Frontier Renewable Resources Center of Energy Excellence Final Report:
Project 3, Life Cycle Environmental Impacts of Forest Biomass Supply Chains

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Abstract:

The goal of this project was to develop measures of the environmental footprint for primary forest products supply chain activities (harvesting and hauling wood) within the supply radius of Frontier Renewable Resources' facility in Kinross, Michigan. We detail a life-cycle assessment procedure, relying on a combination of peer-reviewed literature, national databases, and primary data collected from loggers and truckers within the study area. Several different equipment configurations and operating scenarios for roundwood harvesting are considered. Greenhouse gas emissions and fossil energy demand per unit of wood are calculated with the assistance of SimaPro 7.2 life cycle assessment software and literature values. Results indicated that a full processor / forwarder is the best choice of harvesting equipment configuration due to relatively low inputs and high reported productivity, although the burdens of harvesting depend strongly on the intensity of harvest being conducted. Multimodal truck + rail transport had roughly 3-fold lower environmental burdens than typical log truck transport, which was directly related to the increased fuel efficiency of rail transport. A typical supply chain for forest biomass in northern Michigan would have environmental impacts similar to forest biomass supply chain operations in other regions, in comparison with other reported studies.

1.0 Introduction

Emissions of greenhouse gases from transportation are a major contributor to human-caused climate forcing on a global scale. Recent studies have predicted serious consequences from a "business as usual" approach to energy production and use, including increasing global temperatures, sea level rise, displacements of human populations from submerged lands, changing weather patterns, and increase in incidence of certain diseases (IPCC, 2007a,b). Biofuels made from renewable feedstocks are among the largest expected contributors to the transportation industry's planned emission reductions over the foreseeable future. Additionally, in recent years the U.S. has imported slightly more than half of its oil needs from foreign sources (Goerold, 2008). Such a high dependence increases U.S. strategic vulnerability, and a domestic biofuels industry is increasingly seen as a way to combat this trend while increasing employment in rural areas of the country (Perez-Vardin 2008).

Many industry sectors are addressing sustainability issues by reducing the emission of greenhouse gases across the entire production chain. For example, recently the diary industry has been the subject of a comprehensive dairy milk carbon footprint study (Thoma et al. 2010), the goal of which is to identify opportunities for improvement at various steps along the life cycle. A commercial biofuel operation will rely on inputs of feedstock grown over a large area, with potentially variable supply over the course of a year. Assessing supply chain options and anticipating supply chain issues for this type of emerging industry will be critical for continued success.

This supply chain sustainability assessment project focused on forest-based biomass (specifically, roundwood hardwood logs) grown within the state of Michigan. We were tasked with developing environmental metrics for greenhouse gas emissions and fossil energy demand for roundwood harvesting and transport within the anticipated 150-mile supply zone of Frontier Renewable Resources' (FRR) planned cellulosic ethanol facility in Kinross, Michigan (Figure 1). To this end, we have developed a limited-scope life-cycle assessment (LCA) procedure for a few general scenarios, using well-detailed process assumptions and inventory data. Results and methods from this study may be later used at different levels of data aggregation when considering specific bioenergy projects within the state of Michigan, or may possibly be applicable to forest-based biomass use within the broader Great Lakes region.

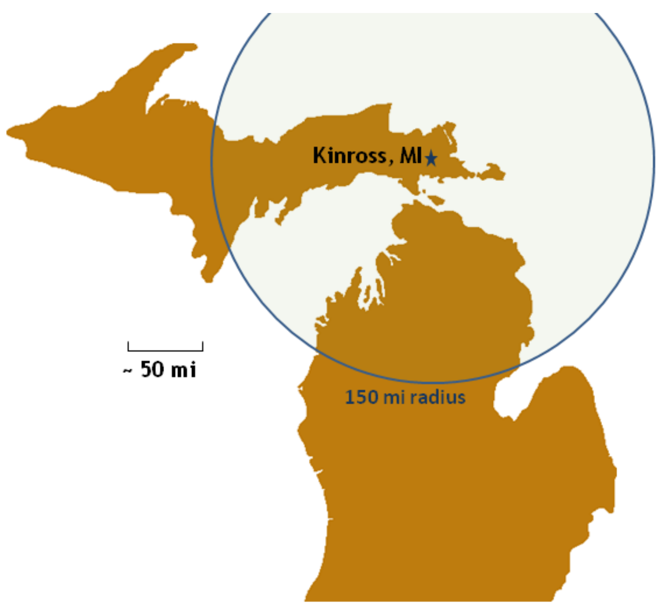

Figure 1: Map displaying the location of the proposed Frontier Renewable Resources cellulosic ethanol facility in Kinross, Michigan, along with the proposed 150-mile supply zone from which the facility plans to source its roundwood hardwood biomass feedstock.

