Regional Assessment of Woody Biomass Physical Availability as an Energy Feedstock for Combined Combustion in the US Northern Region

Michael E. Goerndt, Francisco X. Aguilar, Patrick Miles, Stephen Shifley, Nianfu Song, and Hank Stelzer

ABSTRACT

Woody biomass is a renewable energy feedstock with the potential to reduce current use of nonrenewable fossil fuels. We estimated the physical availability of woody biomass for cocombustion at coal-fired electricity plants in the 20-state US northern region. First, we estimated the total amount of woody biomass needed to replace total annual coal-based electricity consumption at the state level to provide a representation of the potential energy footprints associated with using woody biomass for electric energy. If all woody biomass available were used for electric generation it could replace no more than 19% of coal-based electric generation or 11% of total electric energy generation. Second, we examined annual woody biomass increment at the state level in a series of concentric circles around existing coal-fired electricity plants to examine some of the opportunities and limitations associated with using woody biomass for cofiring at those plants to coincide with state-level renewable portfolio standards. On average, an individual coal-fired power electricity plant could theoretically replace 10% of annual coal use if it obtained 30% of the net annual woody biomass increment within a 34-km radius of the plant. In reality, the irregular spatial distribution of coal-fired power plants means potential biomass supply zones overlap and would greatly diminish opportunities for cofiring with biomass, numerous other regulatory, economic, and social considerations notwithstanding. Given that woody biomass use for electricity will be limited to selected locations, use of woody biomass for energy should be complementary with other forest conservation goals.

Keywords: woody biomass, renewable energy, co-combustion, US Forest Inventory and Analysis

Greater generation of renewable energy has been adopted as a public policy to reduce national dependence on fossil fuels and limit associated emissions of anthropogenic carbon (Schneider and Held 2001, Jacobson 2002). Woody biomass is one of the renewable energy feedstocks capable of reducing carbon emissions by substituting woody biomass for fossil fuels (Malmsheimer et al. 2008). Although burning fossil fuels releases into the atmosphere carbon that was buried underground for millennia, the burning of biomass for energy releases carbon that has been sequestered in plants for no more than a few hundred years. Although it may take several decades, replacement crops can sequester an amount of carbon equivalent to that released by burning biomass (Hoogwijk et al. 2003, Tilman et al. 2006). As a renewable energy source, biomass can be a sustainable, low-carbon feedstock if managed properly (Schlamadinger et al. 1995, Schwaiger and Schlamadinger 1998, Malmsheimer et al. 2008) and in many locations in the United States biomass is being used or considered for use in renewable energy production.

In the United States, the Energy Information Administration (EIA) reports that energy generated from woody biomass in 2008 comprised about 3% of total energy consumption and about 41% of all renewable energy (EIA 2010). Among different

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Michael E. Goerndt (goerndtm@missouri.edu) is postdoctoral fellow, and Francisco X. Aguilar (aguilarf@missouri.edu) is assistant professor, Department of Forestry, University of Missouri, 203 Anheuser-Busch Natural Resources Building, Columbia, MO 65211. Patrick Miles (pmiles@fs.fed.us) is research forester, Northern Research Station, USDA Forest Service, St. Paul, MN 55108. Stephen Shifley (sshifley@fs.fed.us) is research forester, Northern Research Station, USDA Forest Service, Columbia, MO 65211. Nianfu Song (songn@missouri.edu) is postdoctoral fellow, Department of Forestry, University of Missouri, 203 Anheuser-Busch Natural Resources Building, Columbia, MO 65211. Hank Stelzer (stelzerh@missouri.edu) is associate professor, Department of Forestry, University of Missouri, 203 Anheuser-Busch Natural Resources Building, Columbia, MO 65211. *The authors thank Gregg Coffin, Carl Mize, Gene Garrett, and John Dwyer for their good advice and assistance through the development of this article. This research was supported by the Northern Research Station under US Forest Service Agreement 09-PA-11242305-143.*

biomass feedstocks, woody biomass is currently responsible for the greatest share of bioenergy generation at about 53%. Woody biomass can be sourced from logging and other residues, treatments to reduce fuel buildup in fire-prone forests, fuelwood, forest products industry wastes, urban wood residues, and energy plantations (Malmsheimer et al. 2008). Forestlands in the contiguous United States can produce an estimated 368 million dry tons of woody biomass annually. This estimate includes 52 million dry tons of fuelwood harvested from forests, 145 million dry tons of residues from wood processing mills and pulp and paper mills, 47 million dry tons of urban wood residues including construction and demolition debris, 64 million dry tons of residues from logging and site clearing operations, and 60 million dry tons of biomass from fuel treatment operations to reduce fire hazards (Perlack et al. 2005). Emerging biofuels markets may increase values for small-diameter and residue material that previously had little to no merchantable value with the potential to increase revenues during integrated timber and biomass harvesting systems (Hudson and Mitchell 1992). Energy markets for woody biomass may provide sufficient incentives to remove small-diameter woody material while pursing compatible conservation activities such as precommercial thinning, hazardous fuels reduction, woodland habitat restoration, and certain types of wildlife habitat improvement. Studies addressing a wide range of objectives and local conditions have been conducted and continue to be implemented to assess the economic feasibility of harvesting woody biomass from working forests (e.g., Puttock 1995, Becker et al. 2006, Mitchell and Gallagher 2007, Bolding et al. 2009, Saunders et al. 2011).

Using biomass for cocombustion with coal during electric generation can be a viable option for increasing renewable energy production (Baxter 2005). Combustion of woody biomass in conjunction with coal at existing coal-fired electric plants can be a relatively inexpensive and low-risk method of increasing renewable energy generation in the short term. Furthermore, unlike wind and solar energy, woody biomass can be readily stored (e.g., as chips or on the stump) and used when needed. In a survey conducted by Aguilar and Garrett (2009), respondents ranked combustion of woody biomass (including cocombustion with coal) above all other woody biomass energy technologies, including cellulosic ethanol, gasification, and pyrolysis. Therefore, we focused this analysis on the potential capacity to use woody biomass for cocombustion with coal at existing coal-fired electric plants. Woody biomass from native forests exists in large quantities across the region and it is the focus of our analyses. Among energy types, we identified electricity over heating and cooling because electricity represents the primary form of usable energy for the residential, commercial, and industrial sectors and comprises about 41% of total annual energy consumption (EIA 2010). It is worth mentioning the potential of woody and nonwoody (herbaceous) crops to grow energy feedstock. We do not include biomass from dedicated energy crops because these markets are yet to emerge.

