Screening Life Cycle Analysis of a Willow Bioenergy Plantation in Southern Ontario

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Disclaimer:

This screening life cycle analysis study was conducted as an internal study for researchers at the University of Guelph, Guelph, Ontario. The goal of the study was to identify environmental impacts and hot spots in the life cycle of a willow plantation, as well as to identify data gaps so that research could be conducted to provide better data on willow plantation activities for future life cycle assessments. The data presented have not been independently validated or verified and the results of the study should be viewed as preliminary, to be used only for guiding future research and understanding where the major environmental impacts occur in the life cycle of willow plantations. It should not be compared to other studies.

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1 Introduction

An LCA screening study of a willow bioenergy plantation was undertaken in 2009-2010 at the University of Guelph, Guelph, Ontario, Canada. The purpose of this screening study was to quantify the lifecycle greenhouse gas emissions and total energy use for a test willow bioenergy plantation located at the Guelph Turfgrass Institute in Guelph. The site was prepared and planted with willow cuttings in May 2006. It was coppiced in the winter of 2007, and the first 3-year harvest occurred in December 2009.

The screening LCA model used material and energy data collected from the willow plantation; however, not all field data are currently available. The purpose of this report is to describe the life cycle methodology and data sources used, and to present the preliminary results of the cradle-to-farm gate greenhouse gas emissions and total energy use. This report also provides insights into data gaps, potential areas of research, and recommendations for a more complete LCA.

2 Life Cycle Methodology

This study uses a life cycle assessment (LCA) methodology based on the ISO 14040/14044 (2006) standards.

2.1 *Goal and Scope Definition*

The goal of this study was to quantify the greenhouse gases (GHG) and total energy use (TEU) associated with a willow plantation. This is an internal screening study to identify hot spots and data gaps related to modeling the life cycle of the willow plantation and the results are not intended for comparison purposes to other energy systems.

2.1.1 Functional Unit

The function of the system is to produce willow biomass. Since the plantation is still in its early stages, yield data are not available for a mature stand. A conservative willow biomass yield of 7 oven dry tonnes (odt) per hectare per year was assumed. Further, it was assumed that harvesting of willow biomass occurred every three years, with six harvests in total, for a total of 126 odt/ha over the assumed plantation life time of 19 years. Therefore, the functional unit for this study is 126 oven dry tonnes (odt) of willow biomass produced on 1 hectare of land over a 19 year plantation cycle.

2.1.2 System Boundaries

The lifecycle boundaries for this study are shown in Figure 2.1. All processes in the willow bioenergy value chain were identified. The cradle-to- farm gate processes included are willow plantation establishment activities (site preparation and planting, herbicide application, coppicing, fertilizer application) as well as willow plantation and maintenance (herbicide and fertilizer application), and harvesting and baling activities during the mature stage of plantation. The upstream processes that were included were electricity production and distribution, diesel fuel production and distribution, fertilizer manufacturing and transportation, herbicide manufacturing and transportation, and willow cutting production and transportation. Capital equipment manufacturing, transportation, and maintenance were not considered in this screening study.

Although willow bale transport to a pelletization facility, the pelletization facility, and willow plantation decommissioning were initially included in the boundaries for this screening study, there were no data available to analyze these components, and are therefore not considered in this screening study.

2.2 *Life Cycle Inventory*

A data collection sheet was prepared based on the processes and flows identified in the lifecycle boundaries. As much as possible, activity levels were based on the willow plantation (Table 2.1), but for unavailable data, assumptions were made based on expert knowledge and on information provided in Heller at al. (2003). The emission factors for upstream diesel fuel production and distribution, and for fertilizer and herbicide manufacture, were based on Canadian sources where possible (Table 2.2). Soil emissions related to leaf litter fall N inputs and soil C sequestration by the willow plantation were not modeled due to the lack of available data, but an estimate of their impact is provided in Section 3.4.

In order to obtain an emission factor for willow cutting production, material and energy inputs as provided by Heller et al. (2003) were used. The willow cuttings were produced in Edmonton, Alberta, and it was assumed that the cuttings were transported by tractor-trailer from Edmonton to Guelph, Ontario, a distance of 3,400 km. Assuming a vehicle efficiency of 100 km/40L, and that the truck was used solely to transport the cuttings, this requires 1360 L of fuel. The data used and resulting emission factors are provided in Appendix A. A more realistic scenario as willow plantations become established in Southern Ontario is that the willow producer would use cuttings from the coppicing activity to expand the willow plantation or to sell to other producers. This scenario is modeled in Section 3.3.

