Assessment of Carbon Flows Associated with Forest Management and Biomass Procurement for the Laskin Biomass Facility

A report to

Minnesota Power
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Duluth, MN 55802

by

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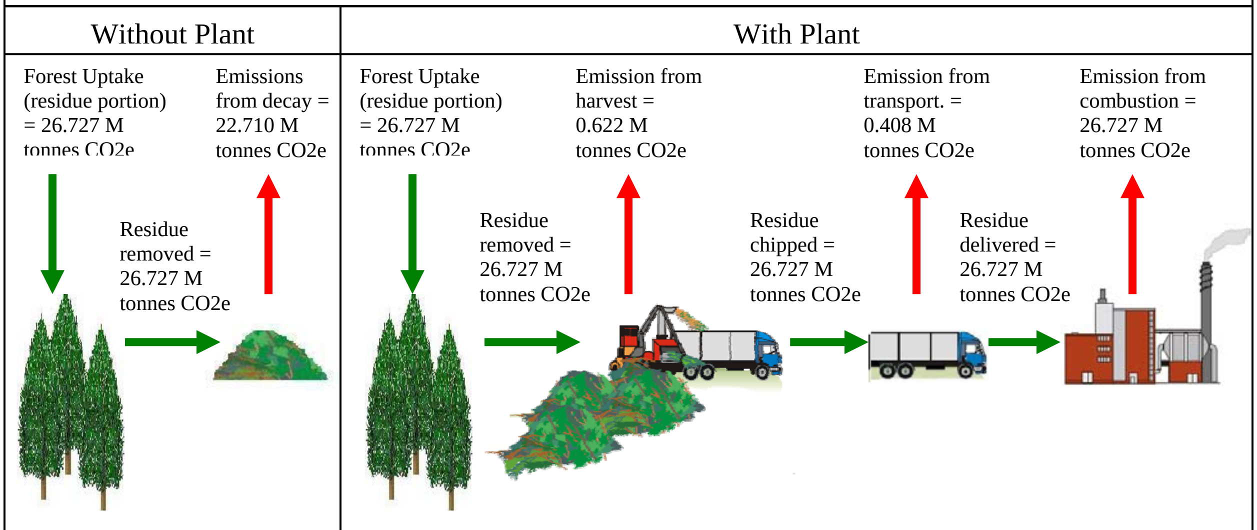
Executive Summary

This carbon life cycle analysis of forest-derived biomass was developed as part of a larger assessment by Minnesota Power detailing fuel supply, fuel procurement plans, and project engineering for a new 26-megawatt biomass generation facility in Hoyt Lakes, Minnesota. Forest-derived biomass is a renewable fuel that can be procured locally from forest harvest residues, mill residues, material from early thinnings and land cleaning, short rotation woody crops, brush, and urban wood waste. Energy generation from renewable fuels like forest biomass may dramatically alter the carbon balance in comparison to the use of fossil fuels like coal or natural gas. This study identifies the source and rate of carbon accumulation by tracking key inputs and outputs from forests through the conversion, regrowth and management activities over a 100-year period—the net carbon impact.

The figure below illustrates the net carbon inputs and outputs measured in this analysis. With the proposed Laskin facility, approximately 27.757 M tonnes (30.597 M short tons) will be emitted over the 100-year planning period. This estimate includes carbon stock (extractable biomass) removed from the harvest site, carbon emissions from extracting biomass, and carbon emissions from transport to and from the generating facility. Without the proposed biomass energy facility, the total decay emissions from extractable biomass left on the harvest site are approximately 22.710 M tonnes CO_2e (25.033 M short tons). The difference between the with- and without project scenarios is approximately 5.047 M tonnes of CO_2e (5.577 M short tons) for the production of approximately 18.221 M MWh of electricity, resulting in a net CO_2e emission value of 0.277 tonnes CO_2e/MWh over the 100-year period. This value (0.277 tonnes CO_2e/MWh) would be reduced to just emissions from harvesting and transport (0.057 tonnes of CO_2e/MWh) if the planning horizon were extended to allow the accumulated biomass from the 100-year planning period (which would otherwise be utilized in the Laskin facility) to decompose completely. Approximately 90-95% of this decomposition would be achieved within 20 years after plant operations cease, resulting in a net CO_2e emission value of 0.068-0.079 tonnes of CO_2e/MWh. Complete decomposition would take approximately 250-350 years for most species based on the exponential decay rate model assumed in this study.

In addition to the carbon dioxide (CO_2) flows associated with the removal and/or decay of woody biomass, other gases, namely nitrous oxide (N_2O) and methane (CH_4) have the potential to alter the overall carbon budget over the 100-year planning period. The methane emitted through litter decomposition is offset, in part, by soil bacteria (methanotrophs) which use methane as a source of carbon in a process known as methane oxidation. This examination presumes that trace gas fluxes are small in the context of the study. Future studies of this type would benefit from further research on trace gas emissions from decomposition of logging residues. Should methane from biomass decomposition prove to be present in traceable quantities, utilization for energy could substantially decrease the net carbon foot print of biomass energy facilities. This analysis did not include secondary gases in the quantitative study balance.

Estimated Carbon Inputs and Outputs over the 100-year Planning Period



Net CO_2e Emissions = Total Emissions with Plant – Total Emissions without Plant

= (0.622 + 0.408 + 26.727) – (22.710) = 5.047 M tonnes CO_2e

Net CO_2e Emissions per MWh = 5.047 M tonnes CO_2e / 18.221 M MWh = 0.277 tonnes CO_2e/MWh*

* Note: Continued decomposition that would occur 20-years after plant operations cease, reduces the net CO_2e Emissions per MWh value to 0.068-0.079 tonnes CO_2e/MWh.

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Introduction and Rationale

Minnesota Power, an investor-owned electric utility serving the forested region of northern Minnesota, currently owns and operates two biomass-fueled combined heat and power (CHP) facilities associated with large paper production facilities. As part of its planning to develop additional renewable energy resources pursuant to the Next Generation Energy Act of 2007, Minnesota Power completed a detailed assessment of a new 26-megawatt biomass generation facility in Hoyt Lakes, Minnesota. The assessment includes a detailed fuel supply study, fuels procurement plan, and project engineering. Minnesota Power also sought to expand the analysis by completing a carbon life cycle analysis to inform decision making on investments in renewable energy. The Department of Forest Resources at the University of Minnesota was subsequently asked to complete this additional analysis for biomass derived from forests surrounding the Hoyt Lakes facility.

Forest-derived biomass is a renewable fuel that can be procured locally from forest harvest residues, mill residues, material from early thinnings and cleanings, short rotation woody crops, brush, and urban wood waste. Energy generation from renewable fuels like forest biomass may dramatically alter the carbon balance in comparison to the use of fossil fuels like coal or natural gas. The Minnesota Power proposal for a commercial-scale power generation facility at the Laskin Energy Center at Hoyt Lakes, Minnesota is one key example (TSS Consultants, 2007).

Estimating the flow of carbon from standing forests to the generation of energy involves consideration of diverse factors, some of which are highly variable and site dependent. Key factors in the analysis include the carbon content of forest-based raw material utilized (by species and forest type), carbon released through the energy expended in harvesting and transportation of the raw material, the conversion technology used to produce energy at the plant, and the accumulation of carbon in the regrowth and management of forests over time. This study identifies the source and rate of carbon accumulation by tracking key inputs and outputs from standing trees through the conversion, regrowth, and management activities over a 100-year period—the net carbon impact. In doing so, carbon lost to the atmosphere is estimated as well as that stored and sequestered in standing forests and durable wood products over that period of time.

Goals and study components

The goal of this study is to characterize the net carbon stock changes associated with operation of the proposed 26-megawatt Laskin biomass facility, from a full life cycle assessment (LCA) perspective. Comparisons with and without the Laskin biomass facility are made under a variety of harvesting, transportation, and forest management scenarios to document the potential range of carbon flux. Estimates of carbon accumulation and sequestration are reported for only biomass decay on timberlands and emissions from the extraction and transport of harvest residues from forested sites to the Laskin facility. Key assumptions used in the analysis are provided. The results of this report can be used in conjunction with previous reports and analyses pertaining to the use of forest biomass for the Laskin facility operated by Minnesota Power. The key components of this project are:

1. A *review and synthesis of the literature* linking forest management, harvesting and utilization practices with carbon flows;
2. The *development of a model*, including parameterization, to describe the flow of carbon associated with forest harvesting, transportation of raw material to the energy facility, and

net carbon balances associated with different forest management regimes in the Laskin study area; and

3. A *life cycle analysis of net carbon flow* related to the Laskin facility focused on the use of renewable resources and associated practices, present and potential, to suggest how this use affects carbon lost to the atmosphere, and how it affects the amount of carbon sequestered.

Review and synthesis of the literature

Forest ecosystems represent the primary terrestrial carbon sink storing more than 80 percent of all terrestrial aboveground carbon (Dixon et al. 1994). Over the course of forest stand development, carbon is absorbed from the atmosphere by forest vegetation and stored in several components, including living biomass, dead woody material, and soil organic matter (Pregitzer and Euskirchen 2004). Overall, per unit time the amount of carbon fixed by a given forest ecosystem and stored in live and dead organic matter is quantified as the net ecosystem productivity (NEP), which equates to gross primary production minus total ecosystem respiration (Janisch and Harmon 2002). Gross primary production (GPP) is by definition total gross photosynthesis. Total ecosystem respiration is the sum of plant respiration and the consumer and decomposer respirations, which one can think of as the use of carbon (C) by the plant for its living activities and the use of live and primarily dead plant C by microbes for their life activities. By definition, when total (gross) photosynthetic rates are greater than total ecosystem respiration rates, forests are carbon sinks, whereas systems are considered carbon sources when respiration exceeds photosynthesis (Dixon et al. 1994). Young forests (0-10 years) generally represent carbon sources as ecosystem respiration rates exceed primary production in these systems (Pregitzer and Euskirchen 2004). This is because substantial amounts of carbon are respired that were generated from the prior stand. In contrast, intermediate-aged (30-120 years) and older forests (120-200 years) are almost always carbon sinks, with forests between 11-30 years likely having the highest net ecosystem productivity (Pregitzer and Euskirchen 2004), although those values are not well quantified and are highly variable depending on forest type, soil environment, climate, and location.

As a consequence of differences between GPP and ecosystem respiration, the amount of carbon accumulated (or “stored”) in living and dead biomass, as well as in forest soils, also changes over the course of stand development. The size of forest ecosystem carbon pools generally increases over time following disturbances (Curtis et al. 2002, Hooker and Compton 2003, Yanai et al. 2003). For example, the amount of carbon stored in living and dead biomass typically increases with stand age following harvesting disturbances (Bormann and Likens 1994). In contrast, changes in soil carbon stores in the years immediate following forest harvesting are often negligible and may increase if harvest residues are left on site (Hendrickson et al. 1989, Johnson et al. 1991, Johnson 1992, Johnson and Curtis 2001).

