The basic POLYSYS model utilizes a naive price expectation or a 3-year lag structure. To better account for the impacts of large changes in land-use resulting from large-scale production of bioenergy crops, a rational expectation hypothesis is implemented, with changes estimated through an iterative approach. Pasture acres are permitted to shift to switchgrass or other crop production, but the number of acres that can shift are constrained by the requirement that the regional loss of forage production from pasture acres must be replaced by new regional hay production. This limits the amount of pasture acres that can switch to the production of other crops to substantially less than the 56 million acres of cropland pasture.

A. Switchgrass Assumptions.

Switchgrass (*Panicum virgatum*) is a perennial prairie grass native to the U.S. east of the Rocky Mountains and extending into Canada and Mexico. It can theoretically be produced anywhere in the U.S. but this analysis limits production to eastern two-thirds of the U.S. due to the assumption that all production is rain-fed (no irrigation), and the lack of research regarding switchgrass production and yields in the western Plains and Pacific regions.

Switchgrass is assumed to be planted once every 10 years using no-till practices at a rate of 8 pounds pure live seed/acre. Herbicide applications include 1 pre-emergent application and 1or 2 post-emergent applications of the appropriate herbicides in the establishment year. No fertilizers are applied during the establishment year. In subsequent years, an annual application of 50 lb/acre nitrogen is assumed in all regions except the South Plains where it is doubled. Phosphorus is added in all regions at a rate of 17.5 lbs of P per acre if soil tests indicate low levels--otherwise, no phosphorous is added. For the purpose of estimating phosphorus costs, it is assumed that 1/2 of the acres will require phosphorus applications annually. Potassium is added only in regions east of the Mississippi River. Soils in the Western U.S. are naturally high in potassium and additional K is generally not needed. Potassium is added at an annual rate of 25 lbs K per acre in the eastern U.S.

A workshop of experts determined regional yields, expected yield increases, and management practices used in the original analysis. The yields from this workshop serve as a starting point for the updated analysis, but have been modified in several ways. Specifically, previous analysis assumed a one percent per annum (simple rather than compound—a 10 percent increase in 10 years) increase in yields for all regions, however, much of the existing research is focused on developing synthetic cultivars (hybrids) suitable for the southern U.S. and the new analysis assumes different regional yield increases (table 16). Yield increases are based on the performance of the synthetic cultivars in current field tests in the south, and adjusted for the time needed to complete field performance trials and to scale-up seed production to provide quantities of improved cultivars sufficient for large-scale commercial production (Taliaferro, 2000, 2002).