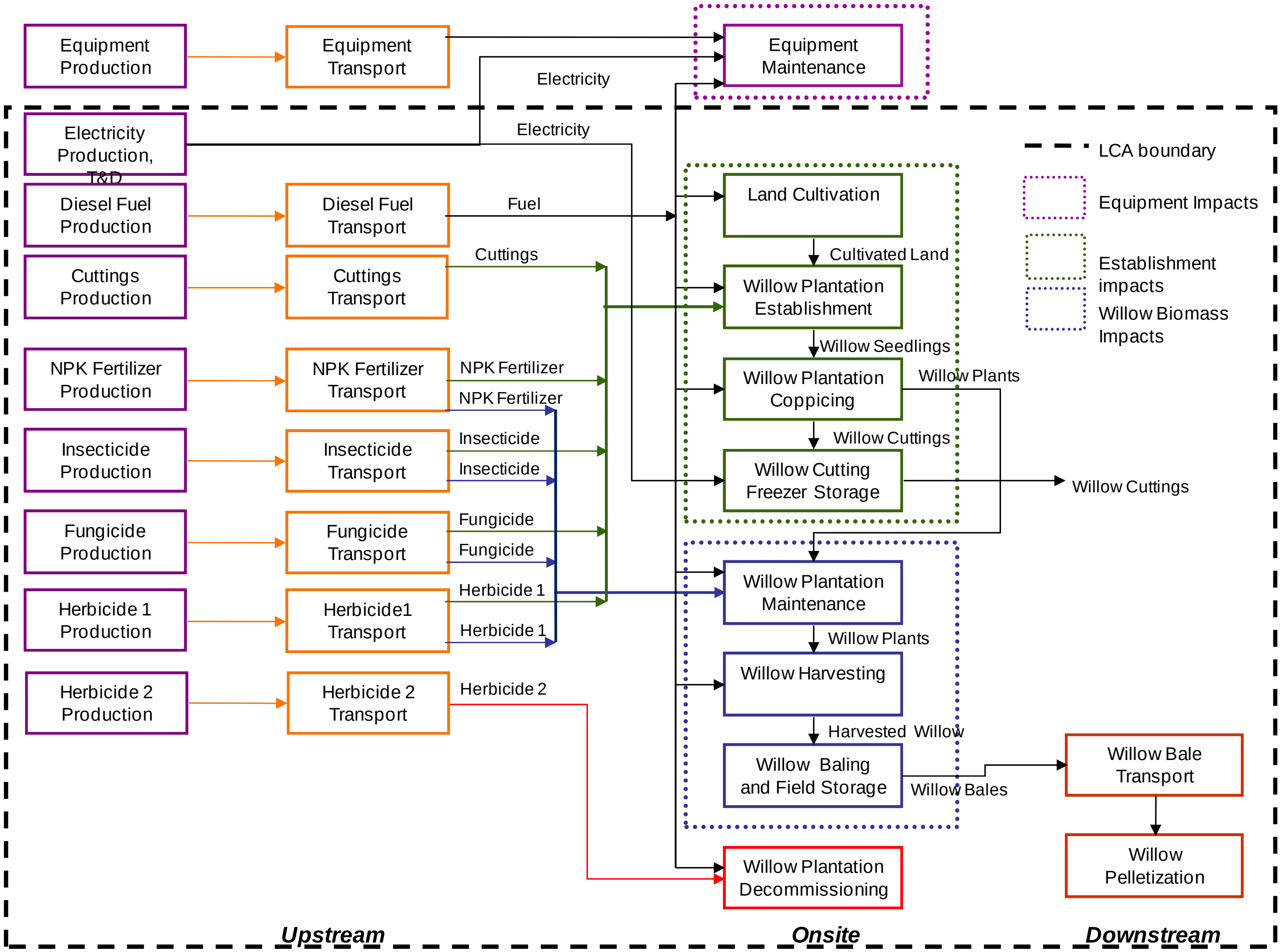

Figure 2.1 Life cycle boundaries used in screening study for willow plantation.

Table 2.1 Life cycle inventory for cradle-to-farm gate of willow plantation. Data are based on actual plantation data, expert judgement and literature review.