Our regional approach concentrated on the 20-state northern region of the United States as defined by the US Forest Service (Smith et al. 2009) including 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 selected for various reasons. First, woody biomass combustion was identified as a major potential source of renewable energy in the region (Aguilar and Garrett 2009). Second, the region is endowed with large acreages of forestland that potentially could benefit from additional forest management practices associated with sustainable woody biomass harvests (Smith et al. 2009). Third, it hosts a large number of coal-fired power plants (Department of Energy [DOE] 2010), many of which could add biomass as a supplemental fuel in a short time with relatively low levels of modification.

We aimed to evaluate the potential to produce energy and replace coal in power plants in the northern region based on physically available woody biomass. Three specific objectives in this study examined energy consumption equivalence relative to woody biomass at multiple spatial scales: the northern region, individual states, and in proximity to major coal-fired electric generation facilities. First, we summarized data on electricity consumption and biomass resources at state and regional scales to compare current electricity use with an estimate of the maximum capacity of woody biomass to generate electricity. Second, at the state level we estimated the apparent capacity of woody biomass on timberland to replace various proportions of current coal-fired electric production motivated by renewable energy portfolio standards (RPS). Third, we examined the woody biomass resources in the area surrounding each of the existing coal-fired electric plants as a first approximation of the potential capacity of timberland to supply energy feedstocks to local power plants. Note that this assessment focuses on the *physical* capacity of the timberland woody biomass as a feedstock for cocombustion in coal-fired power plants irrespective of plant-level conversion issues such as pulverized coal boilers.

Methods

Forest Resource Energy Footprint—Volumes and Area

An energy footprint is a measure of how much material or area is needed to meet energy consumption by a particular country, region, state, person, or other group (Wackernagel et al. 2004). Although there are alternative ways to measure energy footprints, we computed the amount of woody biomass that would be required to produce a quantity of electricity equivalent to current electricity consumption for each state in the northern region. Total electrical energy use and percentage of generation by fuel type is shown for each state in Table 1 (EIA 2010). Coal is the primary source of electricity in the region so we compute the electric energy footprint for total electricity consumption and for coal-fire electrical consumption.

We used data from the Forest Inventory and Analysis (FIA) National Program with the associated EVALIDator software (Northern Research Station, USDA Forest Service, Newtown Square, PA) (Miles 2011, US Forest Service 2011) and the conversion factors provided in the Appendix to equate current levels of electricity consumption with the corresponding quantity of aboveground woody biomass (dry tons) and the area (hectares) of timberland [1] that would be necessary to produce an equivalent amount of electricity (EIA 2010). This is an estimate of the biophysical maximum aboveground biomass that could conceivably be used as bioenergy feedstock. To estimate electric energy footprints, we estimated mean metric dry tons (MDT) of total aboveground biomass per hectare of timberland for each state based on the most recent FIA data available (Miles 2011), and we used estimates of 2008 electricity consump-

Table 1. Electrical consumption by state (in million megawatt hours) and percentages by source for the US northern region in 2008.

State	Total (MMwh)	Percentage by source (%) Coal	Natural gas	Petroleum	Nuclear	Hydroelectric	Biomass	Wind	Net imports
Rhode Island	6	0	88	<1	0	<1	3	0	9
Delaware	7	80	16	2	0	0	2	0	0
Vermont	9	0	<1	<1	52	16	6	<1	26
Maine	13	3	31	2	0	29	26	1	8
New Hampshire	23	18	23	1	41	7	7	<1	4
Connecticut	31	15	20	2	50	2	4	0	7
Massachusetts	42	25	38	5	14	3	5	<1	10
Maryland	48	59	4	1	30	4	2	0	0
Iowa	55	78	3	<1	10	1	<1	7	0
New Jersey	62	16	29	<1	52	<1	2	<1	0
Minnesota	64	53	4	<1	20	1	3	7	12
Wisconsin	65	69	7	1	19	2	1	1	<1
West Virginia	92	98	<1	<1	0	1	0	<1	0
Missouri	94	83	5	<1	10	2	<1	<1	<1
Michigan	120	60	8	<1	26	1	2	<1	2
Indiana	134	97	3	<1	0	<1	<1	<1	<1
New York	152	13	27	3	28	18	2	1	9
Ohio	156	86	2	1	11	<1	<1	<1	0
Illinois	204	50	2	<1	47	<1	<1	1	<1
Pennsylvania	222	54	7	<1	35	1	1	<1	<1
Northern Region	1,600	58	9	1	24	3	1	1	2

Net imports = electricity imported in 2008 after accounting for exports (EIA 2010); MMwh, million megawatt hours. Totals may not be cumulative because of rounding and variation in conversion factors from heat energy to megawatt hours between different energy sources.
Source: Adapted from EIA 2010.

tion from the EIA (EIA 2010) to calculate the metric tonnage and corresponding hectares of timberland that would be needed to replace the current total and coal-based electrical consumption for the region and for individual states. We used a conversion factor of 1.7 megawatt hours of electricity per MDT of biomass to estimate the quantity of biomass needed to offset a given amount of coal-fired electric production (EIA 2010). We converted that quantity of woody biomass to a corresponding timberland area based on the mean aboveground tree biomass per hectare of timberland.

Renewable Energy Scenarios at State and Energy Plant Levels

One type of renewable energy policy that will have a significant impact on the future of woody biomass energy in the northern region is the adoption of RPSs (Aguilar and Garrett 2009). As of September 2010, 46 US states and all states in the northern region except Indiana had adopted renewable RPSs (Database of State Incentives for Renewables and Efficiency [DSIRE] 2010). The specifics of these standards vary by state, but all require renewable energy to be a component of state energy production. For example, Pennsylvania recently set a mandate that 18% of state energy must come from renewable fuels by 2021. Missouri has a mandate for 15% renewable electricity by 2021 (Bird and Lokey 2008). Renewable energy standards encompass many forms of renewable energy such as wind, geothermal, and solar as well as biomass and usually have compliance dates within the next 15 years.

We evaluated the potential to use woody biomass for compliance with various levels of renewable energy mandates in the region. We first used state-level woody biomass statistics described in the previous section to assess the maximum percentage of coal-based electrical power consumption that potentially could be replaced with woody biomass at the state level. Next, we used a spatially explicit approach to more precisely estimate the potential capacity to use woody biomass in conjunction with coal at 350 coal-fired electricity plants in the northern region. This part of the analysis was restricted to eight different energy scenarios, including 3, 5, 8, 10, 12, 15, 18, and 20% substitution of woody biomass for coal. These levels were chosen because they span the range of existing RPSs for states in the US northern region, although most coal-fired power plants would probably not be able to cofire at 20% without additional equipment modifications, which could increase costs considerably (DSIRE 2010). This component of the analysis captured the spatial dimension inherent to using woody biomass for cocombustion with coal by exploring forest biomass resources in proximity to existing coal-fired power plants. The underlying assumption is that for at least some of these facilities cocombustion of woody biomass with coal can provide a relatively rapid and simple way to boost renewable energy production (Baxter 2005).

