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Resource potential for renewable energy generation from co-firing of woody biomass with coal in the Northern U.S.

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ABSTRACT

Past studies have established measures of co-firing potential at varying spatial scales to assess opportunities for renewable energy generation from woody biomass. This study estimated physical availability, within ecological and public policy constraints, and associated harvesting and delivery costs of woody biomass for co-firing in selected power plants of the Northern U.S. Procurement regimes were assessed for direct sources of woody biomass from timberland including logging residues (slash, by-products), small-diameter trees, and integrated harvest (logging residues and small-diameter trees). Concentric woody biomass procurement areas were estimated for each power plant using county-level estimates and varying procurement radii. Delivered fuel cost estimates were calculated for each power plant and procurement regime based on incremental maximum transport distances. Procurement regimes focused on small-diameter trees can potentially produce the most electric power, but are constrained by lower economical transport distances than logging residues. These estimates enabled us to assess which power plants in the Northern U.S. had the highest electricity generation potential. For most procurement regimes, an average power plant co-firing had the potential to replace greater than 30% of coal electricity generation if there was no competition for the feedstock. However, woody biomass resource competition from adjacent co-firing plants could reduce this generation potential to less than 10%.

1. Introduction

Increasing interest in utilizing wood for bioenergy in the U.S. has been motivated by environmental concerns, costs of fossil fuels, and public opinion regarding renewable energy. Among different biomass feedstocks, wood and wood waste currently account for the greatest share of bioenergy generation in the U.S. at about 53% according to the U.S. Energy Information Administration [1]. Renewable energy markets can help provide incentives to remove small-diameter trees (i.e. trees <25 cm in diameter measured at 140 cm from the ground) and other non-timber woody material during compatible silvicultural treatments such as pre-commercial thinning, hazardous fuel reduction, woodland restoration, and certain types of wildlife habitat improvement. Forests and waste wood sources on a dry

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basis in the contiguous U.S. could have provided about 88 Tg of energy feedstock if priced at 66 $ Mg^{-1} at roadside or mill gate in 2012 [2].

Wood used for bioenergy generation can be currently obtained from several sources, including directly from forest (e.g. residues from timber harvesting operations, and forest-derived biomass from removal or thinning of trees), indirectly from primary and secondary wood product manufacturing (e.g. chips, briquettes, mill residues, pellets) and recovered from post-consumption (e.g. urban residues from demolition, packaging materials) [3]. In the U.S., indirect sources supply 78.9%, direct sources 19.3%, and recovered sources 1.8% of all wood energy consumed in the country [4]. Indirect sources are highly dependent on output from the wood products industry [5] and large amounts of this material are already utilized or under contract. Recovered wood is a component of potentially available wood for energy, but this source is mainly limited to urban areas [2]. Direct sources have the greatest potential for future growth for bioenergy at various price levels [2] and their production can be complementary to other forest management objectives [6]. Wood sourced directly from a forest, woodland, or rangeland environment may be broadly defined as woody biomass, encompassing by-products of forest management including trees and woody plants (limbs, tops, needles, leaves, and other woody parts) [7].

Prominent technological platforms that convert wood to energy include: (1) direct firing or co-firing biomass with coal for electricity, heating and cooling, (2) production of liquid biofuels [8], and (3) gasification [9–12]. Co-firing refers to the practice of introducing biofuels as a supplementary energy source in high efficiency utility boilers [13,14]. There are currently 89 coal-fired power plants in the U.S. that utilize some quantity of biomass [1,15]. Compared to alternatives such as liquid biofuels or gasification, co-firing facilities (coal-fired electric plants) can often incorporate biomass into the existing fuel storage and handling systems with relatively minor modifications [6,16–19]. Also, unlike wind and solar energy, wood energy can be readily stored (e.g., as chips or on the stump) and utilized when needed [20]. In a survey conducted by Aguilar and Garrett [6], various wood energy stakeholders ranked the perceived practical potential of woody biomass co-firing higher than other energy conversion methods including cellulosic ethanol, gasification and pyrolysis.

Many studies have focused on woody biomass resource assessments at varying spatial scales to determine the broad-scale feasibility of co-firing across the U.S. [20,21]. Nevertheless, there has been considerably less research assessing the localized resource availability and coinciding costs for specific areas identified as having high potential for biomass co-firing. Aguilar et al. [22] used an array of information to estimate woody biomass resource availability and elicit the likelihood of co-firing in counties of the Northern U.S. This methodology served as a “coarse screen” for identifying counties with the highest probability of co-firing based on several internal, external, and location specific physical factors. However, Aguilar et al. [22] did not estimate localized biomass supply potential for the areas identified as having a high probability of co-firing based on transport distance, source of feedstocks, and alternative woody biomass procurement regimes. These are important factors nonetheless, as they will all have an effect on delivered costs of different biomass feedstocks, as well as limitations to annual net generation in co-firing facilities.

The purpose of this study was to estimate 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. For each power plant, woody biomass procurement areas, maximum transport distances, and resulting delivered fuel costs were estimated for four different forest procurement regimes including: (1) removal of small-diameter trees based on stand density, (2) removal of small-diameter trees using a biological maximum, (3) removal of logging residues (slash), and (4) integrated removal of logging residues and small-diameter trees. For each power plant and procurement regime, supply potential and delivered costs were estimated using concentric circles to represent woody biomass procurement area and to calculate maximum transport distance to the plant. Results from these analyses identified power plants best poised to co-fire based on cost and electricity generation potential. The first section of this paper describes the study area and background information for the selection of power plants and woody biomass availability assessments. The next section describes the methods used to estimate woody biomass availability and production costs. This is followed by results, discussion and conclusions.

2. Theoretical background and study area

Recent studies have shown that past placement of co-firing facilities is highly correlated with power plant physical (e.g. feeding systems), external (energy markets) and location-specific (e.g. transportation infrastructure) factors [22,23]. Aguilar et al. [22] developed econometric models to estimate the likelihood of co-firing at the county-level using explanatory variables such as electricity demand, technical feasibility, coal price, availability of wood mill by-products, renewable portfolio standards (RPS), and transportation infrastructure.

For this study, we focused on coal-fired power plants residing within selected counties in the Northern U.S. that have been identified with a high likelihood of co-firing based on the econometric models developed by Aguilar et al. [22]. Specifically, the counties of interest were identified as being in the top 25% of all counties in terms of estimated probability of co-firing. We restricted this study to applicable counties in the U.S. Northeastern and North-central states – hereafter referred to simply as the Northern U.S. The Northern U.S. is comprised of the 20 following 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 was chosen for this assessment due to lack of necessary data at the county-level for the entire U.S., as well as large fluctuations and uncertainty in production costs amongst major U.S. regions. Aside from data restrictions, there were two other important reasons for focusing on this region. First, woody biomass has been identified as a major potential source of renewable energy in the region [6,15]. Second, this region contains about 53% of all coal-fired power plants in the U.S. Out of the 1037 counties in the Northern U.S., 246 currently have at least one coal-fired power plant [15]. The locations of counties and power plants selected for this study are shown in Fig. 1. Based on the selection of counties, there were 219 plants selected in the Northern U.S. for this study. Only 20 (9%) of these power plants were using biomass as of 2007, the most recent estimate available at the time of the study from the EPA [15].

