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Potential for Coal Power Plants to Co-Fire with Woody Biomass in the U.S. North, 2010–2030

A Technical Document Supporting the Northern Forest Futures Project

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Abstract

Future use of woody biomass to produce electric power in the U.S. North can have an important influence on timber production, carbon storage in forests, and net carbon emissions from producing electric power. The Northern Forest Futures Project (NFFP) has provided regional- and state-level projections of standing forest biomass, land-use change, and timber harvest, which all influence forest contributions to global carbon cycles. This study supports the NFFP study of global carbon cycles by estimating potential local woody biomass supply under alternate procurement regimes and associated delivered costs to coal power plants for co-firing for 2010 and 2030. We estimated supply and delivered costs for 2010 and 2030 with concentric supply circles around individual power plant locations by using county-level estimates of woody biomass availability, harvesting and haul costs, and two different procurement regimes—one to remove logging residue and one to obtain woody biomass from forest thinning. Results of this analysis indicate that an average power plant in the U.S. North with the appropriate feedstock feeding technology has the potential to replace up to 10% of coal electricity generation with woody biomass, accounting for feedstock competition from adjacent power plants. We did not find that there would be a significant increase or decrease in wood co-firing potential between 2010 and 2030.

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Keywords: renewable energy, electricity generation, feedstock, supply radius, future scenarios

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The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

Contents

Conversion table

English unit	Conversion factor	SI unit
acre	4.0469	square meter (m^2)
mile	1.6093	kilometer (km)
inch (in.)	25.4	millimeter (mm)

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1. Introduction

The Northern Forest Futures Project (NFFP) is a joint venture between the USDA Forest Service Northern Research Station, the USDA Forest Products Laboratory, and several regional- and state-level stakeholders intended to indicate how current trends and choices can change forests and forest uses in the 20 states of the northeastern quadrant of the United States. As such, the NFFP focuses on future changes in factors such as tree and forest health, water and soil conservation, carbon sequestration, forest products, land-use change, and forest fragmentation, among others. To anticipate these forest changes, NFFP has focused on assessing potential impacts of several drivers of forest change including population, economy, public policy, invasive species, energy production/consumption, climate change, forest growth, and species succession. Because of future uncertainty for several of these drivers, NFFP made projections for several alternative future scenarios that are driven by alternate values of external drivers. NFFP has provided information about estimated future conditions under seven broad criteria categories for the conservation and sustainable management of temperate and boreal forests as identified by the Montréal Process Working Group (2013). One criterion is “maintenance of forest contribution to global carbon cycles” (FS, In press) chapter 7; Montréal Process Working Group (2013). The three indicators for this criterion are (1) total forest ecosystem biomass and carbon pool, (2) contribution of forest ecosystems to the total global carbon budget, including absorption and release of carbon, and (3) contribution of forest products to the global carbon budget.

Estimating future potential for woody biomass bioenergy generation is one indicator of the potential to reduce overall release of carbon by using woody biomass and associated forest carbon recovery in place of coal carbon emissions. The most recent NFFP report, *Future Forests of the Northern United States*, provides regional- and state-level projections for forest biomass use for energy but does not indicate local feedstock supply potential for individual power plants (FS 2012b). This report provides methods and findings for an analysis of current and future potential to co-fire woody biomass with coal to produce electric power.

Co-firing with woody biomass is one of the most common forms of renewable energy generation in the United States, building on the widespread use of biomass combustion to provide heat and power in the forest sector. Wood and wood waste currently account for about 53% of non-hydroelectric renewable electricity consumption in the United States (EIA 2012). Renewable energy markets are beginning to provide incentives for removal of logging by-products (logging residue), small-diameter trees, and other non-timber woody material during silvicultural treatments such as sawlog harvesting, precommercial thinning, hazardous fuel reduction, and forestland restoration. Forest biomass from logging by-products and thinning operations accounts for the largest share of biomass feedstocks used by U.S. power plants that are co-firing or have co-fired with biomass in the past (Goerndt et al. 2013b).

A number of studies have estimated woody biomass resource supply to help determine feasibility of renewable energy from biomass (DOE 2011). Others have estimated local biomass availability and costs for individual power plants co-firing with biomass (Goerndt et al. 2012; Nicholls et al. 2006; Goerndt et al. 2013a). Goerndt et al. (2013a) estimated the supply potential and costs of harvesting, processing, and transporting woody biomass and unused mill by-products for co-firing in selected coal-fired power plants in the U.S. North. But that study did not include the effect of changes in woody biomass availability and costs over time resulting from changes in forest management, tree species composition, and operational costs of woody biomass procurement.

This study builds on methods used by Aguilar et al. (2012) and Goerndt et al. (2013a) to project woody biomass

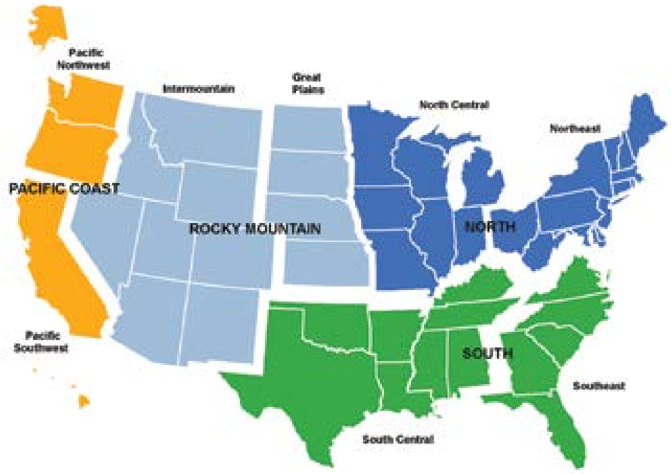

Figure 1. Delineation of major U.S. regions, with region of interest (North) in dark blue.

supply and costs. We estimate costs for obtaining biomass at two points in time from three sources in the U.S. North: biomass from two forest harvesting and procurement regimes and biomass in the form of unused wood residue from wood products mills. Costs for biomass from forest thinning include costs for stumpage, harvest, chipping, and hauling. Costs for biomass from mills include the price at the mill and hauling cost. For each coal-fired power plant considered, we defined woody biomass procurement areas, maximum transport distances, and for those areas we estimated delivered fuel costs for two different forest procurement regimes including (1) removal of logging by-products (slash) from traditional harvest operations and (2) removal, in integrated operations, of logging by-products and small-diameter trees for bioenergy use as well as sawtimber trees for solidwood product production. For each coal-fired power plant and procurement regime, biomass supply potential and delivered costs were estimated for a sequence of land areas defined by successively larger concentric circles around each power plant. Note that this study does not directly address competing resources such as natural gas, which has experienced an increase in use in recent years caused by low prices. Results of this analysis were directly compared to the 2010 estimates of supply potential and costs for power plants based on the two procurement regimes (Goerndt et al. 2013a; Wear et al. 2013).

2. Conceptual Background and Study Area

The study area includes 20 states: Connecticut, Delaware, Illinois, Indiana, Iowa, Maine, Maryland, Massachusetts, Michigan, Minnesota, Missouri, New Hampshire, New Jersey, New York, Ohio, Pennsylvania, Rhode Island, Vermont, West Virginia, and Wisconsin. This region, as shown in Figure 1, is hereafter referred to as the U.S. North.

The U.S. North has states located in five of the electricity supply subregions as defined by the EIA including West North Central, East North Central, Middle Atlantic, New England, and South Atlantic (Fig. 2). There are several important reasons for focusing on this region. Biomass was identified as a major potential source of renewable energy in the region (EPA 2012; Aguilar and Garrett 2009). This region also hosts a large concentration of coal power plants (EPA 2012). Figure 2 shows EIA sub-regions and locations of coal-fired power plants and co-firing status in 2007 for the U.S. North (EPA 2012).

2.1 Econometric Analysis

Aguilar et al. (2012) developed econometric models to estimate the current probability of co-firing coal and biomass at the county level in the U.S. North using drivers (variables) such as electricity demand, technical feasibility, coal price, availability of wood mill by-products, state renewable portfolio standards (RPS), and transportation infrastructure. We estimated the probability of co-firing at the county level in 2030 by applying the model from Aguilar et al. (2012) to projected values for drivers. For a description of variables used to estimate county-level probability of co-firing and which variables were projected to 2030, see Appendix Table A1.

Econometric models were used to estimate which counties in the U.S. North have a high probability of co-firing in 2010 and how much the probability may change by 2030. The econometric analysis was used to provide a “coarse screen” to identify counties well suited to host co-firing facilities. Specifically, local woody biomass resource availability and costs were estimated for counties that were in the top 25% in estimated probability of co-firing in 2010.

