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Carbon emissions associated with the procurement and utilization of forest harvest residues for energy, northern Minnesota, USA

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ABSTRACT

Interest in the use of forest-derived biomass for energy has prompted comparisons to fossil fuels and led to controversy over the atmospheric consequences of its utilization. Much of the debate has centered on the carbon storage implications of utilizing whole trees for energy and the time frame necessary to offset the carbon emissions associated with fixed-life bioenergy facilities. Forest harvest residues may provide a cost-effective, carbon friendly alternative; however, robust empirical estimates of the carbon consequences of utilizing this feedstock are needed to inform policy and management related to forest-based bioenergy. This study used a modeling approach to assess the availability of harvest residues in northern Minnesota and compared the estimated carbon emissions from in-forest decomposition with emissions from processing, transport, and utilization of residues in a proposed 26 MW bioenergy facility. Model results suggest that the combined emissions from the proposed facility would be 42 percent greater – a net difference of 2,888,751 Mg of CO_2 – than in-forest decomposition emissions over a 25-year period. The disparity in carbon emissions with and without the proposed facility decreases with increasing time, ultimately reducing to solely emissions from harvesting and transport 190+ years after establishment. These findings have important implications for the development of renewable energy standards including incentives aimed at increasing the use of forest-derived biomass.

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1. Introduction

Interest in using renewable resources for energy has increased substantially in the United States over the last several decades. These increases have been driven, in large part, by energy policy aimed at reducing dependence on foreign oil, boosting economic development, and curbing fossil fuel emissions [1,2]. Utilization of forest biomass has emerged as a key strategy in this pursuit, both because of its potential to offset fossil fuel use [3], and concomitant benefits achieved through forest health and wildfire risk reduction treatments [4,5].

Early federal legislation resulting from the 1973 Arab oil embargo resulted in the Public Utility Regulatory Policies Act

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of 1978 [6], which dramatically increased attention on domestic renewable energy production, including forest biomass. Subsequent policies like the Energy Policy Act of 1992 [7] and 2005 [8], the Biomass Research and Development Act of 2000 [9], and production tax credit allowances as authorized in Section 45 of the Internal Revenue Code of 1986 [10] further incentivize biomass production for energy. In recent years, state governments have also passed various policies aimed at reducing greenhouse gas emissions and increasing use of renewables [11]. For example, 35 states and the District of Columbia have passed renewable portfolio standards incentivizing production of renewable energy. Of those, states like Minnesota, which passed the Next Generation Energy Act of 2007 [12], have specifically incentivized forest biomass production.

Despite the significant potential for the expansion of bioenergy production from forest biomass in the Lake States [13], uncertainty exists over feedstock availability and the ecological impacts of expanded levels of utilization. Typically, estimates of feedstock availability have focused on total physical biomass available e.g. [3], ignoring constraints imposed by transportation distances, differences in forest ownership, harvest costs, and site access and suitability. Furthermore, harvesting guidelines aimed at protecting wildlife habitat, soil productivity, and water quality often do not exist or are ignored. Failing to account for these constraints can potentially lead to overestimation of feedstock supply, thus complicating efforts to site new bioenergy facilities, as well as determine sustainable feedstock harvest levels for a region [14,15].

Substitution of forest-derived bioenergy for fossil fuels may also dramatically alter regional carbon balances due to the net change in carbon dioxide (CO_2) emissions associated with bioenergy [16]. The degree to which these substitutions lower CO_2 emissions is dependent upon numerous factors, including the impacts of feedstock harvests on ecosystem carbon fluxes and stores, the species and portion of the tree utilized, the amount of fossil fuels used for harvesting, preparation, and transport of feedstocks, and the conversion technology used [17,18]. Identifying the differential importance of each of these factors on overall CO_2 emissions is essential for generating accurate estimates of the impacts of expanded bioenergy production on regional and national carbon cycles. Characterizing these differences at landscape and regional scales is also necessary in order to tailor state and federal carbon emissions policies to account for differences between forest systems.

A recent proposal for a 26 MW forest biomass generation facility in northern Minnesota provided an opportunity to examine the range of factors affecting levels of sustainable forest biomass feedstock supply as well as the carbon emissions associated with the processing, transport, and utilization of harvest residues for generating renewable energy. In particular, this study focuses on biomass availability and carbon emissions associated with the processing, transport, and utilization of forest harvest residues for energy over 25-, 50-, and 100-year time horizons for this 26 MW bioenergy facility. The objectives were to 1) characterize the availability of biomass residues (tree tops and branches) following harvesting operations by forest type within a 160 km radius of the proposed bioenergy facility; 2) estimate the carbon emissions associated with in-forest decomposition of the available harvest residues; 3) estimate the carbon emissions associated with processing, transport, and utilization of available harvest residues; and 4) provide a carbon emissions timeline (debt–dividend profile) for northern forests associated with the production of energy from harvested residues for comparison to other fuel sources.