2.0 Methods

2.1 Goal and scope

The goal of our LCA is to determine greenhouse gas (GHG) emissions and fossil energy demand associated with harvesting and transport of forest-based biomass within the planned Michigan supply zone of FRR, up to 150 miles from the facility. For our purposes, harvesting includes cutting and moving wood to a forest landing, and transport refers to movements of wood from the forest landing to a processing facility. Our scope will be limited in the sense that our focus is only on major stages in the forest-based biomass supply chain that occur prior to biomass conversion at the processing facility into biofuels and co-products. Material inputs used directly during feedstock supply chain activities, i.e. wood harvesting and transport, will be considered. Of these inputs, fuel is the most important, but other inputs are also included, including major equipment used to harvest and transport wood (harvesters, forwarders, log trucks, etc.).

2.2 Functional unit

The functional unit for this study will be one green ton of forest biomass. Harvesting activity will be normalized to this unit, while transportation activity will be normalized on the basis of a ton-mile, due to the dependence of transport burdens on the particular distance moved. In forest biomass systems, there are typically no specific origin-destination pairs of feedstock location and processing facilities, so this unit can be utilized by parties interested in specific case studies by multiplying environmental burdens per ton-mile by the mileage of the specific transport step, as we have done in a few examples presented here.

2.3 Life cycle inventory data

Data and assumptions required to develop our environmental burdens for harvesting and transport of wood within the FRR supply zone came from a variety of sources. Environmental impacts of the production of material and energetic inputs, in addition to their direct use in this supply chain, were included as part of this assessment through use of the Ecoinvent 2.1 database (Frischknecht 2005), peer-reviewed literature, expert opinion, or other sources. An important component of our life cycle inventory was the use of primary data from loggers within the state of Michigan. In two separate survey campaigns led by Michigan State University researchers, loggers were identified and mailed a survey to gain information on their current equipment and operations for handling forest products in harvesting and transportation stages. The survey campaigns each covered different areas of the state and asked about forestry operations in different years (2009 and 2010), but in combination the results of over 220 unique survey respondents represent the most current and accurate picture of forest products operations over the entire state of Michigan. Please refer to COEE reports from Michigan State University Project 3 for a detailed summary of survey methods and results beyond the results utilized here for our LCA work. In the following sections, we detail how life cycle inventory data was developed for harvesting and transport of forest biomass.

Estimates of harvesting and forwarding activity were taken primarily from the state of Michigan logger survey, with supplementary information from other sources (Table 1). Three main harvesting/forwarding equipment configurations were used to characterize the logging industry in Michigan:

a) full cut-to-length processor / forwarder
b) feller-buncher / skidder / slasher
c) chainsaw / skidder

From the logger survey results, we were able to obtain the average fuel use of various key pieces of forestry equipment for operators in the COEE supply region, in gallons/hour. From Table 1, the amount of variability in fuel use estimates is large, and would be worthy of future sensitivity analysis investigations to determine the impacts of fuel use on overall forest biomass supply chain burdens.

Estimates of lubricants and grease came from industry experts. In an effort to convert data to a consistent format and make valid comparisons, it was essential to make several key assumptions regarding the treatment of this data. Major assumptions are listed below in Table 2.

Table 1: Summary of inputs for harvesting configurations

Configuration A: Full Processor / Forwarder			
Item	Units	Total	Data Source / Comments
Fuel use	gal/hr	8.40 ± 3.19	Logger survey data, COEE region, full processor = 5.1 ± 2.3(n[a]=77), forwarder = 3.3 ± 2.4 (n=89)
Lubricants	gal / d	6.68	J.M. Longyear, no variability given
Grease	lb / d	2.00	J.M. Longyear, no variability given
Equipment	units	2	Major pieces of equipment
Configuration B: Feller-buncher / Grapple Skidder / Slasher			
Item	Units	Total	Data Source / Comments
Fuel use	gal/hr	14.91 ± 3.92	Logger survey data, COEE region, feller buncher = 7.0 ± 2.7 (n=25), slasher = 3.5 ± 1.8 (n=10), weighted average of grapple skidders (4.7 ± 2.2, n=18) and cable skidders (2.7 ± 0.6, n=3)
Lubricants	gal / d	2.48	J.M. Longyear, no variability given
Grease	lb / d	1.00	J.M. Longyear, no variability given
Saw gas	gal / d	1.00	J.M. Longyear, no variability given
Equipment	units	3	Major pieces of equipment
Configuration C: Chainsaw / Cable Skidder			
Item	Units	Total	Data Source / Comments
Fuel use	gal/hr	6.16 ± 2.26	Logger survey data, COEE region chainsaws = 0.7 ± 0.5 (n=11), 2.5 average chainsaws used per logging crew, weighted average of grapple skidders (4.7 ± 2.2, n=18) and cable skidders (2.7 ± 0.6, n=3)
Lubricants	gal / d	0.40	J.M. Longyear, no variability given
Equipment	units	1	Major piece of equipment

