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Forest-Based Biomass Supply Curves for the United States

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Nationwide, county-level supply curves have been estimated for forest-based biomass to evaluate their potential contributions to producing biofuels. This study builds on the estimates of potential supply in the Billion Ton Supply study prepared by the U.S. Department of Agriculture and the U.S. Department of Energy. Forest biomass sources include logging residue, thinnings, other removals, unused mill residue, urban wood waste, and conventionally sourced wood (pulpwood size material). To make the estimates, we assume that lower cost forest biomass will be supplied from integrated harvesting operations that also remove sawlogs and pulpwood. We also assume that such removals can be estimated at the county level in two ways: first, as a portion of recent estimates of logging residues; and second, by simulated thinning operations that use tops, branches, and small trees for biomass. Supply from thinning dense forest stands is assumed to occur over 30 yr. Harvest and stumpage costs are estimated for each of these methods. Final supply estimates for each county assume supply that is half-way between the two estimates. Forest and agricultural biomass supply estimates have been used to indicate that for a cost of $44 per oven dry ton (odt) at forest roadside or farm gate, we could produce

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produce 20-billion gal of advanced biofuels as called for under the 2007 Energy Independence and Security Act. Forests could provide about 40-million odt to produce 4-billion gal, and agricultural feedstocks could provide about 200-million odt and produce 16-billion gal of biofuel.

KEYWORDS *wood biomass supply, bioenergy, forest inventory, supply curves*

INTRODUCTION

In 2005, researchers from U.S. Department of Agriculture (USDA) and the U.S. Department of Energy (DOE) prepared estimates of potential biomass supply for bioenergy and biobased products from forest and agricultural sources (Perlack et al., 2005). That report suggested a potential supply of 1.3-billion dry tons of biomass per year (one dry ton equals 0.907 dry metric ton). The estimates reported in the present study build on the methods in the *Billion Ton Supply* report and estimate biomass supply amounts and forest roadside costs (supply curves) for each county in the United States. Roadside cost is the price a buyer would pay for wood biomass chips at roadside in the forest or at a mill location in the case of mill residue, prior to any transport to the end-use location. The costs estimated are marginal costs or costs to supply each successively more expensive ton of wood biomass in each county. We assume that buyers would be facing landowners who are aware of the cost for the most expensive units of biomass supply in a county and that there would be enough buyers (competitive market) that landowners would only sell to buyers offering the price for the most expensive unit. Prices paid may be less for a given amount of biomass supply depending on the extent that landowners are not informed about the highest price being offered or are not interested in maximizing profit, or to the extent that there are few buyers to compete for the biomass.

This article provides estimates of potential biomass supply for bioenergy for the United States from selected forest-based sources. In this article, we use the term “biomass” to mean material that may be used for biopower or biofuels production, and exclude—with one exception—wood sources that are currently used to make wood products. The sources include (a) logging residue; (b) thinnings from timberland and other forestland; (c) wood from “other forest removals,” such as land clearing and forest cultural operations; (d) wood and bark residue from primary wood products mills; (e) urban wood waste; and (f) conventionally sourced wood, such as pulpwood-sized roundwood. These sources include kinds and amounts of wood that are not currently used for products such as logging residue and biomass from thinnings. They also include some sources that are already used extensively for products, including mill residue and conventionally sourced wood (pulpwood).

We do not include estimates of pulp liquor from pulp and paper mills that are already using the liquor for production of heat and power, nor do we include estimates of supply from short-rotation woody crops that are being developed separately in conjunction with estimates for other agricultural sources. We expect that woody crops will be grown on agricultural and pastureland, and they are not considered part of the forestland resource base. We also do not include in these initial estimates potential amounts of wood from "other forest" land. "Other forest" includes a large area of pinyon-juniper forest in the West that could provide biomass but currently at a much higher cost than biomass from timberland—a current estimate is over $60 per oven dry ton (odt) at roadside (Western Governors Association, 2008).