2. Methods

2.1. Study area

The procurement area includes productive, non-reserved forest land (timberland) located within a 160 km radius of a proposed bioenergy facility in Hoyt Lakes, Minnesota (47.5597 Lat., −92.1196 Long., Fig. 1). The climate in the study area is continental with warm summers (mean July temperature 20 °C), cold winters (mean January temperature −14 °C), and 731 mm of precipitation, about half of which occurs during the growing season [19]. The procurement radius was selected because it is consistent with the existing supply area for the energy utility and because it includes nearly half (3,182,875 ha) of the timberland in Minnesota and 564,468 ha in northwest Wisconsin for an estimated total of 3,747,341 ha (approximately 8 percent of the total study area in northwest Ontario was excluded due to data limitations). Using FIA-defined forest type groups, aspen/birch and spruce/fir types account for an estimated 70 percent of the timberland in the study area (Table 1). Stands dominated by these forest types are typically even-aged and managed using either coppice (aspen/birch) or clearcutting (spruce/fir and aspen/birch) regeneration methods [20–22]. Because the majority of the study area was in the state of Minnesota, the harvest targets and guidelines for each forest type were based on five-year statewide average harvest levels from 2004 to 2008 in Minnesota [23] in proportion to the study area forest types (Table 1).

Data used to characterize the forest resources in the study area were based on 3742 USDA Forest Service Forest Inventory and Analysis (FIA) field plots located within this area. Data from the FIA program's network of plots [24] is available online from the FIA DataMart [25]. FIA plots are measured according to a nationally consistent protocol and are distributed in a quasi-systematic design across all ownerships throughout the United States [26].

2.2. Biomass definitions

This study focused on the utilization of forest harvest residues, which were assumed to be tops and branches from merchantable timber species. The FIA definitions of merchantable bole (MBB) and top and branch biomass (TBB) were used to develop yield curves necessary for biomass availability estimates. Merchantable bole biomass was assumed to be the sound wood in live trees ≥12.7 cm dbh, including bark, from a 30.5 cm stump height to a minimum 10.2 cm top diameter outside the bark [27]. Harvest residues (TBB) included the tip, portion of the stem above the merchantable bole, all branches, and excluded foliage [27].

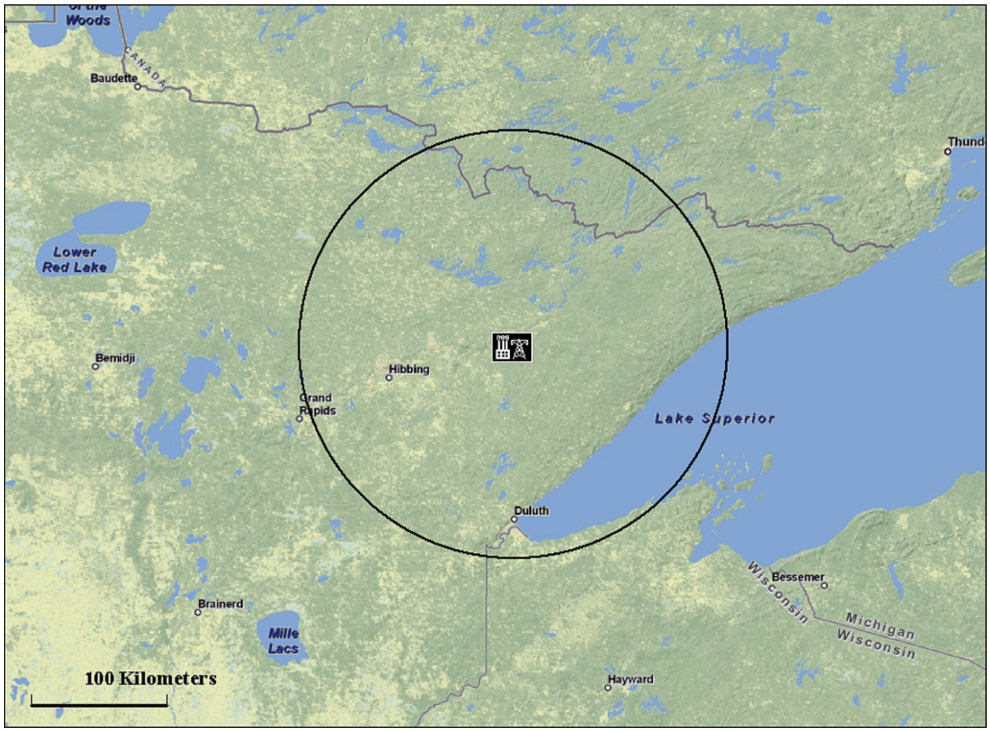

Fig. 1 – Map of the 160 km radius study area around the proposed 26 MW bioenergy facility in Hoyt Lakes, MN. Only non-reserved productive forest land in MN and WI are included in the supply assessment.