Methods

Study area

The study area includes forest resources located within a 100-mile radius of the proposed Laskin facility (47.5597 N, -92.1197 W) near Hoyt Lakes, MN. The area represents 7,859,660 acres of productive timberland in northeast Minnesota and 1,417,649 acres in northwest Wisconsin for a total of 9,277,309 acres (Table 1). There are several forest types within the Laskin study area but only a few species and forest types dominate. The aspen forest, which is dominated by *Populus tremuloides* and to a lesser extent *P. grandidentata* occupies more than 36 percent of the study area or 3,209,306 acres (Figure 1 and Table 1). More than 7 percent of the aspen forest type is occupied by balsam fir (*Abies balsamea*) and approximately 6 percent is occupied by paper birch (*Betula papyrifera*) (Figure 2). The spruce forest type, which is dominated by *Picea mariana* and *P. glauca*, represents nearly 12 percent of the total acres and paper birch occupies about 8 percent (Figure 1). Northern white-cedar (*Thuja occidentalis*) is included in the total acreage but not in the analysis due to the relatively small proportion of cedar harvested annually. The average live biomass per acre for each age class and forest type in the Laskin study area is listed in Table 2. The maple-basswood and northern hardwood forest types have the greatest volume per acre across all age classes while tamarack and spruce have the lowest biomass per acre. This is not surprising as the majority of tamarack and spruce stands within the Laskin study area are growing on low to moderately productive sites. Due to limited information on harvest levels and transportation networks for the Wisconsin portion of the study area, information from Minnesota was used in the development of the carbon flow model.

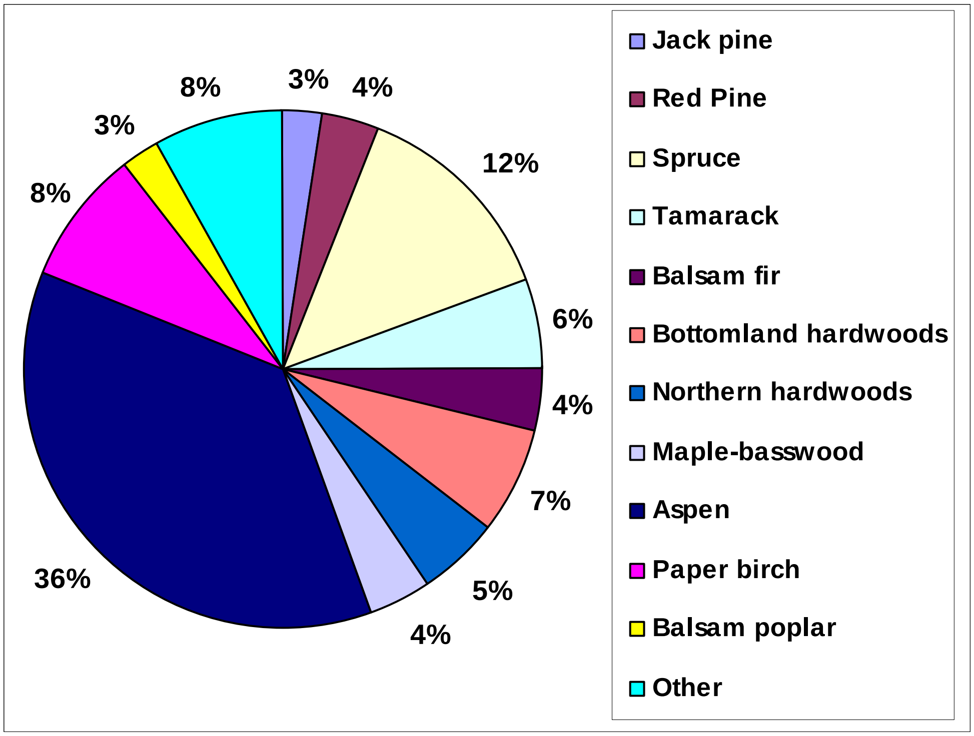


Figure 1. Proportion of timberland (acres) for each forest type in the Laskin study area.

Table 1. Forest types by acres and age class for the Laskin study area.

Age Class	Jack pine	Red pine	Balsam fir	Spruce	Tamarack	N. white-cedar	Bottomland hardwoods
0-10	9,067	21,642	24,563	32,087	21,275	2,188	26,298
11-20	25,955	36,236	53,321	39,790	22,225	2,349	11,398
21-30	43,344	46,787	28,101	50,107	24,521	7,627	25,837
31-40	52,881	48,213	34,689	71,585	38,916	6,940	19,172
41-50	18,096	46,900	58,880	160,567	56,239	13,143	28,374
51-60	16,799	37,874	55,171	160,850	46,797	28,220	83,935
61-70	17,343	32,484	26,395	195,300	88,756	26,328	89,013
71-80	21,111	16,898	14,574	148,696	68,490	36,026	114,271
81-90	15,492	13,149	9,463	96,546	51,076	34,472	68,947
91-100	0	8,825	13,801	56,068	35,835	35,213	21,378
100+	0	15,157	12,184	144,885	48,531	189,435	106,354
Total	**220,088**	**324,165**	**331,142**	**1,156,481**	**502,661**	**381,941**	**594,977**

Age Class	Northern hardwoods	Maple-basswood	Aspen	Paper birch	Balsam poplar	Other	Total
0-10	33,352	27,079	618,543	49,668	36,624	235,467	**1,137,853**
11-20	10,506	2,987	467,036	48,896	27,418	58,652	**806,769**
21-30	25,410	6,078	376,090	33,657	17,993	27,664	**713,216**
31-40	29,584	12,857	310,188	31,547	26,705	59,064	**742,341**
41-50	19,006	23,032	402,221	49,094	27,972	77,736	**981,260**
51-60	67,430	29,808	397,732	151,218	32,268	80,845	**1,188,947**
61-70	99,199	83,271	350,585	168,699	24,451	105,681	**1,307,505**
71-80	64,369	82,998	200,964	110,330	18,699	82,190	**979,616**
81-90	49,372	52,274	56,896	42,515	6,080	53,503	**549,785**
91-100	15,239	7,061	17,674	33,031	2,334	24,901	**271,360**
100+	13,692	11,185	11,377	12,760	3,182	29,915	**598,657**
Total	**427,159**	**338,630**	**3,209,306**	**731,415**	**223,726**	**835,618**	**9,277,309**

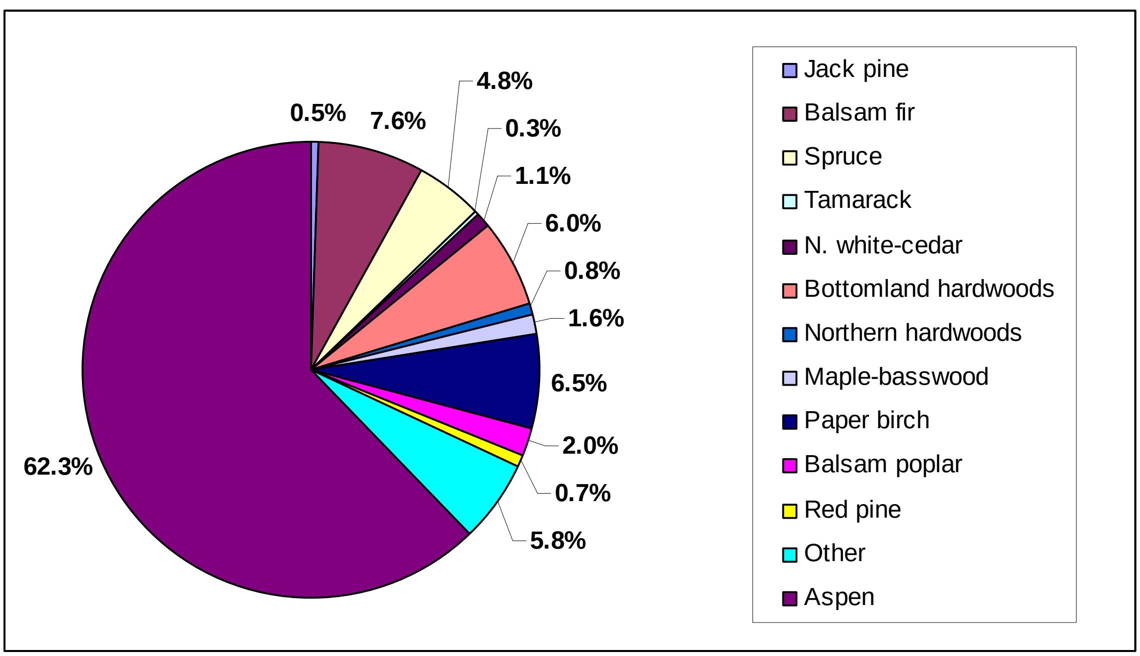


Figure 2. Species mix within the aspen forest type in the Laskin study area.

Table 2. Average biomass per acre (tonnes) by age class and forest type for the Laskin study area.

Age Class	Red pine	Jack pine	Balsam fir	Spruce	Tamarack	Bottomland hardwoods
0-10	5.76	5.20	11.01	7.6	10.41	11.86
11-20	17.14	10.04	14.28	8.2	5.96	10.27
21-30	30.19	15.62	13.94	12.6	8.81	12.75
31-40	34.49	17.65	19.63	13.7	11.67	8.48
41-50	38.42	23.08	21.73	16.8	10.45	19.09
51-60	37.18	23.37	19.13	19.3	16.99	25.85
61-70	48.79	32.47	17.32	18.1	19.67	31.74
71-80	64.91	34.53	18.16	19.8	16.62	32.32
81-90	49.35	26.04	21.56	19.2	19.71	39.84
91-100	49.85	31.04	20.19	12.6	18.51	41.18
100+	52.38	35.44	15.63	13.9	18.64	36.47

Age Class	Northern hardwoods	Maple-basswood	Aspen	Paper birch	Balsam poplar	Other
0-10	13.33	20.14	8.48	13.06	10.0	9.07
11-20	15.16	25.29	14.74	13.44	11.9	10.22
21-30	17.89	48.85	19.56	12.40	23.5	15.94
31-40	28.18	36.84	24.95	28.32	24.4	22.01
41-50	45.87	38.12	33.40	27.18	31.2	31.57
51-60	44.84	55.95	34.66	36.95	32.1	33.74
61-70	44.75	53.34	39.90	37.89	28.3	29.64
71-80	47.07	59.76	43.08	35.72	28.5	47.10
81-90	55.69	64.93	40.06	42.55	46.2	45.06
91-100	46.82	56.58	56.28	42.26	--	40.98
100+	56.20	60.84	41.34	39.35	--	54.38

The model form chosen to derive carbon flows is based on the idea of *area control* in forest management, which is where specification of the acreage harvested annually is used to manage (or control) the development of the forest over several decades (Buongiorno and Gilless 2003). The model, through the description of changes in forest type acreage by age class, is then used to relate the impacts associated with forest harvesting, transportation of raw material to the Laskin facility, and estimated net carbon balances associated with forest management in northeast Minnesota and northwest Wisconsin over the 100-year planning horizon.