The forest-based biomass supply curves that we estimate have been used in combination with estimates of agricultural biomass supply curves to determine the mix and cost of forest and agricultural biomass supply that would be needed to meet cellulosic biofuels production targets for the year 2022 that have been set by the 2007 Energy Independence and Security Act (EISA; Biomass Research and Development Initiative [BRDI], 2008). This article uses inch-pound units of measure. Conversion factors to metric units are as follows:

1 ton = 0.907 metric tonnes
1 inch = 2.54 centimeters
1 cubic foot = 0.0283 cubic meters

METHODS

Because only limited markets currently use forest biomass for biopower and biofuels, empirical data are not as widely available on the amounts of biomass available for different costs as there are for pulpwood or sawlog markets. To make estimates of biomass supply, we generated cost estimates for several types of forest treatment and harvesting operations that can provide biomass. These treatment and harvesting operations must also consider sustainability constraints.

Estimates were developed for several sources by first identifying sustainability principles to guide their use. Specific guidelines are noted for each source discussed. In general terms, sustainability means today's management actions will not degrade the ecological functioning of a natural system (Helms, 1998). One detailed definition from the United Nations Conference on Environment and Development, Rio De Janeiro, 1992, cited by Helms (1998) is, "Sustainable forest management involves practicing a land stewardship ethic that integrates the reforestation, managing, growing, nurturing, and harvesting of trees for useful products, with the conservation of soil, air and water quality, wildlife and fish habitat, and aesthetics" (p. 181).

In the context of biomass removal from forests, the question of sustainability requires consideration of a wide range of issues—including nutrient cycling and soil productivity, maintenance of biodiversity, water quality, and wildlife habitat. These factors, and resulting constraints on forest operations to address these concerns, are generally very site-specific. Soil productivity in certain soil types, for example, may be more sensitive to micro-nutrient levels and thus require retention of some level of woody residue. Wildlife habitat requirements may stipulate retention of snags or maintenance of coarse woody debris. Again, ecological factors including wildlife and endangered species need careful site-specific evaluations in determining biomass availability.

Sustainability is addressed in this analysis through several assumptions. The potential forest biomass supply that is modeled here is a secondary output of other management objectives. We consider biomass that would be available from forest health treatments, fire hazard reduction work, or treatment of activity fuels after logging where questions of sustainability are addressed in the larger management plan. The assessment also assumes ecological considerations, and practical limitations would reduce the amount of biomass available for removal and utilization. The process used models of silvicultural treatments and estimates total available biomass (Shepperd, 2007). The total available biomass is then further reduced to reflect material left on site to meet ecological constraints or is otherwise impractical to remove. We used reductions identical or similar to those in the *Billion Ton Supply* report (Perlack et al., 2005). The reduced amount is the net biomass available for removal.

In this article, we provide detailed methods and county-level supply curves for biomass from (a) integrated harvesting operations that provide biomass as well as pulpwood and sawlogs, (b) other forest removals, and (c) wood and bark from mill residue. For urban wood waste and conventionally sourced wood, we show national supply estimates.

For the first three sources of the six noted above, county-level forest biomass supply curves are estimated for (a) non-federal forestland alone and (b) all forestland. The estimates are for forest biomass supply in the near term—for the next 5–10 yr—and presume a recovery of harvest in the forest sector to levels of production similar to those experienced in 2006–2007.

Integrated Harvesting Operations—Thinnings and/or Logging Residue from Timberland

We assume that a key source of lower cost biomass will be wood and bark taken from harvest sites where sawlogs and pulpwood are also taken in integrated harvesting operations. This removes wood fuels that would otherwise contribute to fire hazard. We assume that integrated harvesting would take the form of removing whole trees to roadside, where tops and branches are removed and chipped for biomass for fuel. Integrated operations would also remove small trees (less than 5 in.) to roadside where they could be chipped.