a- the n-values listed in Comments refer to the number of survey responses included in the reported average

Table 2- Key assumptions for developing harvesting / forwarding LCA estimates

Item	Assumption	Additional Comment
Duration of workday	8-hour productive workday, machines are in use continuously	Used to average hourly consumption of lubricants
Harvest Productivity	Harvest levels are sustained throughout an 8-hour productive workday	Used to normalize harvest inputs
Lifetime productivity of major piece of harvesting equipment	160,000 green tons (10 years, 40 weeks/year, 8 loads / week, 50 tons/ load)	Can change if better estimates are found, but overall LCA burdens for equipment fabrication and repair are likely to be small, as shown in results.

In order to transform life cycle inventory data for harvesting and forwarding, reported on the basis of hourly usage rates, into inputs normalized on the basis of one green ton of forest biomass, it is necessary to know the productivity of each equipment configuration in tons of wood per hour. In the state of Michigan logger surveys, respondents were asked to list their average harvest productivity (in tons or cords of green timber per hr) for three theoretical harvest types – clearcutting, a 70% (shelterwood) cut, and a 30% (selective cut) treatment. In each case, respondents were also asked to list which of the harvest equipment configurations, listed in a previous survey section, they would likely use in each treatment. For each of these treatment scenarios, there were also separate entry sections for entering productivity estimates for each of four potential forest types – natural hardwood stands, natural softwood stands, mixed hardwood/softwood stands, and softwood plantations. Because FRR will operate on hardwood during initial operations, we only included data from natural hardwood and mixed hardwood/softwood stands. Data for all forest stand types can be seen in the Appendix.

Estimates of harvest productivity were wide-ranging, and this analysis required some standardization to ensure that accurate comparisons were being made. In previous survey sections, respondents were asked which equipment configurations (processor/ forwarder, feller-buncher/skidder, etc.) they used in their operations, along with the number of pieces of equipment owned. For the full processor and feller-buncher configurations, only respondents indicating that one or two pieces of harvesting equipment (one or two processors, one or two feller-bunchers) were included in the productivity analysis. In situations where respondents indicated three or more processors or feller bunchers, it was more likely that these pieces of equipment were working on different sites, or not all working at the same time, and therefore would not yield productivity data was reflective of the capability of each machine. This distinction was not made for the equipment configurations involving chainsaws as the main harvesting equipment, however an average of 2.5 chainsaws was indicated in the survey responses for loggers who used chainsaws as a tool to cut more than 50% of their total production in 2009-2010.

Weighted averages for each category were calculated as follows:

Average Productivity (cords / hr) = (N1*P1 + N2*P2)/(N1 + N2*2)

Where N1 and N2 are the number of 1-harvster and 2-harvster respondents, respectively, and P1 and P2 represent average productivity values for 1-harvester and 2-harvester respondents (in cords / hr).

Below in Table 3 is a summary of productivity estimates (average cords green timber / hr) for survey respondents that indicated a particular equipment configuration would be used in each cutting prescription and forest type. To convert these values into green tons / hour, an average conversion factor of 2.35 tons per cord has been applied. This value can vary between regions and tree species, and more specific data may be substituted if values are known for target species in a certain area. As expected, average productivity for chainsaws is lower than the more mechanized systems, roughly 2.3 cords / hour across most harvest types and forest types. (Table 3). In both fully-mechanized systems (A and B), productivity increased as harvest treatment intensity rose from 30% to 70% to 100%, with feller-bunchers slightly more productive than full processors in all operations. Data shown here representing the COEE supply zone is consistent with the larger sample of statewide harvest productivities (Appendix).