2.3. *Biomass energy system*

The 26 MW bioenergy system modeled in this study utilized forest harvest residues for generation of electric power. Specifically, electricity would be generated from turbines powered by high pressure steam produced in boilers fueled by forest-derived biomass [28].

2.4. *Simulation model development and validation*

The model developed to estimate biomass availability and carbon stocks was based on volume control approaches to forest management, where specification of the volume harvested annually is used to manage (or control) the development of the forest over time. The Forest Age Class Change Simulator (FACCS) model, which was used in the analysis, runs on a series of spreadsheets that can be adapted to a wide array of forest management and harvesting scenarios [29,30]. Each forest type has a unique change matrix that is linked to timberland area estimates from FIA inventory data (2005–2009). Area within each age-class moves as a function of time, harvesting, and user-defined mortality. The change matrices are linked to specific age-class yield models developed from current FIA data, which allows for estimation of biomass availability for multiple harvested areas over time. The validity of FACCS-generated MBB and TBB and individual age-class yield models were checked against estimates generated from the FIA database to ensure unbiased, consistent starting values.

The analysis assumed that forest type area remained fixed during the three modeled time horizons. No natural disturbance induced mortality was assumed beyond that which was inherent in the FIA data used to generate age-class yield models. Harvest targets (Table 1) were assumed to remain at current levels (2004–2008) over the modeled time horizons, and rotation lengths for each forest type followed recommendations from the MN DNR Forest Development Manual [22].

Table 1 – Summary of estimated timberland area (ha), merchantable bole biomass (MBB, oven-dry Mg), and annual merchantable bole biomass (oven-dry Mg) harvest targets for each forest type group in the procurement area.

Forest type group	*n*	Area	MBB	Annual harvest
White/red/jack pine	286	259,577	14,929,781	265,023
Spruce/fir	950	975,399	24,045,447	291,679
Oak/hickory[a]	204	204,339	9,083,711	19,847
Elm/ash/cottonwood	333	297,426	11,658,142	30,523
Maple/beech/birch[b]	363	363,797	20,901,787	124,742
Aspen/birch	1606	1,646,802	51,187,660	1,291,470
Total	3742	3,747,341	131,806,528	2,023,284

a Includes the oak/pine (400) forest type group.
b Includes the other hardwood (962) forest type group.

2.5. *Statistical model selection*

FACCS relies on continuous yield curves for each biomass attribute of interest to produce biomass estimates. Current FIA inventory data were used along with non-linear regression techniques in R [31] to develop age-class yield models for each forest type and biomass attribute (MBB and TBB) in the study. Since stand age and biomass estimates are often heteroscedastic and non-linear [32], 12 different model forms were tested and weights were use in order to obtain the best fit for the data. The models tested were, for the most part, not nested, so likelihood-ratio based tests would not have been appropriate for comparison [33]. Instead, Akaike Information Criterion (AIC) [34] and Bayesian Information Criterion (BIC) [35] were used. Given the variability of pooled (many species within each forest type) biomass and stand age data and the long time horizons modeled, confidence intervals ($\alpha = 0.05$) were calculated for each regression fit and incorporated into FACCS so that a range of biomass estimates were produced, in addition to the predicted values.

2.6. Decay emissions

Decomposition of residual forest biomass was assumed to follow the negative exponential decay model described by Olson [36]:

$$D_t = D_0 \exp^{(-kt)}$$

where D_t is the annual decomposition, D_0 is the available harvest residues produced each year, t is the time of decomposition (years), and k is the decay rate constant. Decay rate constants were compiled from existing literature for the species comprising the six forest types in the study (Table 2). Where possible, studies proximal to the procurement area were selected to reflect decay dynamics in the region. Multiple decay rate constants were used for each forest type and averaged to account for variability in residual biomass size, species mix, location, and decay class. The range of values from the literature for each forest type was also included in the analysis to illustrate the variation in decomposition and the effect it has on carbon debt dynamics. Decay rate constants were integrated over the entire study area at multiple time horizons to estimate carbon emissions from decomposition.