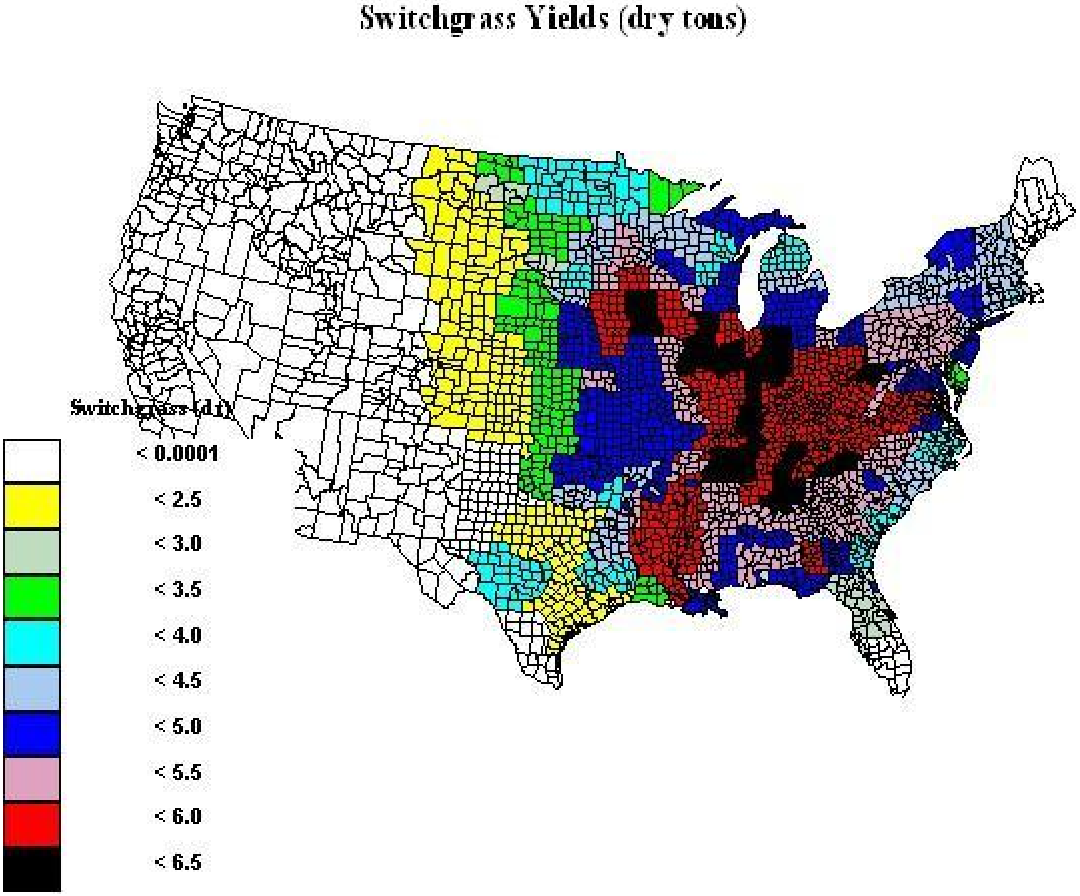
Table 16. Regional annual yield increases

Region	Annual Increases in Yield
Lake States	1.00 percent
Corn Belt	1.75 percent
Northeast	1.25 percent
Appalachia	2.50 percent
Southeast	3.00 percent
North Plains	1.25 percent
South Plains	1.00 percent

Lake States = MI,MN,WI; Corn Belt = IA,IL,IN,MO,OH; Northeast = CT,DE,MA,ME,NH,NJ, NY,PA,RI,VT; Appalachia = KY,MD,NC,TN,VA,WV; Southeast = AL,AR,FL,GA,LA,MS,SC; North Plains = KS,NE,ND,SD; South Plains = OK,TX

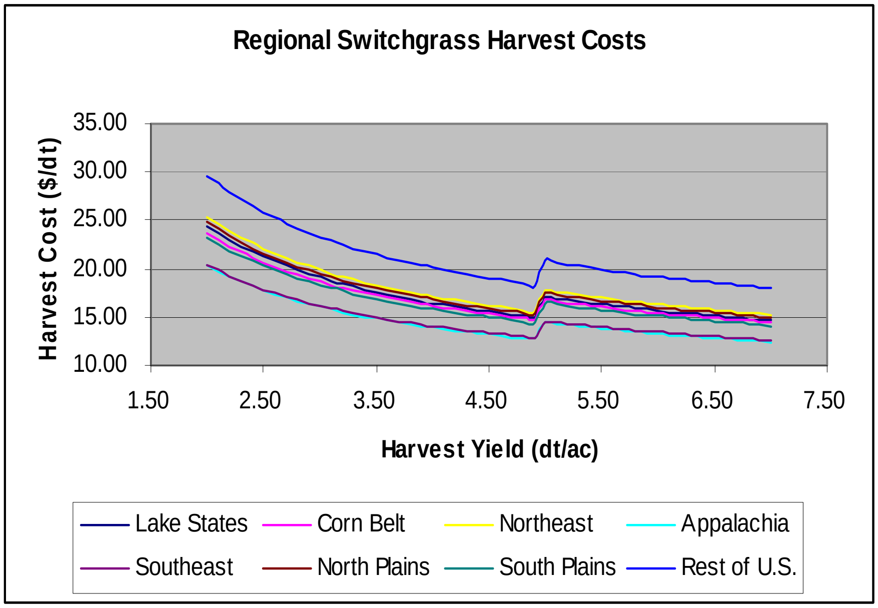
ASD yields in the Southern Plains region have been revised downward compared to the previous analysis and limitations in equipment (i.e., harvest at a higher cutting height) have been included resulting in new expected mature ASD harvest yields ranging from 78 to 95 percent of those assumed in the previous analysis. These adjustments are based on the final project reports (McLaughlin and Kszos, 2005; Ocumpaugh, 2003; Parrish, 2003; Taliaferro, 2002; Vogel and Jung, 2000) and personal communications with switchgrass researchers. The 2005 yield distribution (dry tons/acre) assumed in the current analysis is graphically presented in figure 7. Switchgrass generally takes about 3 years to reach full yield maturity. For this analysis, assumed yields are 25 and 75% of expected mature yields for the establishment and second year of the rotation.