We envision two separate methods to estimate the amount of biomass that may be provided by integrated harvesting and their roadside costs. After making separate estimates of county-level supply curves using the two methods, we combine them in a single estimate. We combine them by taking an average of the two supply curves (average of the two supply amounts at each supply cost). Essentially, we are assuming that real-world supply will be half-way between the two estimates. For each of the two estimates, we determine roadside costs and stumpage price for successively larger amounts of supply. Roadside costs include the cost to harvest and move wood to roadside and cost of chipping at roadside. These estimates were made using the Fuel Reduction Cost Simulator (FRCS) model (Dykstra, Hartsough, & Stokes, 2009). Stumpage costs (cost per ton for biomass in standing trees) are estimated as an increasing fraction of pulpwood stumpage costs as the amount supplied increases. We use pulpwood stumpage costs for 2007 as noted in Table 1. The first step to estimate county-level supply curves is based on estimates of recent amounts of logging residue that are generated and the second step is based on simulated silvicultural treatments on overstocked timberland that produce biomass, as well as pulpwood and sawlogs.

Logging-Residue-Based Estimates

The first way we estimate biomass supply by county is to take a fraction of estimated logging residue left from recent harvesting operations as estimated in the USDA Forest Service timber product output database for 2007 (USDA Forest Service, 2008). We assume that 65% of logging residue

TABLE 1 Pulpwood Stumpage and Delivered Prices (Dollars per Oven Dry Tons) by Region, 2007

	Delivered price	Stumpage price
Hardwoods		
North	64.0	15.4
South	57.6	13.3
West	—	—
Softwoods		
North	67.2	20.7
South	58.0	15.7
West	80.6	27.6

Sources: Resource Information Systems Inc., 2008; Fuel Reduction Cost Simulator (FRCS) model (Dykstra et al., 2009).

can be moved to roadside from private and public forestland. This is the same removal fraction assumed in the *Billion Ton Supply* report (Perlack et al., 2005). We assume that most of the logging residue is moved to roadside as part of whole trees, and the only additional costs to supply the biomass will be for chipping at roadside and the cost for stumpage. Chipping costs, which vary by region and average about $13/odt, were determined by the FRCS model (Dykstra et al., 2009; Fight, Hartsough, & Noordijk, 2006).

The stumpage cost is assumed to be zero for logging residue biomass from federal land and range from $4/odt to 90% of pulpwood stumpage price for private land and other public land. The stumpage price for logging residue from private land is assumed to increase from $4/odt when the first ton of logging residue is used up to 90% of pulpwood stumpage price (see Table 1) when 100% of available logging residue is used. The 100% level of available logging residue is estimated to be 65% of total logging residue generated as noted above.

Thinning-Simulation-Based Estimates

The second way we estimate biomass supply by county for integrated operations is to simulate uneven-aged thinning operations on all timberland in the United States—as represented by Forest Service forest inventory (FIA) plots on timberland (Smith, Miles, Vissage, & Pugh, 2004)—where stand density index is greater than 30% of maximum stand density index for the given forest type (Shepperd, 2007). This simulates thinnings to reduce fire hazard and to improve forest health on overstocked stand. Uneven-aged thinnings are simulated and estimates are made of the amounts of biomass, poletimber, and sawtimber that are removed. For the West, biomass removals include (a) all wood from trees 1- to 7-in. diameter at breast height (DBH) and (b) tops and branches of trees greater than 7-in. DBH. For the North and South, biomass removals include (a) all wood from trees 1- to 5-in. DBH and (b) tops and branches of trees greater than 5-in. DBH.

We assume that all of the small-tree biomass can be extracted to roadside, but that only 80% of the volume in tops and branches of larger trees will make it to roadside because of breakage.

We assume that the only costs for tops and branches will be for chipping at roadside and the cost for stumpage. We assume that the cost to remove small trees will be the total cost for harvesting and hauling them to roadside as estimated by the FRCS model (which includes a cost for chipping) plus a cost for stumpage. The Biomass Treatment Evaluator (BTE), a SAS program written by Patti Lebow, was used to prepare county-level supply curves by (a) estimating biomass and industrial roundwood removals from thinning treatments on FIA plots on timberland, (b) assigning stumpage costs, and (c) assigning harvest and chipping costs using the FRCS model.