2.7. Harvesting emissions

The harvest system assumed in this analysis is described as a conventional, whole-tree operation where the merchantable bole and tops and branches are processed at the harvest landing. This system is commonly used in the study area and throughout Minnesota [37]. Equipment horsepower, delay-free productive machine hours (PMH), and diesel fuel consumption rates for each piece of equipment were used to calculate the carbon dioxide (CO_2) emitted per Mg of wood chips processed. Carbon emissions conversion factors for diesel fuel were used from the Climate Registry [38].

The whole-tree harvest system was modeled using a feller buncher, skidder, and self-loading chipper. Productivity and horsepower ratings used for each piece of equipment are based on studies of comparable harvest conditions, forest types, and size classes in the Lake States [39,40]. Fuel consumption rates per PMH were calculated based on estimates from Brinker et al. [41].

There is limited information available on residual biomass extraction efficiency for the forest types found in the study area, so a conservative estimate of 50 percent of the total TBB was assumed to be extractable. This estimate is in accordance with recommendations from the MN DNR [42] Logged Area Residue Analysis and recent empirical estimates from harvest sites within the state [D'Amato, unpublished data]. The assumed residual biomass left on-site is well above the minimum amount recommended to sustain soil productivity, biological diversity, and wildlife habitat on forest lands in the region [43].

2.8. Transportation emissions

To estimate carbon emissions from transport of harvest residuals, an average roundtrip distance (~270 km) was determined using a GIS roads layer combined with FIA plot locations to calculate the average plot distance and associated road distance (135 km) from the bioenergy facility in Hoyt Lakes, MN. The roundtrip haul estimate was used in conjunction with road type data to calculate haul speeds and associated fuel consumption. A survey of logging professionals operating in the study area determined the average fuel consumption for haul trucks was 2.02 km/L and trucks typically haul 22.7 green Mg of material. The annual roundtrip CO_2 emissions from transport were based on a conservative utilization target of 291,304 Mg of green wood chips (145,652 oven-dry Mg) to fuel the 26 MW bioenergy facility. The harvest residue moisture content (MC) was assumed to be 50 percent, which is consistent with other studies [44] and reflects minimal storage and processing time at the harvest site.

3. Results

3.1. Statistical model selection and simulation model validation

Based on the goodness of fit criteria used in this study, four different age-class yield model forms were selected for MBB

Table 2 – Summary of mean decay rate constants (*k*), range (Min and Max) of published decay rate constants, and the estimated decay life (yrs), which represents the mean time to complete decomposition for residual biomass in each forest type group.

Forest type	*k*	Min	Max	Decay life	References
White/red/jack pine	0.0428	0.0210	0.0800	23	[51,58,61,65]
Spruce/fir	0.0473	0.0265	0.1000	21	[51,54,56,57,63,64]
Oak/hickory	0.0622	0.0175	0.1660	16	[59–61]
Elm/ash/cottonwood	0.0947	0.0810	0.1140	11	[53,58,61]
Maple/beech/birch	0.0773	0.0189	0.1490	13	[52,60,61]
Aspen/birch	0.1085	0.0500	0.1970	9	[51,55,58,62]

Table 3 – Regression statistics for fitted age-class yield models developed for merchantable bole biomass. Note that *e* represents the exponential function which is equal to approximately 2.7183 and A is the independent variable for stand age.

Forest type	Function	Parameter	Estimate	SE
White/red/jack pine	$MBB = a/(1+e^{((b-A)/c)})$	*a*	68.5650	4.6340
		b	24.9230	1.9230
		c	6.8730	1.0540
Spruce/fir	$MBB = ae^{(-b*c^{A})}$	*a*	28.9183	1.5787
		b	4.1974	0.7223
		c	0.9432	0.0090
Oak/hickory	$MBB = a - be^{(-e^{c \bullet A^{d}})}$	*a*	99.8920	27.6500
		b	91.1560	28.6720
		c	−13.4580	4.3950
		d	3.1900	1.1360
Elm/ash/cottonwood	$MBB = a - be^{(-e^{c \bullet A^{d}})}$	*a*	60.6284	6.2107
		b	55.3844	6.5943
		c	−13.611	2.1015
		d	3.2246	0.5322
Maple/beech/birch	$MBB = a + ((b-a)/(1+e^{((c-A)/d)}))$	*a*	4.1020	4.2200
		b	87.9270	11.1030
		c	49.0900	4.7030
Aspen/birch	$MBB = a + ((b-a)/(1+e^{((c-A)/d)}))$	*a*	14.7960	4.5040
		b	3.1700	1.0270
		c	56.2780	2.8850
		d	37.8380	1.6420

(Table 3) and TBB (Table 4). Several model forms had comparable AIC and BIC values for each forest type and biomass attribute but the model with the lowest combined AIC and BIC value was selected. Confidence intervals were calculated for predicted values at each age-class and were linked to the associated forest type area change matrices in FACCS. Current FIA estimates were well within the FACCS-generated confidence intervals for each forest type and biomass attribute (Table 5).