Data sources

Data for this study were collected from a variety of sources. The geographic location of the Laskin facility was determined using the US Census Bureau Gazetteer (United States Census Bureau 2008), which was used to retrieve specific USDA Forest Service Forest Inventory and Analysis (FIA) plot locations within the Laskin study area using Forest Inventory Mapmaker Version 3.0 (Miles 2008). The FIA Data Mart (http://www.ncrs2.fs.fed.us/FIADatamart/fiadatamart.aspx) was then used to retrieve empirical data on the 4,716 FIA plots within the study area. This information was used to characterize the forest resources in the study area and to develop the model for projecting carbon flows over the 100-year time horizon.

Estimates of logging residues (slash) were taken from the Minnesota Department of Natural Resources (MN DNR) (2006a) *Minnesota Logged Area Residue Analysis*. The cords of coarse and fine woody debris reported for “Aspen” and the broad categories, “Other hardwoods,” “Lowland conifers,” and “Upland conifers” were used in conjunction with specific weights reported in the MN DNR (1981) *Timber Scaling Manual* to derive forest type and species specific residue biomass values. Those values were then divided by the average live harvestable biomass per acre for each species and forest type to determine the proportion of roundwood that is left as residual biomass (see Appendix Table 19). The values were then compared with other studies estimating residual biomass in similar forest types (e.g., black spruce and jack pine) to ensure that residual estimates were realistic (M. Ryans, FPInnovations-FERIC, personal communication).

Data on the extraction and processing of logging slash were gathered from existing literature (Sturos et al. 1983, Binker et al. 2002), as well as from personal communications with logging professionals in the Laskin study area (see Appendix Tables 16 and 17). Due to a lack of information on harvesting efficiency for those species found in the study area, a conservative estimate of 50 percent of the total residual biomass available was assumed to be extractable. This estimate is based on recommendations from the MN DNR (2006a) *Logged Area Residue Analysis*, as well as from unpublished work in whole-tree harvested black spruce stands in Kapuskasing, Ontario (FPInnovations 2008 presentation). The remaining 50 percent left on site exceeds the 33 percent recommended by the Minnesota Forest Resources Council (MFRC) *Biomass Harvesting on Forest Management Sites* (2007). This recommendation assumes that 20 percent of the fine woody debris (tops and limbs) is intentionally retained with an additional 10-15 percent retention achieved by incidental breakage during removal. These assumptions will vary depending on the type of equipment used, silvicultural prescription, season of harvest, and forest type and condition. Due to this variation and the more conservative estimates used in other studies, the analysis was not adjusted to account for the disparity between the MFRC recommended retention level (33 percent) and the estimated retention level (50 percent) used in this study.

To characterize transportation routes and estimate carbon emissions for transport of biomass to the Laskin facility, an ArcView GIS layer was created with FIA plot coordinates and the Laskin facility coordinates overlaid on a roads layer allowing for calculating transportation distances to and from various harvesting sites. To calculate annual carbon emissions resulting from transport of harvested residuals, an average one-way transportation distance of 135 kilometers (84 miles) was calculated within the Laskin study area. This value was then doubled to arrive at the roundtrip transportation distance of 270 kilometers (169 miles). This value was used in conjunction with fuel consumption information of 2.02 kilometers per liter (4.74 MPG) for log trucks and chip vans and an annual utilization estimate of 251,336 green tonnes (277,050 short tons) of biomass required at the Laskin facility to produce 182,208 Megawatt hours (MWh) of power (F. Frederickson, Minnesota Power, personal communication). The following describes the analyses that were conducted to assess the annual carbon stock flux with the Laskin facility.

Carbon flow model

The carbon flow model developed for this study is a series of spreadsheet models working together to calculate current and future carbon stocks on timberlands within the Laskin study area, as well as carbon flows associated with forest management activities. The following provides a description of each spreadsheet model, key inputs, and assumptions used.

Area-control model—the area control model was developed using the most recent FIA inventory period data to grow timberland acres over the 100-year planning horizon. Acres within the study area were partitioned into 10-year age classes and each year 10 percent of those acres were assumed to move into the next age-class. Acres at the end of the final age class (110 yrs) were assumed to die and return to the 0-10 age class in each forest type in order to create a closed system with no loss of acres over the 100-year planning horizon.

Rotation length and harvest intensity varied by species and forest type. Baseline rotation ages were taken from the *Forest Development Manual* (MN DNR 1997) and adjusted based on professional judgment and current harvesting conditions reported in the *Minnesota's Forest Resources* report (MN DNR 2007). Harvest intensity, based on the volume harvested annually, was proportionally rated based on Minnesota statewide harvest levels reported in the *Minnesota's Forest Resources* report (MN DNR 2007). Appendix Table 18 displays the volume in cords and tonnes cut by species and forest type within the Laskin study area. Since harvest levels vary from year to year, the average statewide harvest over the past five years (2001-2005) was used as the starting average volume cut by forest type. In reality, some but not all stands are cut at or near the rotation age. In fact, harvesting continues throughout all harvestable age classes until all available stands are harvested, die, or succeed to another forest type. An example harvest rate is shown in the "percent harvested" column of Appendix Table 14. Additionally, Table 6 summarizes the forest type acres harvested annually (based on the percent of each forest type harvested from Appendix Table 14) and Table 7 summarizes the total forest type acres harvested over the 100-year planning period.

The model was then used to develop a 100-year scenario for each forest type (Appendix Table 15). Figure 3 shows the current year (2008) and projected 50- and 100-year acres by age class for the aspen forest type. The harvested acres in each age class were then multiplied by the average biomass derived from FIA data for each 10-year age class (Table 2). The biomass factor for each age class was based on the oven-dry weight (in tonnes) of all live stems in each age class >1-inch diameter at breast height. All biomass values were then converted to carbon using an equation developed by Birdsey (1992) that assumes the dry mass of wood is approximately 50 percent carbon.

Carbon accumulation—carbon accumulation rates are a function of tree growth, which follows a nonlinear, asymptotic pattern (slows) with age. To account for this, growth was modeled using FIA data and the Carbon Online Estimator (COLEv2.0 USDA FS 2005). Sensitivity analysis showed that growth curves for all forest types in the study area (FIA analysis) and Minnesota (COLE) change their slope at approximately age 40, which allowed us to derive two separate carbon accumulation rates for stands <40-years of age and ≥40-years of age using linear regression. Appendix Figure 9 illustrates the sensitivity analysis that was run for the aspen forest type and all other forest types in the study area to determine the age at which the rate of carbon accumulation changes.

For forest stands <40-years of age, carbon accumulation rates were estimated simultaneously by two methods that were then compared for consistency. The first method used empirical information from the FIA analysis within the Laskin study area and the other used data generated by the COLE for all forest types in Minnesota. Regression analysis was used in both methods to determine the rate of carbon accrual by stand age, based on rotation length. Due to the high levels of uncertainty associated with temporal changes in other carbon pools, we assumed that all other pools of carbon in the ecosystem did not vary over the 100-year projections.

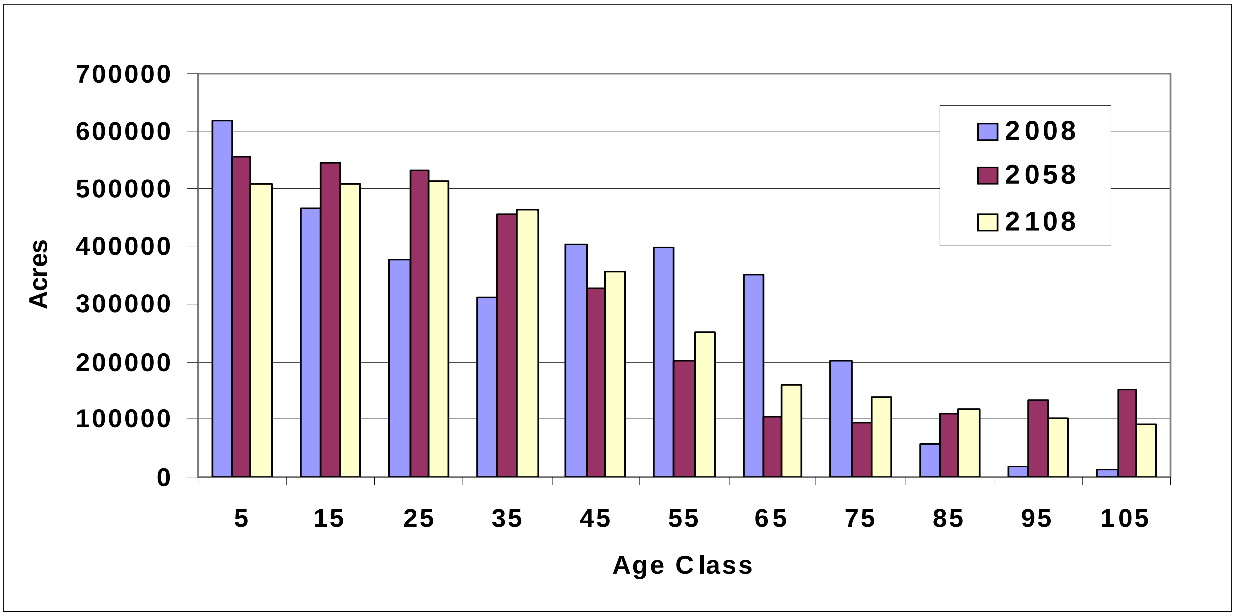


Figure 3. Area control model output displaying current, 50-year, and 100-year aspen forest type acres by age class for the Laskin study area.

Moreover, the change in total carbon (C) in accumulating wood vastly outweighs other changes—thus for purposes of this exercise, we can treat wood as the sole variable needing to be accounted for. Both methods provided estimates of annual carbon (in tonnes) sequestered per acre. The empirically derived estimate was 0.70 tonnes C/acre/year (Figure 4) and the modeled rate was 0.58 tonnes C/acre/year (Figure 5). These estimates were averaged to provide a parsimonious accumulation rate for stands <40 years of age for all forest types within the study area (Table 3). For stands >40 years, a carbon accumulation rate of 0.11 tonnes C/acre/year was derived from linear regression analysis using COLE for the all forest types in Minnesota (Figure 6). FIA data were not used for the >40-year analysis due to large variability for many forest types. Table 3 lists the carbon accumulation rates per acre per year for the forest types in the study area.