The FRCS estimates the cost of providing biomass at roadside by whichever is the least expensive of three alternative harvesting systems—ground-based, whole-tree harvesting with mechanized felling; ground-based, whole-tree harvesting with manual felling; or cable yarding of whole trees that have been manually felled. Cable yarding is used only when the average ground slope exceeds 40%.

We assume that the simulated amounts of biomass supply will be harvested over a 30-yr period. This is the same period assumed for thinnings estimates provided in the *Billion Ton Supply* report (Perlack et al., 2005).

Stumpage cost is assumed to be zero for biomass from federal land and \$4/odt to 90% of pulpwood stumpage price for private land. The stumpage price for private land is assumed to increase linearly from \$4/odt for the first ton of biomass produced to 90% of pulpwood stumpage price (Table 1) when the simulated removal of sawlogs plus pulpwood for a state reaches the year 2006 level of total sawlog plus pulpwood harvest. This state-level restriction is to assure that the estimated biomass supply from integrated operations can be supported by the recent (Yr 2006) level of sawlog and pulpwood harvest in each state.

Combining the Logging-Residue- and Thinning-Based Estimates

We assume that as demand for biomass for biopower and biofuels increases, there will be a shift *from* integrated harvesting operations of a type and location that produce amounts similar to our logging residue estimates, *toward* integrated operations of the type and location represented by our thinning estimates. For our near-term estimates, we assume that supply (for each county) will be represented by one-half of the logging residue supply estimate and one-half of the thinning supply estimate.

The possible error in our county-level estimates of biomass supply from integrated harvesting could be substantial. Combining estimates from several counties around a point would reduce the error in estimating the supply for that specific location. Sources of error for a county supply amount from integrated harvesting at a given price include model specification error, error in logging residue amounts and fraction available, error in amount estimated based on few FIA plots, error in the future levels of harvest for pulpwood and sawlogs, error in harvest cost estimates, and error in stumpage cost estimates.

We assume—by using logging residue estimates, in part—that within 10 yr or so, harvesting patterns will return to mid-2000 levels and will also shift to locations and treatment types simulated, broadly, by uneven-age thinning treatments. Actual levels and patterns will differ. Logging residue estimates have a possible error because they are based on surveys of harvesting and studies of residue generated. Biomass estimates based on thinning simulation have possible error in that they use a limited number of plots to represent all possible treatments in a county.

One rough indicator of the possible error for thinning-based estimates is the sampling error (67% confidence interval) associated with estimates of total standing forest biomass in a given locality from FIA plot data. For example, we can estimate sampling error for total forest biomass in overstocked stands in selected local areas using FIA data. Within 10 miles of Athens, Georgia, and Bend, Oregon, are FIA plots which estimate 154,000 and 134,000 odt of total forest biomass which could be removed by uneven-aged thinnings from overstocked stands. The sampling error (67% confidence interval) for these estimates is 75 and 90%, respectively (USDA Forest Service, 2009). Our county-level estimates of biomass supply are mostly under 50,000 for $50/odt or less. Combining all sources of error for the thinning estimates, it is plausible the standard error for county-level biomass supply estimates may be 200 or 300% of the estimated value at a given price. If 10 equal county-level thinning estimates are combined, each with a county sampling error of 250%, then the standard error of the total estimate would be 79% (assuming normal distributions for sample estimates). If this estimate were averaged with logging residue estimates (identical to the thinning estimates) from the 10 counties with standard error of 10%, then the combined standard error would be about 40%. The 95% confidence level, versus a 67% confidence level, for the 10-county estimate would be about double the 40% level, or 80%. So, actual biomass supply for multi-county areas could potentially be notably lower or higher than our estimates. The error on the upward side is limited because higher biomass amounts could only be supplied in combination with removal of sawlogs or pulpwood roundwood and the removal of this roundwood is limited by recent demand levels for roundwood. The error on the downward side on a state scale would similarly be limited by the need to obtain sufficient sawlogs and pulpwood to meet recent demand levels. This discussion is given only to suggest a rough order of magnitude for error in the estimates of biomass supply from integrated harvesting operations.