3.2. *Biomass availability*

The proposed 26 MW bioenergy facility would require an estimated 145,652 oven-dry Mg of TBB annually. Under current levels of forest management and commercial harvesting, there would be an estimated 259,457 (±21,627) oven-dry Mg of TBB available annually for utilization (Table 6). More than 70 percent of the available TBB would come from the aspen/birch forest type with an additional 11 percent

Table 4 – Regression statistics for fitted age-class yield models developed for top and branch biomass. Note that Exp represents the exponential function which is equal to approximately 2.7183 and A is the independent variable for stand age.

Forest type	Function	Parameter	Estimate	SE
White/red/jack pine	$MBB = a/(1+e^{((b-A)/c)})$	*a*	13.0140	0.8081
		b	24.0644	1.7641
		c	6.6677	1.0076
Spruce/fir	$MBB = ae^{(-b*c^{A})}$	*a*	5.3164	0.2681
		b	5.0405	1.0944
		c	0.9313	0.0118
Oak/hickory	$MBB = a - be^{(-e^{c \bullet A^{d}})}$	*a*	23.9250	4.8410
		b	21.7450	5.0490
		c	−13.2060	4.2000
		d	3.2000	1.0890
Elm/ash/cottonwood	$MBB = a - be^{(-e^{c \bullet A^{d}})}$	*a*	17.2973	1.7508
		b	15.4875	1.8895
		c	−13.9899	2.4018
		d	3.3141	0.6028
Maple/beech/birch	$MBB = a + ((b-a)/(1+e^{((c-A)/d)}))$	*a*	24.2210	2.4530
		b	44.7110	5.3100
		c	17.4290	2.2370
Aspen/birch	$MBB = a + ((b-a)/(1+e^{((c-A)/d)}))$	*a*	1.0114	0.2362
		b	14.8146	0.5246
		c	32.3351	1.129
		d	7.8517	0.9242

Table 5 – Comparison of current (2009) standing merchantable bole and top and branch biomass (oven-dry Mg) estimates from FIA and FACCS for the study area. Values in parentheses represent the 95 percent confidence intervals for the FACCS-generated biomass estimates.

Forest type	FIA		FACCS	
	MBB	TBB	MBB	TBB
White/red/jack pine	14,929,879	2,837,699	13,479,107 (±2,011,100)	2,598,807 (±360,945)
Spruce/fir	24,045,604	4,626,736	22,925,544 (±2,195,684)	4,387,670 (±433,600)
Oak/hickory	9,083,771	2,403,154	8,099,831 (±2,541,477)	2,170,451 (±599,044)
Elm/ash/cottonwood	11,658,219	3,360,139	11,460,813 (±1,581,802)	3,305,340 (±469,216)
Maple/beech/birch	20,901,924	5,838,818	20,022,273 (±2,757,744)	5,592,620 (±691,078)
Aspen/birch	51,187,995	14,945,871	50,613,723 (±4,395,667)	14,811,543 (±1,117,971)
Total	131,807,393	34,012,417	126,601,291 (±15,483,478)	32,866,432 (±3,671,855)

available from the spruce/fir type and 10 percent from the white/red/jack pine type. The remaining 9 percent would come primarily from the maple/beech/birch forest type with a small amount available from the oak/hickory and elm/ash/cottonwood types (Table 6).

3.3. *Decay emissions*

Total estimated CO_2 emissions from decomposition of available TBB, which would otherwise be utilized in the bioenergy facility, are listed in Table 7 for the modeled time horizons. Estimated decomposition is most rapid immediately following harvest and cumulatively increases until approximately year 50, when decay emissions stabilize and approach emissions from the bioenergy facility (Fig. 2). The solid areas in Fig. 2 illustrate estimated decay emissions over the 25-, 50-, and 100-year time horizons where the TBB would otherwise be used for energy. The bars in Fig. 2 illustrate estimated decay emissions which continue after each modeled time horizon reaching near zero (<0.5 Mg of CO_2 yr^{-1}) at 349, 378, and 430 yrs, respectively for the mean decay rates in Table 2. Incorporating the range of decay rate constants from Table 2 changes the modeled decomposition dynamics (Fig. 3) and associated years to neutrality for the modeled time horizons. Using minimum decay rates increases the time to neutrality to 769, 824, and 889 yrs, respectively, while using the maximum decay rates decreases the time to neutrality to 192, 216, and 267 yrs, respectively for the modeled time horizons.