Figure 7. Switchgrass Mature Harvest Yields (dry tons/acre), 2005



Switchgrass is harvested annually (including the establishment year) and involves mowing, raking, and round baling. Costs include the costs of picking up the bales and moving them to the edge of the field where they are stacked (staging costs). Harvest costs are a function of yields (figure 8) and machine performance parameters are adjusted for yields of greater than 5 dt/ac. Regional harvest costs vary due to different yields and different machinery, labor, and fuel costs in each region. The analysis assumes that over time, improvements in switchgrass harvest will occur and reduces the harvest costs to 95 percent of current costs from 2011 to 2015, to 85 percent of current costs from 2016 to 2020, and to 75 percent of current costs from 2021 to 2025.

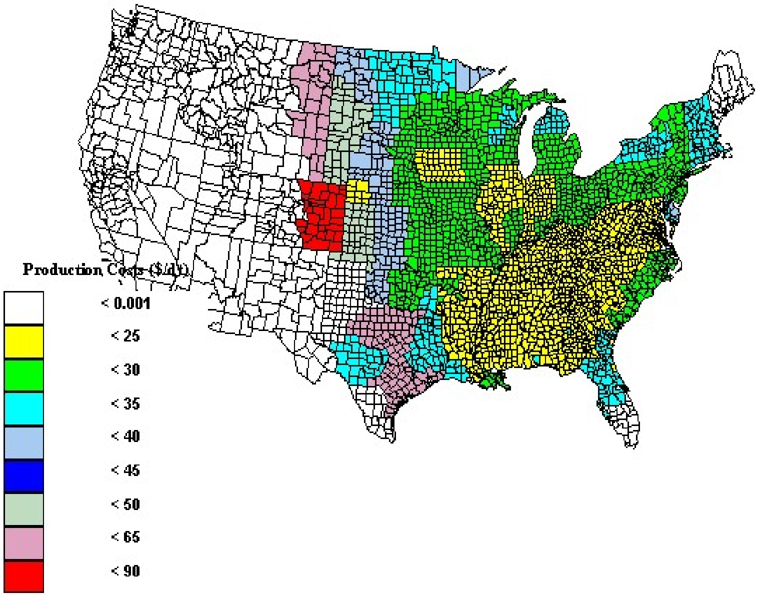
Figure 8. Regional switchgrass harvest costs ($/dt) as a function of yield (dt/ac), 2005



Costs are in $2002

Machinery costs are estimated using the American Agricultural Economics Association recommended methodology (AAEA, 2000). Machinery operating parameters are obtained from the American Society of Agricultural Engineer Standards (2001). Equipment prices are obtained from the Hotline 2004 Farm Equipment Guide and equipment manufacturers. Labor, fuel, fertilizer, and chemical costs are obtained from the USDA National Agricultural Statistical Service (NASS 2003 a,b). Seed costs are obtained from seed companies. A 6 percent discount rate is assumed. Switchgrass establishment and maintenance costs remain unchanged over the period of the analysis (2005 to 2025). Machinery, labor, fuel and fertilizer prices vary by region. All costs are in $2002. Production costs represent edge-of-field costs; no storage or transportation costs are included. The estimated regional costs of producing switchgrass are shown in figure 9.