National and region-level estimates of biomass physical availability indicate broad bioenergy potential [20,24,25] but do not include details on resource availability and economic feasibility of co-firing for individual power plants. The "U.S. Billion-ton Update" by the U.S. Department of Energy made estimates of forest-based biomass supply at the county level at various roadside or mill gate prices but did not estimate amounts that could be economically supplied to particular plant locations [2]. Perez-Verdin et al. [26] and Huang et al. [27] both used methods developed by Overend [28] to estimate radii for concentric supply circles around hypothetical bio-ethanol plant locations and resulting production costs. We used a variation of this methodology to obtain maximum transport distances and marginal delivered cost estimates of woody biomass for selected power plants.

3. Methods

The methods section is organized as follows: (2.1) Conversion of biomass supply to electric power, (2.2) Estimating availability of woody biomass and unused mill by-products, (2.3) Amount and costs to deliver woody biomass to power plant (2.4) Power plants poised to co-fire with woody biomass based on supply potential and costs, (2.5) Selective sensitivity analysis, and (2.6) Study limitations. Estimates of woody biomass availability were generated in two steps. First, woody biomass availability was estimated by selected power plant location for each proposed procurement regime. This was achieved using county-level forest inventory data and products output data reported by the U.S. Forest Service Forest Inventory and Analysis (FIA) [29–32]. To avoid inclusion of protected or otherwise unavailable biomass, estimated supply of biomass was limited to timberland, defined by Smith et al. [33] as forest land that is producing or is capable of producing crops of industrial wood and not withdrawn from timber utilization by statute or administrative regulation. Woody biomass availability also incorporated ecological and policy restrictions regarding on-site retention rates and inaccessibility. Second, estimates were comprised of costs to harvest and deliver biomass itemized to encompass forest operations, stumpage, and transport. Throughout the rest of this paper, all woody biomass weight estimates presented in the text are given in dry (i.e. moisture-free) weight.

3.1. *Conversion of biomass supply to electric power*

To estimate the amount of electric power that may potentially be generated by co-firing with woody biomass, information was needed on both feedstock availability and the efficiency

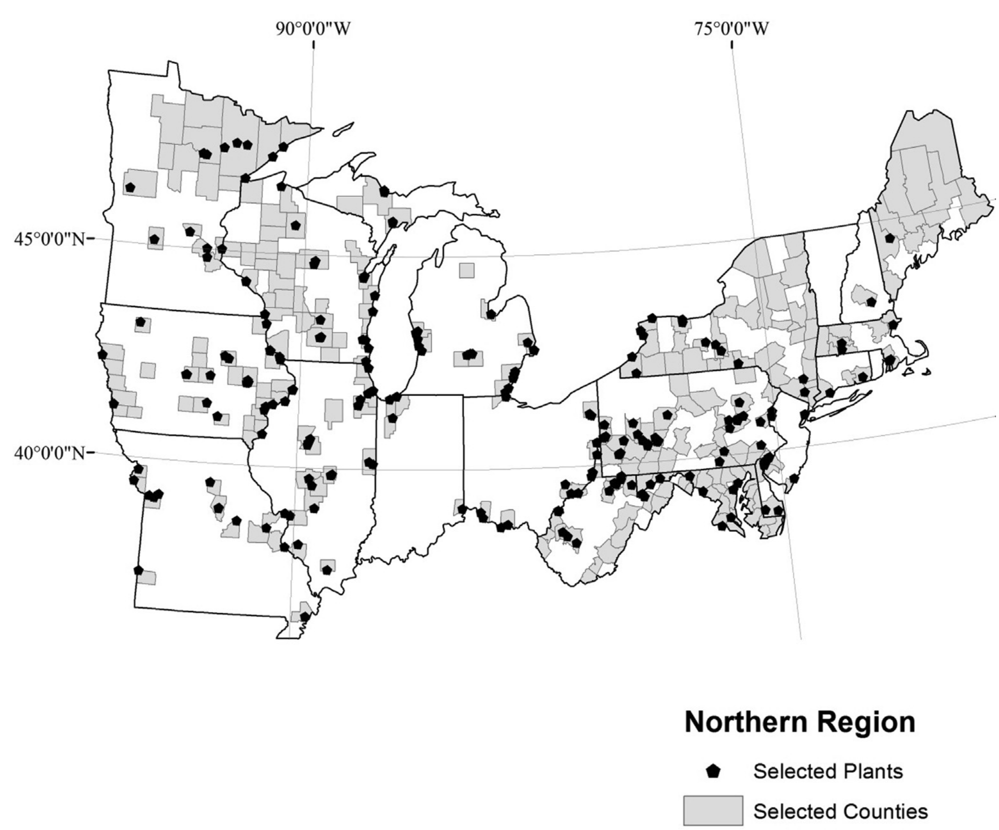

Fig. 1 – Map of the Northern U.S. with power plants selected for the study of woody biomass and unused mill by-product co-firing potential. Latitude and longitude are represented in GCS North America 1983 datum.

of available energy conversion technology. This analysis used the conversion efficiency reported by Goerndt et al. [20] of 1.7 MWh Mg^{-1} of woody biomass. This corresponds to a conversion of 33% of the heat energy value of woody biomass to electric power by coal-fired power plants [1].

3.2. Estimation of woody biomass and unused millby-product availability

Initial estimates of woody biomass and unused mill residue availability for each procurement regime were derived for every county in the Northern U.S., as well as several adjacent states including: North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Tennessee, Kentucky, Arkansas, and Virginia. Sections 3.2.1 through 3.2.4 describe methods used to derive county-level estimates of woody biomass availability for each procurement regime.

3.2.1. Removal of conventional logging residues (slash)

County-level estimates of potential logging residues supply were obtained from the Forest Service Timber Product Output (TPO) database [32]. We assumed that logging residues would be removed during the harvest of commercial roundwood/pulpwood and be chipped and loaded on site [2]. Not all logging residues are available for co-firing. Excessive removal of logging residues can promote soil erosion, as well as reduce productivity of unproductive soils and reduce soil nutrient levels [34,35]. The required amount of residue to be retained on site following harvesting varies by state, forest type, and slope but is considered to be in the range of 15–40% [2]. For this study, we used a residue retention rate of 35% as a biological threshold to sustain ecosystem functions.

3.2.2. Removal of small-diameter trees

Our analysis included two procurement regimes to supply biomass from small-diameter trees. The amount of small-diameter material annually available under each regime was based on forest density for each county and potential to thin timberland. Estimates were made of the fraction of timber that could be removed by thinning and fraction of thinnings that would be in the form of small-diameter trees (i.e. thinning from below). Two estimates were made of the amount by which forest density could be reduced, one based on reducing Stand Density Index (SDI) and one based on Net Annual Woody Biomass Increase (NAWI). In both cases, we limited removals to 65% of the estimated amount to account for unavailability due to ecological factors and an additional 20% retention rate to incorporate physical inaccessibility [2,26].