3.4. *Bioenergy facility emissions*

Combustion of 145,652 oven-dry Mg of TBB would produce an estimated 267,029 Mg of CO_2 emissions annually at the bioenergy facility (Table 7). The net boiler efficiency, and thus, emissions efficiency at the facility would depend on the MC of the fuel source. Fuel with high MC would reduce the net boiler efficiency [45] requiring more biomass to achieve the same energy output at a lower MC. The net carbon dioxide emissions per megawatt hour (CO_2 MWh^{-1}) – which incorporate in-forest decomposition emissions – at different fuel MC decreased over time at the proposed 26 MW facility (Fig. 4). The trend reflects the difference between decomposition emissions and the annual burning of the biomass at the energy facility.

3.5. *Harvest and transport emissions*

Harvesting and transport emissions represent a relatively small proportion of the collective carbon emissions associated with the proposed bioenergy facility (Table 7). Harvesting and chipping the 145,652 Mg of TBB produces an estimated 6537 Mg of CO_2 emissions annually. Transporting the material to the facility produces an estimated 4734 Mg of CO_2 annually. Harvesting and transport combined contribute between 0.062 (0% MC) and 0.074 (50% MC) Mg of CO_2 MWh^{-1} annually to the total estimated carbon emissions, or approximately 4 percent of the total emissions modeled.

Table 6 – Estimated annual biomass availability (oven-dry Mg) by forest type and stand attribute for the procurement area. Values in parentheses represent the 95 percent confidence intervals for the FACCS-generated biomass estimates.

Forest type	MBB	TBB
White/red/jack pine	265,023 (±35,500)	25,227 (±3124)
Spruce/fir	291,679 (±26,125)	27,635 (±2506)
Oak/hickory	19,847 (±6840)	2575 (±749)
Elm/ash/cottonwood	30,523 (±4437)	4379 (±646)
Maple/beech/birch	124,742 (±19,087)	17,184 (±2315)
Aspen/birch	1,291,470 (±108,138)	182,457 (±12,284)
Total	2,023,284 (±200,128)	259,457 (±21,627)

Table 7 – Estimated carbon emissions (Mg of CO_2) over the modeled time horizons (yrs) with (facility, harvest, and transport emissions) and without (decay emissions) the proposed 26 MW bioenergy facility. Net emissions represent the difference with and without the facility and are based on annual utilization of 145,652 oven-dry Mg of TBB.

Time horizon	Decay	Facility	Harvesting	Transport	Net
25	4,068,749	6,675,717	163,434	118,349	2,888,751
50	10,370,771	13,351,433	326,869	236,697	3,544,228
100	23,663,664	26,702,867	653,738	473,395	4,166,335

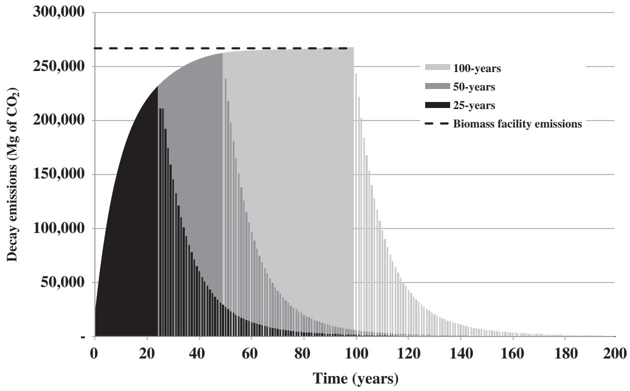

Fig. 2 – Estimated carbon debt and repayment (Mg of CO_2) for 25-, 50-, and 100-year time horizons. The initial difference in decay and bioenergy facility emissions represents carbon debt. The solid areas represent repayment from decomposition during the fixed-life of the bioenergy facility and the bars represent carbon repayment from decay emissions which continue beyond the fixed-life of the bioenergy facility.

3.6. *Emissions comparisons*

The collective estimated carbon emissions from harvesting, transport, and utilization at the bioenergy facility are 42 percent greater than in-forest decomposition emissions over the first 25-years in this study. This represents an estimated net difference of 2,888,751 M Mg of CO_2 (Table 7). The disparity in emissions decreases over time, despite increases in the net difference with and without the proposed facility. Estimated combined emissions are 25 percent greater (3,544,228 M Mg of CO_2) than decay emissions over 50 years and 15 percent greater (4,166,335 M Mg of CO_2) over 100-years (Table 7).