Process	Parameter	Amount	Units
Site Preparation	Fuel for plowing, discing, cultivating	20.8	L/ha
	Fuel for cutting transportation	1,360	L/ha
	Fuel used for planting willow cuttings	5.2	L/ha
	Number of cuttings	15,000	#/ha
	Fuel for herbicide 1 and second herbicide transport	0.024	L/ha
	Fuel used to apply herbicide	1.1	L/ha
	Amount of herbicide 1	0.9	kg ai/ha
	Fuel used to apply second herbicide	1.1	L/ha
	Amount of second herbicide	1.1	kg ai/ha
Willow Plantation Establishment	Fuel for fertilizer transport	4.2	L/ha
	Fuel for fertilizer application	2.3	L/ha
	Amount of N fertilizer	74.1	kg N/ha
	Amount of P fertilizer	42.3	kg P2O5/ha
	Amount of K fertilizer	57.0	kg K2O/ha
Willow Plantation Coppicing	Fuel used for coppicing	13.6	L/ha
Willow Cutting Freezer Storage	Fuel used to transport cuttings from field to storage	N/A	L/ha
	Electricity used for 1 ha cuttings	N/A	kWh/ha
Willow Plantation Maintenance	Fuel for fertilizer transport	21.0	L/ha
	Fuel for fertilizer application	11.7	L/ha
	Amount of N fertilizer	370	kg N/ha
	Amount of P fertilizer	212	kg P2O5/ha
	Amount of K fertilizer	285	kg K2O/ha
Willow Harvesting	Fuel for harvesting willow biomass	33.6	L/ha
Willow Baling and Field Storage	Fuel for baling willow biomass	1,024	L/ha

Table 2.2 Emission factors for various processes.

Process Description	Emission Factor				Units	Reference
	CO_2	CH_4	N_2O	CO_2e		
Upstream Processes						
Electricity Production, transmission and distribution (Alberta)				0.272	kg CO_2e / kWh	Environment Canada (2004)
Diesel fuel production				0.56	kg CO_2e /L	Environment Canada (2004)
Cuttings production (nursery operations) [1]				0.13	kg CO_2e/cutting	Heller et al.(2003)
N fertilizer production and distribution (urea)				4.1	kg CO_2e/kg N	Nagy (2000)
P fertilizer production and distribution (triple superphosphate)				0.57	kg CO_2e/kg P_2O_5	Nagy (2000)
K fertilizer production and distribution (muriate of potash)				0.24	kg CO_2e/kg K_2O	Nagy (2000)
Herbicide 1 production and distribution [2]				31.9	kg CO_2e/kg ai[*]	Nagy (2000)
Roundup herbicide production and distribution				17.2	kg CO_2e/kg ai	Nagy (2000)
Onsite Processes						
Diesel combustion (light duty vehicle)	2.73	0.0015	0.06	2.8	kg CO_2e/L	Environment Canada (2004)
Diesel combustion (heavy farm equipment)	2.73	0.0029	0.34	3.1	kg CO_2e/L	Environment Canada (2004)
Soil N_2O emissions [3]			0.017		kg N_2O-N kg^{-1} N	Rochette et al. (2009)

[1] Calculated based on inputs for cutting production.
[2] No data available for herbicide used therefore worst case energy and GHG emissions given for herbicides were assumed.
[3] Based on fertilizer N input. N input from leaf fall was not considered due to lack of information on leaf litter fall N input from willow plantation.

[*] Active ingredient.

3 Life Cycle Impact Results

The life cycle model allocates total energy use and greenhouse gases for all processes in the lifecycle boundaries evenly across the total biomass harvested on 1 ha of land over a 19-year plantation lifetime. The greenhouse gas emissions and total energy use results for the cradle-to-farm gate activities associated with the willow plantation are reported based on the functional unit of 126 odt, which is the amount of biomass produced on 1 ha of land over the 19-year plantation lifetime.

3.1 *GHGs*

The emissions by lifecycle stage are shown in Figure 3.1. Processes occurring upstream of the willow plantation activities account for about 60% of the 16,800 kg CO_2e of cradle-to-farm gate GHGs per 126 odt. These processes include willow cutting production and transportation, fertilizer and herbicide manufacture and transport, and diesel production and distribution.