Figure 9. Estimated switchgrass production costs by region, 2005



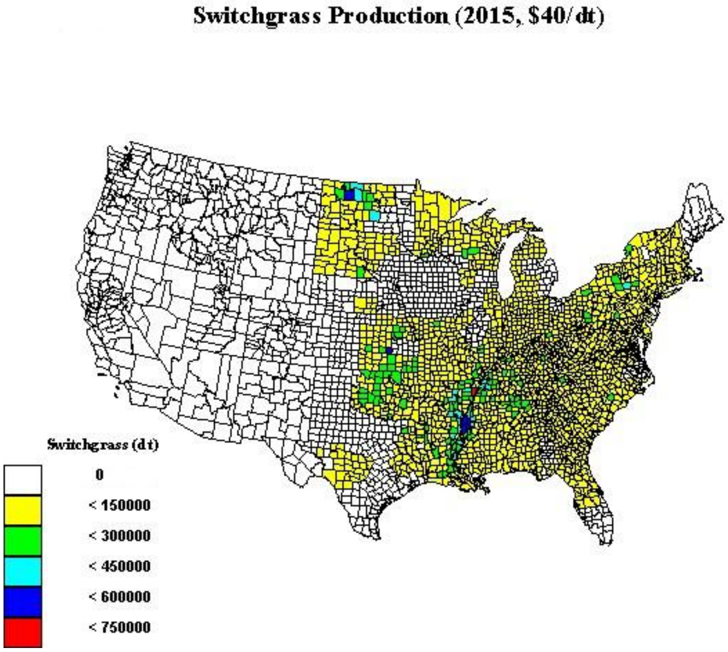
Switchgrass production was assumed to begin in 2007. Estimated potential national production at select prices is presented in table 17.

Table 17. Estimated switchgrass supplies (million dry tons)

Year	$20/dt	$30/dt	$40/dt	$50/dt	$60/dt	$75/dt	$100/dt
2005	0	0	0	0	0	0	0
2010	0.37	12.49	20.50	27.38	32.29	34.16	34.87
2015	7.62	64.36	101.51	136.20	162.14	179.93	193.98
2020	38.15	119.94	176.83	238.00	277.09	312.59	340.78
2025	59.54	161.82	228.55	293.10	323.64	363.48	382.36

Switchgrass supplies have been apportioned to each county in an ASD based on a weighted percent of traditional crop acres that shift to switchgrass production. The estimated distribution of switchgrass production for the year 2015 ($40/dt) is shown in figure 10.

Figure 10. Switchgrass production, 2015 ($40/dt)



VI. Total Biomass Quantities

Potential total wood resources (i.e., forest residues, mill residues, and clean urban wood wastes) are graphically depicted for four price levels and two years in figure 11 and potential herbaceous feedstocks (i.e., corn stover, wheat straw, and switchgrass) are depicted in figure 12.