Decay emissions—to determine the carbon emissions associated with the decay of forest biomass left following harvest, the following equation was used:

$$D_t = D_0 e^{(-kt)}$$

where D_t is the annual decomposition, D_0 is the residual biomass produced each year, t is the time of decomposition (years), and k is the decomposition constant. Decomposition constants were used from existing literature when available or were derived from published values used for other species in this study. Table 4 lists the decay constants used for each forest type in the Laskin study area. The annual decomposition values were integrated over the entire harvest area and time until nearly all (< 0.1 tonnes) biomass was decomposed. In all cases this required more than 100 years. Consequently, the biomass decayed over the 100 year planning horizon is reported along with the range in time necessary for nearly complete (< 0.1 tonnes) decomposition. Note that only the extractable biomass, which is equivalent to 50 percent of the available harvest residuals, was included in the analysis since the remaining biomass would remain on site with or without the Laskin project.

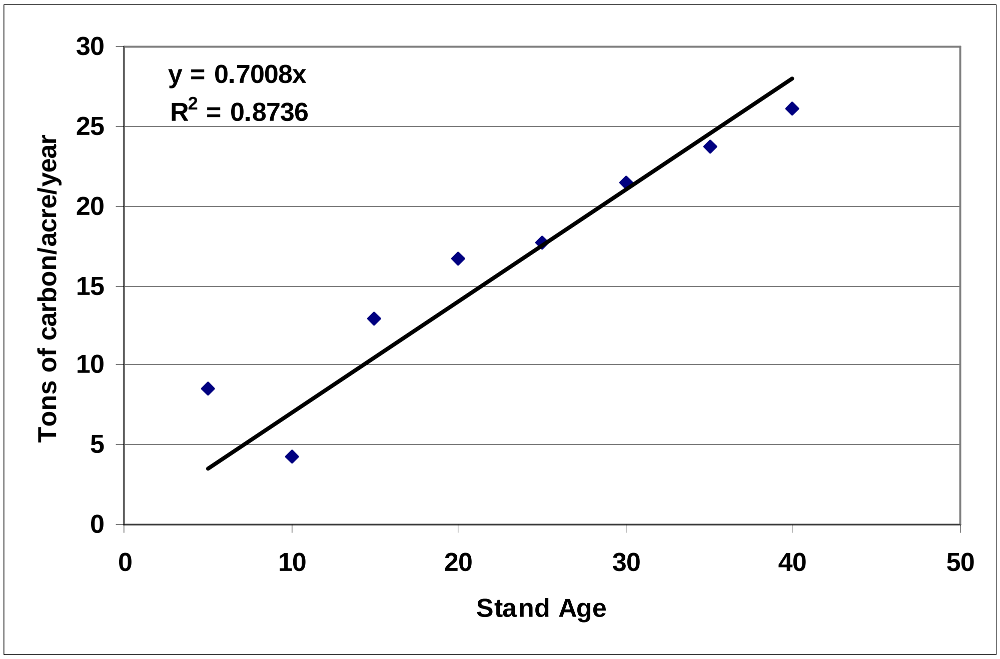


Figure 4. Regression analysis (empirical) used to calculate the annual accumulation rate per acre for stands < 40-years for the aspen forest type within the Laskin study area.

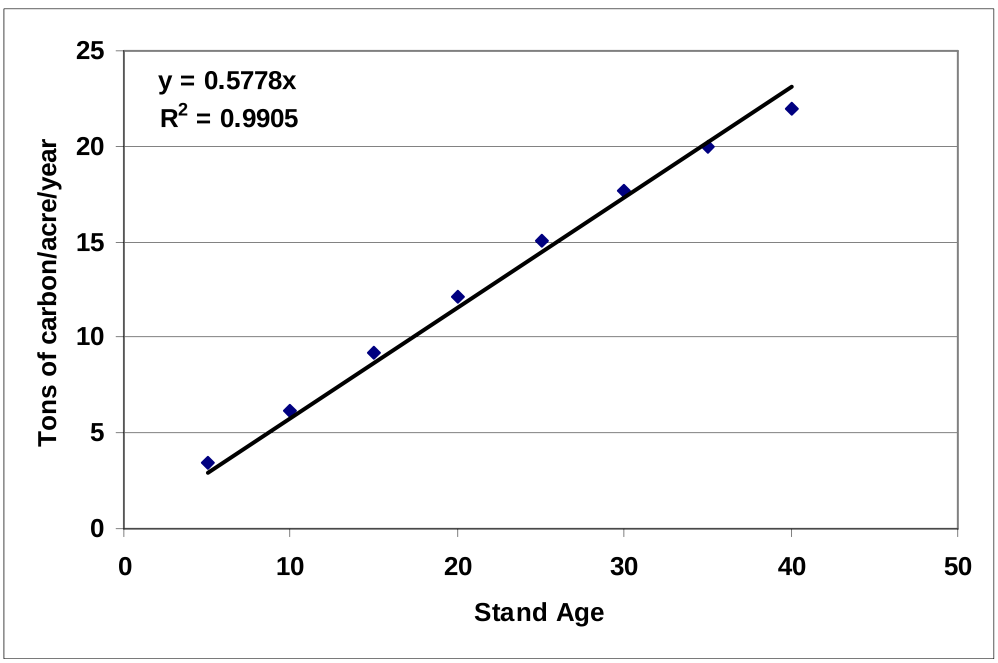


Figure 5. Regression analysis using COLE—generated carbon stocks to calculate the annual carbon accumulation rate per acre for stands < 40 years of age for the aspen forest type in Minnesota.

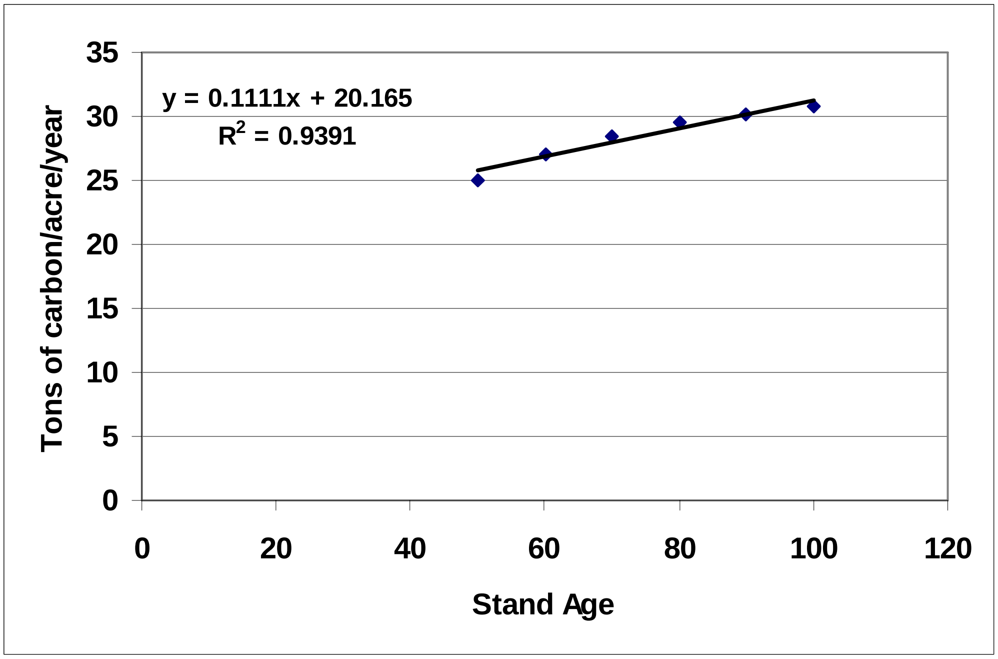


Figure 6. Regression analysis using COLE - generated carbon stocks to calculate the annual carbon accumulation rate per acre for stands > 40 years of age for the aspen forest type in Minnesota.

Table 3. Annual carbon accumulation rates per acre (tonnes C) for the forest types in the Laskin study area calculated using FIA and COLE data and linear regression.

	< 40 years			≥ 40 years
	------------------Data Source------------------			Data Source
Species	**COLE**	**FIA**	**Average**	**COLE**
Jack pine	0.52	0.53	0.53	0.08
Red pine	0.75	0.97	0.86	0.10
Balsam fir	0.69	0.56	0.63	0.05
Spruce	0.53	0.41	0.47	0.11
Tamarack	0.48	0.32	0.40	0.14
Bottomland hardwoods	0.46	0.37	0.42	0.18
Northern hardwoods	0.90	0.75	0.83	0.07
Maple-basswood	0.77	0.50	0.64	0.14
Aspen	0.58	0.70	0.64	0.11
Paper birch	0.51	0.66	0.59	0.09
Balsam poplar	0.52	0.72	0.62	0.05
Other	0.64	0.60	0.62	0.16

Harvesting emissions—per communication with Mark Ryans, Ontario Registered Professional Forester and Group Leader for Silviculture Operations and Bioenergy for FPInnovations (FERIC), the biomass harvesting system assumed in this analysis is similar to the biomass harvesting system commonly used in Ontario, Canada, on Crown Land forests. This system is described as a conventional, whole-tree harvest operation that processes the tree and residual biomass (limbs and tops) at the harvest landing. Once at the landing, the biomass is processed using either a chipper or grinder, then transported to the mill in a chip van (Figure 7). FPInnovations has monitored the recoverable biomass volume removed from the harvest site using this harvesting and processing configuration. Their results based on field studies estimate the amount of biomass removed from the harvest site ranges from 10 to 16 percent of the merchantable roundwood volume removed (M. Ryans, FPInnovations-FERIC, personal communication) (see Appendix Table 19 for estimates used in this study). Tree species mix, size class, and wood quality, as well as site conditions and management and regeneration objectives are key determinants of recoverable biomass volume on a given harvest site, which may vary greatly depending on these factors.

Table 4. Decay constants used to calculate the annual decomposition of extractable biomass within the Laskin study area.

Forest type	Decay rate (K)	Source
Aspen	0.080	Alban and Pastor 1993
Balsam poplar	0.080	Assumed the same K as aspen in Alban and Pastor 1993
Paper birch	0.068	Harmon et al. 2000
Maple-basswood	0.045	MacMillian 1988
Northern hardwood	0.096	Arthur et al. 1993
Bottomland hardwood	0.089	Chueng and Brown 1995
Other	0.076	Mean of all published values in this table
Balsam fir	0.011	Lambert et al. 1980
Jack pine	0.042	Alban and Pastor 1993
Red pine	0.055	Alban and Pastor 1993
Spruce	0.071	Alban and Pastor 1993
Tamarack	0.045	Mean of published conifer values in this table

To assess total carbon emissions from logging equipment during the residue extraction process, a whole-tree harvest system was assumed. Equipment horsepower, productive machine hours delay-free (PMH), and diesel fuel consumption rates for each piece of equipment were used to calculate the carbon dioxide (CO_2) emitted per tonne of wood chips processed. Carbon emissions conversion factors for diesel fuel were used from the Climate Registry (2005).