Table 3 : Combined state of MI productivity estimates for different logging equipment configurations

A: Full Processor / Forwarder

			Productivity per harvester (cords/ hr)	
Treatment	Forest Type	N[a]	Average	Std. Dev
30% Cut (Selective)	Natural Hardwoods	30	3.40	1.00
	Mixed Hardwood / Softwood	26	3.65	1.06
70% Cut (Shelterwood)	Natural Hardwoods	24	4.00	1.59
	Mixed Hardwood / Softwood	20	4.40	1.49
Clearcutting	Natural Hardwoods	19	5.63	2.28
	Mixed Hardwood / Softwood	23	5.55	1.82

B: Feller-buncher / Skidder / Slasher

			Productivity per harvester (cords/ hr)	
Treatment	Forest Type	N	Average	Std. Dev
30% Cut (Selective)	Natural Hardwoods	8	3.63	1.92
	Mixed Hardwood / Softwood	8	3.75	1.47
70%Cut (Shelterwood)	Natural Hardwoods	7	4.28	1.05
	Mixed Hardwood / Softwood	8	4.50	1.12
Clearcutting	Natural Hardwoods	6	6.33	1.63
	Mixed Hardwood / Softwood	6	6.17	2.33

C: Chainsaws / Skidder

			Productivity (cords/ hr)	
Treatment	Forest Type	N	Average	Std. Dev
30% Cut (Selective)	Natural Hardwoods	10	2.4	1.9
	Mixed Hardwood / Softwood	8	2.25	2.05
70% Cut (Shelterwood)	Natural Hardwoods	5	2.4	2.61
	Mixed Hardwood / Softwood	6	2.33	2.34
Clearcutting	Natural Hardwoods	3	1.33	0.58
	Mixed Hardwood / Softwood	5	1.4	0.55

a- the n-values listed in Comments refer to the number of survey responses included in the reported average

In order to simplify the analysis for this report, the following data aggregation steps have been made. Productivities for natural hardwood and mixed hardwood/softwood stands were averaged for each harvest configuration in each harvest type, resulting in 9 total productivity estimates. Additionally, we added a fourth harvest scenario for each equipment type, representing a 30% selective cut on especially difficult terrain. Logger survey estimates indicating that costs on difficult terrain increased by roughly 28%, so to account for this we reduced productivity in the difficult terrain scenario by 28% compared to a typical 30% selective cut. In order to arrive at an estimate of productivity for each harvest scenario, the data for different equipment configurations was combined with COEE Steering Committee input to yield a weighted average for each harvest scenario in the following manner (Table 4). In this way, we now have one estimate of productivity for each of the four harvest scenarios. If one single metric to encompass all potential harvest activity is desired, the data could be further aggregated by taking a weighted average of the four harvest scenarios to represent their relative importance in terms of the overall harvest of forest biomass within the FRR supply zone in the state of Michigan. An example of these weighted averages was discussed with the COEE steering committee and is presented in Table 4, but these estimates can be altered based on any new data that becomes available from planned operations of the Kinross facility in regard to its wood procurement strategy.

Table 4: Proportion of harvesting done in each scenario by each equipment configuration (%)

	Percentage of harvest using each equipment configuration				Percentage of total harvest
Harvest scenario (example forest type)	A: Full Processor	B: Feller-buncher	C: Chainsaws	Total	
Clearcut (Aspen)	90	10	0	**100**	15
70 % Shelterwood (Oak)	45	50	5	**100**	13
30% Selective Cut (Mixed hardwoods)	45	45	10	**100**	57
30% Selective Cut – Difficult terrain	30	50	20	**100**	15
					100

For forest biomass transportation from a forest landing to a conversion facility, the two modes of transportation considered here are road and rail. Over-the-road transport can occur in log trucks (roundwood logs) or chip vans (processed biomass). In Michigan, log trucks are allowed to attain a gross vehicle weight of 164,000 lbs, which is considerably larger than other northern states such as MN or WI (80,000 lbs). These large trucks are the primary method of roundwood transport in the state. We have developed LCA profiles of transport based on an average log truck reported within the state of Michigan, but include estimates of fuel use for larger MI-only trucks (10 or 11 axles) and wood chip vans if LCA burdens for these modes of transport are desired in future work. Rail transport of forest biomass is typically performed by 80-ton log cars with roundwood logs. Rail is commonly perceived as being more fuel efficient than truck transport by a factor of 4-5X. Our estimates of fuel use for rail cars operating in MI come from national averages of a major rail company operating in the Upper Peninsula, and are in agreement with general estimates of rail fuel use (Table 5). We also consider the fuel use required to power hydraulic loaders present on most MI log trucks, incorporating one loading and unloading cycle into estimates of fuel use for transport (Table 5).