Figure 11. Total wood residue supplies, select prices, 2010 and 2020

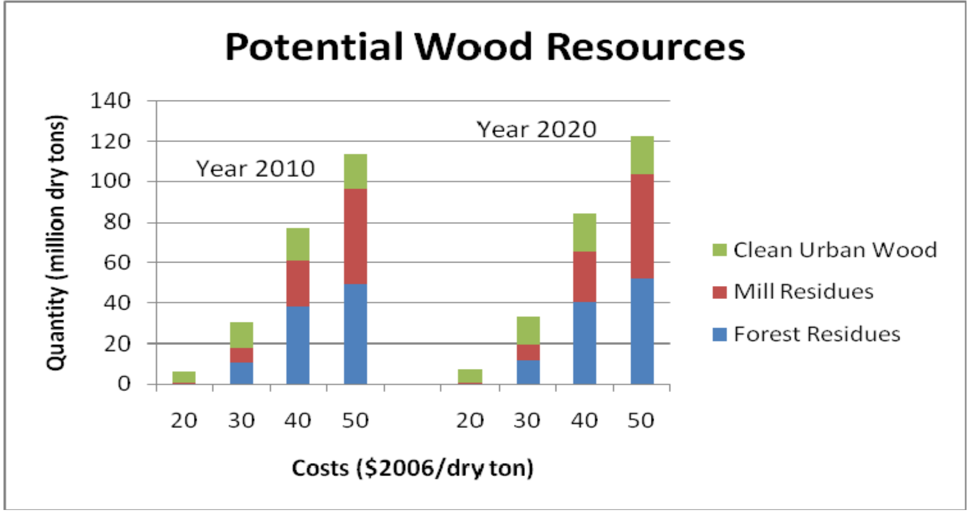


Figure 12. Total herbaceous supplies, select prices, 2010 and 2020

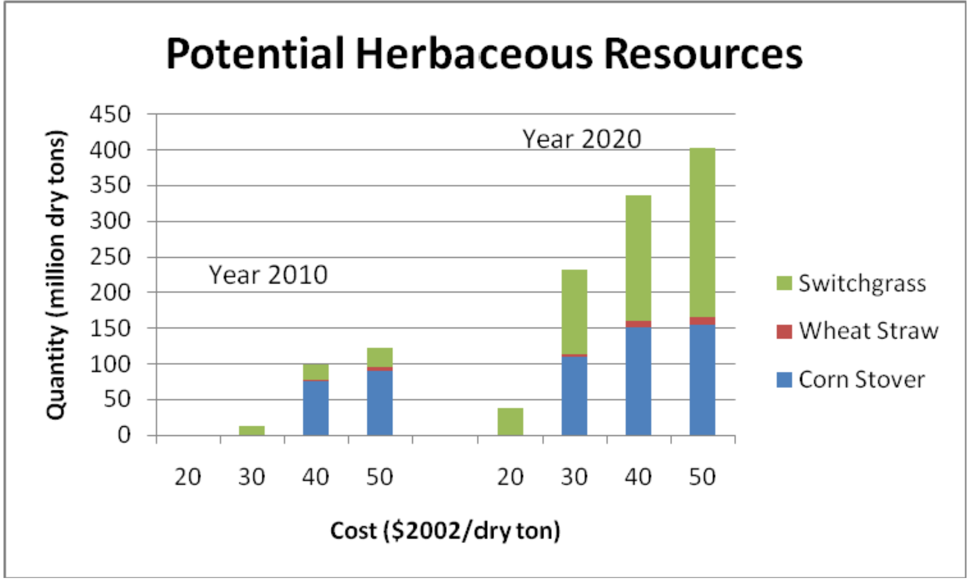
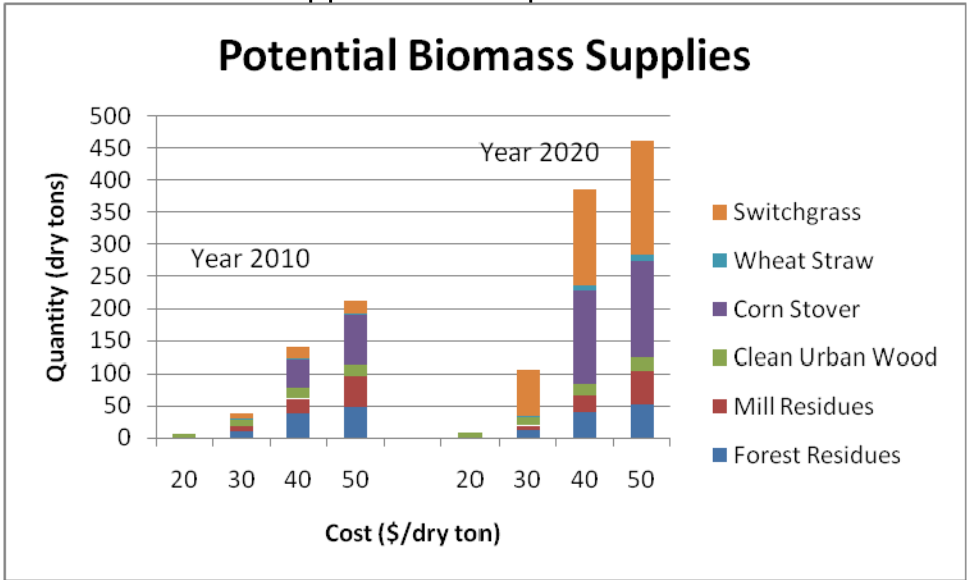