The whole-tree harvest system was modeled as a Drott 40 LC Feller/Buncher, John Deere 740 Skidder, and a Morbark self-loading chipper (Figure 7). Productivity and horsepower ratings used for each piece of equipment are reported in Appendix Tables 16 and 17 based on studies of comparable harvest conditions, species, and size class (Sturos et al. 1983, Gingas and Favreua 1996). Fuel consumption rates per PMH were calculated based on estimates from Brinker et al. (2002).

Total productivity was modeled for both small diameter material (< 5-in dbh) and chips from slash generated from the harvest of roundwood (> 5-in dbh). Productivity and fuel usage is affected by the size of machines used, horsepower rating, and equipment specifications. Other factors affecting productivity include tree species, size, taper, and site operability, which may vary greatly from one location to another. The productivity equations used in this study are estimates and may not reflect the full range of possible harvest systems in use in Minnesota today.

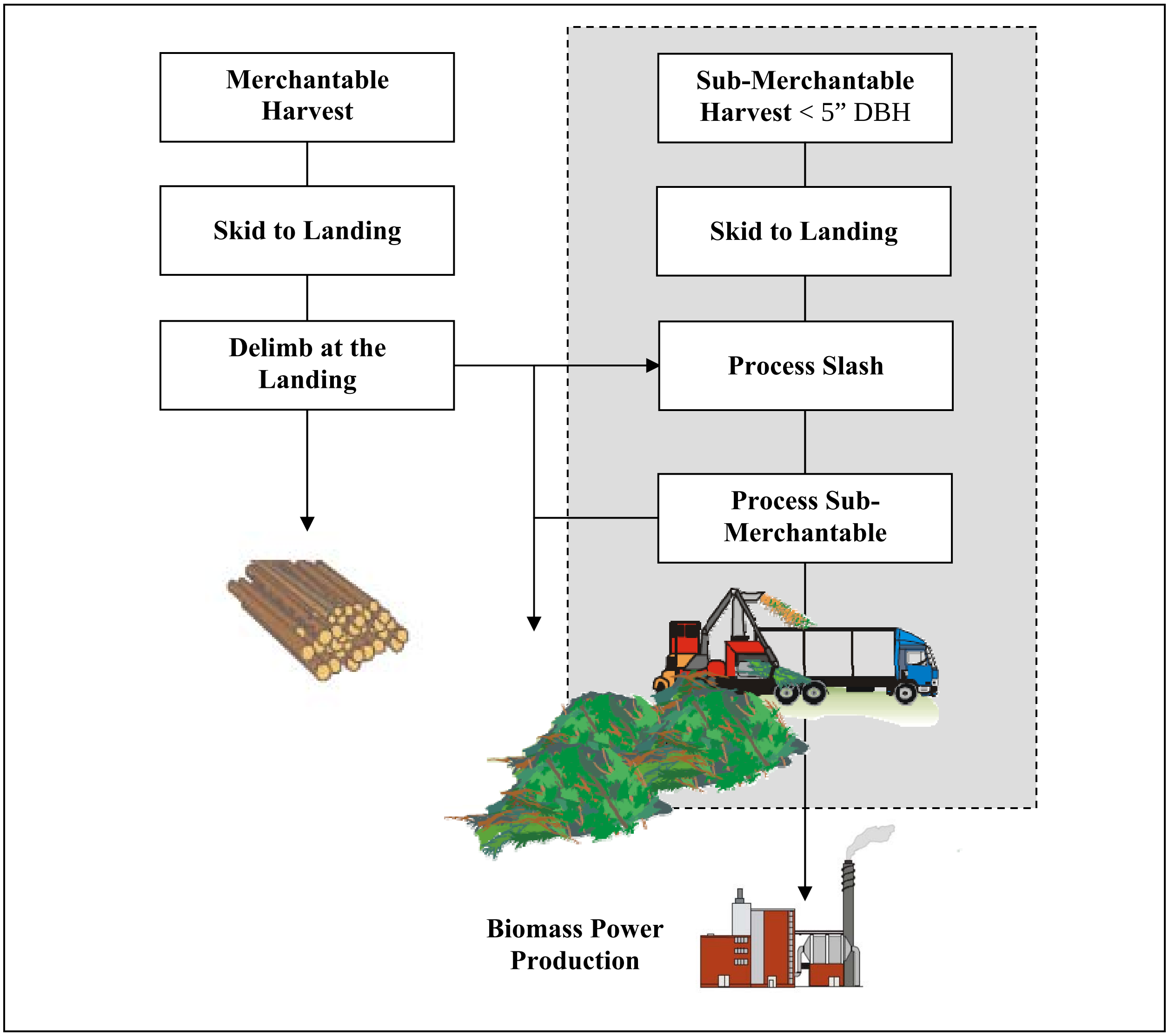


Figure 7. Harvest, transport, and processing system assumed for the Laskin Energy Facility.

Transportation—the emissions from transporting biomass residue to the Laskin facility were calculated using data from a recent survey of logging companies within the Laskin study area. Companies were asked to provide average annual fuel consumption for chip hauling equipment. This information was used in conjunction with the average FIA plot distance computed in ArcView to calculate transport emissions based on a 22.7-tonne (25-short ton) load from within the appropriate fuel procurement radius. Road type was used to calculate speeds and associated fuel usage and emissions, which were then scaled up for all biomass processed to determine the annual CO_2 emissions of transporting residue to the Laskin facility. This analysis assumes transportation trucks are making round-trips from the Laskin facility.

Carbon flow model assumptions—due to the nature of this analysis, it was necessary to make assumptions in the development of the area-control model. Below is a detailed list of those key assumptions with associated values used to develop the carbon flow estimates:

- The total timberland acres within the LSA remained fixed at 9,277,309 acres and all acres assigned to each forest type (Table 1) remained fixed with no conversion to other types or addition from changing land use.
- The annual biomass necessary to fuel the Laskin facility was assumed to be 145,652 oven-dry tonnes (ODT) (251,340 green tonnes; 277,050 green short tons) for annual generation of 182,208 MWh.
- The model assumes that there are no disturbances (e.g., insects, disease, fire) other than forest management to setback stand ages. One tenth of the acres in each age class moved to the next age class annually unless harvested.
- Rotation lengths assigned to each forest type in the model were based on the *Forest Development Manual* (MN DNR 1997) and professional judgment.
- Harvest intensity measured as the percent cut in each age class for each forest type was adjusted based on rotation length and the proportion of the total harvest assigned to each forest type. Appendix Table 19 was used to fine-tune each forest type-specific model to reflect the volume removed annually over the last five years reported in the *Minnesota's Forest Resources* report (MN DNR 2007). To clarify, the fitting process using the aspen forest type, Table 2 reports the modeled volume of roundwood harvested annually (1,066,338 ODT) and Table 6 reports the proportion of the aspen forest type harvested in the Laskin study area (1,066,739 ODT).
- Biomass estimates for each forest type and age class were based on the most recent FIA inventory data and represent averages over each 10-year age class within the study area.
- The proportion of extractable biomass from logging slash (limbs and tops) and small diameter material (> 1 inch) for each forest type were calculated from the volumes reported in the *Logged Area Residue Analysis* (MN DNR 2006). Because the categories were broad, professional judgment was used to assign weights based on the *Timber Scaling Manual* (MN DNR 1981).
- FIA plot coordinates were used to represent harvest locations when calculating average harvest site distance.
- All transport emissions were based on roundtrips (270 kilometers; 168 miles) from the Laskin facility in Hoyt Lakes, MN.
- Machine productivity for Minnesota forests is similar to the estimated productivity reported in Sturos et al. (1993) and Gingas and Favreua (1996). Equations were compared to observations of harvesting in Minnesota and estimates provided by local logging contractors.
- All slash and small diameter material available for use from the site is included in estimates of total available biomass. The analysis does not consider economic feasibility of removal or optimization by species type and landowner.
- Carbon contributions from the manufacture and delivery of the harvesting equipment are not included in the modeled system. Nor was the carbon contribution from construction of highways used for access to forests and to the Laskin Energy Facility.
- Loss from chipping is estimated from values obtained by Stokes and Watson (1991). For clean and dirty chips, flail chain loss is estimated at 15.10 percent of total chips, and for clean chips only, screening reject is 4.90 percent.
- Average fuel moisture content was assumed to be 42 percent.
- Carbon conversions were based on Birdsey (1992) where approximately 50 percent of oven dry wood content is carbon.

- Extractable residue removed values have been adjusted based on total plant capacity of 145,652 ODT.
- Conversion from C to carbon dioxide equivalent (CO_2e) was based on the atomic mass of C and CO_2 where one carbon atom is 12 u and one oxygen atom is 16 u. Therefore the conversion factor used was 44/12 or 3.67.

Other greenhouse gas assumptions—in addition to the carbon dioxide (CO_2) flows associated with the removal and/or decay of woody biomass, other gases, namely nitrous oxide (N_2O) and methane (CH_4) have the potential to alter the overall carbon budget over the 100-year planning period. To compare these gases with CO_2 emissions, the Global Warming Potential (GWP) of each gas was used. GWP is intended as a quantified measure of the globally averaged radiative forcing impacts of a particular greenhouse gas (EPA 2002). GWP is expressed on a relative basis using carbon dioxide as the reference gas in which all other greenhouse gases are compared (i.e. the GWP of CO_2 over 100-year period is 1). While GWP values are a useful measure for estimating the relative impacts of emissions and reductions of different gases, they typically have an uncertainty of ca. ±35 percent (EPA 2002). Nitrous oxide has a GWP 310 times that of CO_2 so even minor emissions or reductions of this gas have significant consequences.

There are many anthropogenic sources of nitrous oxide, including fertilization in agricultural situations, combustion of fossil fuels, wastewater treatment, and waste combustion; however, the only source potentially relevant to this study is biomass burning. Minimal information exists for quantities of logging residues subjected to open field burning, prescribed burning, or wildland fire and their effective N_2O emissions. N_2O emission factors for boiler combustion of woody biomass vary between EPA and IPCC publications from 0.013 lbs/MMBtu (0.03 tonnes CO_2e/MWh) to 0.009 lbs/MMBtu (0.02 tonnes CO_2e/MWh), respectively (EPA 1995, Gomez et al 2006). The potential contribution of N_2O was not included in the calculated CO_2e balance for reasons described below.

Methane, which is primarily produced through anaerobic decomposition of organic matter, has a GWP 21 times that of CO_2 (EPA 2002). Anthropogenic sources of CH_4 include agricultural processes such as rice cultivation, enteric fermentation in livestock, and the decomposition of animal wastes. Methane is also emitted during incomplete fossil fuel combustion, and during the production and distribution of natural gas. The primary methane source of concern in this study is the decomposition of organic matter (leaf material, tops, and limbs from harvest and natural mortality and breakage) on or near the forest floor (Megonigal and Guenther 2008, Mukhin and Voronin 2008). The methane emitted through litter decomposition is offset, in part, by soil bacteria (methanotrophs) which use methane as a source of carbon in a process known as methane oxidation (Adamsen and King 1993, Schnell and King 1994, Sitaula et al. 1995). Table 5 provides a range of situations with varying ratios of anaerobic versus aerobic decomposition and methane's potential contribution to the CO_2e balance.