We simulate thinning in each county by removing trees in small-diameter classes when current SDI is greater than 30% of maximum SDI. SDI is a measure used to guide thinning in the U.S. Forest Service fuel treatment evaluator and the U.S. Forest Service forest vegetation simulator (Please refer to Appendix for SDI equation). A maximum SDI was identified for each species group. Maximum SDI is defined as the maximum density (stems per unit area) that can exist for a given species group for an assumed size (quadratic mean diameter) in a self-thinning population [36,37]. Following Perez-Verdin et al. [26] and Woodall et al. [38] the maximum SDI for hardwoods, mixed forests, and softwood forests were assumed to be 2028 ha^{-1}, 1176 ha^{-1}, and 1242 ha^{-1}, respectively. Using data on the average per ha distribution of number of trees by diameter class in a county, thinning was simulated for counties that have an estimated SDI greater than 30% (assumed full crown closure) of the assumed maximum SDI as determined by the mix of hardwood and softwood forest types in the county. We used an iterative process in which one tree per ha was removed from each diameter class lower than 25 cm during each iteration and SDI was recalculated. This process was repeated until either the county-level SDI was brought down to 30% of the maximum, or there was no small-diameter material left to remove. Due to intensive tree removal implied by application of SDI, we assumed a 30-year thinning cycle [24]. This means that available woody biomass per county was divided by 30 to estimate total annually available woody biomass from small-diameter trees.

Although SDI is a common criterion of stand density in forestry, thinning small-diameter trees to reduce either density or overall stocking is often considered to be a short-term management activity [39]. Hence, the second procurement regime estimated small-diameter trees using a biological maximum growth. The amount of biomass that could be supplied was determined by the amount of extra harvest possible without exceeding the net annual growth of the forest. To set this biological maximum, we estimated the NAWI for each county as described by Goerndt et al. [20] (Please refer to Appendix for NAWI equation). NAWI was computed as a ratio of the corresponding total cubic volume annual growth after discounting annual removals through harvest and mortality [20]. Because volume growth and removal estimates included small-diameter as well as large diameter trees, NAWI was simply applied to the total available woody biomass per county. To maintain an assumption of small-diameter removal, NAWI was limited to maximum available standing biomass of trees 25 cm in diameter at 140 cm from the ground, and below.

3.2.3. Removal of small-diameter trees, tops and branches through integrated harvest

Integrated harvest systems consist of harvesting both conventional solid products and woody biomass for energy use in a single operation and processing biomass (e.g. chipping) on site [40,41]. For this study, the integrated harvest regime combined the woody biomass availability per county from logging residues and small-diameter trees. In the integrated harvest regime, we opted to use the SDI method for small-diameter material due to its wide application as a forest management tool. Unlike the NAWI approach, removal of trees to achieve 30% maximum SDI is a more specific stand-level treatment that can be performed in conjunction with removal of roundwood products, whereas NAWI would often allow for little to no additional removal depending upon the volume being removed for roundwood products and the annual growth rates for that area.

3.2.4. Unused mill by-products

By-products from the manufacturing of wood products (e.g. mill residues) were not distinguished as a separate procurement regime but included in each procurement regime analysis for two reasons. First, the availability of mill by-products is relatively low to absent compared to standing forest biomass in many counties because by-products are already used or there are no wood processing mills. Second, aside from a possible selling price at the mill, mill by-products typically do not include many costs in addition to transport costs unlike logging residues and small-diameter trees. Therefore, currently unused mill by-products were added to the estimated availability of woody biomass for each procurement regime. County-level estimates were obtained from the TPO database [32].

3.3. *Amount and costs to deliver woody biomass to power plant*

The amount of biomass that can be used by a particular power plant will be limited by amount that can be delivered at a feasible cost. The cost for a given amount of woody biomass was determined by costs for stumpage, harvesting, chipping and transport. For any procurement regime, the amount available at a given cost is highly dependent upon transport distance. The objective of this part of the assessment was to determine amounts available and associated delivered costs for successively larger procurement areas. The following subsections describe the methods and assumptions used to estimate woody biomass availability to power plants for given delivered costs.

3.3.1. *Woody biomass and unused mill by-product supply for a procurement area*

Although woody biomass amounts were estimated for each procurement regime for each county, we were interested in estimating biomass availability and costs for each selected power plant. We estimated biomass amounts and delivered costs for simulated concentric procurement radii (R) from 10 km to 100 km by 10 km intervals around the selected power plant locations using ArcGIS [42]. For larger procurement radii, the total procurement area around most plants consisted of several counties and county fragments. Therefore, it was necessary to estimate the total annually available woody biomass (B) for each procurement regime and procurement area from the county-level estimates as follows:

$$B = \sum_{i=1}^{m} a_i b_i, \tag{1}$$

where b_i is the total annually available woody biomass for county i and a_i is the percentage of the area of county i that falls within the procurement area (circle). Equation (1) relies on the assumption that the woody biomass resource within each county is uniformly distributed across the entire county.

3.3.2. *Delivered costs for a procurement area*

To estimate delivered costs of dry woody biomass for selected procurement areas around selected power plants we estimated the marginal operational costs (stumpage costs, harvest, chipping) and transportation costs (fixed and incremental). A portion of transport cost is dependent upon maximum transport distance of woody biomass to the power plant. 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 megagram of biomass is calculated as follows [27,28]:

$$d = R\tau, \tag{2}$$

where R is the procurement radius in kilometers, andτ is a tortuosity factor representing a ratio of road transport distance to line-of-sight distance and is generally assumed to be within the range of 1.2–1.5 in the Northern and Eastern parts of the U.S [26,27]. For this study, tortuosity was adjusted by EIA energy sub-region 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 U.S. compared to the Central U.S. For each procurement radius and procurement regime, total delivered cost (C) was estimated as follows:

$$C = (T_v d) + T_f, \tag{3}$$

where d is the maximum transport distance for biomass, T_f is operational cost including loading/unloading of trucks, and T_v is the incremental transport cost. All cost assumptions for the analysis are shown in Table 1.

The largest observed cost difference was between harvest costs for logging residues and harvest costs for small-diameter trees. This is based on an assumption that logging residues would be removed from the felled trees at the landing and subsequently chipped at the same location. Therefore, most of the harvest operational cost is covered by the sale of timber [41]. However, there were still assumed harvest costs associated with logging residues, which can include handling at the landing prior to chipping. Harvest cost for small-diameter trees was greater because these trees have to be found, felled and transported to the landing as with round/pulp wood material.