Figure 13 presents the combined wood and herbaceous supplies. Due to the fact that the wood resources are in $2006 and the herbaceous resources are in $2002, the herbaceous costs were adjusted to $2006 using the Consumer Price Index. This adjustment had the affect of shifting the herbaceous supplies by about $5.00/dt so that quantities available at $30/dt in $2002 are now available at $35/dt in $2006. The adjusted quantities are presented in table 18.

Figure 13. Total biomass supplies, select prices, 2010 and 2020



*herbaceous feedstock quantities and prices adjusted from $2002 to $2006 to permit adding of all feedstocks

Table 18. Total biomass supplies, select prices, 2010 and 2020

	Biomass Quantities (million dry tons)--2010					
	$20/dt	$30/dt	$40/dt	$50/dt	$75/dt	$100/dt
Forest Residues	0.01	10.76	38.08	49.17	56.69	60.04
Mill Residues	0.55	7.23	22.97	47.66	56.52	57.58
Urban Wastes	5.92	12.14	16.45	17.36	19.91	20.06
Corn Stover	0.00	0.00	44.47	76.11	101.82	104.70
Wheat Straw	0.00	0.16	0.87	1.60	5.61	6.00
Switchgrass	0.00	7.62	17.33	20.50	33.52	34.35
Total	6.48	37.93	140.16	212.40	274.08	282.72
	Biomass Quantities (million dry tons)--2020					
	$20/dt	$30/dt	$40/dt	$50/dt	$75/dt	$100/dt
Forest Residues	0.01	11.80	40.57	52.04	59.84	63.31
Mill Residues	0.57	7.70	24.93	51.65	61.12	62.17
Urban Wastes	6.59	13.62	18.42	19.46	22.07	22.23
Corn Stover	0.00	0.43	143.98	151.80	156.44	153.48
Wheat Straw	0.00	0.57	7.32	9.95	11.12	11.28
Switchgrass	000	72.29	150.57	176.83	285.88	324.83
Total	7.17	106.42	385.79	461.74	596.47	637.30

*Corn stover, wheat straw, and switchgrass prices and quantities adjusted from $2002 to $2006.

VII. Limitations and Interpretation of the Analysis

The analysis suffers from a number of methodology and data limitations. Specifically, in a number of cases (i.e., urban wood wastes, mill residues) the models used are very simple, use a static rather than dynamic framework, and use a one-size-fits-all approach. The analysis would benefit from a more sophisticated approach. The economic model used to estimate forest residue costs is dated and also needs to be replaced. Future projections and distribution of residues often lock in an historical distribution which may not hold in the future.

The data, in many cases is either non-existent or of poor quality. This is especially true of the urban wood waste data. Data is often 10-15 years old, and only available at a national level or is site-specific data. A number of simplifying assumptions were necessary.