Table 5. Potential methane emissions scenarios for the Laskin study area (tonnes CO_2e/MWh).

Scenario	No Methane	Methane Decay 99:1 Aerobic:Anaerobic	Methane Decay 97:3 Aerobic:Anaerobic	Methane Decay 95:5 Aerobic:Anaerobic
100-year period	0.277	0.186	0.003	-0.180
20-years after plant[1]	0.079	-0.027	-0.239	-0.451

[1] Assumes 90% residual decomposition achieved within 20 years beyond the planning period.

Additionally, our examination suggested that trace gas fluxes were very small in the context of the study. Consequently, analysis was limited to the CO_2 emissions and did not include secondary gases in the quantitative study balance.

Results

Availability

Under current levels of forest management and commercial harvesting, the proposed bioenergy facility would utilize approximately 145,652 ODT of woody biomass annually to generate 182,208 MWh per year of electricity. Based on the study assumptions, sufficient biomass is available within the assumed procurement radius of approximately 160 km (100 miles).

Carbon stocks

Table 6 lists the current average annual harvest acres and the average annual carbon stocks expressed as M (million) tonnes of carbon dioxide equivalent (CO_2e). The average annual carbon stock within the Laskin study area is 405.597 M tonnes CO_2e (447.090 M short tons). The average annual harvest of roundwood in the study area is 3.462 M tonnes CO_2e (3.816 M short tons) and the average annual residual is 0.596 M tonnes CO_2e (0.657 short tons). Of the 0.596 M tonnes of residual biomass produced from the annual harvest, 50 percent is considered operationally feasible to remove, which results in an average annual extractable biomass availability in the study area of 0.298 M tonnes CO_2e (0.328 M short tons).

Table 7 lists the total harvest acres and carbon stocks over the 100-year planning period within the Laskin study area. The total carbon stock over the 100-year planning horizon is 40,965.315 M tonnes CO_2e (45,156.067 M short tons). The total harvest of roundwood over the 100-year planning horizon (based on the current average statewide harvest level) is 349.627 M tonnes CO_2e (385.394 M short tons) and the total extractable biomass produced from harvesting over the 100-year period is 30.069 M tonnes CO_2e (33.145 M short tons).

Table 6. Current average annual carbon stocks (CO_2e) by forest type within the Laskin study area.

Forest type	**Total Acres 0-100+**	**Annual harvest (acres)**	**Total live tree volume**	**Annual harvest**	**Annual extractable residue removed**
			---------- (M tonnes CO_2e) ----------		
Aspen	3,209,306	41,274	148.090	2.247	0.172
B. poplar	223,726	2,068	8.963	0.086	0.011
Paper birch	731,415	5,310	36.611	0.289	0.032
Maple-basswood	338,630	1,488	28.578	0.042	0.003
Northern hardwood	427,159	2,464	29.374	0.056	0.005
Bottomland hardwood	594,977	3,358	26.530	0.042	0.005
Other	835,618	5,276	45.101	0.088	0.010
Balsam fir	331,142	4,288	9.925	0.117	0.015
Jack pine	220,088	2,092	8.003	0.087	0.007
Red pine	324,165	2,062	21.456	0.183	0.009
Spruce	1,156,481	6,725	30.372	0.176	0.021
Tamarack	502,661	4,421	12.594	0.048	0.007
TOTAL	**8,895,368**	**80,827**	**405.597**	**3.462**	**0.298**

Table 7. Total carbon stocks (CO_2e) by forest type over 100-year planning period within the Laskin study area.

Forest type	Total Acres 0-100+	Annual harvest (acres)	Live tree volume	Annual harvest	Extractable residue removed
			---------- (M tonnes CO_2e) ----------		
Aspen	3,209,306	4,168,642	149.571	226.993	17.400
B. poplar	223,726	208,895	9.052	8.692	1.075
Paper birch	731,415	536,328	36.977	29.194	3.190
Maple-basswood	338,630	150,313	28.864	4.205	0.310
Northern hardwood	427,159	248,853	29.668	5.629	0.528
Bottomland hardwood	594,977	339,206	26.796	4.203	0.495
Other	835,618	532,879	45.552	8.863	1.029
Balsam fir	331,142	433,096	10.024	11.861	1.520
Jack pine	220,088	211,342	8.083	8.831	0.753
Red pine	324,165	208,310	21.670	18.494	0.901
Spruce	1,156,481	679,181	30.676	17.781	2.126
Tamarack	502,661	446,478	12.720	4.881	0.740
TOTAL	**8,895,368**	**8,163,524**	**409.653**	**349.627**	**30.069**

Carbon accumulation

The carbon accumulation estimated for the forest types within the study area are listed in Table 8. Average annual carbon accumulation is 2.550 M tonnes CO_2e (2.811 M short tons). The total carbon accumulation over the 100-year planning period for each forest type is 254.989 M tonnes CO_2e (281.074 M short tons).

Table 8. Average annual carbon accumulation and total carbon accumulation (over the 100-year planning period) by forest type within the Laskin study area.

Forest type	Annual Accumulation	Total Accumulation
	--------- (M tonnes CO2e) --------	
Aspen	0.340	34.008
B. poplar	0.060	6.031
Paper birch	0.139	13.946
Maple-basswood	0.196	19.621
Northern hardwood	0.267	26.691
Bottomland hardwood	0.316	31.563
Other	0.440	44.007
Balsam fir	0.106	10.629
Jack pine	0.039	3.916
Red pine	0.075	7.461
Spruce	0.388	38.762
Tamarack	0.184	18.354
TOTAL	**2.550**	**254.989**

Biomass decay emissions

The average annual emissions from decay of extractable biomass, which would otherwise be utilized in the Laskin facility, are listed in Table 9. Total average annual decay emissions are 0.227 M tonnes CO2e (0.250 M short tons). Total decay emissions from extractable residual biomass (50 percent of the total available biomass) left on harvest sites over the 100-year planning period are 22.710 M tonnes CO_2e (25.033 M short tons) (Table 9).

Table 9. Average annual decay emissions and total decay emissions (over the 100-year planning horizon) from extractable biomass left on the harvest site for each forest type.

Forest type	Annual Decay	Total Decay
	------ (M tonnes CO_2e) ------	
Aspen	0.136	13.617
B. poplar	0.008	0.844
Paper birch	0.025	2.496
Maple-basswood	0.002	0.223
Northern hardwood	0.004	0.430
Bottomland hardwood	0.004	0.396
Other	0.008	0.796
Balsam fir	0.006	0.552
Jack pine	0.005	0.524
Red pine	0.007	0.667
Spruce	0.016	1.645
Tamarack	0.005	0.520
TOTAL	**0.227**	**22.710**

Harvesting and transport emissions

Harvesting and transport emissions represent a relatively small proportion of the total carbon flux within the Laskin study area when comparing with project and without project scenarios. However, the harvest and transport emissions in the *with project* scenario are not offset by any emissions in the *without project* scenario and contribute a net positive CO_2e to the results. Table 10 lists the average annual harvest and transport emissions to extract and haul 145,652 ODT of woody biomass to the Laskin facility. The average annual harvest emissions are 0.0062 M tonnes CO_2e (0.0068 M short tons) while the annual transport emissions are 0.0041 M tonnes of CO_2e (0.0045 M short tons) (Table 10). The total harvest and transport emissions over the 100-year planning horizon are 0.622 M tonnes CO_2e (0.686 M short tons) and 0.408 M tonnes CO_2e (0.450 M short tons) respectively (Table 11).

Carbon flow summary

The *annual* carbon flows with and without the Laskin facility are listed in Table 12. With the proposed facility, the annual CO_2e is 0.278 M tonnes (0.306 M short tons). This estimate includes carbon stock removed from the harvest site, carbon emissions from extracting biomass, and carbon emissions from transport to and from the facility. Without the proposed Laskin facility the annual decay of CO_2e from the extractable biomass left on the harvest site is 0.227 M tonnes (0.250 M short tons). The difference between the with- and without project scenarios is 0.050 M tonnes of CO_2e (0.055 M short tons). With an estimated production of 182,208 MWh/yr, the difference in with- and without project scenarios is a net positive production of 0.003 tonnes of CO_2e/MWh. This represents the average annual carbon footprint of the Laskin facility from extracting residual biomass from harvesting sites and transporting that material to the Laskin facility in Hoyt Lakes, MN, when this is calculated against a background where that residual biomass would decompose on site.

Table 10. Average annual harvest and transport emissions by forest type for the Laskin study area.

Forest type	Emissions Harvesting	Emissions Transport
	------- (M tonnes CO_2e) ------	
Aspen	0.0036	0.0024
B. poplar	0.0002	0.0001
Paper birch	0.0007	0.0004
Maple-basswood	0.0001	0.0000
Northern hardwood	0.0001	0.0001
Bottomland hardwood	0.0001	0.0001
Other	0.0002	0.0001
Balsam fir	0.0003	0.0002
Jack pine	0.0002	0.0001
Red pine	0.0002	0.0001
Spruce	0.0004	0.0003
Tamarack	0.0002	0.0001
TOTAL	**0.0062**	**0.0041**

Table 11. Total harvest and transport emissions in M tonnes CO_2e for the 100-year planning horizon by forest type.

Forest type	Emissions Harvesting	Emissions Transport
	-------(M tonnes CO_2e) -------	
Aspen	0.360	0.236
B. poplar	0.022	0.015
Paper birch	0.066	0.043
Maple-basswood	0.006	0.004
Northern hardwood	0.011	0.007
Bottomland hardwood	0.010	0.007
Other	0.021	0.014
Balsam fir	0.031	0.021
Jack pine	0.016	0.010
Red pine	0.019	0.012
Spruce	0.044	0.029
Tamarack	0.015	0.010
TOTAL	**0.622**	**0.408**

The *total* carbon flow with and without the Laskin facility is described in Table 13. With the proposed facility the total CO_2e is 27.757 M tonnes (30.596 M short tons). The estimate includes carbon stock removed from the harvest site, carbon emissions from extracting biomass, and carbon emissions from transport to and from the facility. Without the proposed Laskin facility the total decay in CO_2e from the extractable biomass left on the harvest site is 22.710 M tonnes (25.033 M short tons). The difference between the with- and without project scenarios is 5.047 M tonnes of CO_2e (5.563 M short tons). With an estimated production of 182,208 MWh/yr (18.2208 M MWh/100yrs), the difference in with- and without project scenarios is a net positive production of 0.277 tonnes of CO_2e/MWh. This represents the total carbon footprint of the Laskin facility from extracting residual biomass from harvesting sites and transporting that material to the Laskin facility in Hoyt Lakes, MN.