Table 5: Key input data and assumptions regarding transport of forest biomass in Michigan.

Item	Data	Comment
Loading/Unloading		
Fuel use required per ton of green timber	4.5 gallons / hour 1 hour to load or unload 40 green ton average load **0.225 gal / ton**	Average of one full-day trial conducted with 2007 MI log truck equipped with self-loader
Truck transportation		
Log truck fuel use per ton-mile	4.48 ± 1.8 miles / gallon 40 green ton loaded average 50% loaded miles **0.0112 gal / ton-mile**	Logger survey, MI statewide average Fuel use for average of all forest biomass hauling trucks reported in survey (large 10-11 axle trucks = 3.66 ± 0.87 miles/ gallon, chip vans = 4.19 ± 0.99 miles/ gallon
Lifetime ton-miles of log truck	15 yr productive life 55,000 miles / yr 40 ton loads, 50% loaded miles	Logger survey data, estimates from industry experts
Rail transportation		
Rail fuel use per ton-mile	**0.00253 gal / ton-mile**	CN Railroad (2010), no variability given
Lifetime ton-miles of rail equipment	20,000,000 lifetime miles 2,000 tons loaded	Assumed values

2.4 Environmental impacts

We combined the life cycle inventory data detailed above with estimates of greenhouse gas emissions and fossil energy demand resulting from production and use of each of the inputs listed in the inventory. Environmental impact factors and their sources are detailed in Table 6. A majority of the factors are derived from national or regional databases and peer-reviewed literature sources. Emissions of different greenhouse gases (CO_2, N_2O, CH_4, etc.) are normalized on the basis of global warming potential (CO_2 – equivalents, CO_2eq) using either the IPCC GWP 100-year average (Ecoinvent data) or other means (see Table 6) and aggregated to estimate the overall impact of a product or process.

Table 6: Environmental impact factors and major assumptions

Item	Data	Comment
GHG emissions factor for fuels	27.37 lb CO_2eq / gal diesel, 24.75 lb CO_2eq / gal gasoline	(Skone 2008), combining data on emissions per MJ of fuel, energy content of fuels, density of fuels
Energy demand of fuels	153.5 MJ/gal , used for diesel and for gasoline	(Klvac 2003), cited in previous COEE reports, roughly 10% due to production of fuels
GHG Emissions factor for oils, lubricants	4.22 kg CO_2eq / kg material	1.05 kg GHG emissions from production (Ecoinvent) (Frischknecht 2005) + estimate for mineralization to CO_2
Energy demand of oils, lubricants	219 MJ/gal	(Klvac 2003) values for synthetic oil
Emissions factor of grease	0	Assumed to be fairly recalcitrant, not combusted
Energy demand of Grease	35 MJ/lb	Ecoinvent factor for lubricating oil production
Emissions factors of harvesting / forwarding machine fabrication and repair	0.86 lb CO_2eq / Green ton, for each large machine involved	(Athanadiassis 2002) calculations based on Swedish forwarder, 41,873 kg CO_2 eq per original machine, plus 50% extra for lifetime of repairs and maintenance, normalized to lifetime production
Energy demand for machine fabrication and repair	9.3 MJ/ Green ton, for full processor / feller/bunchers 7.4 MJ / Green ton for forwarders/skidders	(Athanadiassis 2002) calculations based on Swedish forwarder 66 MJ/kg for original machine, assumed 15,000 kg for harvesters and 12,000 kg for forwarders/skidders, plus 50% extra for lifetime of repairs and maintenance, normalized to assumed lifetime production
Emissions for log truck production, maintenance	55,400 kg CO_2eq	Ecoinvent for 40-t lorry production, maintenance
Energy demand for log truck production, maintenance	1,308,350 MJ	Ecoinvent for 40-t lorry production, maintenance
Emissions for rail equipment production, maintenance	2,537,000 kg CO_2eq	Ecoinvent for long-distance train production, maintenance
Energy demand for rail equipment production, maintenance	54,368,890 MJ	Ecoinvent for long-distance train production, maintenance

3.0 Results and Discussion

Combining the life cycle inventory with the environmental impacts listed above and normalizing the data to the basis of one green ton, we arrive at greenhouse gas emissions and fossil energy demand per green ton of forest biomass for harvesting and transportation stages within the state of Michigan. Due to the different units commonly employed in the areas of life-cycle assessment and forest products (English vs. metric units, green freshly cut wood vs. dry biomass), we shall present the main results using a variety of unit configurations. For conversions between green recently harvested timber and dry biomass, a moisture content of 50% was assumed in all cases. Due to the conversions between lb vs. kg and US short tons vs. metric tonnes, it appears that our unit conversions scale the data up or down by factors of 2 for the GHG emissions results.