Perlack et al. [2] assumed that woody biomass stumpage prices from non-federal land will range from about 4 $\$$ Mg^{-1} up to 90% of pulpwood prices. The stumpage values for non-federal land were set to 50% of the pulpwood stumpage values for the Northern U.S. as estimated by Perlack et al. [2]. These values are similar to those from other biomass procurement studies for the Northern U.S. [41]. Stumpage prices for federal land were assumed to be zero because woody biomass removal on federal land is usually part of a fuel treatment or restoration activity [2].

Chipping prices can vary depending on whether the woody biomass is chipped loose or bundled before chipping. Estimates from past studies show chipping costs ranging from 2.50 $\$$ Mg^{-1} to as high as 10 $\$$ Mg^{-1} [41,45]. The assumed value for chipping was calculated as an average between maximum costs for loose material and bundled material to account for both possibilities. 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 by-products directly from mills and is assumed to be in the range of 4 $\$$–6 $\$$ Mg^{-1} [26].

For each procurement regime the stumpage cost was adjusted to account for the mix of both federal and non-federal land. We calculated a weighted mean of stumpage cost based on the percentages of total timberland area that were federal and non-federal for each county. Additionally, it was necessary to estimate average operational costs for integrated harvesting where biomass is provided from both logging residues and

Table 1 – Operational and transport cost assumptions for woody biomass procurement in the Northern U.S.

Costs	Federal		Non-federal		Mill by-products
	Logging residues	Small-diameter trees	Logging residues	Small-diameter trees	
Harvest ($ Mg^{-1})[a]	6.42	16.04	6.42	16.04	n/a
Transportation					
Fixed ($ Mg^{-1})[b]	7.50	7.50	7.50	7.50	7.50
Incremental ($ Mg^{-1} km^{-1})[c]	0.15	0.15	0.15	0.15	0.15
Stumpage value ($ Mg^{-1})[d]	0	0	7.16	7.16	n/a
Chipping costs ($ Mg^{-1})[e]	5.51	5.51	5.51	5.51	n/a
Selling ($ Mg^{-1})[f]	n/a	n/a	n/a	n/a	4.96

[a] Derived from hardwood and softwood values in the Northern Region [2,41].
[b] Fixed cost for operation and loading/unloading of trucks [24,43,44].
[c] [2,24,26].
[d] Derived as 50% of average of hardwood and softwood pulpwood values in the Northern Region for federal and non-federal land [2,41].
[e] Average chipping costs calculated using values from Saunders et al. [41] and Harrill [45].
[f] [26].

small-diameter trees using SDI thinning treatments. Weighted average costs were estimated that accounted for land ownership and supply structure for each power plant individually. Marginal cost was estimated for all counties within each procurement radius ranging from 10 to 100 km in 10 km increments.

3.4. *Power plants poised to co-fire with woody biomass based on supply potential and costs*

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 in the U.S. pay less for biomass (per unit of energy output) than for coal. Therefore, for this assessment we set a maximum cost for woody biomass feedstocks based on the 2010 weighted average market cost of coal utilization for U.S. power plants as reported by the EIA [46] and based on a wood to electricity conversion factor of 1.7 MWh Mg^{-1}. This average market cost of coal was used to estimate the marginal delivered wood fuel costs that could be paid. This enabled us to identify the procurement radius which provided wood biomass at a break-even cost with coal. Using the amount of wood biomass available at that break-even radius we estimated the amount of electricity that could be generated annually using wood biomass for each selected plant by using the factor of 1.7 MWh Mg^{-1}. Co-firing potential by power plant was estimated using the biomass provided at the maximum procurement radius where wood biomass feedstock costs would be less than or equal to coal costs.

3.5. *Selective sensitivity analysis*

The economic feasibility of woody biomass co-firing can fluctuate depending upon the elasticity of various cost components. Therefore, we performed a sensitivity analysis to estimate the change in marginal delivered costs of woody biomass given changes in individual cost components described in Table 1. The sensitivity analysis was only applied to integrated harvesting because it was the only procurement regime that utilized all operational and stumpage costs for comparison. Specific cost components for harvest cost of logging residues, harvest cost of small diameter trees, incremental transport cost, stumpage cost, and chipping cost were included in the sensitivity analysis. Results for the sensitivity of other procurement regimes are available upon request from the authors.

3.6. *Study limitations*

The broad scope of this study means that the analyses for both woody biomass supply and delivered costs relied on many assumptions. One limitation is the assumption that current harvest rates, as well as total annual growth and removals will remain steady in years to come. We did not make adjustments to account for possible future increases or decreases in harvesting, mortality, or land use change. Another limitation is that the cost assumptions are average values for the entire region rather than fluid values which change geographically. Costs such as stumpage rates can vary by state and sub-region and be influenced by dynamic changes in biomass demand and utilization. However, it is difficult to derive accurate estimates by state or even sub-region as many states do not have developed markets for biomass or pulpwood from which to obtain reliable estimates. Additionally, this study relied on county-level FIA and TPO data, which made it necessary to assume uniform distribution of woody biomass across each county. Finally, estimates of delivered costs rely upon an assumption of 33% conversion efficiency from heat to electricity, as is typical in most coal-fired power plants. However, efficiency may increase in the future as some plants are upgraded with new technology, and in some cases converted from electricity facilities to co-generation (heat and power) facilities [47].

4. Results and discussion

The results and discussion section is organized as follows: (4.1) physical availability of woody biomass, (4.2) limitations on cost of biomass, procurement radius and transport distance (4.3) potential electrical power generation from co-firing, (4.4) power plants poised to co-fire with woody biomass, (4.5) and sensitivity of costs and public policy.

4.1. *Physical availability of woody biomass*

Assessment of total woody biomass availability by state from all counties can be a useful prelude to identifying locations of power plants with high potential for woody biomass co-firing as spatial distribution and concentration of the woody biomass resource are important factors in estimating the electricity generation capacity of individual plants. Table 2 shows estimates of total woody biomass availability and spatial distribution for each procurement regime using all counties and aggregated by state.

Northern states with a large timber resource base such as Wisconsin, Minnesota, and Maine consistently had the highest available woody biomass from logging residues and integrated harvest. This is primarily due to greater availability of residues from harvest of timber and/or pulpwood products. However, the higher rates of timber removal for counties in these states can also lead to reductions in available small-diameter trees, particularly when using NAWI (Table 2).

High total available woody biomass does not necessarily equate to high density in spatial distribution of biomass. States such as Minnesota, Wisconsin, and Michigan had fairly high estimates for total available woody biomass, but relatively low to midrange estimates per hectare compared to other Northern states, denoting a wider spatial distribution of the resource (Table 2). A wide spatial distribution of woody biomass may be a hindrance for co-firing as greater transport distances can be required to satisfy a power plant's demand for biomass. Therefore, assuming that marginal delivered fuel costs are the same, one area with relatively high spatial distribution density may be better poised to supply woody biomass to a power plant than another area with greater total available biomass if a high proportion of timberland is within close proximity to the power plant.