Wood from "Other Forest Removals" Such as Land Clearing and Cultural Operations

Amounts of other forest removals, by county, are obtained from the Timber Products Output (TPO) database for 2007 (USDA Forest Service, 2008). We assume that 50% is available for use (Perlack et al., 2005). We also assume that 34% of the amount available costs $20/odt at roadside and the remainder costs $30/odt at roadside.

Wood and Bark Residue from Primary Wood Products Mills

Amounts of wood and bark residue, by county, are obtained from the TPO database for 2007 (USDA Forest Service, 2008). For our initial supply estimates, we assumed that only unused mill residue was available. We assume that the cost for unused residues was up to $10/odt at mills. To be sure, mill residue currently used for low-value uses, such as mulch, could easily move to bioenergy applications in the range of prices considered here.

Urban Wood Waste

The amount of available urban wood waste is estimated to be about 28 million odt per year out of about 62-million tons generated per year (McKeever, 2004). These estimates for 2002 are assumed to approximate the current level available. But we assumed that only 10% of the amount available can be collected at a realistic cost. Cost at collection points is assumed to be $20 per odt.

Conventionally Sourced Wood (Pulpwood)

Conventional products (pulpwood) could be used for bioenergy and biofuels if priced competitively with other end-use markets. An initial estimate of a minimum amount that could be supplied is the amount by which annual pulpwood harvest has declined over the last decade or so—about 15-million odt. If pulpwood stumpage prices are at least $13–$27 per odt as shown in Table 1, and roadside chipping costs are $13; then even without covering any harvest costs, the cost for pulpwood at roadside would be $26–$40 per odt. So it is plausible that relatively little pulpwood would be supplied for roadside costs for less than $35–$50 per odt. As an initial estimate, we assume pulpwood supply will begin about $40 per odt at roadside and increase from there.

RESULTS AND DISCUSSION

The forest-based biomass supply curves for biomass from non-federal land prepared using the methods above are shown in Figure 1 and were used in combination with estimates of agricultural biomass supply curves to determine the mix and cost of forest and agricultural biomass supply that would be needed to meet cellulosic biofuels production targets under the 2007 Energy Independence and Security Act (EISA; BRDI, 2008). These targets call for production of 21-billion gal of advanced biofuels (including cellulosic biofuels) by 2022. One scenario developed for that report indicates a 20-billion gal target for advanced biofuels could be met by using by producing 4- and 16-billion gal from forest biomass and agricultural biomass, respectively. For about $44 per odt at forest roadside or farm gate, we could make this biofuel from approximately 40- and 200-million odt of forest biomass and agricultural biomass, respectively. To meet restrictions in

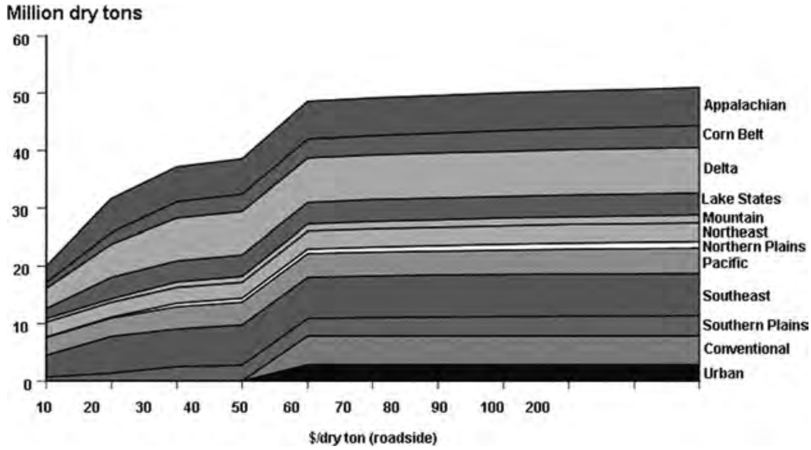

FIGURE 1 Potential biomass supply from forests, mill residue, and urban wood waste by region (color figure available online).