A clear limitation on the sustainability of using woody biomass for energy is whether or not biomass can be attained without depleting the amount of available biomass over time. To address this issue, we estimated the net annual woody biomass increase (NAWI) for each state as follows:

$$\mathrm{NAWI}_i = \frac{\mathrm{Vol\_g}_i - \mathrm{Vol\_r}_i}{\mathrm{Vol\_t}_i} * \mathrm{Bio}_i,$$

where $\mathrm{Vol\_g}_i$ represents the estimated total annual net cubic foot volume growth [2] on timberland for state *i*, $\mathrm{Vol\_r}_i$ is the estimated total annual cubic foot volume of removals on timberland for state *i*, $\mathrm{Vol\_t}_i$ is the estimated total live standing cubic foot volume on timberland for state *i*, and Bio_i the estimated total aboveground tree biomass on timberland for state *i* (US Forest Service 2011). Annual volume growth and removals were calculated from FIA using sequential plot measurements from 1999 to 2008 (US Forest Service 2007, Woudenberg et al. 2010, Miles 2011). We computed the net biomass increment as a ratio of the corresponding cubic volume increment because (a) biomass is highly correlated with cubic volume and (b) cubic volume growth and removals can be computed directly using FIA databases although there currently is no corresponding option for directly computing biomass growth and removals. NAWI is similar to the biological maxima criterion used by Perlack et al. (2005) to assess sustainable annual biomass availability. We used NAWI to estimate the maximum quantity of woody biomass per state that could be used annually for cocombustion without reducing total forest biomass over time. However, some proportion of NAWI consists of wood that has value as sawtimber or veneer. To address this issue, we calculated the proportion of total aboveground biomass on timberland by tree class and merchantability class by state. We used these

Table 2. State level estimates of the quantity of woody biomass on timberland and approximate annual harvest area needed to replace annual consumption of coal-fired electricity and total electricity generation as well as current consumption of biomass for electricity.

	Coal electricity		Total electricity		Current biomass consumption for electric generation	
State	MMDT (%[b])	Equivalent area[a] 1,000 ha (%[b])	MMDT (%[c])	Equivalent area 1,000 ha (%[b])	MMDT (%[c])	Equivalent area 1,000 ha (%[b])
Rhode Island	0 (0)	0 (0)	3 (16)	22 (16)	0.1 (0.5)	1 (0.5)
Delaware	3 (15)	21 (15)	4 (19)	26 (19)	0.1 (0.5)	1 (0.5)
Vermont	0 (0)	0 (0)	4 (2)	31 (2)	0.3 (0.1)	2 (0.1)
Maine	<1 (<1)	2 (<1)	6 (1)	75 (1)	1.8 (0.3)	21 (0.3)
New Hampshire	2 (1)	16 (1)	12 (5)	91 (5)	0.9 (0.4)	7 (0.4)
Connecticut	2 (2)	15 (2)	16 (15)	100 (15)	0.7 (0.7)	4 (0.7)
Massachusetts	6 (3)	36 (3)	21 (12)	136 (12)	1.1 (0.6)	7 (0.6)
Maryland	15 (10)	93 (10)	26 (17)	162 (17)	0.4 (0.3)	3 (0.3)
Iowa	22 (22)	265 (22)	29 (28)	342 (28)	0.1 (<0.1)	1 (<0.1)
Minnesota	18 (5)	285 (5)	31 (8)	505 (8)	0.9 (0.2)	15 (0.2)
New Jersey	5 (6)	42 (6)	33 (36)	270 (36)	0.7 (0.8)	6 (0.8)
Wisconsin	23 (4)	284 (4)	34 (6)	418 (6)	0.5 (0.1)	6 (0.1)
West Virginia	47 (7)	321 (7)	48 (7)	327 (7)	0 (0)	0 (0)
Missouri	40 (7)	447 (7)	49 (9)	544 (9)	<0.1 (<0.1)	<0.1 (<0.1)
Michigan	38 (5)	417 (5)	63 (9)	694 (9)	1.2 (0.2)	13 (0.2)
Indiana	67 (30)	557 (30)	70 (31)	577 (31)	0.2 (<0.1)	1 (<0.1)
New York	10 (1)	83 (1)	76 (10)	613 (10)	1.6 (0.2)	13 (0.2)
Ohio	70 (17)	539 (17)	82 (20)	632 (20)	0.2 (<0.1)	1 (<0.1)
Illinois	53 (25)	484 (25)	109 (53)	997 (53)	0.5 (0.2)	5 (0.2)
Pennsylvania	63 (7)	459 (7)	118 (13)	862 (13)	1.5 (0.2)	11 (0.2)
Northern region	484 (6)	4365 (6)	832 (11)	7421 (11)	12.8 (0.2)	119 (0.2)

[a] Number of hectares that would need to be harvested to produce the quantity of biomass indicated assuming each hectare had the statewide mean biomass per hectare and percent of all timberland.
[b] Percentages of current existing timberland woody biomass or timberland hectares are given in parentheses.
MMDT, million metric dry tons and percent of total state biomass.

and other considerations such as proportion of small-diameter material to arrive at a reduced estimate (30% of NAWI) of biomass availability that we also applied to estimate the proportion of available biomass for co-firing. Thus, we used a 70% reduction from the biophysical maximum annual wood biomass (NAWI) as an additional constraint on scenario analyses.

We used the spatial coordinates of 350 existing coal-fired electric plants in the study area to query FIA data in concentric circular rings around each one and estimate the corresponding NAWI within each ring using computations analogous to those outlined in Equation 1 (Woudenberg et al. 2010, Miles 2011). Computations mirrored those used for statewide biomass estimates, but in this case computations were spatially explicit within the concentric circles surrounding each coal-fired plant. Concentric circles around each power plant increased in 8-km radial increments. We extended radii to a maximum of 160 km for analytical purposes.

When coupled with 2007 estimates of net coal plant electrical generation from DOE (2010), calculation of NAWI made it possible to estimate the upper bound on the proportion of annual coal-fired electricity generation that woody biomass could supplant for a particular facility and woody biomass supply radius. We considered scenarios based on use of total NAWI and 30% of NAWI within multiple radii around each coal-fired electricity plant as outlined previously.