The estimated costs represent break-even costs and should not be interpreted as the price that must be paid for resources, but rather viewed as a minimum starting price. Specifically, no transportation costs are included and no explicit return to the feedstock supplier is included. Estimated quantities are upper bound (maximum) quantities. Thus the actual quantities that could be supplied will be lower than estimated and the price higher.

Acknowledgements: Thanks to Daniel de la Torre Ugarte and Richard Nelson for their analysis and to the many others who contributed in various ways including Burt English, Robert Perlack, Anthony Turhollow, Robin Graham, Sandy McLaughlin, Jerry Tuskan, Denny Becker, Stephen Slinsky, Jamey Menard, Chad Hellwinckel, and Hosein Shapouri.

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APPENDIX

Table 1. Projected and extrapolated timber harvest by geographic region, select years

	Softwood Harvests (billion ft^3)							
	1996	**2002**	**Roundwood Removals 2007**	**Projected 2010**	**Extrapolated 2015**	**Projected 2020**	**Extrapolated 2025**	**Projected 2030**
Northeast	0.62	0.58	0.445	0.58	0.55	0.53	0.52	0.51
North Central	0.33	0.26	0.276	0.28	0.29	0.30	0.30	0.30
Southeast	2.63	2.92	2.703	2.67	2.92	3.17	3.29	3.41
South Central	3.48	3.69	3.339	3.21	3.425	3.64	3.82	4.00
North Rocky Mountains	0.57	0.50	0.462	0.44	0.435	0.43	0.435	0.44
South Rocky Mountains	0.28	0.10	0.152	0.25	0.265	0.28	0.30	0.32
West Pacific Northwest	1.73	1.55	1.564	1.65	1.615	1.58	1.575	1.57
East Pacific Northwest	0.39	0.20	0.319	0.24	0.25	0.26	0.275	0.29
Pacific Southwest	0.66	0.72	0.580	0.46	0.465	0.47	0.47	0.47
	Hardwood Harvests (billion ft^3)							
	1996	**2002**	**Roundwood Removals 2007**	**Projected 2010**	**Extrapolated 2015**	**Projected 2020**	**Extrapolated 2025**	**Projected 2030**
Northeast	1.42	1.29	1.013	1.51	1.53	1.55	1.57	1.59
North Central	1.62	1.42	1.354	1.43	1.45	1.47	1.49	1.51
Southeast	1.46	1.19	1.012	1.55	1.59	1.63	1.665	1.7
South Central	2.45	1.84	1.50	2.28	2.36	2.44	2.51	2.58
West	0.55	0.25	0.186	0.63	0.625	0.62	0.62	0.62

Historical and projected harvest quantities from Haynes, 2007, Table 10: Timber harvests from forest land in the contiguous States, by region, Specified Years, 1952-2002 with projections through 2050, page 66. Extrapolated quantities made by Walsh. Northeast includes CT, DE, MA, MD, ME, NH, NJ, NY, PA, RI, VT, and WV; North Central includes IA, IL, IN, KS, MI, MN, MO, NE, ND, OH, and WI; Southeast includes FL, GA, NC, SC, and VA; South Central includes AL, AR, KY, LA, MS, OK, TN, and TX; North Rocky Mountains includes ID and MT; South Rocky Mountains includes AZ, CO, NM, NV, SD, UT, and WY; West Pacific Northwest includes western OR and WA; East Pacific Northwest includes eastern OR and WA; Pacific Southwest includes CA; West includes the North and South Rocky Mountains, the East and West Pacific Northwest, and the Pacific Southwest Regions.

Table 2. Regional logging residue multipliers, softwood and hardwood, by year.