2.2 Description of Future Scenarios

Woody biomass availability in 2030 will be influenced by drivers of forest growth and wood harvest. These drivers include future population change, land use change, greenhouse gas emissions, and climate change. We used projections of forest growth and harvest from the USDA Resources Planning Act (RPA) assessment (FS 2012a; FS 2012b; Wear et al. 2013). The RPA projections used scenarios that were defined by a socioeconomic storyline, and use of a particular global circulation model (GCM) to project changes in temperature and precipitation worldwide. A GCM models the operation of the global climate system over time based on physical, chemical, and biological processes and can project future changes in patterns of temperature and precipitation by geographic region under varying scenarios for greenhouse gas emissions. Each storyline is comprised of a set of assumptions about future population change, economic activity, land use, quantity of wood used for energy, and greenhouse gas emissions. The RPA assessment (and this study) used three of the storylines described by the

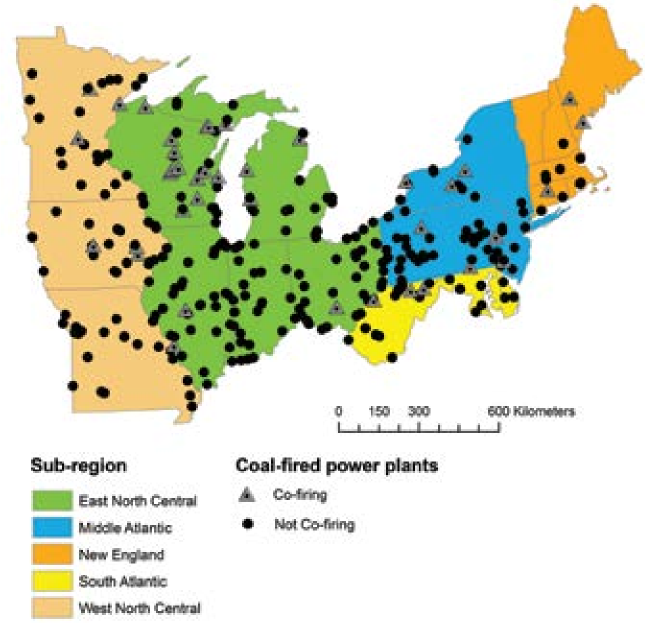

Figure 2. U.S. Energy Information Administration sub-regions and 2007 location and co-firing status for coal-fired power plants in the U.S. North.

Intergovernmental Panel on Climate Change (IPCC) (Nakicenovic et al. 2000; IPCC 2014; Solomon et al. 2007).

- Storyline A1—a future where the rest of the world approaches the U.S. per capita wealth, technology use, and population growth. It is characterized by rapid economic growth and increasing global trade. Global population peaks in mid-century and then declines. It assumes balanced use of fossil and renewable fuels with initial dependence on fossil fuel but a relatively rapid increase in renewable energy sources. A variation of storyline A1, storyline A1B, predicts a balanced use of fossil and renewable fuels, with an early dependence on fossil fuel followed by a relatively rapid increase in renewable energy sources.
- Storyline A2—a future where the world is not converging on the U.S. experience, but rather is much more regionally focused. It assumes a continuously increasing global population and more regionally centered economic growth. Among these storylines, it has the highest total global population growth but the lowest long-term economic growth.
- Storyline B2—a future of global sustainable development, with some regional economic convergence. The B2 storyline is similar to A2, in that regional and local institutions as well as economies are emphasized over global integration. Economic growth is intermediate, but population growth is significantly lower than for the other two scenarios. Thus, per capita income for scenario B2 is closer to A2 than to A1. Scenario B2 also has the lowest projected growth in biomass energy for the global region that encompasses the United States.

For the remainder of this paper, we use forest growth outcomes projected by using these three storylines where each is paired with a single GCM. These scenarios include the effects of climate change and land-use change on forest area and forest growth. However, future timber harvest was projected based on an assumed continuation of recent harvest levels (FS, In press). The scenarios are labeled A1B-C, A2-C, and B2-C as used for the NFFP. These scenarios include the effects of climate change on forest growth and composition and include projected land-use change, but they also project future harvesting rates, based on the recent past probability of harvesting. Thus, they use a continuation of recent harvest rates as a baseline for projections of harvest rates into the future. Full details of storylines and GCM are provided in Appendix Tables A2 and A3.

3. Empirical Methods

This study uses empirical methods (1) to identify counties with high potential of co-firing both now and in the future based on the econometric analysis, (2) to estimate woody biomass resource availability and costs for the selected counties in 2010 and in 2030 under three alternate scenarios. All biomass quantities and costs per ton are for oven-dry tons of wood. The methods section is organized as follows: (3.1) econometric analysis, (3.2) available woody biomass, (3.3) biomass cost assumptions, (3.4) woody biomass availability for procurement areas, (3.5) delivered costs, and (3.6) power plants well suited to co-fire with woody biomass.

3.1 Econometric Analysis

Not all econometric drivers of co-firing used in Aguilar et al. (2012) were projected to 2030 for this analysis. For example, the presence of roadways, railways, and waterways was considered fixed between 2012 and 2030. Also, state-level renewable portfolio standards were considered constant at 2001 levels for 2010 and 2030 because of this variable's representation of state-level desire to increase bioenergy generation (as of 2010, only one state in the Northern United States has not adopted a RPS). Median house value will most likely change between 2010 and 2030, but we did not find regional projection data for this variable. Likewise, it is possible, though unlikely, that some states currently producing coal would stop producing coal by 2030, but there are no reliable sources to project this possibility between now and 2030. Variables projected to 2030 include percentage of urban area (by county) (U.S. Census Bureau 2013), average electricity price (national level), and average coal price (national level) (EIA 2012). Total annual wood mill by-products were projected at the state level by increasing 2010 levels by the percentage change in growing stock removals between 2010 and 2030 by state under scenario A2-C (Fig. 3) (FS 2012a; Wear 2011).

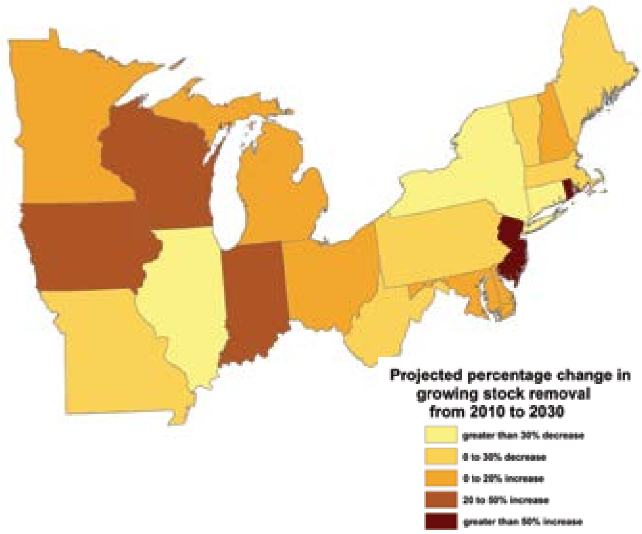

Figure 3. Percentage change in annual growing stock removals from 2010 to 2030 based on scenario A2-C.

There is a notable difference among states in the U.S. North in projected growing stock removals by 2030. This is due in part to harvest associated with land-use change. Removals increase in states such as Rhode Island and Connecticut where there is a projected 4% to 5% loss (harvest) of forestland from urbanization by 2030 (FS, In press). Conversely, there is an increase in removals in states such as Iowa, Wisconsin, and Indiana where there is a projected increase in forestland greater than 100 years old and a lower projected loss of forestland to urban expansion.

3.2 Availability of Woody Biomass

For 2010, estimation of biomass availability for all procurement regimes was based on county-level Timber Products Output (TPO) database and timber inventory and harvest (FIA) data reported by the USDA Forest Service (USDA 2012; Woundenberg et al. 2010; Miles 2012). Estimates based on FIA data were limited to timberland to avoid including biomass from protected forest lands or sites otherwise unavailable for biomass utilization. Timberland is defined as forestland that is producing or is capable of industrial wood production and not withdrawn from timber utilization by statute or administrative regulation (Smith et al. 2009). All woody biomass projections for 2030 were based on projections of timber inventory and harvest for scenarios A1B-C, A2-C, and B2-C (FS 2012a; Wear 2011). The following subsections describe methods used to estimate county-level woody biomass availability by procurement regime for 2010 and for 2030 by projection scenario.

3.2.1 Conventional Logging By-Products (Slash)

2010 Estimates**—**County-level estimates of logging by-products supply associated with current commercial harvests were obtained from the USDA Forest Service Timber Product Output (TPO) database (USDA 2012). We assumed that logging by-products would be removed during the harvest operations used to remove commercial roundwood and be chipped on site prior to transport (DOE 2011).

Projections**—**Logging by-products were projected to 2030 at the county level, for each scenario by increasing the 2010 amounts by the corresponding state-level percentage increase in growing stock harvest removals between 2010 and 2030 estimated by scenario from the NFFP database (FS 2012a; Wear 2011). In doing so, we assumed that future logging by-products would hold a constant ratio to total harvest volumes for each scenario.

3.2.2 Integrated Harvest

2010 Estimates**—**Integrated harvest operations remove both conventional solid hardwood products and woody biomass for energy use in a single operation and include chipping of biomass on site (Saunders et al. 2012; Bolding et al. 2009). Integrated harvest provides woody biomass from logging by-products and small-diameter trees that are not going to be used for commercial products. For this analysis, we used two different size class ranges to represent "small trees," <5-in. diameter and <10-in. diameter. Whereas trees <10-in. diameter can be considered non-merchantable throughout most of the U.S. North for sawtimber, pulpwood harvesting often consists of removing trees between 5- and 10-in. diameter. Therefore, the available biomass from small trees resulting from the following methods was adjusted to include only material from trees <5-in. diameter for counties with any output of pulpwood products based on the TPO database (USDA 2012).