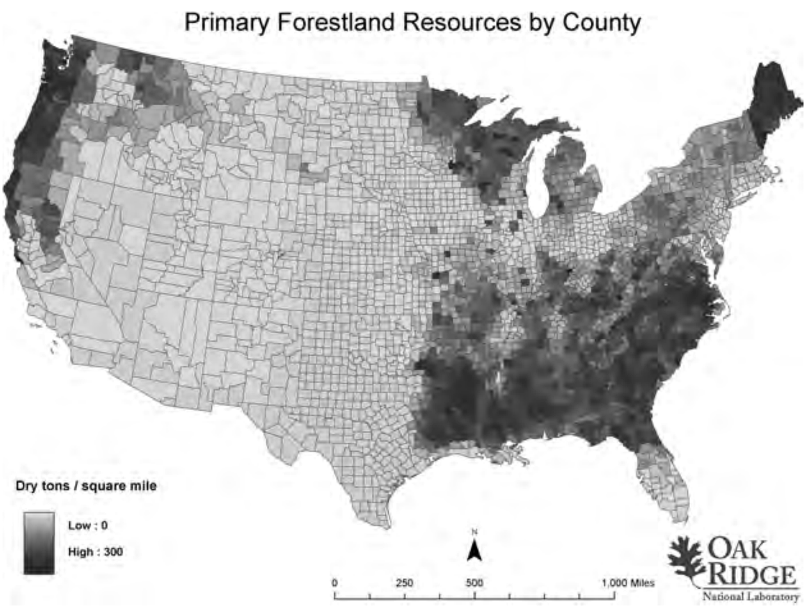

FIGURE 2 Potential biomass supply from forests by county (oven dry tons per square mile per year; color figure available online).

EISA, the approximate 40-million odt of forestland supply excludes biomass from federal lands (Figure 2). The components of this forest-based supply at $44 per odt are shown in Table 2 and total 43.8-million odt. Additional information on the kinds, amounts, and costs of agricultural biomass identified to make 16-billion gal of biofuels are in BRDI (2008).

For this analysis, we have not provided detailed methods to estimate how much wood biomass supply may come from pulpwood size material at

TABLE 2 Estimated Forest-Based Biomass Supply for the United States with Conventional Harvest at 2006 Levels

Source	Forestland resources excluding federally owned land		All forestland resources		Increase when federal forestland is included	
	Estimated supply at $44 per odt[a] at roadside	Extended supply	Estimated supply at $44 per odt at roadside	Extended supply	Estimated supply at $44 per odt at roadside	Extended supply
			Million oven dry tons			
Integrated harvesting						
Logging residue method × 0.5	20.0	20.0	22.0	22.0	2.0	2.0
Thinning simulation method × 0.5	11.2	22.3	13.7	25.3	2.5	3.1
Total integrated harvesting	31.3	42.3	35.7	45.4	4.5	5.1
Other removal residues	8	12	8	12	0.0	0.0
Primary mill residues (unused)	1.3	1.3	1.3	1.3	0.0	0.0
Urban wood residue	3.2	16	3.2	16	0.0	0.0
Conventionally sourced wood	<5–15	15–40[a]	<5–15	15–40[b]	0.0	0.0
Total	43.8–58.8	71.6–111.6	48.2–63.2	74.7–114.7	4.5	5.1

[a]Oven dry tons. [b]The 40-million odt estimate for pulpwood supply is given as an example of possible level of supply if pulpwood prices increase notably. More analysis is needed to determine the pulpwood supply level as prices increase.