4.2. *Limitations on cost of biomass, procurement distance and transport distance*

The Northern U.S. has the potential to generate a substantial amount of woody biomass for co-firing based on physical resource availability, particularly for removal of small-diameter trees and integrated harvesting (Table 2). However, costs of biomass procurement and transport limit the co-firing potential in areas where spatial distribution density of biomass is low, particularly for procurement regimes focused on removal of small diameter trees which also have higher average operational costs than simply utilizing logging residues (Table 1). While total woody biomass supply potential is driven by procurement radius (area) and spatial distribution density, the delivered fuel costs are greatly influenced by maximum transport distance (Equation (2)). Therefore, it is important to show delivered cost of woody biomass based on both procurement radius and maximum transport distance. Fig. 2 shows the average (among power plants) of marginal

Table 2 – Estimates of total available woody biomass and spatial distribution by state from timberland in the Northern U.S.

State	n[a]	Total (Gg)				Spatial distribution (Mg ha^{-1})			
		Logging res	NAWI	SDI	Integrated	Logging res	NAWI	SDI	Integrated
Rhode Island	5	1.7	259.9	30.7	32.4	0.01	1.88	0.22	0.23
Connecticut	8	8.1	771.1	512.2	520.3	0.01	1.13	0.75	0.76
New Jersey	21	8.7	1037.6	524.6	533.2	0.01	1.38	0.70	0.71
Delaware	3	33.8	330.0	110.4	144.2	0.24	2.37	0.79	1.03
Massachusetts	14	74.7	1679.0	885.8	960.5	0.06	1.43	0.76	0.82
Iowa	99	101.7	1239.2	334.9	436.5	0.08	1.03	0.28	0.36
Maryland	24	184.9	1575.0	703.0	887.9	0.19	1.64	0.73	0.93
Vermont	14	203.2	713.9	1614.6	1817.8	0.11	0.39	0.89	1.00
Illinois	102	292.1	2828.5	883.1	1175.2	0.15	1.49	0.47	0.62
New Hampshire	10	314.6	1194.0	1748.1	2062.6	0.17	0.64	0.94	1.11
Ohio	88	389.3	3923.0	2041.5	2430.8	0.12	1.24	0.64	0.77
Indiana	93	531.8	3034.6	958.2	1490.0	0.28	1.60	0.51	0.79
New York	62	767.4	6575.0	5812.9	6580.3	0.12	1.02	0.90	1.02
Missouri	115	787.1	5019.4	3124.7	3911.7	0.13	0.82	0.51	0.64
West Virginia	55	890.5	3782.2	3385.0	4275.5	0.19	0.80	0.71	0.90
Michigan	83	892.0	3966.8	5223.0	6115.0	0.11	0.51	0.67	0.79
Pennsylvania	67	1173.8	4519.3	5024.9	6198.8	0.18	0.69	0.77	0.95
Minnesota	87	1283.1	2104.9	3173.0	4456.0	0.20	0.33	0.50	0.71
Wisconsin	72	1378.7	2781.8	3526.9	4905.6	0.21	0.42	0.53	0.74
Maine	16	2346.3	733.8	5256.2	7602.5	0.34	0.11	0.76	1.10
Northern U.S.	1038	11663.3	48069.1	44873.6	56536.9	0.17	0.72	0.67	0.84

[a] Number of selected counties per state and for the entire Northern U.S.

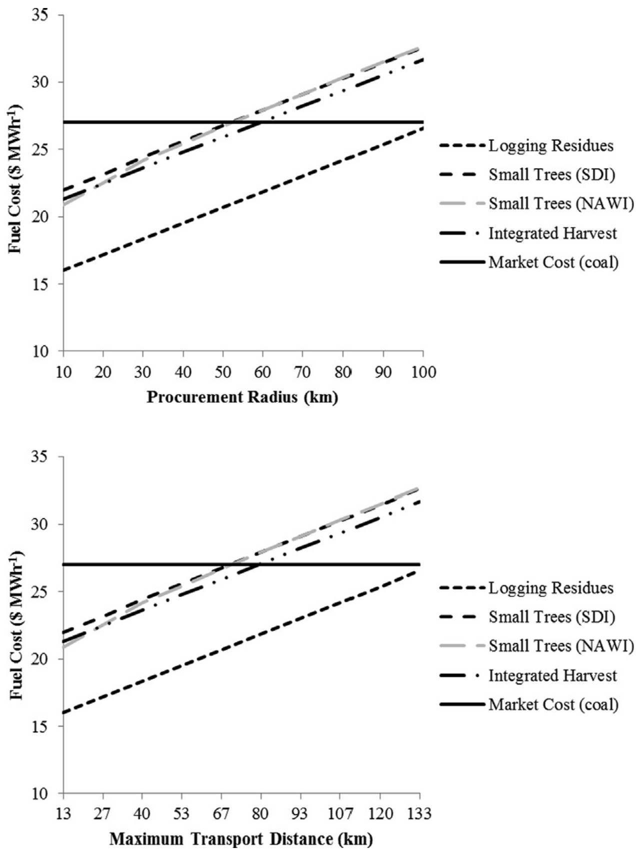

Fig. 2 – Estimated averages in marginal delivered cost of woody biomass by procurement radius and transport distance based on cost per unit energy.

delivered cost of woody biomass by procurement radius and maximum transport distance for the 219 selected power plants for all procurement regimes.

As indicated by the cost assumptions in Table 1, procurement regimes focused on removal of small-diameter trees had the highest delivered costs for woody biomass. Delivered fuel costs from integrated harvesting were only slightly lower due to high percentages of small-diameter material making up the total available biomass through integrated harvest. Marginal delivered costs of logging residues were less than 75% of the cost for biomass from integrated harvesting, due to lower operational costs. Consequently, woody biomass from logging residues could be obtained from a much greater transport distance than small-diameter trees or integrated harvest. The relatively abrupt increase in marginal fuel cost for NAWI at low transport distances is caused primarily by individual counties with zero values for NAWI, in which operational costs are indicative of unused mill by-products. The break-even point for all procurement regimes except logging residues occurs at around a 55–65 km procurement radius or 75–85 km maximum transport distance. This coincides with findings by Sami et al. [18] and Nicholls et al. [21] indicating that on average 90–97 km is the maximum economically feasible transport distance for woody biomass to power plants.

4.3. *Potential electric power generation from co-firing*

The assessment of co-firing potential for individual plants required knowledge of both delivered fuel costs and biomass electricity generation that could be achieved by plants based on the concentric procurement areas. Therefore, an important comparison between the procurement regimes is an estimate of the average annual amount of electricity that could be generated by selected power plants at varying procurement radii. Annual electricity generation was calculated by applying the 1.7 MWh Mg^{-1} conversion rate to average available woody biomass for each procurement radius. For comparison, we estimated the average annual net generation from coal (3.007 TWh) of all selected power plants and calculated percentages of that value to represent possible levels of coal replacement with woody biomass [15]. Note that these estimates do not account for overlapping procurement areas between power plants, meaning that we assumed each plant was co-firing individually without resource competition from nearby power plants. However, the effects of procurement area overlap on annual net generation potential will be discussed. Fig. 3 shows the estimated mean annual electricity generation among selected power plants by procurement regime and transport distance.