Discussion

Carbon flows

The total carbon flows over the 100-year planning horizon with- and without the Laskin project were developed under various assumptions listed above. Figure 8 illustrates the net carbon inputs and outputs described in this study. With the proposed facility the total CO_2e emitted over the life cycle of the project is 27.757 M tonnes (30.597 M short tons). This includes carbon stock removed from the harvest site, carbon emissions from extracting biomass, and carbon emissions from transport to and from the facility. Without the proposed facility the total decay in CO_2e from the extractable biomass left on the harvest site is 22.710 M tonnes (25.033 M short tons). The difference between the with- and without project scenarios is 5.047 M tonnes of CO_2e (5.563 M short tons). With the 100-year production of 18.22 M MWh from the Laskin Facility, the resulting CO_2e per unit production is 0.277 tonnes CO_2e/MWh. This value (0.277 tonnes CO_2e/MWh) would be reduced to just emissions from harvesting and transport (0.057 tonnes of CO_2e/MWh) if the planning horizon were extended to allow the accumulated biomass over the 100 year planning period (which would otherwise be utilized in the Laskin facility) to decompose completely. Approximately 90-95% decomposition would be achieved within 20 years after plant operations cease, resulting in a net CO_2e emission value of 0.068-0.079 tonnes of CO_2e/MWh. Complete decomposition would take approximately 250-350 years for most species based on the exponential decay rate model assumed in this study. Importantly, decay processes vary substantially by material size, woody decay class, location, climate, and species. Thus the decay rate model and associated rate estimates should be used with caution.

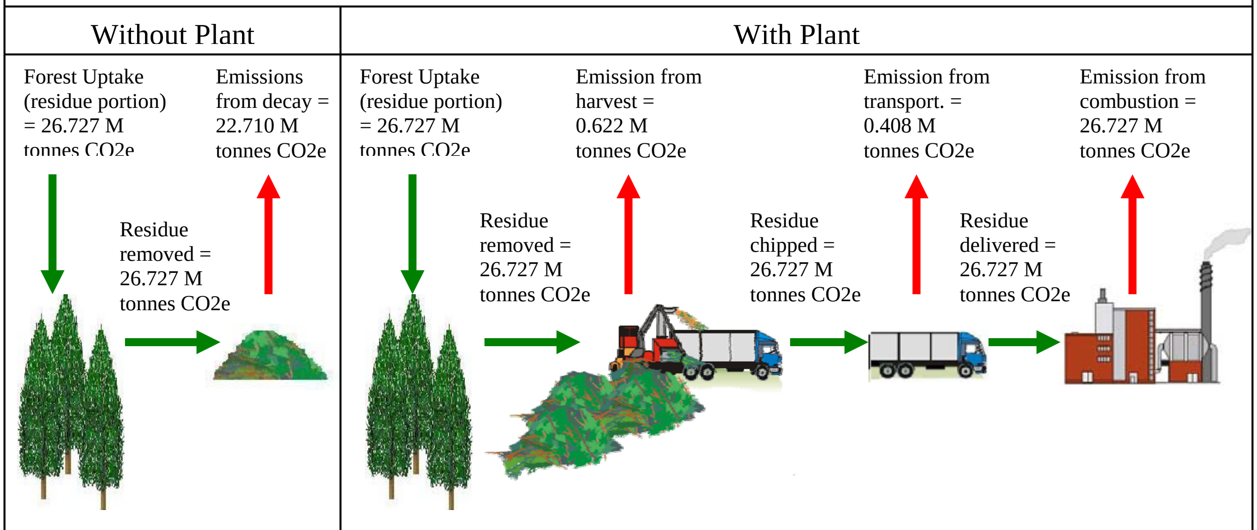
The carbon flow values presented here would also change under different methane and nitrous oxide emissions assumptions. As previously stated, our examination suggested that trace gas fluxes would be very small in the context of this study. Consequently, analysis was limited to the CO_2 emissions and did not include secondary gases. Future studies of this type would benefit from further research on trace gas emissions from decomposition of logging residues. Should methane from biomass decomposition prove to be present in traceable quantities, utilization for energy could substantially decrease the net carbon foot print of biomass energy facilities.

Improvements in forest management and harvesting

Currently, widespread removal of logging residues is limited in part by available harvesting equipment, fuel costs, roundwood market fluctuations, and landowner interests. Importantly, the biomass estimates in this study do not fully incorporate these economic or social constraints. To compensate for tight supplies, the supply distance would need to be expanded or management practices intensified to increase productivity.

Increases in yields are possible with intensified forest stand management. With investment in combinations of practices such as using improved planting stock, improved site preparation, early vegetation management including early and commercial thinnings, the yields per-acre as shown in Appendix Table 14 for the aspen type, may be increased by as much as 50-100 percent in the coming decades (Ek 2007). In this study, trials indicated yields were sensitive to rotation length. Shortening rotations tended to increase supply over the 100-year planning horizon, particularly for the short lived species (i.e., aspen, birch, jack pine). This investment would maximize the carbon storage potential of our forests and also result in more residual biomass available for utilization. Advancements in harvesting technologies have created opportunities for harvesting small diameter material. Should this trend continue the interest in thinnings and logging residues may also increase.

Estimated Carbon Inputs and Outputs over the 100-year Planning Period



Net CO2e Emissions = Total Emissions with Plant – Total Emissions without Plant
= (0.622 + 0.408 + 26.727) – (22.710) = 5.047 M tonnes CO2e

Net CO2e Emissions per MWh = 5.047 M tonnes CO2e / 18.221 M MWh = 0.277 tonnes CO2e/MWh*

* Note: Continued decomposition that would occur 20-years after plant operations cease, reduces the net CO2e Emissions per MWh value to 0.068-0.079 tonnes CO2e/MWh.

Figure 8. Estimated carbon inputs and outputs (in M tonnes of CO_2e/MWh) over the 100-year planning period for the Laskin facility.

Table 12. Average annual carbon stock changes with and without the Laskin facility. Extractable residue removed values have been adjusted based on total plant capacity (ca. 89 percent of total extractable residue available).

Forest type	WITH				WITHOUT		Difference
	Extractable Residue Removed	Emissions Harvesting	Emissions Transport	Total	Decay	Total	
	(M tonnes CO_2e)						
Aspen	0.155	0.004	0.002	0.161	0.136	0.136	0.024
B. poplar	0.010	0.000	0.000	0.010	0.008	0.008	0.001
Paper birch	0.028	0.001	0.000	0.029	0.025	0.025	0.004
Maple-basswood	0.003	0.000	0.000	0.003	0.002	0.002	0.001
Northern hardwood	0.005	0.000	0.000	0.005	0.004	0.004	0.001
Bottomland hardwood	0.004	0.000	0.000	0.005	0.004	0.004	0.001
Other	0.009	0.000	0.000	0.010	0.008	0.008	0.002
Balsam fir	0.014	0.000	0.000	0.014	0.006	0.006	0.009
Jack pine	0.007	0.000	0.000	0.007	0.005	0.005	0.002
Red pine	0.008	0.000	0.000	0.008	0.007	0.007	0.002
Spruce	0.019	0.000	0.000	0.020	0.016	0.016	0.003
Tamarack	0.007	0.000	0.000	0.007	0.005	0.005	0.002
TOTAL	**0.267**	**0.006**	**0.004**	**0.278**	**0.227**	**0.227**	**0.050**

Table 13. Total carbon (CO_2e) stock changes over the 100-year planning horizon with and without the Laskin facility. Extractable residue removed values have been adjusted based on total plant capacity (ca. 89 percent of total extractable residue available).

Forest type	WITH				WITHOUT		Difference
	Extractable Residue Removed	Emissions Harvesting	Emissions Transport	Total	Decay	Total	
	(M tonnes CO_2e)						
Aspen	15.466	0.360	0.236	16.063	13.617	13.617	2.446
B. poplar	0.956	0.022	0.015	0.993	0.844	0.844	0.149
Paper birch	2.836	0.066	0.043	2.945	2.496	2.496	0.449
Maple-basswood	0.276	0.006	0.004	0.286	0.223	0.223	0.064
Northern hardwood	0.470	0.011	0.007	0.488	0.430	0.430	0.058
Bottomland hardwood	0.440	0.010	0.007	0.457	0.396	0.396	0.061
Other	0.915	0.021	0.014	0.950	0.796	0.796	0.154
Balsam fir	1.351	0.031	0.021	1.403	0.552	0.552	0.851
Jack pine	0.670	0.016	0.010	0.696	0.524	0.524	0.172
Red pine	0.801	0.019	0.012	0.832	0.667	0.667	0.165
Spruce	1.889	0.044	0.029	1.962	1.645	1.645	0.318
Tamarack	0.657	0.015	0.010	0.683	0.520	0.520	0.163
TOTAL	**26.727**	**0.622**	**0.408**	**27.758**	**22.710**	**22.710**	**5.047**

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Appendix 1. Glossary

Biomass: Organic materials produced by plants, such as leaves, roots, seeds, and stalks. In the case of this study, biomass was considered tree tops and limbs left following a roundwood harvesting operation along with small diameter stems less than 4 inches in diameter at breast height.

Chip: Small piece of woody material that can be used manufacture pulp/paper and engineered wood products, fuel for power/heat generation, and landscape cover/soil amendment.

CO_2e: Describes how much global warming a given type and amount of greenhouse gas may cause, using the functionally equivalent amount or concentration of carbon dioxide (CO_2) as the reference. The atomic weight of oxygen (O) is ca. 16 and the atomic weight of carbon (C) is ca. 12 so the conversion factor from C to CO_2e is (12+16*2)/12 or 3.67.

Cord: Common unit of measure for roundwood delivered to a forest products facility. One standard cord is a stacked pile approximately 4 feet x 4 feet x 8 feet in size containing 128 cubic feet of wood, air and bark. A cord contains approximately 79 cubic feet of wood (minus airspace and bark) and approximately 92 cubic feet of wood and bark.

M: Is the SI prefix used to represent mega or 10^6 which is equivalent to 1 million.

Megawatt: One thousand kilowatts. Enough electricity to support approximately 750 to 1,000 households.

MWh: One megawatt hour. 10,000 lbs of steam will generate 1 megawatt hour of electricity.

Methanotroph: Soil bacteria that use methane as their only source of carbon and energy for growth and development.

Moisture content: The amount of moisture contained in woody material. Typically expressed as a percentage of total weight.

Oven dry ton (ODT): Wood weight at zero percent moisture content.

Roundwood: Logs, bolts, or other round sections cut from the bole of trees, typically in lengths of 8 feet or greater.

Tonne: Metric unit of mass equivalent to 1,000 kilograms or ca. 2,205 lbs.

Short ton: A unit of mass equivalent to 2,000 lbs or ca. 907 kilograms.

Appendix 2. Tables and Figures

Table 14. Forest type acreage and stand table with yield and harvest rates for the most recent FIA inventory period within the Laskin study area.