Harvesting activity is the most complicated part of this analysis (Table 7) due to the many possible levels of data aggregation. Chainsaw harvesting does not rate as the option with the lowest environmental footprint despite the low relative material requirements, due to the low efficiency of production compared to other harvesting scenarios. Within the full processor and feller-buncher harvesting scenarios, overall environmental impacts fall drastically as harvest intensity is increased from 30% to clearcutting, due to the increase in productivity in cords per hour. We only have one estimate of fuel use for each piece of harvest equipment, which we are then using as input data for several different harvesting scenarios with different productivities, which might not capture the variation in fuel use between the different harvest scenarios. This was a potential drawback of our survey method, but in any analysis there are tradeoffs between complexity and broad utility. Environmental impacts from fabrication and maintenance of equipment represents between 1.5-9% of overall greenhouse gas emissions and 2-15% of fossil energy demand, a small but non-trivial component of the environmental burdens for this life cycle stage.

Table 7: Environmental impacts of harvesting / forwarding at different levels of data aggregation

	Greenhouse gas emissions			Fossil Energy Demand		
	lb CO_2eq green ton[a]	kg CO_2eq green tonne[b]	kg CO_2eq dry tonne	MJ green ton	MJ green tonne	MJ dry tonne
A: Full Processor / Forwarder						
Clearcutting	21.0	10.5	21.0	129.2	142.4	284.7
70% Cut (shelterwood)	26.2	13.1	26.1	159.5	175.8	351.5
30% Cut (Selective)	32.3	16.2	32.3	195.5	215.5	431.0
30% Cut (Selective) – difficult terrain	44.2	22.1	44.2	265.0	292.1	584.3
B: Feller-buncher / Skidder / Slasher						
Clearcutting	27.8	13.9	27.8	166.0	183.0	366.0
70% Cut (shelterwood)	38.5	19.2	38.5	226.0	249.1	498.3
30% Cut (Selective)	51.0	25.5	51.0	296.8	327.2	654.3
30% Cut (Selective) – difficult terrain	69.9	34.9	69.9	402.9	444.1	888.1
C: Chainsaws / Skidder						
Clearcutting	33.6	16.8	33.6	191.8	211.5	422.9
70% Cut (shelterwood)	38.2	19.1	38.2	217.2	239.5	478.9
30% Cut (Selective)	41.3	20.6	41.3	234.9	258.9	517.8
30% Cut (Selective) – difficult terrain	57.0	28.5	57.0	323.3	356.4	712.8
All Clearcut harvesting	21.7	10.8	21.6	132.8	146.4	292.9
All 70% shelterwood cut harvesting	32.9	16.5	32.9	195.6	215.6	431.3
All 30% selective cut harvesting	41.6	20.8	41.6	245.0	270.1	540.2
All 30% selective cut harvesting – difficult terrain	59.6	29.8	59.6	345.6	381.0	761.9
All harvesting activity	**40.2**	**20.1**	**40.2**	**236.9**	**261.1**	**522.2**

a – ‘ton’ refers to U.S. short ton
b – ‘tonne’ refers to metric tonne

Transportation of bioenergy feedstocks is potentially the largest source of environmental impacts in the entire supply chain (e.g. Sonne 2006), and this supply chain stage deserves serious attention in regards to potential optimization. Environmental metrics displayed here (Table 8) are normalized on the basis of a ton-mile as opposed to a ton, so multiplication of these values by an actual transport distance will yield an environmental burden with the same functional unit as the harvesting life cycle stage. For instance, if biomass is to be transported by truck 100 miles, GHG emissions for one-way transport become 0.313 lb CO_2eq /ton-mile x 100 miles = 31.3 lb CO_2eq /ton feedstock, comparable to emissions during the harvesting stage. If no backhauls are possible from the end-use facility, which is often the case in roundwood truck transport, then the impacts of the entire truck return trip must also be allocated to the feedstock, doubling the impact of the transport stage. A range of possible environmental burdens for sample truck trips is presented below in Table 9, indicating that transportation can easily be the most significant stage of the biomass supply chain if backhaul opportunities are limited and transport distance is increased. Multimodal transportation, combining a short truck movement with a longer rail transport step, has the ability to move forest products with much less environmental burden, as the example in Table 9 shows. A multimodal trip of 190 km (30 km of truck transport to a rail yard followed by 160 km of rail transport) would reduce greenhouse gas emissions by over 65% compared to the baseline 161 km (100-mile) truck trip considered here. As expected, environmental burdens from the equipment fabrication and maintenance considered in both truck and rail cases represents a small component of the overall environmental footprint (Table 8). Other transportation infrastructure could be considered, such as roads or rail lines, but normalization of this specific use among the lifetime of potential use experienced by that transportation infrastructure would inevitably make the impacts small enough to be disregarded in this type of analysis. Not shown in Tables 8 or 9 below is the environmental impact of the loading/unloading steps in the forest feedstock supply chain, which amount to 3.1 kg CO_2eq /green tonne and 17.3 MJ / green tonne for greenhouse gas emissions and fossil energy demand, respectively.