Based on the analysis of delivered fuel costs, potential mean annual electricity generation at 60 km procurement radius is of particular interest in Fig. 3. Removal of small-diameter trees under NAWI had the greatest potential for electricity generation (~19% of coal generation at 60 km), mainly due to high values for woody biomass spatial distribution density (Table 2). The combination of forest thinning through SDI and logging residues leads to relatively high electricity generation potential through integrated harvest (>15% of coal generation at 60 km), second only to NAWI. Notice that logging residues was the only procurement regime that on average could not supply enough woody biomass to achieve even a 10% replacement of coal within a 60 km procurement radius.

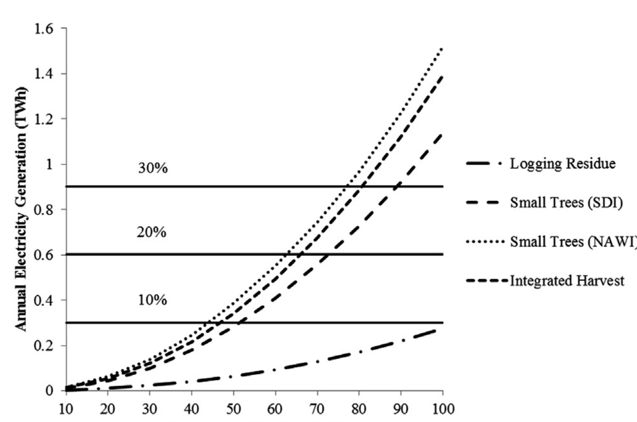

Fig. 3 – Estimated mean annual electricity generation for selected power plants by procurement regime and procurement radius. Percentages of mean annual coal electricity generation from selected power plants are shown as horizontal lines and labeled separately.

Fig. 3 showed that, on average, selected power plants in the Northern U.S. can generate substantial amounts of electricity (>15% of coal generation at 60 km) using biomass for most procurement regimes on an individual basis. However, it is unlikely that many plants will be able to take full advantage of the available woody biomass within the procurement area due to competition from other co-firing power plants. Deducting duplication of biomass electric power production from zones of overlap between the procurement areas of all selected power plants and assuming a 60 km procurement radius yields average woody biomass power estimates of 37.6 GWh, 193.1 GWh, 210.1 GWh, and 157.9 GWh for logging residues, integrated harvest, NAWI, and SDI respectively. This means that if each power plant has to compete for biomass resources with neighboring plants, on average no procurement regime would be able to supply enough woody biomass to achieve even 10% of coal electricity generation. The issue of overlapping procurement areas will be discussed further in the next section.

4.4. Power plants poised to co-fire with biomass

Counties with the highest potential for co-firing were 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. Therefore, we assume a 60 km maximum procurement radius because the delivered fuel cost analysis revealed that it is the approximate break-even point for most procurement regimes between delivered cost of woody biomass and coal market value. For this assessment, we focused on the logging residues and integrated harvest procurement regimes as they represent two different extremes regarding average woody biomass availability for co-firing. In this case, co-firing potential for individual plants was gauged by the percentage of annual coal net generation that could be generated using woody biomass (Fig. 4). We calculated this percentage for each plant based on two contrasting assumptions: (1) each plant would co-fire individually with no deduction of biomass availability for overlapping procurement areas with other plants, and (2) woody biomass availability for each plant was deducted for procurement area overlap. In reality, it would not be physically possible for all plants to co-fire independently without procurement area overlap, but this comparison serves to illustrate the change in spatial distribution of power plants by co-firing potential in the presence of procurement area overlap.

Aside from the relatively higher levels of co-firing generation potential from integrated harvest compared to logging residues which was expected, there is a noticeable trend in spatial distribution of power plants with high co-firing potential between these two regimes (Fig. 4, A and C). Many plants in the Great Lake states and the Northeast sub-region have a very high co-firing potential for both integrated harvest and logging residues. Areas that are intensively harvested, and therefore have high availability of logging residues, can also have low SDI estimates due current harvest removals. Therefore, many plants with high co-firing potential for logging residues do not experience a great increase in available biomass with integrated harvest. Both procurement regimes show the highest concentration of power plants with high co-firing potential to occur in eastern states such as 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 residues and mill by-products [20].

When we deducted available biomass for overlapping procurement areas, there was a substantial decrease in the co-firing potential of most power plants (Fig. 4, B and D). Most notable decreases occurred in eastern states such as Pennsylvania, West Virginia, and Maryland. This is due not only to woody biomass availability, but also to the higher density of selected power plants in these areas competing for the same resource. From the standpoint of an individual plants ability to achieve a high percentage of coal electricity generation using woody biomass, many of the plants in the Great Lake states such as Minnesota, Wisconsin, and Michigan are the most stable, due to a combination of biomass availability and relative isolation from other co-firing power plants.

4.5. Sensitivity of costs and public policy

Assuming the average coal cost of 27 $ M Wh^{-1} [46], the break-even point for most procurement regimes occurs at about 60 km procurement radius. However, past trends show that coal market prices can change swiftly due to general changes in fossil fuel costs and fluctuation in the overall economy. The period between 2005 and 2010 averaged market values of coal at 22 to 23 $ M Wh^{-1} [46]. The highest average (32 $ M Wh^{-1}) occurred in 2009 following the start of the global economic recession and represented a 14% increase from the previous year. Theoretically, if the coal market value were to increase by 14%, the procurement radii could increase to 100 km and still be economically feasible (Fig. 2). However, this estimate does not account for increase in the per-unit cost of delivered feedstock as demand increases.

One of the greatest causes of elasticity in harvesting and transport of woody biomass is fluctuation in operational fuel (diesel) prices. Although greatly driven by demand, coal prices can be affected by volatility in petroleum prices as petroleum prices are often considered an indicator of investor attitudes toward energy [48,49]. More importantly, increases in petroleum prices would most likely affect delivered fuel prices of both biomass and coal as both feedstocks depend on petroleum for transport. Based on Fig. 2, the increase in transport distance to meet the break-even point for 1% increase in coal market value could be offset by either a 3.5% increase in incremental transportation cost or a 2.2% increase in total operational costs at the landing (harvesting and chipping), which is certainly possible depending on the region [25]. Results of the sensitivity analysis for the cost function of integrated harvest (Table 3) helps to clarify the importance of transport cost elasticity in economic feasibility of co-firing.

A percentage change in harvest cost of logging residues was the least influential to delivered fuel cost of woody biomass, primarily due to the low percentage of total available woody biomass comprised by logging residues for integrated harvest. In contrast, a 25% change in cost of small-diameter trees led to a 7.2% change (6.6% greater than logging residues) in the delivered cost of woody biomass. Of particular interest is the high sensitivity of the cost function to procurement radius and incremental transport cost. Both show similar changes in delivered cost of woody biomass by percentage above or below the initial estimate. A 25% change in incremental transport cost equates to a change of only 0.04 $ Mg^{-1} km^{-1} in incremental transport cost and leads to a change of 6.5% in delivered cost of woody biomass. Essentially, there is about a 1:1 relationship in sensitivity between procurement radius and incremental transport cost, meaning that to maintain the break-even point with coal price the procurement radius would need to be decreased by nearly the same percentage of increase in incremental transport cost.