To estimate the amount of biomass that could be removed in the form of small trees as part of thinning treatments, we used stand density index (SDI) to guide treatments (Shaw 2006). SDI is used by forest thinning and vegetation simulators such as the U.S. Forest Service fuel treatment evaluator tool and the U.S. Forest Service forest vegetation simulator (Goerndt et al. 2013a). First we estimated a maximum possible SDI value for softwoods, hardwoods, and mixed forests separately. Maximum SDI is defined for a given forest type as the maximum number of trees that can be accommodated on one acre where the quadratic mean diameter of trees is 10 in. (Long 1996; Doruska and Nolan 1999). The maximum SDI for hardwoods, mixed forests, and softwood forests was estimated to be 811, 470, and 496 trees per acre, respectively (Perez-Verdin et al. 2009; Woodall et al. 2005). A thinning treatment was simulated for each county where a forest type in the county (softwoods, hardwoods, mixed) had an estimated SDI greater than 30% of the maximum (full crown closure). We made successive simulated thinnings across all applicable diameter classes until enough trees were removed to leave a forest with an SDI of 30% of the maximum (Goerndt et al. 2012). Thinnings were done in such a way that the number of trees removed in a given size class contributed the same reduction to SDI. The simulations estimated a total amount of timber available by size

Table 1—Operational and transport cost assumptions for woody biomass procurement in the U.S. North in 2010 (Goerndt et al. 2013a)

Costs	Federal		Non-Federal		Mill by-products
	Logging by-products	Small-diameter trees	Logging by-products	Small-diameter trees	
Harvest ($/ton)[a]	5.82	14.55	5.82	14.55	n/a
Transportation					
Fixed ($/ton)[b]	6.80	6.80	6.80	6.80	6.80
Incremental ($/ton/mile)[c]	0.23	0.23	0.23	0.23	0.23
Stumpage value ($/ton) [d]	0	0	6.49	6.49	n/a
Chipping costs ($/ton)[e]	4.99	4.99	4.99	4.99	n/a
Selling ($/ton)[f]	n/a	n/a	n/a	n/a	4.49

[a]Estimate from hardwood and softwood values in the U.S. North (Saunders et al. 2012; DOE 2011).
[b]Fixed cost for operation and loading/unloading of trucks (Perlack et al. 2005; Saunders et al. 2012; Gallagher et al. 2003).
[c]Perlack et al. (2005); Perez-Verdin et al. (2009); DOE (2011).
[d]Estimated as 50% of average of hardwood and softwood pulpwood values in the U.S. North for federal and non-federal land (DOE 2011; Saunders et al. 2012).
[e]Average chipping costs calculated using values from Saunders et al. (2012) and Harrill 2010.
[f]Perez-Verdin et al. (2009).

class in each county based on the <5-in. diameter size class or the <10-in. diameter size class depending upon assumed presence of pulpwood harvesting. We assumed treatments and amount supplied by either applicable diameter class for biomass would be provided over 30 years with each year providing one-thirtieth of the total available supply (Perlack et al. 2005).

Projections—Projections to 2030 were not available for tree data needed to simulate thinnings and the amount of biomass that would be provided from trees <5-in. diameter or trees <10-in. diameter. We projected the biomass available from trees in these diameter classes in 2030 (by scenario) by increasing the county level annual amount estimated for 2010 by the percentage increase, at the state level, in the volume of timber in trees less than 10 in. between 2010 and 2030.

3.2.3 Adjustments for Inaccessibility and Environmental Stability

Because certain areas are physically inaccessible and costs to remove biomass materials are high, not all by-products and small-diameter material can be assumed available for co-firing. Additionally, improper removal of both small-diameter trees and logging by-products can promote soil erosion, as well as reduce productivity of unproductive soils and reduce soil nutrient levels (Sanchez et al. 2003; Scott and Dean 2006). The DOE (2011) stated that the recommended amount of by-products to be retained on site following harvesting varies by state, forest type, and slope, but is in the range of 15% to 40% of total harvest by-products. For this study, we assumed a retention rate of 35% of available biomass for both small logging by-products and biomass from small-diameter trees and to account for inaccessibility and maintenance of ecological functions (Goerndt et al. 2013a).

3.2.4 Mill By-Products (Residues)

2010 Estimates—Although included in the analysis, mill by-products were not considered to be a separate procurement regime for two reasons. First, the availability of unused mill by-products is usually very low compared to forest biomass and is nonexistent in many counties because of either full utilization of residues for other purposes or absence of wood processing mills. Second, aside from a possible selling price at the mill, mill by-products typically do not include many procurement costs in addition to transport costs, unlike logging by-products and small-diameter trees. Therefore, availability of currently unused mill by-products was simply added to the estimated availability of forest biomass for each of the two procurement regimes. County-level estimates of unused mill by-products were obtained from the TPO database (USDA 2012).

Projections—As with logging by-products, estimates of mill by-products were projected to 2030 by increasing the county-level estimate for 2010 by the percentage increase in state level annual growing stock removals for each scenario. County-level estimates of available woody mill by-products were also adjusted using the percentage increase in state level growing stock removals for each scenario.

3.2.5 Biomass Cost Assumptions

Costs for woody biomass procurement were developed for stumpage, woody biomass harvest, field operations (e.g., onsite chipping) and transport. Original cost estimates for 2010 were estimated by Goerndt et al. (2013a) (Table 1). Cost projections for 2030 were made by applying projected increase rates in costs for stumpage, fuel, and labor to the 2010 cost estimates.

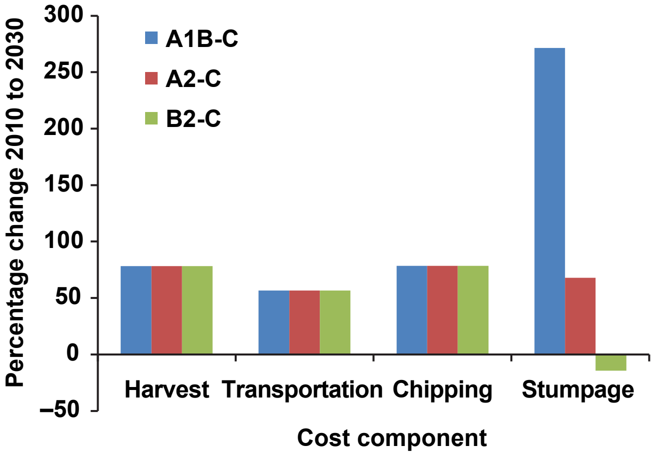

Figure 4. Percentage change in estimated cost components for woody biomass procurement by scenario from 2010 to 2030 (EIA 2013; BLS 2013).

***2010 Estimates*—**Findings by the U.S. Department of Energy (DOE) (2011) suggest that logging by-product stumpage prices can range from about $4 per ton up to 90% of local pulpwood prices depending on the proportion of available logging by-products being harvested. The assumed stumpage values for non-federal land were set to about 50% of the average pulpwood stumpage values for the U.S. North as reported by DOE (2011). Stumpage prices for Federal land were assumed to be zero because biomass removal on Federal land is usually part of a storm or insect salvage operation, or restoration activity (DOE 2011).

Chipping prices can vary depending on whether the biomass is chipped loose or bundled before chipping. Estimates from past studies show chipping costs ranging from $2.50 per ton to as high as $10 per ton (Saunders et al. 2012; Harrill 2010). The assumed value for chipping was calculated as an average between maximum costs for loose material and bundled material to account for both possibilities. Though not yet widely used, slash bundling has shown promise to reduce costs and improve biomass logistics in some situations, particularly biomass storage and handling for base load power. A selling and sorting price only applies to mill by-products and represents costs that can be incurred through separating usable from non-usable material as well as selling prices for unused woody residues directly from mills and is assumed to be in the range of $4 to $6 per ton (Perez-Verdin et al. 2009).

***Projections*—**The components of the original cost assumptions for 2010 were derived from several sources. Therefore, it was necessary to take different steps to project each cost component to 2030. Note that costs were projected in nominal dollars. Figure 4 shows the projected percentage change in cost components for woody biomass from 2010 to 2030.

The biggest challenge with projecting cost assumptions for delivery of woody biomass for co-firing pertained to the generalized nature of the base assumptions in Table 1. The base assumptions were typically derived by estimating midpoints for ranges of regional operational, transport, and stumpage costs for the U.S. North. Therefore, most cost components do not link to one specific data source that may have associated projections. To address this challenge, we identified the percentages of various cost components (in 2010) that are for labor and fuel and used projections of labor and fuel prices. Most cost components include costs of machinery operation, which require fuel and labor for operation. For each cost component that relied on fuel and labor, we assumed that 70% of the cost was labor and 30% was fuel (Saunders et al. 2012). We then used projections of percentage change in fuel costs (EIA 2013) and wages (BLS 2013) to project the cost components. Projected stumpage costs were available for each scenario from Ince et al. (2011) for non-sawtimber (small-diameter trees). Appendix Table A5 shows all 2030 cost estimates.

3.3 Woody Biomass Supply for a Procurement Area

We used ArcGIS to estimate biomass amounts and delivered costs for procurement areas with simulated concentric radii (*R*) from 10 km (6.2 miles) to 100 km (62.1 miles) by 10 km (6.2 mile) intervals around the selected power plant locations. Note that calculation of woody biomass availability within procurement areas was done four times, once for 2010 and for each of the three scenarios for 2030. The estimates for 2030 include changes from 2010 in the power plants selected and changes in county-level woody biomass availability. For larger procurement radii, the total procurement area around most power plants included several entire counties and county fragments. This complexity in spatial information needed to calculate woody biomass availability by procurement radius made it necessary to use fixed procurement radii that could be spatially intersected with county-level data rather than supply areas based directly on local road structure around individual power plants. Estimates were made for the annually available woody biomass for each power plant (*B*) for each procurement regime and procurement area from the county-level estimates as follows (Goerndt et al. 2013a):

$$B = \sum_{i-1}^{m} a_i b_i \qquad (1)$$

where b_i is the total annually available woody biomass for county i, a_i is the percentage of the area of county i that falls within the procurement area (circle), and m is the number of counties residing in the procurement area. Equation (1) assumes that woody biomass within each county is uniformly distributed across the entire county (Goerndt et al. 2013a).