Age Class	Acres	Total biomass (tonnes/acre)	Total roundwood harvest (tonnes/acre)	Total residual harvest (tonnes/acre)	Total residual leave (tonnes/acre)	Percent harvested	Acres harvested	Commercial harvest (tonnes)	Residual harvest (tonnes)
0-10	618,543	8.48	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11-20	467,036	14.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21-30	376,090	19.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00
31-40	310,188	24.95	21.13	3.24	1.62	14.00	5,031	106,295	7,844
41-50	402,221	33.40	28.28	4.34	2.17	28.00	10,062	284,541	20,998
51-60	397,732	34.66	29.35	4.50	2.25	26.00	9,343	284,755	20,235
61-70	350,585	39.90	33.79	5.18	2.59	22.00	7,906	254,975	19,712
71-80	200,964	43.08	36.47	5.59	2.80	4.00	1,437	52,429	3,869
81-90	56,896	40.06	33.92	5.20	2.60	3.00	1,078	36,569	2,699
91-100	17,674	56.28	47.65	7.31	3.65	2.00	719	34,246	2,527
100+	11,377	41.34	35.00	5.37	2.68	1.00	359	12,578	928
Total	**3,209,306**	**356**	**266**	**41**	**20**	**100**	**35,936**	**1,066,388**	**77,883**

Table 15. LSA aspen acreage by age class by decade for 100 year model results. Note that the harvest acres represents the sum of the harvestable age class acres (30-100+ for the aspen forest type) not the total acres harvested.

					Age Class							
Year	**0-10**	**11-20**	**21-30**	**31-40**	**41-50**	**51-60**	**61-70**	**71-80**	**81-90**	**91-100**	**100+**	**Harvest Acres**	**Total Acres**
2008	618,543	467,036	376,090	310,188	402,221	397,732	350,585	200,964	56,896	17,674	11,377	1,747,637	3,209,306
2018	459,019	499,346	457,459	384,475	333,038	322,408	285,718	230,650	1,31,992	72,038	33,163	1,793,482	3,209,306
2028	434,321	459,962	470,170	439,471	352,472	286,600	222,780	195,720	1,50,179	120,547	77,082	1,844,852	3,209,306
2038	455,868	449,987	458,229	455,205	380,087	291,631	192,534	152,619	1,27,980	133,326	111,839	1,845,222	3,209,306
2048	475,085	461,356	456,356	455,757	393,584	306,958	190,925	129,298	98,835	119,322	121,830	1,816,510	3,209,306
2058	477,544	472,035	463,793	458,542	399,534	318,608	200,352	125,531	81,318	99,060	112,990	1,795,934	3,209,306
2068	468,886	472,921	470,015	464,428	404,917	326,398	210,083	131,006	76,709	85,327	98,616	1,797,484	3,209,306
2078	458,830	466,650	469,942	468,394	410,005	332,357	217,441	138,169	79,315	80,390	87,812	1,813,883	3,209,306
2088	452,813	459,180	465,116	467,874	412,458	336,463	222,570	144,186	84,196	81,357	83,093	1,832,197	3,209,306
2098	451,418	454,330	459,365	464,025	411,381	337,843	225,517	148,474	88,925	84,899	83,129	1,844,194	3,209,306
2108	452,940	452,860	455,404	459,470	407,962	336,504	226,162	150,886	92,571	88,867	85,682	1,848,103	3,209,306

Table 16. Equipment productivity for harvesting sub-merchantable biomass, less than 5-in dbh.

Equipment	Horsepower	PMH	Machine Rate (tonnes/PMH)	gal/hp-hr	gal/PMH	gal/tonne chips	kg C/gal	kg C/tonne chips	Tonnes C/Tonne chips
Drott 40 LC Feller/buncher	250	62.0	23.86	0.0263	6.583	0.276	10.391	2.8664	0.0022
740 John Deere Skidder	180	29.1	50.84	0.02800	5.040	0.099	10.391	1.0301	0.0008
Morbark 22-in Chipper	630	27.8	53.22	0.03492	22.00	0.413	10.391	4.2955	0.0034

Table 17. Equipment productivity for harvesting slash (limbs and tops).

Equipment	Horsepower	PMH	Machine Rate (tonnes/PMH)	gal/hp-hr	gal/PMH	gal/tonne chips	kg C/gal	kg C/tonne chips	Tonnes C/Tonne chips
Drott 40 LC Feller/buncher	250	94.8	31.07	0.0263	6.583	0.212	10.391	2.2013	0.0017
740 John Deere Skidder	180	92.1	31.98	0.02800	5.040	0.158	10.391	1.6375	0.0013
Morbark 22-in Chipper	630	61.6	47.82	0.03492	22.00	0.460	10.391	4.7806	0.0037

Table 18. Proportion of Minnesota statewide harvest volume within the Laskin study area.

Forest type	Proportion of 2005 statewide harvest	Proportion of forest type in study area	2001-05 statewide average harvest (cords)	Study area volume (cords)	Study area ODT (tonnes)
Jack pine	0.082	0.501	3,630,000	149,263	155,721
Red pine	0.043	0.525	3,630,000	81,951	85,496
Spruce	0.054	0.768	3,630,000	150,579	143,433
Tamarack	0.017	0.517	3,630,000	31,900	36,174
Balsam fir	0.053	0.800	3,630,000	153,866	160,522
Bottomland hardwoods	0.014	0.577	3,630,000	29,334	33,264
Northern hardwoods	0.018	0.456	3,630,000	29,775	37,141
Maple-basswood	0.034	0.335	3,630,000	41,317	45,448
Aspen	0.510	0.557	3,630,000	1,031,472	1,066,739
Paper birch	0.089	0.699	3,630,000	225,807	256,061
Balsam poplar	0.030	0.478	3,630,000	52,057	56,670
Other	0.053	0.196	3,630,000	37,706	42,758

Table 19. Proportion of roundwood and harvest residual per acre for species and forest types within the Laskin study area. FWD = fine woody debris (1-2 inches or 2.54-5.08 cm), CWD = coarse woody debris (>2 inches or >5.08 cm).

Species	% Residual	% Roundwood	% FWD	% CWD
Jack pine	0.171	0.829	0.053	0.118
Red pine	0.097	0.903	0.030	0.067
Balsam fir	0.256	0.744	0.079	0.177
Spruce	0.239	0.761	0.074	0.165
Tamarack	0.283	0.717	0.088	0.195
Bottomland hardwoods	0.235	0.765	0.073	0.162
Northern hardwoods	0.188	0.812	0.058	0.130
Maple-basswood	0.148	0.852	0.046	0.102
Aspen	0.153	0.847	0.048	0.106
Paper birch	0.219	0.781	0.068	0.151
Balsam poplar	0.247	0.753	0.077	0.171
Other	0.204	0.796	0.063	0.141

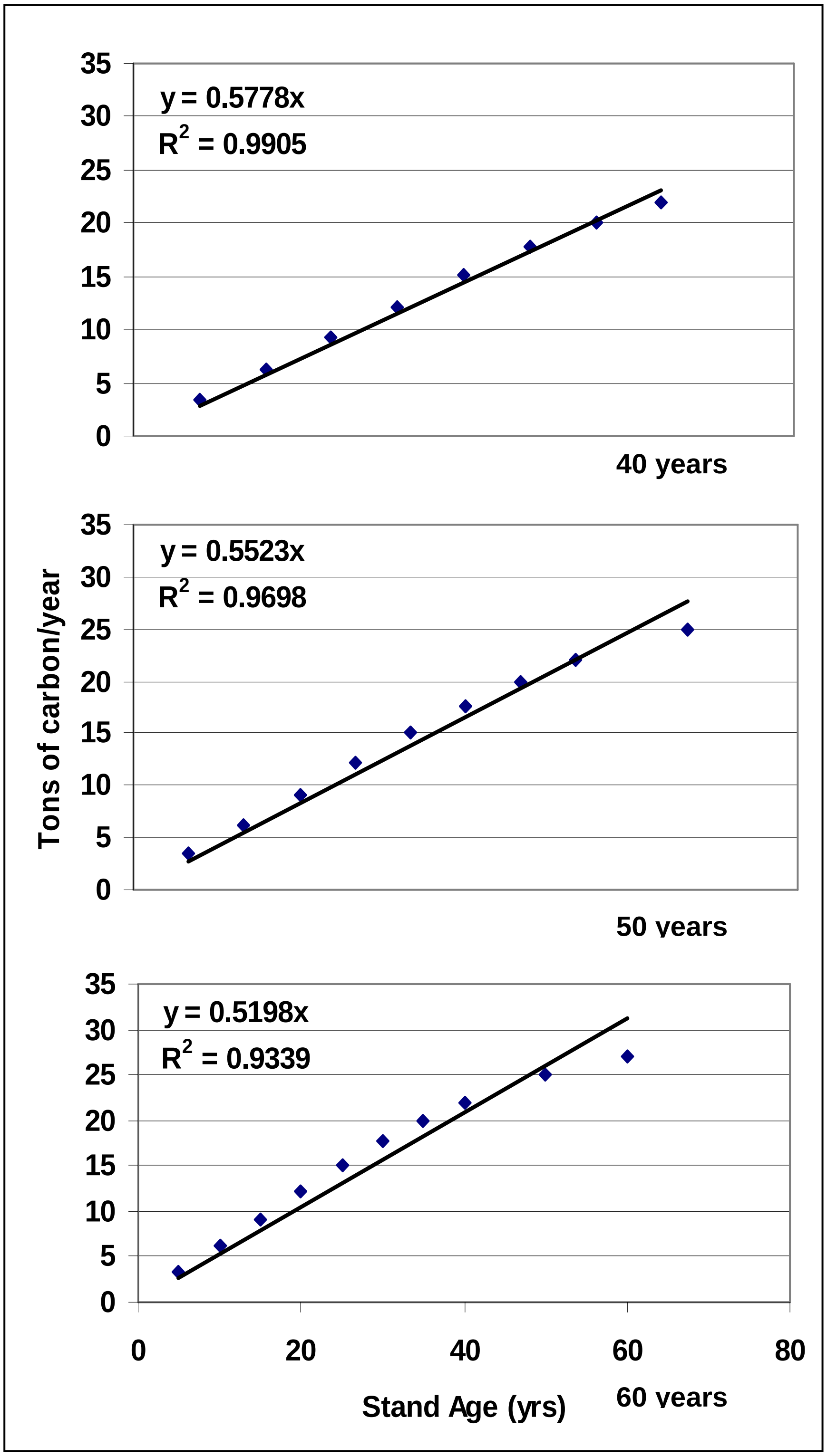

Figure 9. Sensitivity analysis using COLE data and linear regression to determine the age at which carbon accumulation begins to change for the aspen forest type. Stand age with the highest R^2 value for each forest type was used to determine the point of change. For the aspen forest type, the 40-year regression equation produced the highest R^2 value so the rate associated with that regression equation was used to estimate carbon accumulation.