Decreasing supply area due to disproportionate delivered fuel costs of biomass compared to coal highlights a potential renewable energy policy issue with regard to woody biomass usage. Although supply of both coal and biomass feedstocks could increase readily with increasing price, it is unlikely that most power plants would be able to easily adjust supply area for biomass, mainly due to pre-established contracts with local suppliers and transporters [23,50]. Moreover, RPS in some of the Northern States set maximums on the percentage of annual energy production that can come from other renewable energy sources such as solar and wind. For instance, Minnesota set an RPS of 25% of retail electricity being renewable by 2025, with a maximum of 1% that can be solar photovoltaic. Based on the assumptions of this study, it is unlikely that many selected plants would be able to supplement more than 10% of net annual electricity generation with woody biomass, with an even lower percentage when using only logging residues (Fig. 3). However, higher efficiency power units such as co-generation facilities could potentially double this percentage for certain areas.

Increasing demand for woody biomass due to RPS may necessitate the use of compensatory incentives to offset

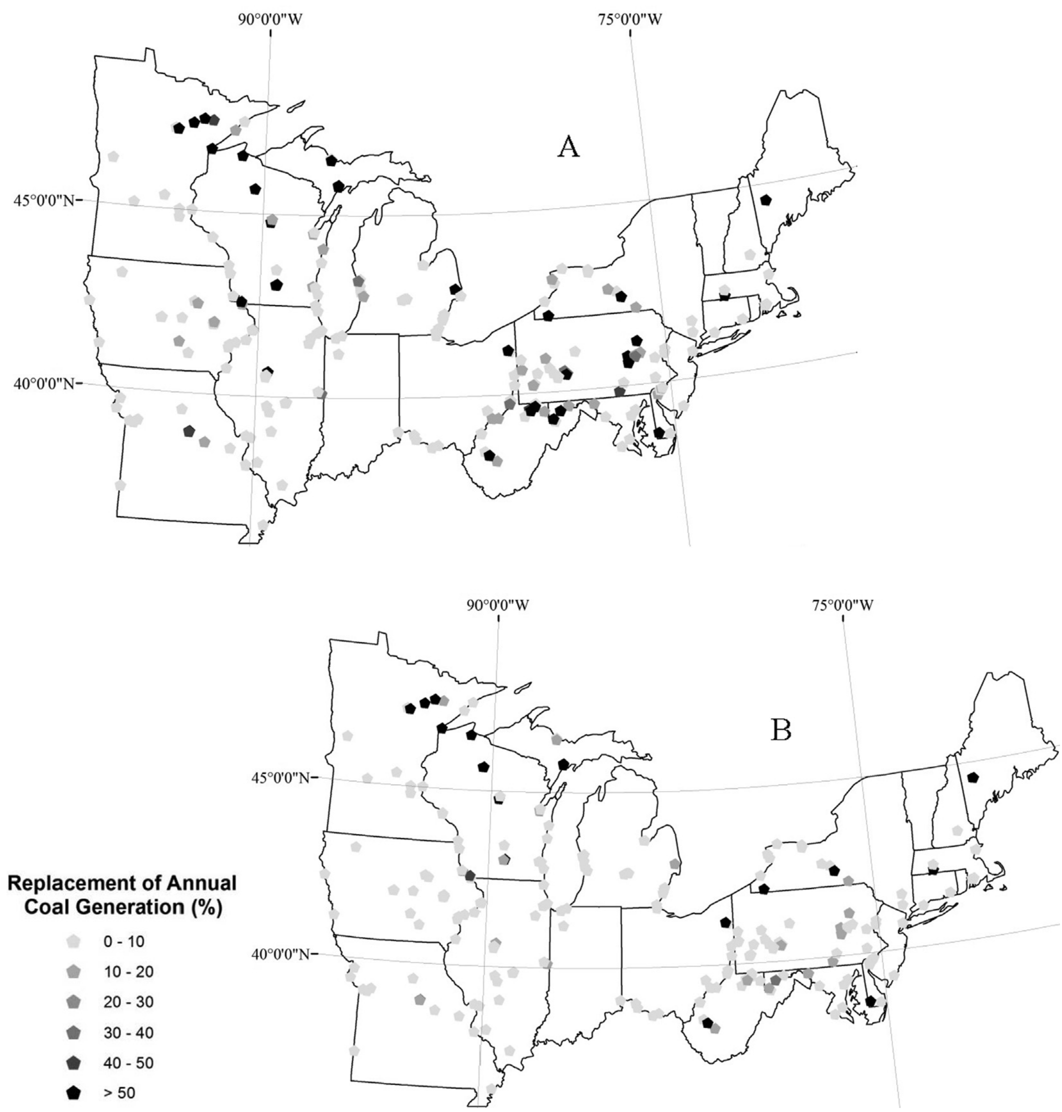

Fig. 4 – Estimated potential percentage of annual coal electricity generation that could be replaced by woody biomass for each selected power plant at a 60 km concentric procurement radius assuming (A) logging residues regime (no deduction for overlap), (B) logging residues regime (deduction for overlap), (C) integrated harvest regime (no deduction for overlap), and (D) integrated harvest regime (deduction for overlap). Latitude and longitude are represented in GCS North America 1983 datum.