Results and Discussion

Statewide Estimates of Biomass Necessary to Offset Coal for Electricity Generation

Table 2 shows the estimated quantity of woody biomass that would be required to supplant total and coal-fired electricity electric generation by state and for the region based on 2008 EIA and FIA data (EIA 2010, US Forest Service 2011). The table also includes estimates of current biomass use for electric generation. These data put electric energy consumption in context with its equivalent quantity of woody biomass. For the entire 20-state region, using biomass to replace the coal used for electric generation would annually require 484 million MDT of biomass or all the aboveground biomass on 4.4 million average acres of timberland. That amounts to 6% of all biomass (and all forest acreage) in the region each year. Consequently, all the woody biomass on timberland in the region would be depleted for energy production within about 17 years if removed at this level. Using biomass combustion to produce total electricity from all sources consumed in the region (as opposed to coal-fired only) would deplete the region's woody biomass in about 9 years (11% per year; Table 2). Based on these numbers it is clear that the quantity of electricity that can be generated from woody biomass will be limited to a relatively small proportion of the total current electric consumption in the region.

Notice that in Table 2 there are no values for coal-fired electricity in Rhode Island or Vermont because of the absence of large coal-fired power plants in these states. Also, the EIA database did not report any significant use of biomass in West Virginia for electricity, which is not unexpected given the prominent coal industry in this state (DOE 2010). Note that for most states a high energy footprint for coal-fired electricity is associated with a high energy footprint in total electricity. Exceptions such as Connecticut, Maine, and New Hampshire are states that have few coal-fired plants and rely on alternatives such as natural gas, nuclear, or hydroelectric for much of their electricity generation. Maine stands out as already producing 26% of electricity with biomass, a far greater proportion than any other state in the study area (Table 1).

The states with the lowest proportion of biomass and or timberland area required to replace coal-fired electric generation are Maine and New Hampshire (less than 1%; Table 2). Both of these states have few coal-fired power plants and an above average amount of forest biomass. These factors indicate that these states have a theoretical capacity in terms of sufficient woody biomass to replace coal combustion within state borders. Within the 20-state study area, only the state of Maine appears to have sufficient woody biomass that generating all current electric consumption with woody biomass might be considered remotely within the realm of possibility. Other factors such as localized supply of woody biomass around the power plants, net cost of transport, competing uses for biomass, and technological aspects of cofiring would greatly affect the feasibility of replacing coal with woody biomass.

Table 3. Estimated state-level woody biomass annual growth, removals, and NAWI on timberland in the US northern region, 2008.

State	Biomass growth (MMDT)	Biomass removal (MMDT)	NAWI (MMDT)[a]
Maine	14.22	15.07	−0.84
Connecticut	2.96	1.52	1.41
Rhode Island	0.58	0.07	0.51
Delaware	0.89	0.19	0.70
Vermont	4.28	3.21	1.07
New Jersey	2.82	0.86	1.95
Iowa	3.58	1.52	2.06
New Hampshire	4.98	2.52	2.46
Maryland	5.00	1.91	3.09
Massachusetts	4.07	0.92	3.14
Minnesota	11.21	7.42	3.79
Illinois	6.65	1.56	5.09
Wisconsin	15.15	9.00	6.15
Indiana	8.46	2.20	6.26
Ohio	12.93	6.08	6.85
West Virginia	18.14	9.97	8.18
Michigan	17.57	8.76	8.81
Pennsylvania	21.98	12.82	9.16
New York	18.35	8.95	9.40
Missouri	16.12	5.96	10.17
Northern region	189.25	100.81	90.26

[a] Adjusted for mortality but not for annual removals, which are shown as a separate column. Removals include timber harvest as well land-use changes that remove forest from timberland status. Based on Miles (2011) with additional adjustments to convert estimated growth and removals of merchantable volume to total biomass.
MMDT, million metric dry tons.

Renewable Energy Mandates Scenarios

The state-level NAWI values in Table 3 are an estimate of the expected annual increase in woody biomass on timberland after accounting for biomass that is currently removed annually through timber harvesting, other forestry operations, and land-use change. This represents the biophysical upper limit of woody biomass increment annually available from timberland based on current growth and removal rates irrespective of location, ownership, socioeconomic, or technological considerations. We used the results in Table 3 to compute the maximum percent of state annual coal-fired electricity consumption that could be replaced if NAWI were used for that purpose (Table 4).

Most states in the northern region have *total* NAWI with sufficient energy potential to offset at least 15% of their current coal-fired electricity consumption at the state level. Included are states such as Pennsylvania and West Virginia, which rely heavily on coal-fired electricity (Table 2). Although Maine has a slightly negative NAWI, it also has a significantly higher percentage of electricity currently generated from biomass (26%) than any other state in the region (Table 1). Consequently, Maine would not need to offset any additional electricity generation with biomass to meet typical RPS targets. Midwestern states such as Iowa and Indiana might have the most difficulty meeting high renewable energy mandates from woody feedstocks, a consequence of relatively low forest area and relatively large coal-fired electricity generation. However, those states have greater potential than most to produce herbaceous biomass, which could be an alternative to woody biomass. Cross-referencing Table 4 with Table 1 indicates that states that derive a relatively small portion of electricity from coal (e.g., Connecticut, New York, and New Hampshire) tend to be those in Table 4 that have the potential to replace a high proportion of coal-fired electricity. Consequently, replacing a relatively high *proportion* of coal-generated electricity (Table 4, column 3) does not necessarily equate with replacing a relatively large total quantity of coal compared with other states (Table 4, column 2). Renewable energy mandates focused on replacing coal-fired electricity are not applicable to Rhode Island and Vermont because they lack coal-fired electric plants.

Although diverting all currently unused woody biomass growth to electricity generation could theoretically offset as much a 19% of coal-based electric production for the entire 20-state study area (Table 4), that would require chipping and burning large

Table 4. Maximum percentage of coal-fired electricity generation that could theoretically be replaced if the entire NAWI on timberland for each state were used for electric generation.[a]

State	NAWI (MMDT)	Coal (%)
Maine	−0.84	0
Iowa	2.06	9
Indiana	6.26	9
Illinois	5.09	10
Ohio	6.85	10
Pennsylvania	9.16	15
West Virginia	8.18	17
Maryland	3.09	21
Minnesota	3.79	22
Delaware	0.70	23
Michigan	8.81	23
Missouri	10.17	25
Wisconsin	6.15	27
New Jersey	1.95	38
Massachusetts	3.14	40
Connecticut	1.41	54
New York	9.40	91
New Hampshire	2.46	100
Rhode Island	0.51	NA
Vermont	1.07	NA
Northern region	90.25	19

[a] Estimates irrespective of other technical or economic considerations. NAWI is adjusted for current levels of removals (see Table 3) but otherwise is assumed to include total aboveground biomass from all trees regardless of alternative product values. Note that percentages are *in addition* to current state-level quantities of biomass used for electricity generation (see also Table 1).
MMDT, million metric dry tons; NA, not applicable due to lack of coal electrical production or negative biomass net increase.