3.4 Delivered Costs

To estimate delivered costs of dry woody biomass for selected procurement areas around selected power plants, we added together the operational costs (stumpage costs, harvest, chipping) and the transportation cost for the maximum transport distance. A portion of transport cost per ton is dependent upon maximum transport distance of woody biomass to the power plant and a portion is fixed. If we assume that biomass being collected is evenly distributed within a given radius of a plant, then the maximum transport distance (*d*) for a ton of biomass is calculated as follows (Huang et al. 2009; Overend 1982; Goerndt et al. 2013a):

$$d = R\tau \quad (2)$$

where R is the procurement radius in miles, and τ is a tortuosity factor representing a ratio of road transport distance to line-of-sight distance and is generally assumed to be 1.2 to 1.5 in the U.S. North (Perez-Verdin et al. 2009; Huang et al. 2009). The tortuosity was adjusted by EIA energy sub-region (Fig. 2) with a value of 1.2 for West North Central, 1.3 for East North Central, 1.4 for Middle Atlantic, and 1.5 for New England and South Atlantic to adjust for winding roads and hilly terrain found in the Northeast United States compared to the Central United States (Goerndt et al. 2013a). For each procurement radius and procurement regime, total delivered cost (C) was estimated as follows:

$$C = (T_v d) + T_f \quad (3)$$

where d is the maximum transport distance for biomass, T_f is operational cost including loading/unloading of trucks, chipping, stumpage and harvest, and T_v is the transport cost per mile.

3.5 Power Plants Suited to Co-Fire with Woody Biomass

The cost of biomass compared to coal is a major factor in a decision to co-fire with biomass, and the majority of power plants already co-firing pay less for biomass (per unit of energy output) than for coal (Goerndt et al. 2013b). Therefore, for this assessment we set a maximum cost for woody biomass feedstocks based on either the 2010 and 2030 average cost (in nominal dollars) of coal used for U.S. power plants as reported (or projected) by the EIA. Conversion of woody biomass to electricity generation was based on a factor of 1.7 MWh per ton as estimated by Goerndt et al. (2012). Maximum potential biomass that could be used for co-firing by a given power plant was estimated as the amount that could be delivered from the procurement area at a delivered price at or below the allowed coal equivalent cost.

4. Results and Discussion

4.1 Spatial Distribution of Woody Biomass

Goerndt et al. (2013a) found that many U.S. North states currently have substantial potential supply of both logging by-products and small-diameter trees. Additionally, Goerndt et al. (2013b) determined that many states with high total available woody biomass do not necessarily have high density (tons per acre) of woody biomass because of a large timberland area. Wide spatial distribution of woody biomass (low density) can be a hindrance to co-firing because of high cost for long transport distances needed to obtain substantial supply for an individual power plant. We estimated changes in density of biomass supply between 2010 and 2030. Figure 5 shows estimated percentage change in woody biomass tons per acre by state from 2010 to 2030 based on scenario A2-C for all procurement regimes. Availability for logging by-products changes more over time and space than biomass availability from integrated harvesting. There are decreases in woody biomass availability per acre in the Northeast and increases in the Midwest. Availability of biomass from small trees and integrated harvest has less variability when compared to logging by-products only. Logging by-products availability varies widely because of wide variation in projected increase in growing stock removals across the region. Increase in woody biomass from small-diameter trees was estimated based on the increase in volume of small trees, which varies less by state between 2010 and 2030 than the increases in growing stock removals. The tendency for logging by-products to fluctuate across the region has an effect on the change in net generation potential from woody biomass between 2010 and 2030 as described in Section 4.3. For details on projected changes in woody biomass spatial density, see Appendix Table A4.

4.2 Potential of Co-Firing and County Selection

Aguilar et al. (2012) found that many of the counties with estimated high potential for biomass and coal co-firing are in the Lakes States, West Virginia, and Pennsylvania. This is not unexpected as these states have either a large amount of available woody biomass, a large number of coal-fired power plants, or both. Of greater importance to this study was the contrast between 2010 and 2030 regarding the spatial distribution of counties with high probability of co-firing. Figure 6 shows the expected probability of co-firing for 2010 and 2030.

There is not a dramatic increase in total co-combustion probability across the region from 2010 to 2030. Because of projected increases in available wood mill by-products in the future, the states that showed increases in the number of counties with high probability of co-combustion were primarily the Lake States (Fig. 5; Aguilar et al. 2012; Goerndt et al. 2013a). There is not a substantial difference in the number of counties with high probability of co-firing from 2010 to 2030. Although increases in population and electricity demand in the eastern states could encourage increased co-firing, projected decreases in timber harvesting and therefore wood mill by-products in many states counteract this effect (Fig. 5). One limitation of this analysis is that it did not adjust for the expectation that a notable number of older coal-fired power plants will be retired in the next

Figure 5. Percentage change in mean woody biomass spatial distribution density (tons/acre) by state from 2010 to 2030 based on scenario A2-C for logging by-products only (A), small-diameter trees only (B), and integrated harvest (C).

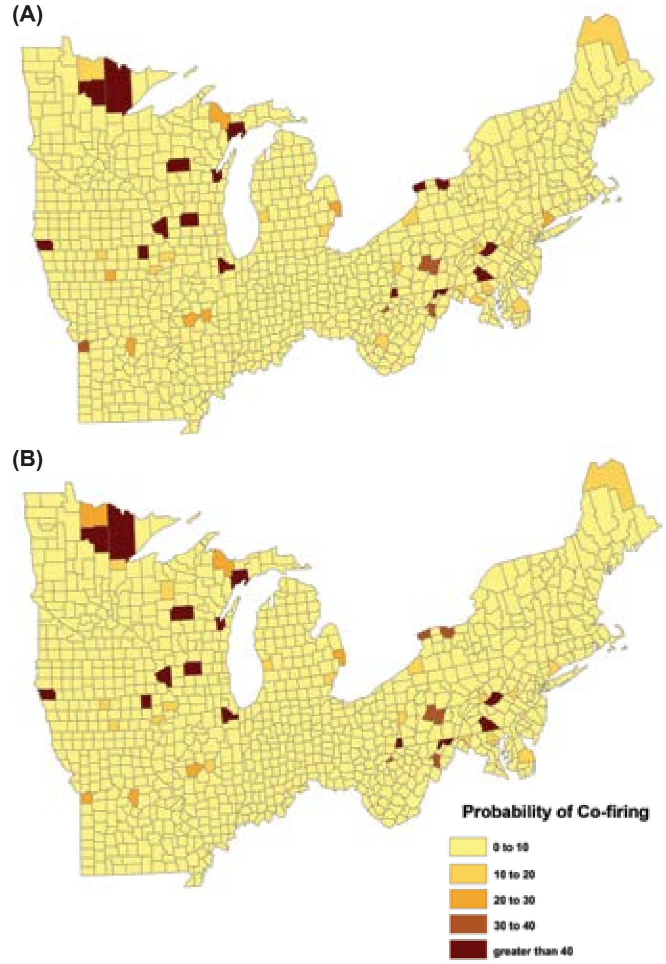

Figure 6. Modeled probability of co-firing wood with coal for electricity production by county for the U.S. North based on the econometric analysis. Maps illustrate differences in the expected probability by county between (A) 2010 and (B) 2030.

decade. The EIA projects that retiring power plants will lead to a 60-gigawatt decrease in coal electricity generation in the United States by 2020 (EIA 2014). Whereas this factor could have an effect on which counties have high potential for co-firing, the econometric analysis included significant variables not directly dependent upon the presence of coal-fired power plants (e.g., road and rail infrastructure, electricity demand, woody biomass availability). Given these factors, combined with technical feasibility, it is likely that the counties identified as having the highest co-firing potential will continue to have operating coal-fired power plants, as well as the infrastructure and biomass supply needed to co-fire. Because of the similarity in county-level co-firing probability between 2010 and 2030, the list of individual power plants used for the projections for 2030 contained 219 plants, which is the same number of plants used in the 2010 analysis with only two plants being different between the two datasets.

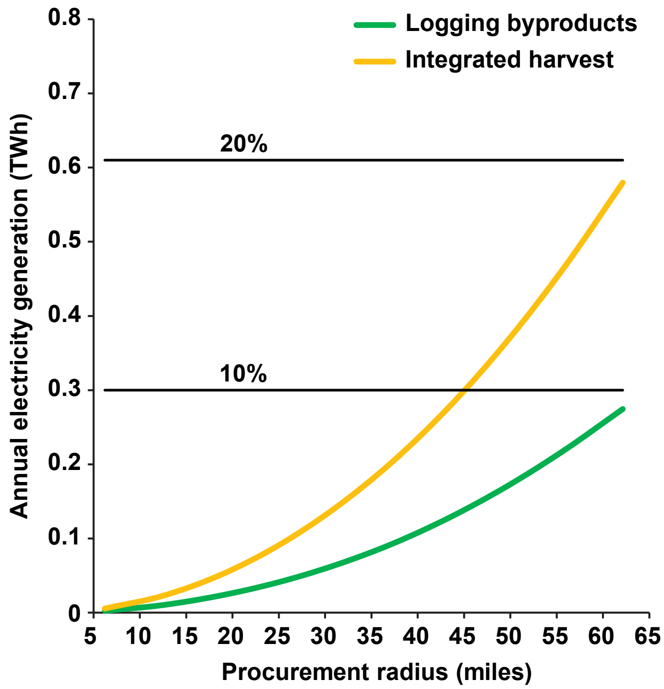

Figure 7. Estimated 2010 mean annual wood power generation for selected power plants by procurement regime and procurement radius. Horizontal lines indicate percentages of coal electricity generation in 2007 from selected power plants.