4. Discussion

Harvest residues left at logging sites have been targeted as a potential cost-effective, carbon friendly alternative to the use of whole trees or other fuel sources for energy [46]. The

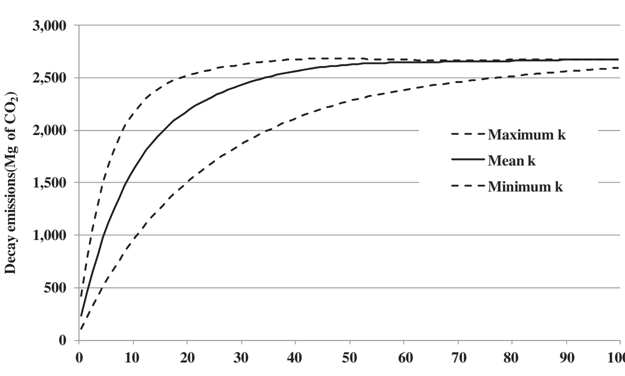

Fig. 3 – Estimated carbon emissions (Mg of CO_2) from TBB decomposition using the mean, minimum, and maximum decay rate constants (*k*) in Table 2.

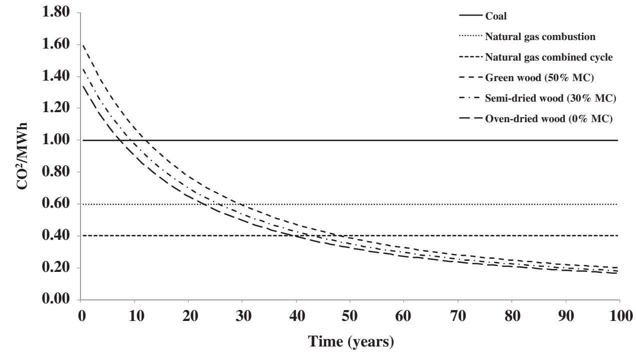

Fig. 4 – Estimated net emissions (facility emissions – decomposition emissions; Mg of CO_2 MWh^{-1}) at different fuel moisture contents over time for the 26 MW bioenergy facility and for fossil fuel energy production reported in the Electric Power Annual [48].

availability of harvest residues is contingent on bole wood (roundwood) harvests. In Minnesota, more than 3.5 million oven-dry Mg of bole wood are harvested annually, leaving considerable TBB in the forest. An energy utility in northern Minnesota proposed the development of a 26 MW bioenergy facility using TBB to offset emissions from their fossil fuel powered facilities. Based on current forest management practices, harvest levels, and the assumed extraction potential, it is estimated that there is sufficient TBB within the proposed supply area to meet the annual fuel demand at the facility.

Modeling the atmospheric fate of TBB left in the forest provides a method for discounting the emissions from utilization of the material in the proposed facility. Decomposition of TBB occurs relatively rapidly after harvest; however, the time lag between complete decay and annual combustion represents an initial carbon debt. The estimated carbon debt decreases as emissions from decomposition increase over time. The estimated carbon repayment continues after the 25-, 50-, and 100-year time horizons until theoretical neutrality ($<$0.5 Mg CO_2 yr^{-1}) is reached far in the future (190+ years). The decomposition dynamics and timelines in this analysis are consistent with estimates from studies in Europe where comparable harvest systems were assumed [46,47].

The estimated decline in carbon debt from the bioenergy facility reflects the increase in estimated decay emissions from TBB otherwise left on the forest floor. When harvesting and transport emissions are included in the carbon accounting, neutrality is not possible. Unlike facility emissions, harvesting and transport emissions represent carbon debt, which is not repaid. This is important since longer time horizons result in proportionally more harvesting and transport emissions and thus, larger carbon debt.