Table 5. State-level percentages of total aboveground biomass on timberland by tree class and merchantability.

State	Total (MMDT)	Tree class[a] (%)			Merchantable (%)
		Growing stock	Rough cull	Rotten cull	
Rhode Island	20	91	7	2	73
Delaware	21	96	3	0	73
New Jersey	92	95	5	0	73
Iowa	101	70	28	2	72
Connecticut	108	92	7	1	74
Maryland	152	95	4	1	74
Massachusetts	180	89	10	1	74
Illinois	208	84	14	2	73
Indiana	227	89	10	1	73
New Hampshire	245	91	8	2	71
Vermont	245	88	10	2	71
Minnesota	389	85	14	1	64
Ohio	410	89	10	1	73
Wisconsin	540	90	9	0	68
Missouri	550	84	15	1	69
Maine	587	92	7	1	63
West Virginia	695	94	5	1	73
Michigan	702	92	8	0	68
New York	798	89	9	1	71
Pennsylvania	889	93	6	1	72
Northern Region	2,673	89	10	1	68

[a] Growing stock = trees >12.5 cm dbh with commercial sawlog potential based on species and condition, Rough cull = trees >12.5 cm in dbh with no sawlog potential because of bad form and/or damage, Rotten cull = trees >12.5 cm dbh with no sawlog potential due primarily to rot.
MMDT, million metric dry tons.

quantities of merchantable sawtimber and transporting biomass over large distances. Table 5 summarizes state-level percentages of total aboveground tree biomass by tree class and merchantability standard. The values of particular interest in Table 5 are growing stock and merchantable biomass. Note that a very large proportion (around 70%) of the standing biomass on timberland for each state is merchantable stem. Assuming that the distribution of standing biomass is proportionate to annual growth, a large percentage of NAWI is merchantable stem biomass. Also note that the proportions in Table 5 include growing stock trees of 13–28 cm dbh that are not currently sawlog material. Some of these growing stock trees could conceivably be used as feedstock because they have no current sawtimber value. A high percentage of merchantable stem biomass could significantly reduce the amount of NAWI that is actually available for cocombustion. This is because of the fact that much merchantable stem biomass is more valuable or has the potential to be more valuable as sawtimber, veneer, or pulpwood than as a feedstock for cofired electricity generation. Note that the percentage of nonmerchantable biomass shown in Table 5 includes top and limb biomass existing on trees, which are otherwise considered merchantable. This means that some of the nonmerchantable available biomass would only be available after the harvest of merchantable timber. The state-level renewable energy mandate assessment does not account for resource dispersion regarding localized availability of woody biomass for cofiring based on power plant location and transport distance. Consideration of these issues leads to the assessment of renewable energy capacity for individual coal-fired power plants addressed next.

Renewable Woody Biomass Available in Proximity to Coal-Fired Electric Plants

Resource dispersion is a factor that has a major impact on a state's ability to use woody biomass to meet RPS targets. In the previous state-scale scenarios we explored the apparent limits of each state in the northern region to meet renewable energy mandates through cofiring of biomass with coal, provided total NAWI were available for that purpose and there were no other socioeconomic or regulatory constraints. However, the spatial arrangement of woody biomass and of coal-fired electric plants will clearly be important in determining where cocombustion of biomass and coal may or may not be practical. West Virginia, e.g., has most of its coal-fired plants located along the northwest quadrant of the state. This suggests that because of transport limitations most of the power plants will be unable to procure woody biomass from the central or southeastern portions of the state. Additionally, coal-fired power plants may also be restricted with regard to woody biomass supply by localized competition from other nearby power plants. Consequently, the results reported in this section are focused on woody biomass within various radii surrounding each of 350 coal-fired power plants in the study region and how much woody biomass is potentially available at various distances surrounding each coal-fired electric plant. Tables 6 and 7 show summary statistics for an assessment of the minimum radii around individual coal-fired electric plants needed to replace coal-fired electricity with woody biomass in proportions of 3–20%. Table 6 summarizes the

Table 6. Minimum, maximum, mean, and standard deviation of the radii (km) of the smallest sourcing areas around across every coal-fired power plant in the northern region that would be required to meet alternative renewable energy target scenarios for offsetting coal with biomass for electricity production.[a]

Renewable energy mandate scenario (%)	Radius (km)			
	Minimum among all plants	Maximum among all plants	Mean for all plants	Standard deviation for all plants
3	8	113	22	17
5	8	121	25	19
8	8	137	29	22
10	8	137	32	24
12	8	161	35	27
15	8	161	38	29
18	8	161	42	32
20	8	161	44	34

[a] Estimates irrespective of other technical or economic considerations associated with biomass use. See also Figure 1.

Table 7. Minimum, maximum, mean, and standard deviation of the radii (km) of the smallest sourcing areas around each coal-fired power plant in the northern region showing requirements to meet alternative renewable energy scenarios for offsetting coal with biomass for electricity production if available biomass for energy were limited to 30% of the NAWI on timberland.[a]

Renewable energy mandate (%)	Radius (km)			
	Minimum among all plants	Maximum among all plants	Mean for all plants	Standard deviation for all plants
3	8	137	32	25
5	8	161	39	30
8	8	161	48	37
10	8	161	51	40
12	8	161	55	42
15	8	161	59	44
18	8	161	64	47
20	8	161	66	48

[a] Estimates irrespective of other technical or economic considerations associated with biomass use. See also Figure 2 and Table 1.

biomass procurement radius if all biomass increment in excess of current removals were used for cofiring. Table 7 summarizes the more realistic scenario based on the assumption that only 30% of the annual biomass increment in excess of current removals would be available for cofiring. As described in the Methods section, computations take into account the current coal-fired electric generation capacity for each power plant and NAWI estimated in a series of concentric circles that expand in radius at 8-km intervals around each of 350 power plants.