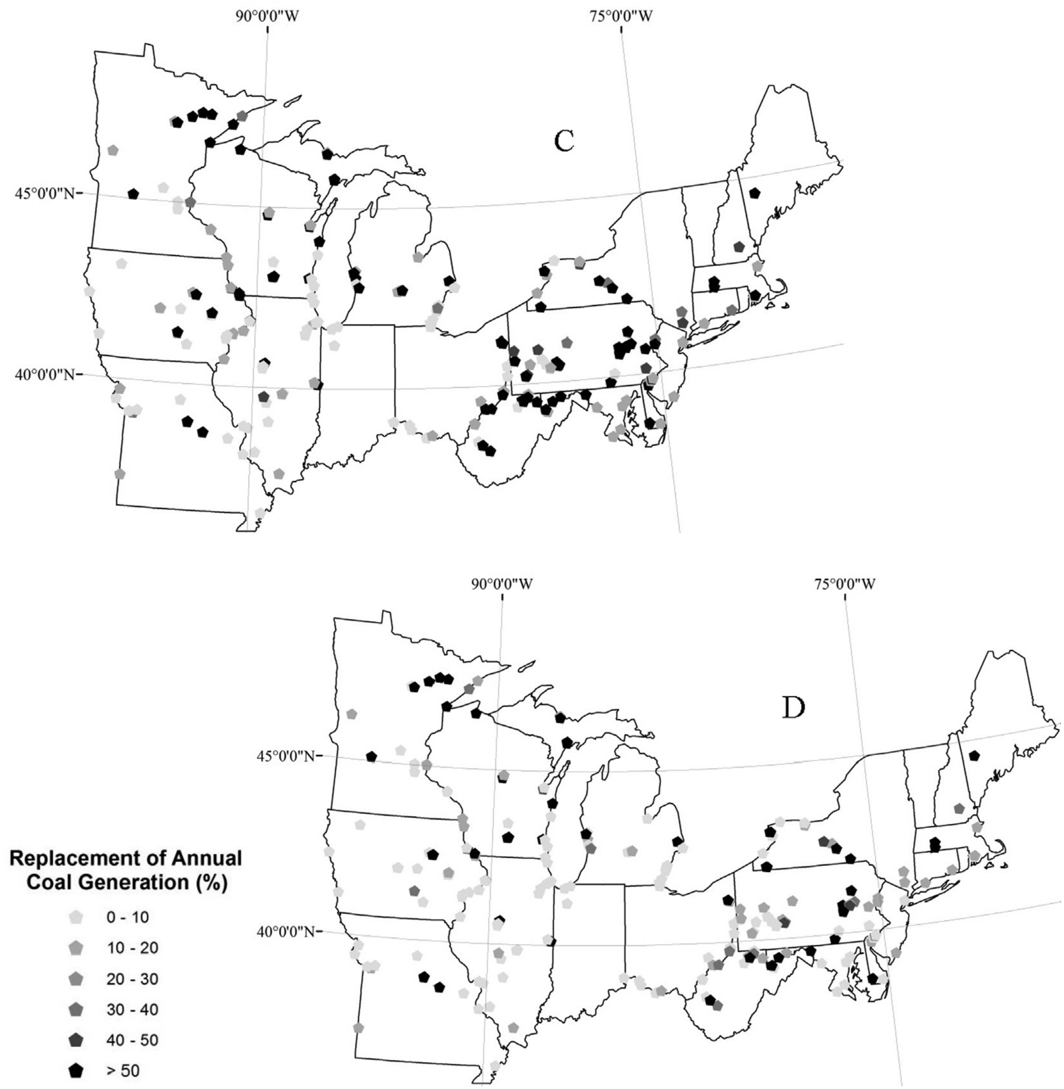

Fig. 4 — (*continued*).

Table 3 — Selective sensitivity analysis for the integrated harvest regime in the Northern U.S.

Cost component	Initial estimate		Component increase							
			−50%		−25%		25%		50%	
	Parameter	Cost[a]	Cost[a]	Change	Cost[a]	Change	Cost[a]	Change	Cost[a]	Change
		$ Mg^{-1}	$ Mg^{-1}	%	$ Mg^{-1}	%	$ Mg^{-1}	%	$ Mg^{-1}	%
Procurement radius (km)	60	46.05	40.04	−13.0	43.04	−6.5	49.05	6.5	52.04	13.0
Harvest ($ Mg^{-1})										
Logging residues	6.42	46.05	45.54	−1.1	45.79	−0.5	46.30	0.5	46.55	1.1
Small-diameter trees	16.04	46.05	39.39	−14.4	42.72	−7.2	49.37	7.2	52.70	14.4
Transport ($ Mg^{-1} km^{-1})	0.15	46.05	40.05	−13.0	43.05	−6.5	49.05	6.5	52.04	13.0
Stumpage ($ Mg^{-1})	7.16	46.05	42.68	−7.3	44.36	−3.7	47.73	3.7	49.41	7.3
Chipping ($ Mg^{-1})	5.51	46.05	43.33	−5.9	44.69	−3.0	47.40	3.0	48.76	5.9

[a] Marginal delivered fuel cost measured in $ Mg^{-1} and averaged between the 219 selected counties.

additional costs associated with transporting biomass feedstocks greater distances. In the absence of such incentives, power plants would either need to pass the extra cost to the consumer through retail price premiums or obtain more biomass from smaller supply areas (shorter transport distances). The latter could lead to ecological sustainability issues if co-firing power plants are pushed to utilize more biomass than can be sustainably procured within an economic transport distance. This is especially true if the annual woody biomass demand is greater than NAWI. Demand for woody biomass from forests could be partially offset by dedicated energy plantations using woody crops such as hybrid poplars and willows on marginal land in close proximity to power plants [2,51,52] However, it may be necessary in some states to set a maximum on the amount of co-fired electricity that can be produced to achieve the RPS – unless conversion efficiencies are enhanced and/or plantation biomass made available. Additionally, ecological concerns may call for the mandatory adoption of best management practices (BMPs) specifically tailored to woody biomass procurement, such as the woody biomass harvesting BMPs developed by the Missouri Department of Conservation [53] and others. Such BMPs incorporate woody biomass harvesting principles to support sustainable forest management [54].

5. Conclusions

Availability of wood biomass from forests and unused mill by-products suggests that numerous power plants in the Northern U.S. have a high potential for woody biomass co-firing. However, biomass spatial distribution and transport distances may greatly limit the levels of coal replacement. Differences in individual plant electricity generation potential are mainly driven by the spatial distribution of woody biomass, and anticipated harvest intensity for sawlogs and pulpwood. Variability in woody biomass spatial distribution and costs shows that a single uniform renewable energy target from biomass for all facilities would not be an adequate public policy approach but tailored state-, or even county-level targets would allow for varying rates of co-firing to match local biomass supply conditions. State-level RPS and restrictions placed on other forms of renewable energy creates pressure on co-firing facilities to utilize more woody (and other types of) biomass than may be sustainably available within economically-feasible procurement distances. Incentives to use woody biomass could expand transport distances and the amounts of woody biomass that are economically feasible for particular facilities, but the need for such incentives may be reduced if facilities are upgraded to use higher efficiency boiler systems. Demand for woody biomass from forests could be partially offset by emerging availability of biomass from dedicated energy plantations.

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Appendix

County-level SDI was calculated as follows [55]:

$$SDI_i = TPH_i \left(\frac{QMD_i}{25}\right)^{1.605}$$

where TPH is the average number of trees per unit area for county i, and QMD is the quadratic mean diameter for county i. Species dominance was determined for each county based on the ratio of softwood volume to total volume on timberland. A county was classified as hardwood if the ratio was $<25\%$, mixed if the ratio was $\geq 25\%$ and $<65\%$, and softwood if the ratio was $\geq 65\%$.

Net annual woody biomass increase (NAWI) for each county was calculated as follows:

$$NAWI_i = \frac{Vol\_g_i - Vol\_r_i}{Vol\_t_i} * Bio_i,$$

where Vol_g_i represents the estimated total annual net volume growth on timberland for county i, Vol_r_i is the estimated total annual volume of removals on timberland for county i, Vol_t_i is the estimated total live standing volume on timberland for county i, and Bio_i is the estimated total aboveground tree biomass on timberland for county i.

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