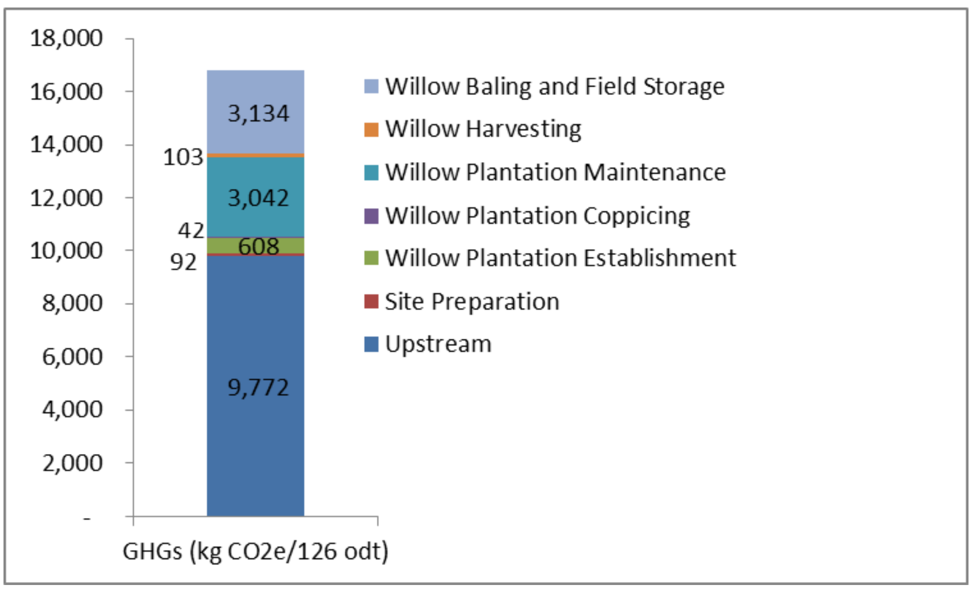

Figure 3.1 Greenhouse gas emissions for 126 odt/ha produced over 19 years and 6 rotations based on life cycle stages.

When individual processes are considered, most of the GHG emissions are due to willow cutting production (12%) and transportation (29%), upstream diesel production and on-farm combustion (25%), and fertilizer production (12%) (Figure 3.2). Soil nitrous oxide emissions from nitrogen application for plantation establishment and maintenance account for (21%) of the GHG emissions, but as mentioned previously, soil emissions related to N input from leaf litter fall and soil carbon sequestration are not included in the modelling. The implications of leaving these out are discussed in Section 3.4.

The single largest contribution is due to the travel distance from the willow cutting production facility in Edmonton, Alberta to the study site in Guelph, Ontario, which is a distance of 3400 km. For actual plantations, the travel distance is likely to be less than 100 km; thus a sensitivity analysis on transport distance was conducted and is discussed in Section 3.3.2.

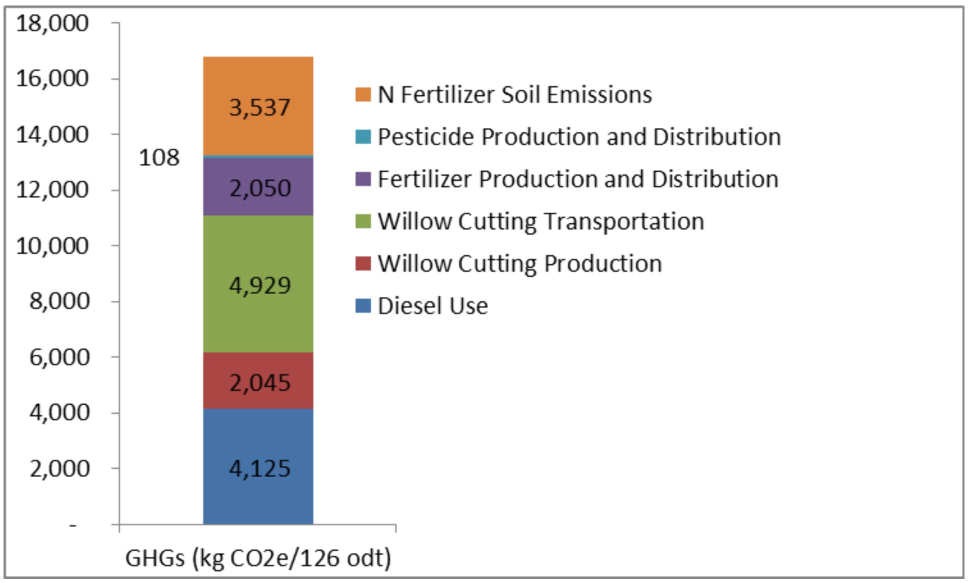

Figure 3.2 Greenhouse gas emissions for 126 odt/ha produced over 19 years and 6 rotations based on various processes.