As indicated in Table 5, about 70% of aboveground woody biomass on timberland is classified as merchantable on average. Assuming proportionality with NAWI, this implies that as much as 70% of NAWI could be merchantable sawtimber and not economically competitive as bioenergy feedstock. Therefore, results were generated based on NAWI estimates with a corresponding increase in nonmerchantable (i.e., woody biomass) material at 30%. Recall that some of the woody biomass classified as nonmerchantable in Table 5 consists of top and branch biomass attached to merchantable stems. This could essentially reduce the biomass available for feedstocks even more if there are not harvesting operations already taking place. However, this can be supplemented by accounting for small-diameter trees (13–28 cm dbh) that are below the minimum dbh to be considered merchantable sawtimber. These small-diameter trees alone comprise 30% of total standing biomass on average per state. This comparison makes it possible to assess the differences between supply areas when assuming the biological maximum availability in contrast to an estimate of practical availability based on merchantability. This is an important assessment as most of the woody biomass that would be considered energy feedstocks in conjunction with forest management activities such as savannah restoration, fuel reduction, and timber stand enhancement would be considered nonmerchantable.

The mean radii across the renewable energy mandate scenarios are surprisingly low, indicating that most of the coal-fired power plants could meet each mandate using the total NAWI within a fairly small radius (Table 6). Also notice there was only a 22-km increase in mean radius across the mandate scenarios from 3 to 20% replacement of coal with woody biomass. Although this is a fairly small marginal increase in the supply radius it represents a significant increase in required supply area. For example, an increase of 22–44 km in radius coincides with an increase of about 4,500 km^2 (a threefold increase) in required supply area because supply area increases exponentially with increasing supply radius. Additionally, the standard errors shown in Table 6 are large relative to the mean radii, indicating high variation in supply radii among power plants.

Note that there is a relatively small difference in the summary statistics between the assumption of using 100% of NAWI estimates for electric generation (Table 6) and using only 30% of it (Table 7). One reason for this similarity is the fact that a small increase in radius can be associated with a relatively large increase in supply area, as mentioned previously. In our analyses, we incremented concentric biomass supply radii by 8 km (5 mi). Hence, the minimum supply radii for an individual power plant based on total NAWI not only met the mandate requirements, but often far exceeded them. In many of these cases, reducing the available woody biomass by 70% did not require a large increase in the required supply radius. Note that the distance that individual facilities will be willing to transport biomass would ultimately depend on the net cost per unit of output from using alternative energy feedstocks. Nicholls et al. (2006) have estimated that transported biomass on average would exceed the cost of coal when transported at distances greater than 95 km.

Although the estimates summarized in Tables 6 and 7 appear favorable in terms of overall potential for coal-fired power plants to meet some renewable energy mandates using woody biomass, they do not account for localized competition between different power plants for woody biomass resources. Depending on the quantity of biomass required, supply radii around coal-fired power plants can overlap, meaning that two or more plants would likely compete in the same area for the available woody biomass. We used spatially explicit analyses to map the minimum estimated woody biomass supply circles surrounding each coal-fired electric plant necessary to replace of 3, 10, and 20% of coal-generated electricity using 100% (Figure 1) and 30% percent of NAWI (Figure 2) within the mapped biomass supply circles. The analyses used to create these maps specifically account for coal-fired power plant locations, the annual coal-fired electricity generation for each plant, and NAWI surrounding each plant. Overlapping supply circles indicate locations where, under the assumptions used for the analyses, there would be overlapping demand for biomass by two or more coal-fired power plants.

In both maps, many of the coal-fired power plants with overlapping radii at 3% mandate (Figure 1, A and B) are concentrated in areas with either a large industrial infrastructure, (e.g., northeastern Illinois) or areas with a high density of coal-fired power plants (e.g., western West Virginia). However, there are many coal-fired power plants in the Midwestern states that have abundant total biomass resources within a small supply radius. Aside from relatively low generation capacity of many of these Midwestern power plants, there is a lower rate of current biomass removal in adjacent timberland than there is in other parts of the region where there is more total standing woody biomass. Notice that although the NAWI for Maine

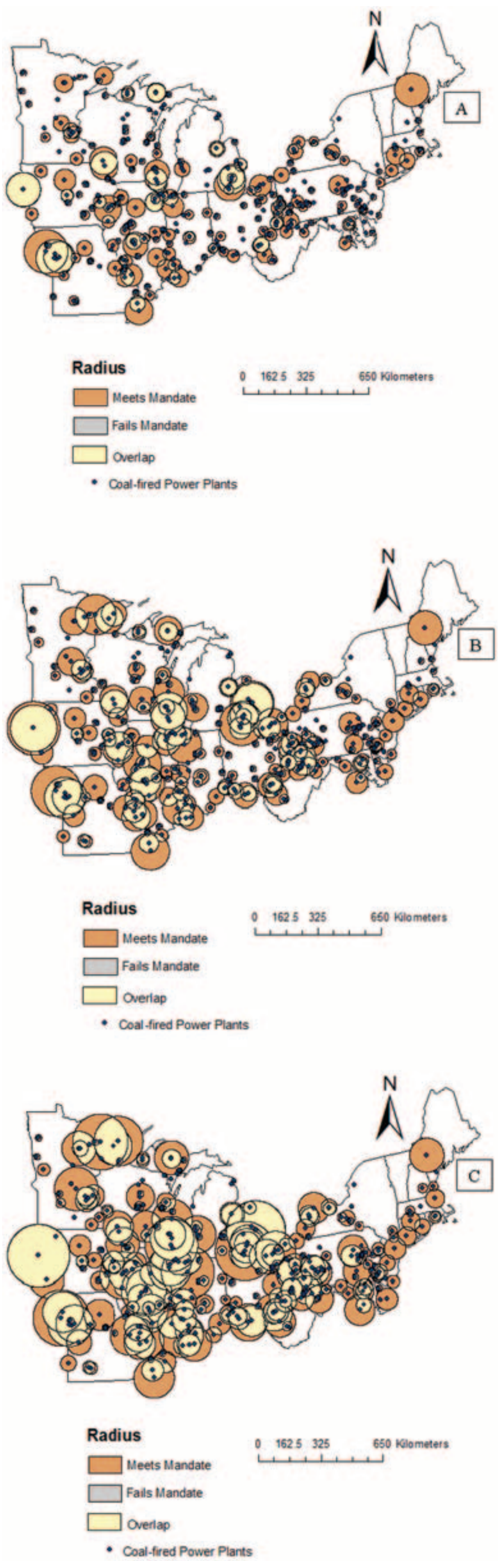

Figure 1. Map showing minimum supply footprint around coal-fired power plants needed to meet renewable energy mandate scenarios of (A) 3%, (B) 10%, and (C) 20% based on FIA data (Department of Energy [DOE] 2010, Miles 2011). A mandate, in this context, implies the maximum proportion of electricity that could be generated if all NAWI within the supply circles was fully available for generating electricity irrespective of technological and economic considerations.

was zero for the state-level energy assessment (Table 4), both of the coal-fired power plants in Maine are located in areas with the apparent capacity to use woody biomass for up to 20% of electrical generation individually without overlapping supply areas.