Tracking carbon debt in this study illustrates how important the temporal component is in greenhouse gas accounting. The energy provider proposing the 26 MW biomass facility did so with the intention of offsetting (i.e., reducing) carbon emissions from their coal-fired facilities. According to Electric Power Annual [48], direct emissions (exclusive of extraction, refinement, and transport) for coal steam turbines are approximately 1.00 Mg CO_2 MWh^{-1}. Top and branch biomass (exclusive of harvesting and transport emissions) at high MC would exceed direct emissions from coal for the first 10 years in the study. Natural gas combustion turbines emit approximately 0.60 Mg CO_2 MWh^{-1} and natural gas combined cycle systems emit approximately 0.40 Mg CO_2 MWh^{-1}. Utilizing TBB (exclusive of harvesting and transport emissions) at high MC (50 percent) would exceed natural gas combustion emissions for the first 30 years of operation and natural gas combined cycle emissions for the first 48 years of operation. Utilizing oven-dry (0 percent MC) TBB would exceed natural gas combustion emissions for the first 23 years of operation and natural gas combined cycle emissions for the first 39 years of operation. These comparisons suggest that accounting for carbon emissions at relatively short time scales ($<$50 years) may not support the development of a bioenergy facility to reduce emissions from fossil fuel fired facilities. Alternatively, at longer time scales, decomposition of in-forest residues repays the carbon debt associated with biomass utilization for energy. These data are important for establishing appropriate regulatory windows for accounting for greenhouse gas emissions from renewable energy projects. They are also important for illustrating the variability in time frames based on differences in assumptions about decay rates, species mix, harvest intervals, and other factors varying by region and source of biomass.

A balance must be struck between residual biomass removals and maintaining productivity, wildlife habitat, and water quality on potential sites. Voluntary biomass harvesting guidelines have been established in Minnesota [43] and elsewhere to help maintain site conditions; however, further work documenting the potential impacts of biomass harvesting on site productivity would be useful. There is also a need for information on the extraction potential of different harvesting systems. Every harvest site is unique and equipment, operators, and silviculture prescriptions influence the availability of harvest residues. Studies describing those conditions and the residual biomass extraction potential would eliminate a major assumption – 50 percent removal – and would improve assessments of biomass availability.

Trace gases such as nitrous oxide (N_2O) and methane (CH_4) have the potential to substantially increase both in-forest decomposition and bioenergy facility GHG emissions estimates [47,49,50]. Additional research on trace gas emissions is necessary to improve carbon emissions estimates in the field and at bioenergy facilities. Fuel MC influences the efficiency of transport and combustion of wood chips and the carbon emissions associated with both. At low MC, more chips could be transported in each load, reducing transport costs and carbon emissions and the efficiency factor at the bioenergy facility would increase, reducing the CO_2 MWh^{-1} produced. Wood chips at high MC may require drying, which would increase carbon emissions or if chips are left in piles to dry, N_2O and CH_4 production could increase emissions [49]. The wood chip mix modeled in this study reflected whole tree utilization trends. The majority of the TBB used came from the aspen/birch forest type which, based on the decay rate and associated mean decay lifetime, is the optimal fuel type to minimize carbon debt. Fuel sources that decay slowly increase the lag time between complete decomposition and annual combustion and thus increase the time to carbon neutrality.

The decay rates used in this study were developed from studies in similar climates for species found within each forest type. Actual decay rates will vary by site, species, harvest conditions, climate, and size of biomass material (e.g., tree tops and branches). Projecting decomposition dynamics using the range of values in this study illustrates the influence natural decomposition has on carbon debt recovery. Further research on long-term biomass decay dynamics will improve model estimates and carbon debt forecasts. Total harvest production was modeled for chips from TBB, which will differ from estimates of roundwood use for energy. All forests were assumed to fully regenerate after harvesting, which is common practice in the region and therefore negate the carbon implications of land use conversion. Furthermore, we modeled net carbon emissions for stand-alone electricity production, which would be less than emissions if TBB were utilized in combined heat and power applications. Other factors affecting net carbon emissions include tree species, size, taper, and site operability, which may vary greatly from one location to another. Finally, care was taken throughout the modeling process to incorporate the most current information possible reflecting a range of possible outcomes. Nevertheless, the results are based on *current* forest conditions, timber markets, and management paradigms, all of which are likely to change over the modeled time horizons.

5. Conclusions

As electric utilities weigh renewable energy options to meet state and federal energy targets, they will need to adopt consistent and scientifically proven methodologies for comparing existing emissions with renewable alternatives. This study employed a methodology for estimating carbon emissions that assumed procurement and utilization of forest harvest residues only. The incorporation of bole wood for energy production or changes in land use could dramatically change the results. As modeled here, the results suggest there is an initial carbon debt associated with the utilization of forest harvest residues for energy but that the debt is repaid over time through emissions from decomposition and ultimately reduces to fossil fuel emissions from harvesting and transport. Whether or not the carbon debt is paid off within an acceptable time frame requires policy analysis beyond the scope of this study, but these findings help shed light on how various factors alter those time frames. Accurate accounting of these temporal dynamics is critical in assessing the long-term carbon implications of forest-derived bioenergy feedstocks.

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