Table 8: Environmental impacts of forest biomass transport

	Greenhouse gas emissions			Fossil Energy Demand		
Item	lb CO_2eq / ton - mile	kg CO_2eq / tonne - km	kg CO_2eq / dry tonne - km	MJ / ton - mile	MJ / tonne-km	MJ / dry tonne-km
Log truck operations and equipment	0.313	0.097	0.194	1.79	1.23	2.46
Percentage due to equipment	2.3%			4.4%		
Rail operations and equipment	0.069	0.022	0.043	0.39	0.27	0.53
Percentage due to equipment	0.2%			0.3%		

Table 9: Potential environmental burdens associated with different trucking distances

One-way trip distance[a]	81 km 50 miles	**161 km[b] 100 miles (baseline)**	242 km 150 miles	30 km truck + 160 km rail (multimodal)
GHG emissions (kg CO_2eq / green tonne)	15.7	**31.3**	47.0	10.8
Fossil energy demand (MJ / green tonne)	197.8	**395.6**	593.3	134.5

a – environmental burdens calculated on the basis of round-trip impacts, assuming no backhauls
b – 100 miles is assumed baseline scenario. Roughly 50% of Michigan supply zone falls within 100 miles of Kinross, MI, and we assume equal distribution of forest biomass around the supply zone

Environmental burdens for supplying forest-based biomass within the state of Michigan calculated in this work can be compared to similar estimates made in the literature, although the comparisons are not often perfect due to different assumptions and scenario boundaries among studies. Below in Table 10 is a comparison of our work with a few published results collected early in the project, before our results were tabulated with data from Michigan loggers. Our results for the state of Michigan are in reasonable agreement with the three studies considering harvesting and transport of forest-based biomass grown in natural stands, from Europe and different regions in the United States. It was unclear from Sonne 2006 what transport distance was used to calculate emissions for this stage of the supply chain, but their GHG emissions value is even larger than our conservative baseline assumption of a 200 mi roundtrip distance. Johnson et al. (2005) consider a transport distance lower than our own assumption, but harvesting systems for the US Southeast and Pacific Northwest appear to be more energy intensive than our Michigan logger survey data and default assumptions indicate – although if we were to assume a combination of feller-buncher and chainsaw harvesting, our harvesting impacts could be much higher.

Table 10: Comparison of MI environmental burdens to forest biomass supply in other studies

Source	GHG Emissions kg CO_2eq / tonne[a]	Fossil Energy Demand MJ / tonne	Comments
Sonne 2006	17.4 Harvesting 38.2 Transport 55.6 Total	--	Pacific NW, 2.9 Mg CO_2eq / 300 m^3 timber and 5.5 Mg CO_2eq / 300 m^3 timber for mechanized harvest and transport, respectively, **Douglass fir density 0.48 g/cm^3 (Seely) used for all density assumptions needed in subsequent comparisons**
Johnson 2005	~ 50–58 Total	~ 615–715 Total	Table 4b, harvesting and hauling fuel use, lubricant data for US Southeast and Pacific NW, 90-120 km one-way transport, CORRIM group
Gonzalez-Garcia 2009	--	283-340 harvesting 226 – 100 transport 509 – 440 total	Data for Spain (eucalyptus plantation, low value) and Sweden (softwoods, high value), 90 km transport, 40% moisture assumed
Slade 2009	23.8 Harvesting 9.2 Transport 33 Total	--	Softwood logs, UK and Swedish data, 107 km transport, assume 50% moisture to convert data from dry tonnes to green tonnes
Klvac 2003	--	214 – 250 Harvesting Only	Estimates from Sweden and Ireland
Keoleian 2005	5.9 Harvesting Only	157.1 Harvesting Only	Willow Plantation, high intensity growth with periodic coppice harvest every 3 years, very different system
This Study	20.1 Harvest 3.1 Loading 31.3 Transport **54.5 Total**	261.1 Harvest 17.3 Loading 395.6 Transport **674 Total**	Assuming aggregated harvest data and baseline transport scenario as discussed above