The estimated woody biomass supply radii around the coal-fired power plants get larger with increases in energy mandate levels, reflecting the greater demand for woody biomass (Figures 1 and 2). As such, there are noticeably fewer overlapping woody biomass supply areas for a 3% offset of coal with biomass (Figures 1A and 2A) than for 10 or 20% (Figures 1, B and C, and 2, B and C). However, even for a 3% mandate about 50% of the power plants have overlapping supply areas. As Figure 1 illustrates graphically, the percentage of overlapping biomass source areas is 63 and 73% for energy mandates of 10 and 20%, respectively.

There are significant changes in supply radii when constraining the analysis so that only 30% of annual woody biomass increment is considered available within a given supply radius (contrast Figure 2 with Figure 1). One of the most apparent changes occurred with a few coal-fired power plants on the east coast, which experience significant expansion in minimum supply radius needed to meet even a 3% mandate. The most obvious explanation is the close proximity of the power plants to the coast, which significantly decreases the available timberland contained within the supply area for a given radius. When the proportion of biomass estimated to be available is limited to 30% of NAWI, the proportion of overlapping supply areas surrounding coal-fired power plants increased to 89, 96, and 99% for energy mandates of 3, 10, and 20% respectively (Figure 2). Under this scenario the vast majority of power plants have overlapping supply areas even with the lowest energy mandate standard.

Taken as a whole, the results suggest that in isolation the majority of the coal-fired power plants in the region potentially have access to sufficient biomass to offset from 3 to 20% of coal-fired electric generation. However, the spatial arrangement of coal-fired power plants and biomass resources reveals overlap among many coal-fired electric plants in the surrounding timberland area that presumably would supply woody biomass for electric energy production. Many of the coal-fired power plants have substantial overlapping biomass source radii, and the radii of some power plants

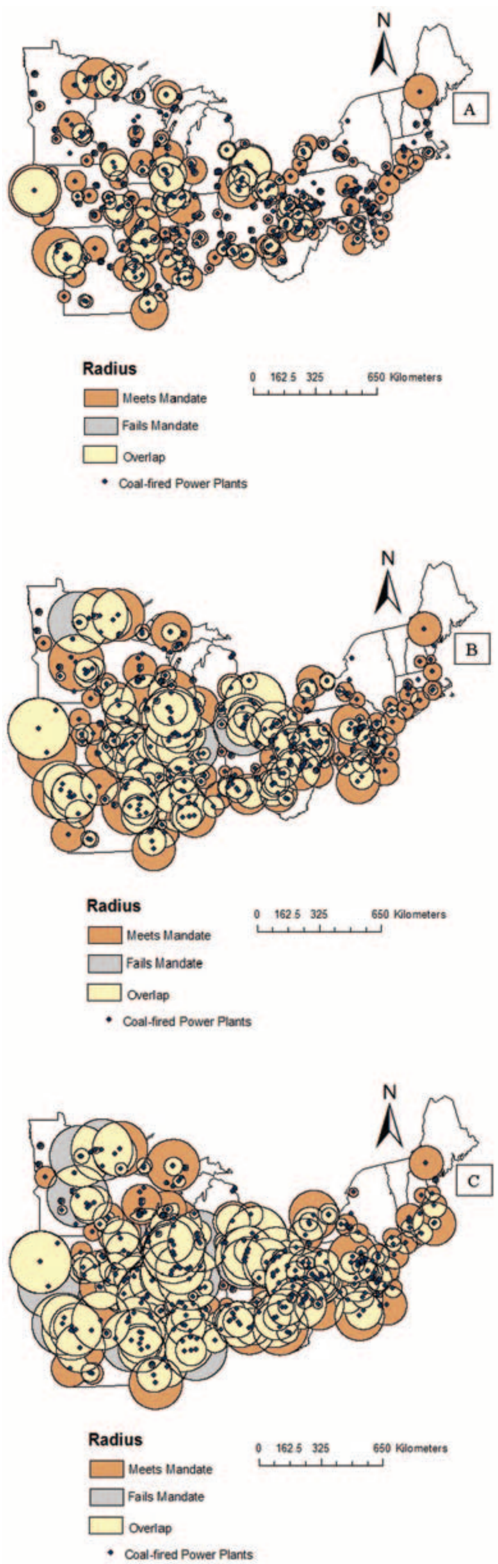

Figure 2. Map showing minimum supply footprint around coal-fired power plants needed to meet renewable energy mandate scenarios of (A) 3%, (B) 10%, and (C) 20% based on 30% of NAWI estimated from FIA (DOE 2010, Miles 2011). Mandate in this context implies the maximum proportion of electricity that could be generated if only 30% NAWI within the supply circles was available for generating electricity irrespective of technological and economic considerations.

are completely encompassed by others. Depending on the capacities and mandate standards for the state in question, this situation would limit the capacity of many coal-fired power plants to use cofiring with biomass.

Although there is potential for meeting renewable energy mandates for coal-fired power plants through cofiring of biomass, there are clearly limitations related to the spatial distribution of existing capacity of coal-fired power plants relative to the location of biomass resources on timberland. One alternative to counteract these limitations would be to increase the supply radii around the coal-fired power plants that are competing for woody biomass. However, there are two major issues associated with increased supply radii. First, increasing the supply radii around the power plants could cause them to compete with even more power plants for woody biomass (e.g., see Figure 2, B and C). Second, an increase in supply radius increases transportation costs, and at some point transportation costs become limiting even when woody biomass is readily available at a distant location.