$44 per odt. We have conjectured that up to 15-million odt may be provided at prices above $44 per odt. This supply would increase the total forestland biomass supply to nearly 59-million odt. However, the amount of pulpwood supplied could be larger if landowners price the costs for biomass (tops, branches, small trees) at nearer the roadside costs for pulpwood.

If forest supply could include biomass from federally owned forestland, then we estimated that wood biomass supply would be at least 4.5-million odt more (Table 2). The actual amount that would be taken from federal forestland would likely be more than 4.5-million odt given the total federal supply is likely to be somewhat less expensive.

For several components of forestland-based resources, Table 2 indicates how much supply may be increased—within our sustainability constraints—if prices were to increase. For integrated supply using the forest thinning method, we estimate supply could increase to 45.4-million odt per year if roadside prices were at least $100 per odt. This thinning supply is still constrained to provide no more than the 2006 level of pulpwood and sawlog harvest. For urban wood waste, we conjecture supply at the source may increase from 10% of production (3.2-million odt) to 50% of production, 16-million odt. For conventionally sourced wood (pulpwood), we estimated supply would at least increase by 15-million odt, an amount that would return production to its peak level in 1998.

It is important to note that the forest-based biomass supply estimated here is in addition to amounts already supplied for residential wood burning and for electric power production. It is also important to note that, given the assumptions and methods used in this article, if wood biomass demand were to reach 40-million odt for biofuels production and demand for wood biomass for electric power production were to increase, then these additional demands would increase use of pulpwood-sized wood for biopower and biofuels. As stumpage prices being offered to use pulpwood for energy increase above recent levels (Table 1), total harvest would increase above recent levels of about 75-million odt per year (USDA Forest Service, 2008). With higher prices, the increment above 75-million odt would go for bioenergy and some of the amount below 75-million odt would shift from pulp and composites use to bioenergy use. As an illustration, if total use increases from 75- to 100-million odt and there is a shift of 15-million odt from pulp and composite use to bioenergy use, then total pulpwood use for bioenergy may be 40-million odt. More analysis is needed to evaluate how much pulpwood would be supplied at pulpwood stumpage price increases.

The amounts of biomass supply estimated here at $44 per odt are notably less than the maximum potential levels identified in the Billion Ton Supply (BTS) study. We estimate 35.7-million odt available from integrated harvesting, compared with 81-million odt in BTS. We estimate 8-million odt from other removals, compared with 9-million odt in BTS. We estimate no supply from other forestland at $44 per odt, compared with 11-million odt in

BTS. We estimate 1.3-million odt from mill residue, compared with 8-million odt in BTS. We estimate 3.2-million odt from urban wood waste, compared with 28-million odt in BTS.

Supply of forest-based biomass from the sources and amounts is indicated in Table 2; both the amounts provided at $44 per odt and the extended amounts would not notably alter the degree to which annual forest growth exceeds removals in the United States. This is partly because of the common way forest growth and removals are measured. The common measurement is annual growth of growing stock; the growth in main stem of trees above 5 in. in diameter. Removals of growing stock—removals from the stock of standing trees—in 2006 were about 233-million odt (15.5-billion ft^3). The removals include amounts left on harvest sites as logging residue. In comparison, net growth was 401-million odt (26.7-billion ft^3; Smith, Miles, Perry, & Pugh, 2009). The amounts of supply noted in Table 2 would not increase removals of growing stock with the exception of conventionally sourced wood. This is because they come from non-growing stock parts of trees or from growing stock parts of trees that would previously have been left on harvest sites and would already be counted as part of the growing stock removals.

To provide a complete set of forest-based biomass estimates detailed county-level estimates are still needed for biomass from pulpwood-sized roundwood and from mill residue that are currently used for fiber products (pulp and panels). Pulpwood supply for pulp and composite panel production was 74-million odt in 2006. Estimated mill residue used for fiber products was 35-million odt in 2006. As biomass price exceeds pulpwood price in a county, pulpwood going to bioenergy would include an amount from expanded harvesting and amounts of pulpwood and mill residue shifted from pulp and composite users to bioenergy users.

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