4.3 Net Electricity Generation Potential

Annual electricity generation from woody biomass was calculated by multiplying the factor of 1.7 MWh per ton times the estimated amount of available woody biomass for each procurement radius (Goerndt et al. 2013a). We compare power generation from wood to the power generation from coal for 2007 (3,007,000 MWh) for all selected power plants and calculated the percentage of possible coal power displacement (EPA 2012). These estimates assume that each plant was co-firing individually without resource competition (overlap) from nearby power plants. The effects of procurement area overlap on wood power potential will be discussed later in the context of counties suited to host co-firing facilities now and in the future. Figure 7 shows the estimated 2010 mean annual electricity generation among selected power plants by procurement regime and transport distance.

Integrated harvest (forest thinning plus logging by-products) could provide wood for a relatively moderate proportion of coal power generation potential (>15% of coal generation at 60 miles). Notice that unlike integrated harvest, logging by-products could not supply enough woody biomass to achieve even a 10% replacement of coal within a 60-mile procurement radius. Figure 8 shows projected mean annual electricity generation for selected power plants in 2030 by scenario and procurement radius.

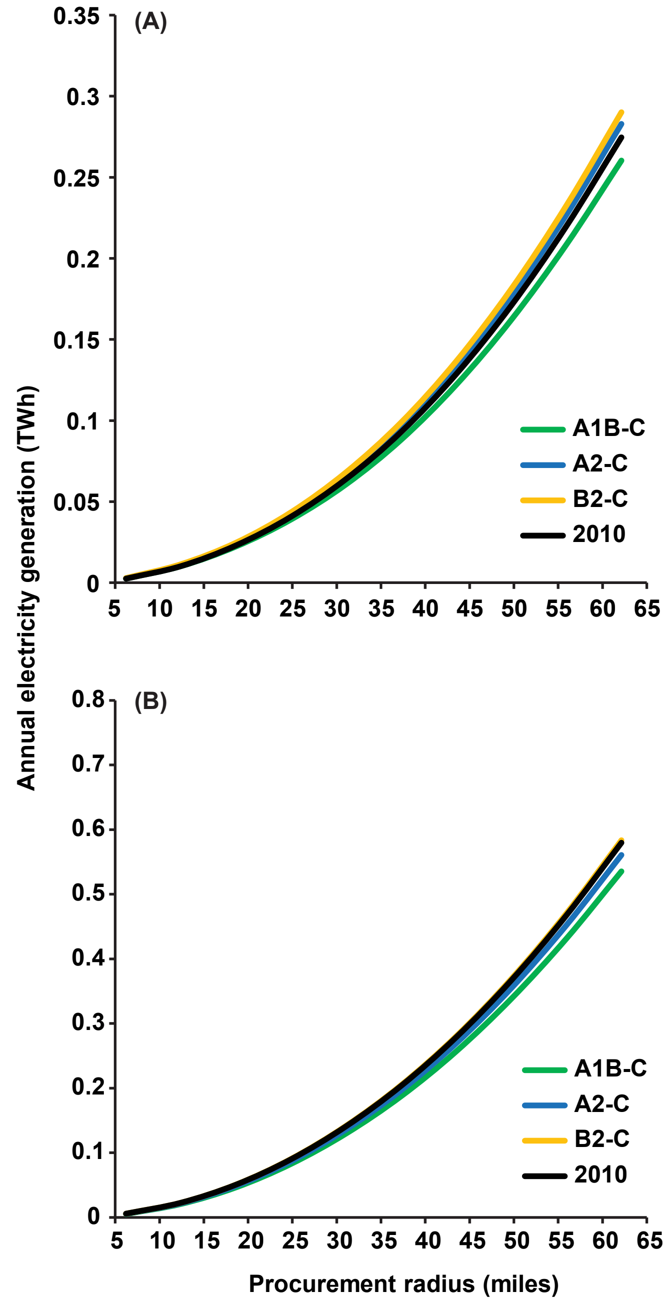

Figure 8. Projected mean annual electricity generation (TWh) from woody biomass for selected power plants in 2030 by scenario and procurement radius for logging by-products (A), and integrated harvest (B).

For integrated harvest, potential annual electricity generation from woody biomass changes very little from 2010 to 2030 for all scenarios. As suggested by the discussion of changes in biomass density in Section 4.1, projected net generation from logging by-products has a greater variability among the scenarios. Also, 2030 estimates of availability of logging by-products differ more from the 2010 estimate than a similar comparison of 2030 and 2010 supply estimates for amounts from integrated harvesting. Whereas

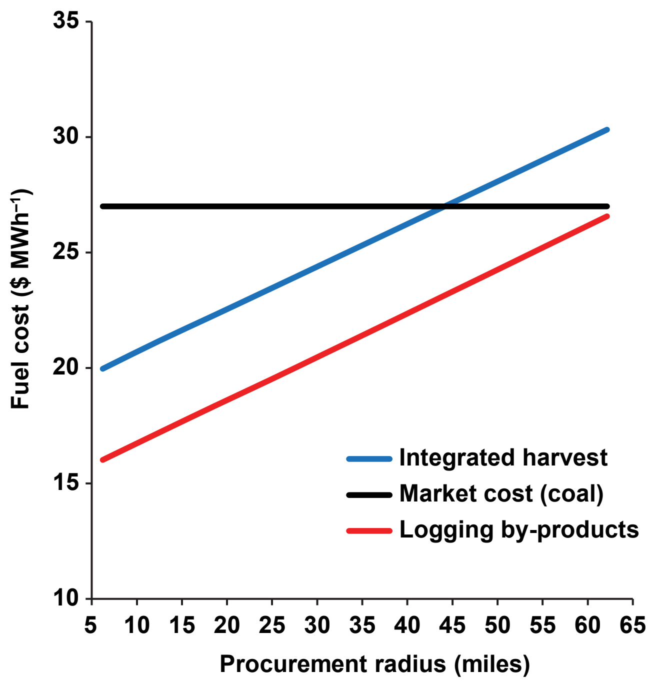

Figure 9. Estimated 2010 averages of marginal delivered cost of woody biomass and coal by procurement radius (Goerndt et al. 2013a).

integrated harvest shows all three scenarios as yielding slightly lower electricity generation than 2010, for logging by-products scenario A1B-C is the only scenario where wood power generation is lower than the 2010 estimate. Even though electricity generation from logging by-products in 2030 for scenarios A2-C and B2-C are greater than the 2010 estimates, most power plants would still not be able to replace more than 10% of coal generation using only this feedstock.

Greater variation in projected electricity generation potential from logging by-products may have substantial economic and policy implications as logging by-products are the most common form of woody biomass feedstock used by co-firing power plants (DOE 2011; Goerndt et al. 2013a; Goerndt et al. 2013b) This is primarily from estimated lower delivered costs for logging by-products.

4.4 Costs of Woody Biomass Procurement

Costs of biomass procurement and transport limit co-firing potential for plants residing in areas of low biomass per unit area. This is particularly true for integrated harvesting that includes removal of small-diameter trees which incur higher operational costs than simply removing logging by-products. Although electricity generation potential of woody biomass from an area is driven by spatial density of available biomass (Fig. 5), the delivered biomass cost is driven primarily by maximum transport distance (Goerndt et al. 2013b; Table 1). Figure 9 shows the 2010 average (across power plants) of marginal delivered cost of woody biomass by procurement radius for selected power plants for both procurement regimes (Goerndt et al. 2013a).

The estimates of delivered biomass costs for 2010 by Goerndt et al. (2013a) show that the woody biomass cost break-even point (equal to coal cost) for integrated harvest occurs at around a 40- to 45-mile procurement radius or 50- to 60-mile maximum transport distance. This coincides with findings by Sami et al. (2001) and Nicholls et al. (2006) indicating that on average 55 to 60 miles is the maximum economically feasible transport distance for woody biomass to power plants.

As indicated by cost assumptions in Table 1, the procurement regime including removal of small-diameter trees (integrated harvest) had the highest delivered costs for woody biomass from high harvest costs. Woody biomass from logging by-products could conceivably be obtained from a greater transport distance than biomass from integrated harvests due to lower overall marginal delivered cost. However, the market cost of coal and many of the cost components for woody biomass are expected to be variable over time. Changes in the breakeven transport distance because of increases or decreases in marginal delivered costs for woody biomass could be offset by changes in coal market value or changes in coal costs could be offset by changes in biomass costs. Figure 10 compares estimates of projected 2030 marginal delivered costs of woody biomass with projected coal market cost (EIA 2012).

As for 2010, marginal delivered cost for logging by-products in 2030 is projected to be lower than for biomass from integrated harvest. Scenario A1B-C has a breakeven procurement radius for logging by-products at about 60 miles, which is about the same as for 2010 (Fig. 9). Scenarios A2-C and B2-C have a breakeven procurement radius greater than 65 miles.

For 2010, the breakeven procurement distance for biomass from integrated harvesting is 35–45 miles. For 2030, the breakeven point for scenario A1B-C is 30–35 miles and breakeven points for A2-C and B2-C are 60–65 miles. The breakeven procurement radius is less for A1B-C because of higher projected stumpage costs (Ince et al. 2011).