	Softwood Multipliers				
	2010	**2015**	**2020**	**2025**	**2030**
Northeast	1.3034	1.2472	1.1910	1.1685	1.1461
North Central	1.0145	1.0507	1.0870	1.0870	1.0870
Southeast	0.9878	1.0803	1.1728	1.2172	1.2616
South Central	0.9614	1.0258	1.0901	1.1441	1.1980
North Rocky Mountains	0.9524	0.9416	0.9307	0.9416	0.9524
South Rocky Mountains	1.6447	1.7434	1.8421	1.9737	2.1053
West Pacific Northwest	1.0550	1.0326	1.0102	1.0070	1.0038
East Pacific Northwest	0.7524	0.7837	0.8150	0.8621	0.9091
Pacific Southwest	0.7931	0.8017	0.8103	0.8103	0.8103
	Hardwood Multipliers				
	2010	**2015**	**2020**	**2025**	**2030**
Northeast	1.4905	1.5102	1.53	1.5497	1.5694
North Central	1.056	1.0707	1.0855	1.1003	1.1150
Southeast	1.5321	1.5716	1.6111	1.6457	1.6803
South Central	1.5201	1.5734	1.16268	1.6734	1.7201
West	3.3835	3.3566	3.3298	3.3298	3.3280

Northeast includes CT, DE, MA, MD, ME, NH, NJ, NY, PA, RI, VT, and WV; North Central includes IA, IL, IN, KS, MI, MN, MO, NE, ND, OH, and WI; Southeast includes FL, GA, NC, SC, and VA; South Central includes AL, AR, KY, LA, MS, OK, TN, and TX; North Rocky Mountains includes ID and MT; South Rocky Mountains includes AZ, CO, NM, NV, SD, UT, and WY; West Pacific Northwest includes western OR and WA; East Pacific Northwest includes eastern OR and WA; Pacific Southwest includes CA; West includes the North and South Rocky Mountains, the East and West Pacific Northwest, and the Pacific Southwest Regions.

Table 3. Distribution of new single family construction housing size by square foot of floor space (percent of total units)

	Percent of New Single Family Construction by Size					
	<1200 ft^2	1200 to 1599 ft^2	1600 to 1999 ft^2	2000 to 2399 ft^2	2400 to 2999 ft^2	>3000 ft^2
Northeast	6.7	12.5	18.3	18.3	21.7	22.5
Midwest	6.7	20.1	24.6	18.3	14.2	16.0
South	6.3	18.0	21.9	18.7	16.6	18.5
West	5.9	18.9	23.8	17.1	17.1	17.1

National Association of Home Builders, Square Foot of Floor Area in New One-Family Houses Completed, www.nahb.org.

Table 4. Distribution of new multi-family construction housing size by square foot of floor space (percent of total units)

	Percent of New Multi-Family Construction by Size				
	<600 ft^2	600 to 799 ft^2	800 to 999 ft^2	1000 to 1199 ft^2	>1200 ft^2
Northeast	3.8	11.5	23.1	23.1	38.5
Midwest	0	10.8	36.9	27.7	24.6
South	1.2	7.9	27.4	31.1	32.3
West	3.8	15.4	26.9	29.5	24.4

National Association of Home Builders, Square Foot of Floor Area in New One-Family Houses Completed, www.nahb.org.

Table 5: Extended POLYSYS Baseline Crop Yield Assumptions

	Year 2006	Year 2010	Year 2015	Year 2020	Year 2025	Rate of Change (percent)
Corn (bushel/acre)	147.7	154.9	163.9	173.3	183.3	1.13
Grain Sorghum (bushel/acre)	65.0	66.8	69.0	71.6	74.2	0.76
Oats (bushel/acre)	62.8	64.4	66.4	68.4	70.6	0.61
Barley (bushel/acre)	64.4	66.8	69.8	72.9	76.2	0.88
Wheat (bushel/acre)	42.7	44.3	46.3	48.4	50.5	0.88
Soybeans (bushel/acre)	40.7	42.3	44.3	46.4	48.5	0.93
Cotton (pounds/acre)	760.0	780.0	805.0	830.6	857.1	0.43
Rice (pounds/acre)	6917.0	7184.0	7477.0	7771.0	8076.5	0.79