a – all values in table listed on the basis of green tonnes

4.0 Conclusions

Using a combination of data from the local forest products industry, expert opinion, literature and database sources, we were able to construct a limited-scope life-cycle assessment of the forest biomass supply chain in for the planned FRR facility in Kinross, Michigan. Greenhouse gas emissions and fossil energy demand for wood harvesting were highly dependent on the equipment configuration used and the intensity of the harvest scenario. Transport of forest biomass by truck carries a higher environmental burden per ton-mile than an equivalent distance of rail transport, usually by a factor of 4-5X. Calculated environmental burdens for a default harvest and transport supply chain in MI were within the range of values reported for similar operations in the literature. Loading and unloading of wood accounted for roughly 6% of overall GHG emissions and 3% of fossil energy demand, while remaining environmental burdens were divided 37% - 57% between harvest and transport steps, respectively. We hope that a detailed summary of our approach to arriving at these values will allow policy makers, business developers, and other stakeholders in the forest biomass industry to utilize these values with some degree of confidence when considering the environmental burdens of the forest biomass supply chain for planned biofuels and bioenergy facilities, or highlight areas where more location-specific data would improve the accuracy of a particular assessment.

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Appendix
Harvest productivity data for entire state of Michigan, including plantation harvests

Combined state of MI productivity estimates for different logging equipment configurations

A: Full Processor / Forwarder

Treatment	Forest Type	N[a]	Productivity per harvester (cords/ hr) Average	Std. Dev
30% Cut (Selective)	Natural Hardwoods	54	3.34	1.38
	Mixed Hardwood / Softwood	48	3.83	1.48
	Natural Softwoods	47	3.95	2.16
	Softwood Plantations	37	4.57	2.11
70% Cut (Shelterwood)	Natural Hardwoods	43	4.09	1.80
	Mixed Hardwood / Softwood	41	4.51	1.81
	Natural Softwoods	38	4.66	2.15
	Softwood Plantations	29	4.97	2.13
Clearcutting	Natural Hardwoods	43	5.51	2.74
	Mixed Hardwood / Softwood	47	5.67	2.50
	Natural Softwoods	40	6.07	2.79
	Softwood Plantations	35	6.97	4.02

B: Feller-buncher / Skidder / Slasher

Treatment	Forest Type	N	Productivity per harvester (cords/ hr) Average	Std. Dev
30% Cut (Selective)	Natural Hardwoods	15	3.72	1.52
	Mixed Hardwood / Softwood	15	3.66	1.31
	Natural Softwoods	13	3.37	1.32
	Softwood Plantations	8	4.01	0.93
70%Cut (Shelterwood)	Natural Hardwoods	14	4.74	1.43
	Mixed Hardwood / Softwood	15	4.63	1.42
	Natural Softwoods	16	5.02	1.60
	Softwood Plantations	9	5.39	1.73
Clearcutting	Natural Hardwoods	13	6.82	2.68
	Mixed Hardwood / Softwood	13	6.59	2.98
	Natural Softwoods	11	6.42	2.83
	Softwood Plantations	9	7.10	4.19

C: Chainsaws / Skidder

Treatment	Forest Type	N	Productivity (cords/ hr) Average	Std. Dev
30% Cut (Selective)	Natural Hardwoods	32	2.02	1.33
	Mixed Hardwood / Softwood	19	1.95	1.46
	Natural Softwoods	17	1.84	1.56
	Softwood Plantations	13	1.76	0.86
70% Cut (Shelterwood)	Natural Hardwoods	20	2.20	1.61
	Mixed Hardwood / Softwood	18	1.94	1.40
	Natural Softwoods	14	1.88	1.48
	Softwood Plantations	12	1.74	1.06
Clearcutting	Natural Hardwoods	12	2.00	1.12
	Mixed Hardwood / Softwood	14	1.91	0.92
	Natural Softwoods	13	1.42	0.60
	Softwood Plantations	9	1.78	1.10

a- the n-values listed in Comments refer to the number of survey responses included in the reported average