4.5 Power Plants Suited to Co-Fire with Woody Biomass

Counties with the potential for co-firing the most biomass with coal are those in which a power plant can obtain the greatest amount of woody biomass at marginal delivered fuel costs that are competitive with the cost of coal (Goerndt et al. 2013a; Goerndt et al. 2013b; FS, In press).To estimate the amounts of biomass plants could obtain we used a 40-mile maximum because the 2010 delivered fuel cost analysis revealed that it is the approximate break-even distance for the integrated harvesting regime that could provide the most biomass. Using these plant-level biomass supply estimates,

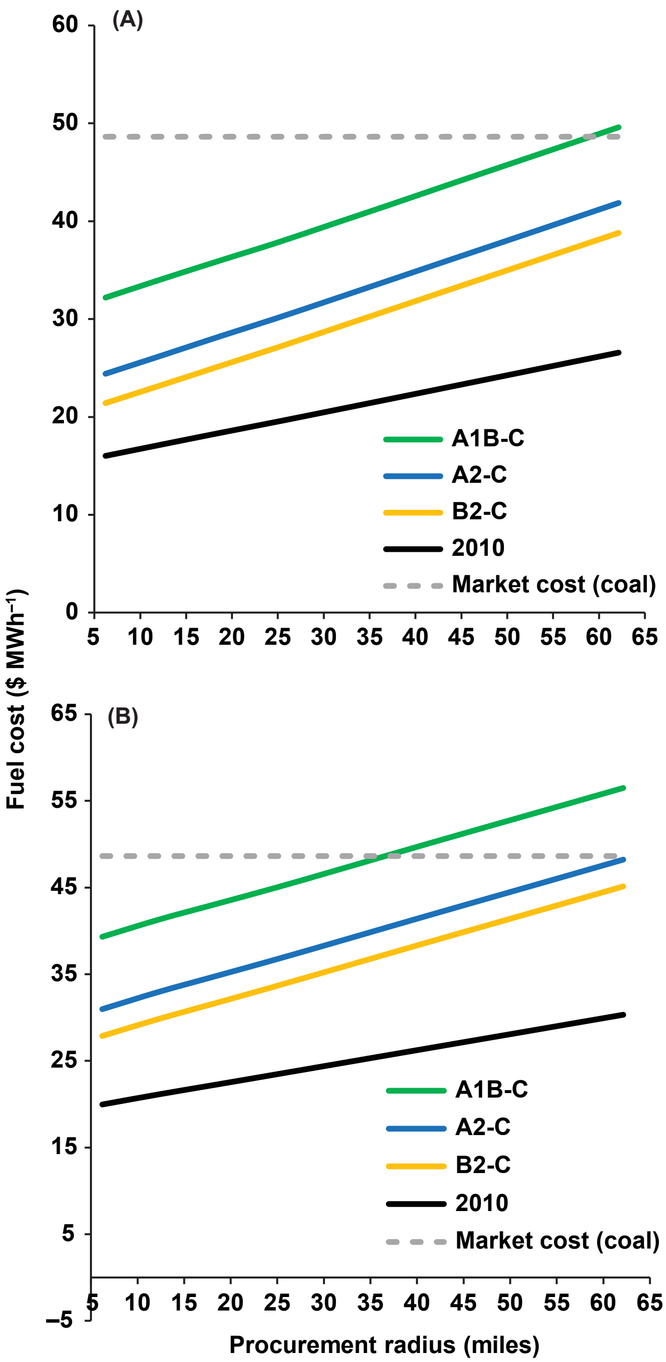

Figure 10. Projected average marginal cost for woody biomass and coal for selected power plants in 2030 by scenario and procurement radius for logging by-products (A), and integrated harvest (B).

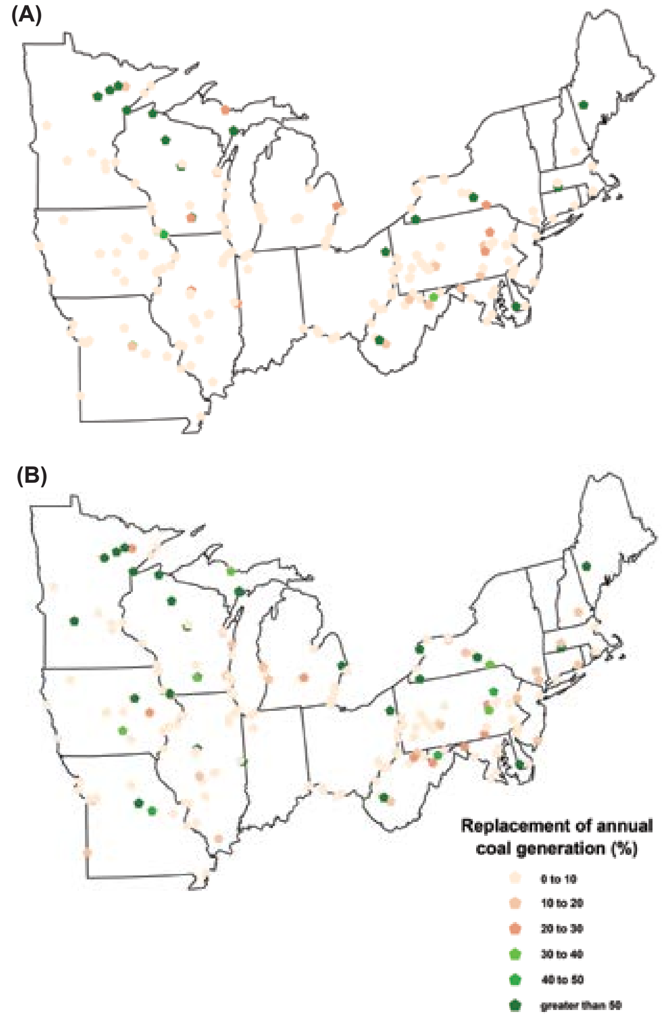

Figure 11. Estimated percentage of annual coal electricity generation that could be replaced by woody biomass for selected power plant at a 40-mile circular procurement radius assuming (A) logging by-products regime 2010 and (B) integrated harvest regime 2010.

Figure 11 shows the percentage of coal power that could be offset at each selected plant in 2010.

Aside from the higher levels of co-firing generation potential from integrated harvest compared to logging by-products, there are noticeable patterns in spatial distribution of power plants (Fig. 11). Many plants in the Lake States and the Northeast sub-region have a relatively high co-firing potential for both integrated harvest and logging by-products. Areas that are intensively harvested, and therefore have high availability of logging by-products, can also have low SDI values for forests because of current harvest removals. Therefore, many plants with high co-firing potential for logging by-products (e.g., Minnesota) do not experience as great an increase in co-firing potential with integrated harvest as many plants in areas with low availability of logging by-products. However, the highest concentration of power plants with high co-firing potential (under both regimes) occur in eastern states: Ohio, Pennsylvania, and West Virginia. This is logical as these states have high concentrations of timberland combined with well-established timber-based industries providing logging by-products and mill by-products (Goerndt et al. 2012). These states also have relatively high coal-firing infrastructure, as well as a strong tradition of coal mining, which may favor coal use

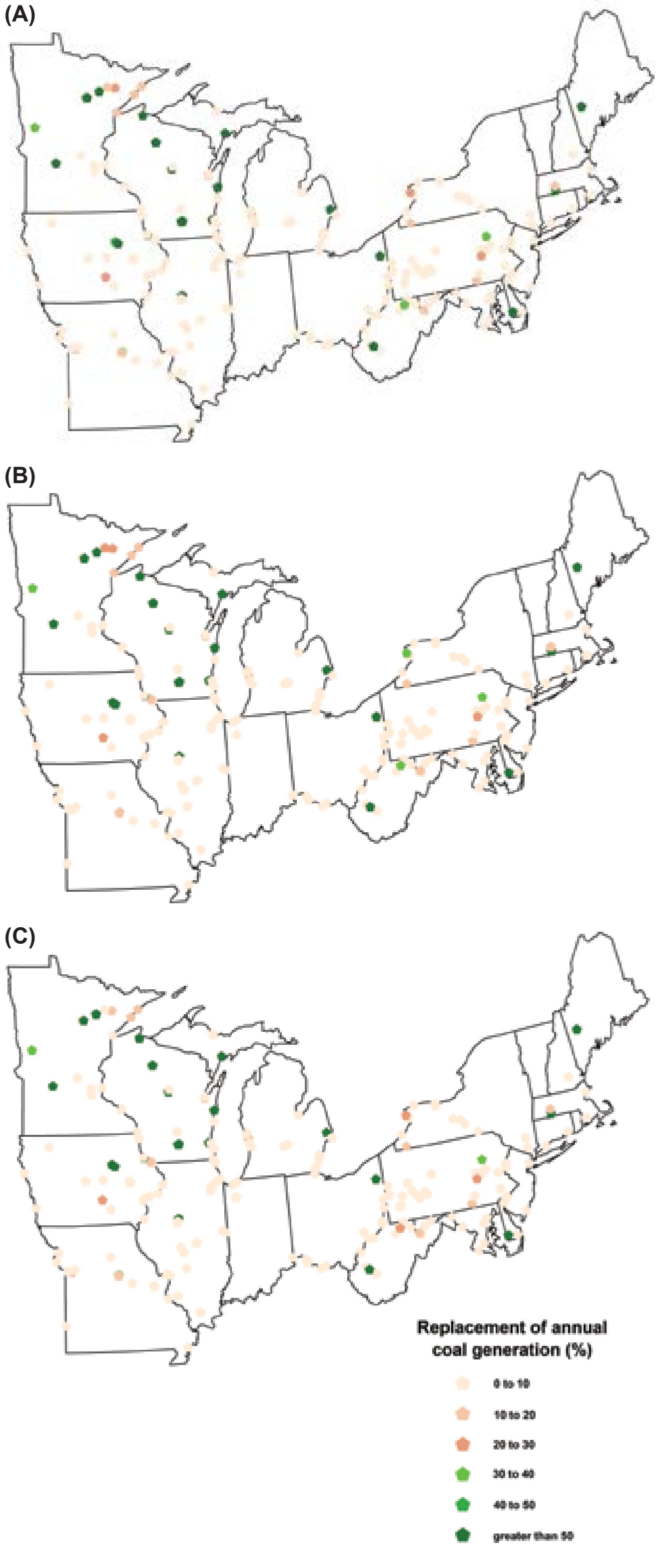

Figure 12. Estimated 2030 percentage of annual coal electricity generation that could be replaced by logging by-products for each selected power plant at a 40-mile concentric procurement radius by scenario.

over biomass use for electricity generation. Figures 12 and 13 show power plants suited to host co-firing operations in 2030 based on percentage of annual coal net generation that could be generated using biomass.