There are a number of limitations associated with the analyses we have presented. First, woody biomass estimates are based on FIA sampling with known sampling errors. Standard errors for FIA estimates can often be high when estimating forest attributes at small spatial scales (e.g., power plant supply area) because of small sample size (McRoberts and Wendt 2004). The spacing between FIA plots can make it difficult to detect subtle changes in attributes such as woody biomass availability across the landscape (Bechtold and Patterson 2005). For detailed analyses of biomass resources in proximity to one or a few specific locations it would be prudent to examine the confidence intervals associated with mean estimates. Second, estimates are based on current electricity demand and existing forest cover. The analyses did not evaluate expected changes in energy demands or in forest cover over time or the potential availability of greater amounts of biomass from dedicated energy crops or from other sources (e.g., agricultural or urban residues). Third, estimates were solely based on the biophysical availability of biomass and did not formally incorporate complex socioeconomic effects (e.g., social availability of woody biomass, stumpage prices, and transportation costs). Determining the difference between socioeconomic and biophysical availability is important for evaluating biomass volumes that can realistically be extracted (Butler et al. 2010). For example, the use of woody biomass for energy could be dramatically affected by landowners' willingness to supply biomass, particularly in a region where 77% of forestlands are in private ownership.[3] Fourth, the renewable energy scenarios in this study focused on replacement of coal-generated electricity with only woody biomass from timberland and did not account for herbaceous biomass, industrial wood residues, urban wood waste, or other renewable energy sources such as solar and wind power. Finally, for each coal-fired power plant there are numerous regulatory and technical issues that must be resolved before cofiring with biomass. These include but are not limited to boiler design, fuel handling, and boiler feed mechanisms; fuel storage capabilities; and effects on atmospheric emissions.

To better assess whether or not specific coal-fired plants would have an adequate supply of biomass and transport infrastructure for cost-effective cofiring, more specific spatial analyses that account for road systems, urban population centers, and landownership are required to complement our regional, spatially explicit analyses. Likewise, logistical and technical constraints to cofiring at a given coal-fired power plant must be considered on a case-by-case basis. Currently, there are programs and institutions that are actively analyzing more localized scenarios at the county or township level to determine both the feasibility of cofiring biomass in individual power plants and identifying areas that would be optimal for placement of new power plants. The BioSat program, which is focused on the US northern and southern regions, is currently using county-level biomass estimates from FIA along with georeferenced data to determine optimal placement for cofiring power plants (Young et al. 2009). The subject of landownership is extremely important when assessing the localized availability of woody biomass for energy, because harvesting operations specifically for biomass are currently not common on federal forestland. Policy changes, including subsidies associated with biomass harvesting, may be important. Additionally, it will be useful to project future changes in biomass availability and electricity demand to reassess the feasibility of woody biomass cocombustion as more states implement renewable RPSs. Upcoming analyses will evaluate more complex scenarios and incorporate additional socioeconomic dimensions.

Conclusions

This article used a series of successive approximations to estimate the potential capacity to apply cofiring with biomass at coal-fired electric plants as a means to increase use of woody biomass for renewable energy production. We focused on cofiring with woody biomass because it provides a near-term strategy for increasing renewable energy production using existing infrastructure. Analyses at the scales of the 20-state northern region, individual states, and individual coal-fired power plants provide insight into the biophysical limitations associated with using woody biomass for electric generation.

Regionally, if the *total* annual woody biomass increment on timberland was used for electric production, it could offset as much as 19% of coal-fired electric generation; that corresponds to about 11% of electric generation from all sources. However, considering other social, economic, and technical limitations as well as the uneven spatial distribution of forest biomass, coal-fired electric plants, and electric consumers it appears the near-term capacity to replace coal-fired electric generation with woody biomass would be less than 5% of total coal-fired electric generation.

Compared with coal, woody biomass is widely dispersed and low in energy content per unit of weight. Biomass transportation costs are limiting, so woody biomass for energy is usually obtained from areas as near as possible to where it will be used. Examination of the quantity of woody biomass surrounding 350 coal-fired electric facilities in the northeastern quadrant of the United States showed that (a) on average the total annual biomass increment within a 45-km radius of a given facility has sufficient energy potential to offset up to 20% of the coal-fired electric production, (b) the uneven spatial distribution of woody biomass and of the current harvest for other products creates substantial variation across the region in the minimum sourcing zone for a given quantity of biomass, and (c) coal-fired power plants are spatially clustered so their potential biomass supply areas overlap. Consequently, using biomass for electric cogeneration will be impractical in some locations, and the decision to use biomass for electricity cogeneration at one facility may limit options to do likewise at another facility more than 80 km away. Because of large overlap in potential source areas for woody biomass that could be used for cofiring at existing coal-fired electricity plants, the regionwide capacity to use woody biomass for cofiring will be substantially less than the sum of the apparent capacities for the individual plants if considered in isolation from one another.

In the foreseeable future, use of woody biomass for energy is likely to increase but nevertheless remain a relatively small component of total energy production for most states in the region. The spatial dispersion of woody biomass across the landscape, the clustered spatial arrangement of coal-fired electricity plants, and the economic limits to long-distance transport suggest that increased biomass use will be spatially uneven. Woody biomass use for energy will be scattered throughout the region; hence, it is important to identify locations where increased use of woody biomass for energy is complementary with other forest conservation goals to achieve multiple benefits. For example, desired savanna and woodland restoration projects on hundreds of thousands of acres in the Ozark Highlands have been limited by the high cost of removing midstory and understory trees for which there currently are no markets. Developing biomass energy markets in areas affected by or in the path of mortality agents such as gypsy moth, hemlock wooly adelgid, spruce budworm, or oak decline may provide a practical mechanism for managing forest health proactively and after damage. In areas dominated by active sawtimber markets, complementary bioenergy markets may be able to increase revenues from timber harvesting and reduce the out-of-pocket costs associated with precommercial thinning or with fuels reduction, slash management, and site preparation after harvests. Our multiscale approach helps frame woody biomass resources by region, states, and individual power plants within the context of current energy consumption. The spatially explicit analyses highlight conditions and places where cofiring with biomass might be a practical way to increase renewable energy production and also where there is high potential for increased competition for woody biomass. Additional finer-scale analyses are necessary to evaluate the social, economic, technical, and regulatory practicalities of using biomass for energy in conjunction with any specific coal-fired electric plant.

Endnotes

[1] Timberland is defined as forestland that is producing or is capable of producing crops of industrial wood and not withdrawn from timber use by statute or administrative regulation. Areas qualifying as timberland are capable of producing in excess of 20 ft^3/ac

per year of industrial wood in natural stands (Smith et al. 2009).

[2] Net growth is equal to gross growth minus mortality.

[3] According to Butler et al. (2010) family forest owners control 54% of the 7,685 million dry tons of wood in the northern region.

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Appendix

Relevant Conversions and Transformations

Unit	Conversion
1 MDT	1.7 megawatt hours
Biomass growth ratio	cubic volume growth (m^3/ha)/cubic volume timberland (m^3/ha)
Biomass removal ratio	cubic volume removal (m^3/ha)/cubic volume timberland (m^3/ha)
NAWI	Biomass growth − biomass removal
Assumed coal-fired plant boiler efficiency	33%
Percentage aboveground woody biomass by tree and merchantability class	(Biomass by class/total biomass) * 100