Plants with low- to mid-range co-firing potential in 2010 generally did not experience significant increase in the 2030 projections (Fig. 12). However, there is a noticeable shift in spatial distribution for plants with high potential for co-firing. There is an increase in co-firing potential in midwest states Iowa, Ohio, and Minnesota, and a decrease in eastern states New York and West Virginia. This is because mid-western states are expected to have an increase in logging by-products availability between 2010 and 2030, whereas the eastern states are expected to have a decrease (Fig. 5).

The shift in spatial distribution of plants with high co-firing potential between 2010 and 2030 is also affected by changes in available mill by-products. Mill by-products are the sole alternative biomass source for power plants that are considering logging by-products as the primary procurement regime. As for logging by-products, 2030 estimates of mill residue availability were made using the projected change in timber harvest between 2010 and 2030 to adjust the 2010 estimates (Section 3.2.5). Many of the power plants with high estimated potential for co-firing in 2010 are spatially clustered in areas with a high number of wood processing mills, which is associated with high local harvest rates (high availability of logging by-products) and relatively high local availability of mill by-products. The average percentage of coal net generation that could be replaced by logging by-products in 2030 for scenarios A2-C and B2-C was 1.1 and 1.3 times that of scenario A1B-C, respectively.

Unlike the shifts in location of potential high co-firing with logging by-products between 2010 and 2030, the projections for potential high co-firing with biomass from integrated harvest do not show a decrease in the Lake States or north-eastern states. This contrast between integrated harvest and logging by-products is due primarily to the dependency of integrated harvest on small-diameter trees in addition to available logging by-products from roundwood harvest. Unlike logging by-products, the availability of biomass from small-diameter trees is not projected to decrease in many of the eastern states between 2010 and 2030 (Fig. 5). Of the three assessed procurement regimes, availability of biomass from small-diameter trees is expected to change the least from 2010 to 2030 (Fig. 5), resulting in greater stability in spatial distribution surrounding power plants with high co-firing potential. This results in low variation among scenarios in estimated co-firing potential based on use of biomass from integrated harvesting in 2030.

4.6 Implications for Public Policy

While scenarios A2-C and B2-C showed general decreases in average delivered woody biomass costs, scenario A1B-C consistently showed increases in delivered fuel costs

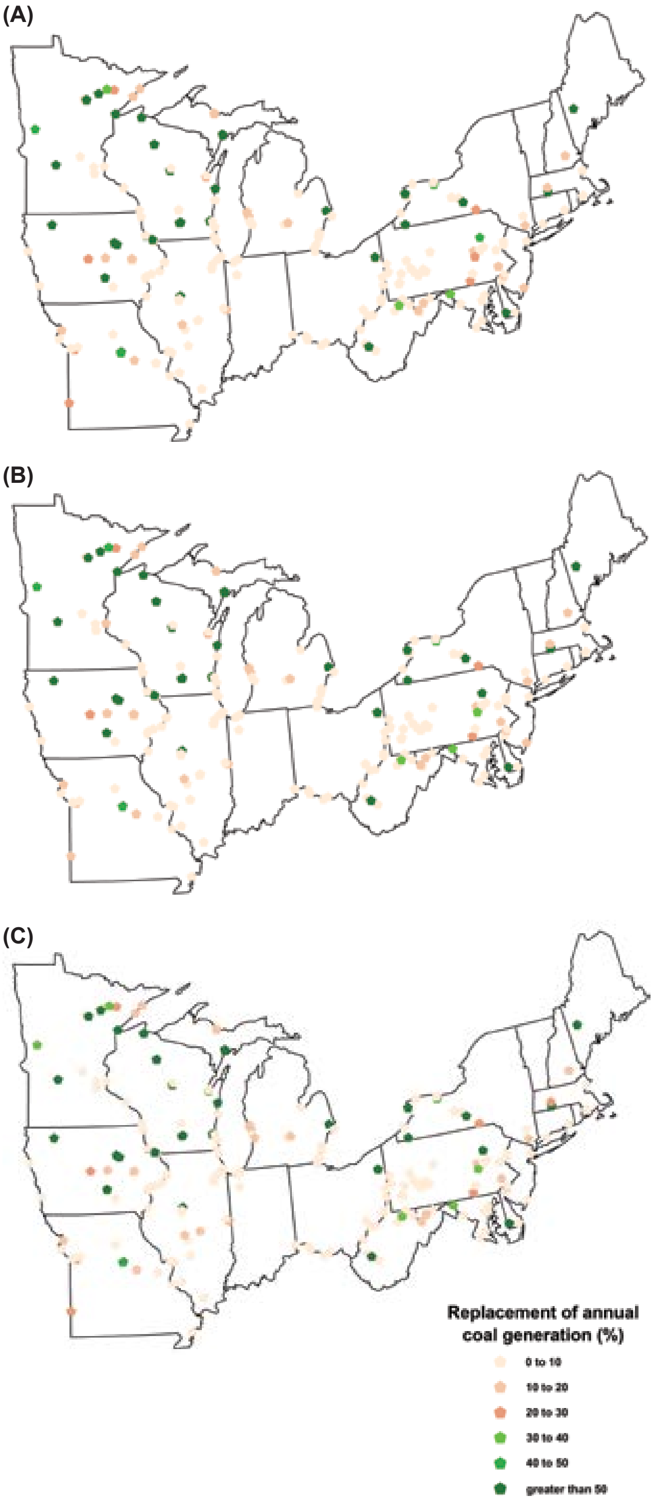

Figure 13. Estimated 2030 percentage of annual coal electricity generation that could be replaced by biomass from integrated harvest for each selected power plant at a 40-mile concentric procurement radius by scenario.

resulting in much lower maximum procurement radii and transport distances for economical procurement of woody biomass. This may necessitate the use of compensatory incentives to offset additional costs associated with transporting biomass feedstocks greater distances, if increased biomass utilization for energy is considered desirable under this scenario. In the absence of incentives, power plants would either need to pass the extra cost to the consumer through retail price premiums or obtain more biomass within shorter transport distances. The latter could lead to ecological sustainability issues if co-firing power plants are pushed to use more biomass than can be sustainably procured within an economic transport distance. One type of policy that could push power plants to utilize more woody biomass within economic transport distances are state RPS.

4.6.1 State-Level Renewable Portfolio Standards

As of 2013, only one of the 20 states included in the study area has not implemented an RPS. Demand for woody biomass from forests could be partially met by dedicated energy plantations using herbaceous or woody crops. However, it may be necessary in some states to set a maximum on the amount of electricity that can be produced from biomass to help achieve an RPS, unless conversion efficiencies are enhanced or some biomass is grown on plantations, or both. Ecological concerns may result in adoption of mandatory best management practices (BMPs) for woody biomass procurement, such as the woody biomass harvesting BMPs developed by the Missouri Department of Conservation (Enyart et al. 2009).

4.6.2 Best Management Practices

Woody biomass harvest for energy that will likely be done in coordination with whole-tree harvesting (integrated harvesting) removes more total biomass per acre than the traditional roundwood harvests in the U.S. North. Traditional roundwood harvest can leave anywhere from 25% to 45% of tree biomass on site (DOE 2011). Removal of more of the tree biomass can require longer operation times for machinery, decreases in ground cover of slash and litter, and fewer small-diameter and non-merchantable (by sawtimber standards) trees left on site. Reduction of material retained on site is one of the primary environmental policy issues for woody biomass procurement for energy. As of 2011, five U.S. states have drafted specific BMPs for removal of woody biomass including Maine, Minnesota, Missouri, Pennsylvania, and Wisconsin (Skog and Stanturf 2011). All these states are within our study area. The most notable changes for woody biomass BMPs concern woody biomass retention on site after harvesting. As procurement of woody biomass for energy generation increases, it is likely that more states will adopt BMPs for woody biomass harvest and procurement. Creation of more BMPs for woody biomass combined with RPS may create situations where power plants simply may not be able to afford procurement of amounts of woody biomass greater than the estimates obtained in this study within economical transport distances without additional financial incentives or increases in available plantation biomass.

5. Conclusions

This study estimated local woody biomass resource supply and delivered costs for individual power plants in the U.S. North. This region has the potential to provide a substantial amount of woody biomass for co-firing based on physical resource availability and spatial distribution density of the timberland biomass resource. However, electricity generation potential is restricted in that most procurement regimes would not replace more than 10% of coal use within an economical transport distance. This percentage would be lower when accounting for resource competition if two or more adjacent power plants are co-firing with biomass simultaneously. Estimated electricity generation potential does not change substantially between 2010 and 2030, with the exception of moderate effects associated with changes in logging by-products because of changes in projected annual harvest. Projections of a decrease in marginal delivered costs for scenarios A2-C and B2-C suggest that economic woody biomass transport distances for most power plants could likely increase by 2030, but economic distance would decrease with higher costs projected for scenario A1B-C. For scenarios A2-C and B2-C, power plants may be able to obtain more woody biomass economically in the future, depending upon the rate of increase in coal market cost and increases in fuel costs for harvest operations and transport.

The scenarios assumed that woody biomass use for energy would increase because of a combination of economic drivers that could include low prices relative to alternative fuels, regulatory mandates to use renewable fuels, or subsidies. Currently, the cost for natural gas is low and offers competition to wood biomass as a fuel to produce electric power. An increase in wood energy use may require regulatory mandates to use renewable fuels or to reduce GHG emissions (or both), which could be met by increased use of wood for energy. With significant mandates and continued use of some older coal boilers, co-firing with wood may be a way to meet those mandates. However if a mandate to reduce GHG emissions in coal fired power plants could be met by co-firing with natural gas then additional wood use for co-firing could be limited.

State-level RPS may push some power plants to procure more biomass than may be ecologically and/or economically sustainable in the long-term. Implementation of woody biomass BMPs in several states may limit such procurement. The results of this research can help power plant owners, forest managers, and policy makers understand the biological, economic and policy factors that will influence the contribution woody biomass can make in producing electric power in specific locations the U.S. North.

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Appendix—Supplementary Information for Projection Scenarios, Econometric Analysis, Cost Assumptions, and Projected Biomass Availability

Table A1—Variables and corresponding data sources for the econometric analysis of probability of woody biomass co-firing for electrical generation in the U.S. North (Aguilar et al. 2012). Variables projected for 2030 estimates[a]

Factors	Proxy variables	Units	Source
Electricity demand indicators	Average electricity price (state)[a]	Per kilowatt-hour (U.S. cents)	EIA 2008
	County area	km^2	U.S. Census Bureau 2000
	County area urbanized (%)[a]		U.S. Census Bureau 2000
Land value	Median house value (state)	Thousands US$ ($\times10^3$)	U.S. Census Bureau 2000, 2013
Transportation infrastructure	Presence of principle highways (county)	Binary (1= infrastructure)	U.S. Census Bureau 2000
	Presence of principle railways (county)	Present (0 = otherwise)	U.S. Census Bureau 2000
	Presence of major rivers and streams (county)		U.S. Census Bureau 2000
Coal availability and price	Presence of coal production (state)	Binary	EIA 2008
	Average coal price (state)[a]	Per ton (US$)	EIA 2008
Implementation of state renewable portfolio standards (RPS)	RPS adopted by 2001 (state)	Binary	DSIRE 2010
Resource availability of non-woody biomass	Annual corn yield	Metric tons	NASS 2008
Resource availability of wood mill by-products	Total annual by-products (county)[a]	Volume (m^3)	USDA 2012
Subregion-level conditions	Subregional binary variables	Binary (1= county within subregion)	U.S. Census Bureau 2000

[a]Variables that were projected to 2030. Subregional binary variables = indicator (0,1) variables for subregions as defined by the U.S. Census Bureau (2000).

Table A2—Overview of IPCC storylines evaluated in U.S. North forest projections. Based on Nakicenovic et al. (2000), Ince et al. (2011), IPCC (2007), and FS 2012a

IPCC storyline characteristics	Storyline A1	Storyline A2	Storyline B2
General development themes	Globalization; economic growth; introduction of new and more efficient energy technologies; capacity building	More differentiated world with less trade compared to storyline A1B; uneven economic growth; slower technological change	Sustainable development; diversified technology; Increased concern for environmental and social sustainability compared to the A2 storyline.
Synopsis	Rapid economic globalization. International mobility of people, ideas, and technology. Strong commitment to market-based solutions. Strong commitment to education. High rates of investment and innovation in education, technology, and institutions at the national and international levels. A balanced energy portfolio including fossil intensive and non-fossil energy sources	Consolidation into economic regions. Self-reliance in terms of resources and less emphasis on economic, social, and cultural interactions between regions. Technology diffuses more slowly than in the other scenarios. International disparities in productivity, and hence income per capita, are largely maintained or increased in absolute terms.	A trend toward local self-reliance and stronger communities. Community-based solutions to social problems. Energy systems differ from region to region, depending on the availability of natural resources. The need to use energy and other resources more efficiently spurs the development of less carbon-intensive technology in some regions.
Global GDP[a] growth	Very high (6.2×)	Medium (3.2×)	Medium (3.5×)
U.S. GDP growth	Medium (3.3×)	Low (2.6×)	Low (2.2×)
Global energy use	Very high	High	Medium
Oil and gas availability	High	Low	Medium
Energy technological pace and sources	Rapid; gas, biomass, and other renewables	Slow; coal and gas	Medium; gas, oil, and biomass
Global population growth	Medium (1.3×)	High (1.7×)	Medium (1.4×)
U.S. population growth	Medium (1.5×)	High (1.7×)	Medium (1.3×)
Global expansion of primary biomass energy production (2010–2060)	High (Highest for USA)	Medium	Medium (lowest for USA)
Relative increase in greenhouse gas emissions	Medium	High	Low

[a]Gross domestic product.

Table A3—Storyline and global circulation model combinations analyzed, and associated text for a description of storylines. The *scenario* names A1B-C, A2-C, and B2-C used in this report refer to the combination of the primary global circulation model with the respective IPCC storyline

Global circulation model	IPCC storyline A1B	IPCC storyline A2	IPCC storyline B2
CGCM3.1[a]	Primary (Scenario A1B-C)	Primary (Scenario A2-C)	
CGCM2[b]			Primary (Scenario B2-C)

[a]CGCM3.1—Canadian Centre for Climate Modeling and Analysis (CCCma) Coupled Global Climate Model (CGCM3), Medium Resolution (T47). http://www.ec.gc.ca/ccmac-cccma (Accessed: July 27, 2012).
[b]CGCM2—Coupled Global Climate Model, Medium Resolution (T47). Canadian Centre for Climate Modelling and Analysis http:// http://www.ec.gc.ca/ccmac-cccma (Accessed: July 27, 2012).

Table A4—Estimates of woody biomass spatial distribution (tons/acre) in 2030 by state and future scenario from timberland in the U.S. North

		Logging by-products			Small trees (SDI)[a]			Integrated harvest		
State	*n*[a]	A1B-C	A2-C	B2-C	A1B-C	A2-C	B2-C	A1B-C	A2-C	B2-C
Connecticut	8	0.004	0.004	0.004	0.308	0.326	0.317	0.308	0.326	0.317
Rhode Island	5	0.004	0.009	0.004	0.094	0.094	0.098	0.098	0.103	0.103
New Jersey	21	0.009	0.004	0.004	0.263	0.272	0.263	0.268	0.277	0.268
New York	62	0.031	0.036	0.031	0.410	0.401	0.406	0.442	0.433	0.437
Massachusetts	14	0.031	0.031	0.027	0.321	0.335	0.330	0.352	0.366	0.357
Michigan	83	0.049	0.054	0.058	0.294	0.294	0.299	0.343	0.348	0.357
Iowa	99	0.049	0.067	0.080	0.125	0.129	0.134	0.178	0.196	0.214
Vermont	14	0.054	0.045	0.040	0.379	0.384	0.388	0.433	0.428	0.428
Maryland	24	0.054	0.062	0.062	0.272	0.263	0.294	0.326	0.321	0.357
Ohio	88	0.058	0.062	0.067	0.285	0.285	0.290	0.343	0.348	0.357
Illinois	102	0.062	0.067	0.062	0.192	0.196	0.196	0.254	0.263	0.259
Missouri	115	0.062	0.054	0.067	0.219	0.219	0.219	0.281	0.268	0.281
Delaware	3	0.067	0.071	0.098	0.330	0.321	0.339	0.397	0.393	0.433
West Virginia	55	0.071	0.076	0.089	0.303	0.308	0.308	0.379	0.384	0.397
Pennsylvania	67	0.071	0.080	0.076	0.343	0.343	0.352	0.415	0.424	0.428
New Hampshire	10	0.089	0.085	0.080	0.393	0.401	0.415	0.482	0.486	0.495
Minnesota	87	0.098	0.103	0.085	0.232	0.236	0.232	0.330	0.339	0.317
Wisconsin	72	0.120	0.120	0.116	0.236	0.232	0.236	0.357	0.352	0.352
Indiana	93	0.152	0.178	0.143	0.214	0.214	0.219	0.366	0.393	0.361
Maine	16	0.152	0.152	0.161	0.343	0.352	0.343	0.495	0.500	0.504
Region total	1038	1.289	1.361	1.356	5.558	5.607	5.679	6.847	6.946	7.021

[a]Stand density index.

Table A5—Projections of operational and transport cost assumptions for woody biomass procurement in the U.S. North to 2030 for all applicable scenarios

	Logging by-products			Small-diameter trees			
Costs	A1B-C	A2-C	B2-C	A1B-C	A2-C	B2-C	Mill by-products
Harvest ($/ton)[a]	10.38	10.38	10.38	25.93	25.93	25.93	na
Transportation							
Fixed ($/ton)[b]	6.80	6.80	6.80	6.80	6.80	6.80	6.80
Incremental ($/ton /mile)[c]	0.36	0.36	0.36	0.36	0.36	0.36	0.36
Stumpage value ($/ton) [d]	24.11	10.90	5.56	24.11	10.90	5.56	na
Chipping costs ($/ton)[e]	8.91	8.91	8.91	8.91	8.91	8.91	na
Selling ($/ton)[f]	na	na	na	na	na	na	4.49

[a]Derived from percentage increases in fuel cost and labor cost (Saunders et al. 2012; BLS 2013; EIA, 2013).
[b]Fixed cost for operation and loading/unloading of trucks (Perlack et al. 2005; Saunders et al. 2012; Gallagher et al. 2003)
[c]Derived from percentage increases in fuel and labor cost (Saunders et al. 2012; BLS 2013; EIA 2013).
[d]Derived using percentage increase in non-timber stumpage value by IPCC scenario (Ince et al. 2011)
[e]Derived from percentage increases in fuel and labor cost (Saunders et al. 2012; BLS 2013; EIA 2013).
[f]Perez-Verdin et al. (2009).