3.2 *Total Energy Use*

The cradle-to-farm gate life cycle total energy use (TEU) is 175,200 MJ/126 odt. As was the case for the GHG results, the biggest contributors to TEU are the activities occurring upstream of the willow plantation activities (Figure 3.3), which contributed to 75% of the TEU. The largest energy use aside from upstream processes was for baling the willow biomass, with the energy use for this process representing almost 23% of the total energy use on a cradle-to-farm gate basis.

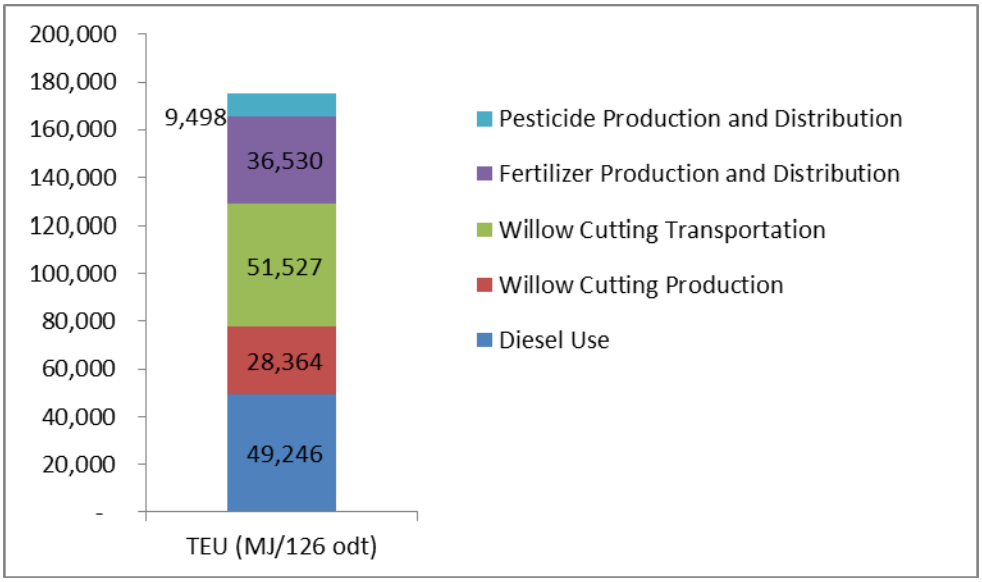

Figure 3.3 Total energy use for 126 odt/ha produced over 19 years and 6 rotations based on life cycle stages.

When individual processes are considered, the biggest contributions to energy use were willow cutting transportation (29%) and upstream diesel production and on-farm use (28%), followed by fertilizer production (21%), and willow cutting production (16%) (Figure 3.4).

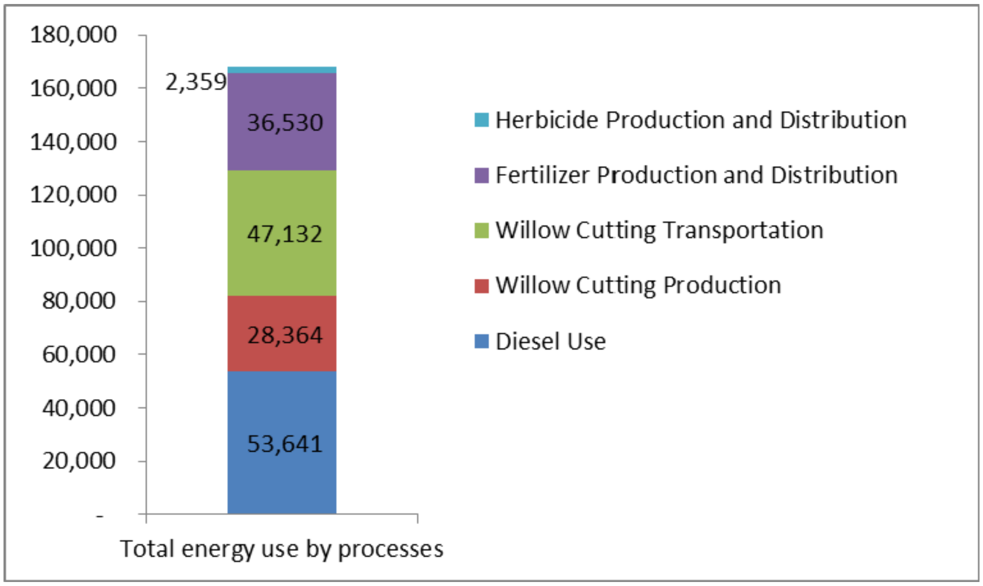

Figure 3.4 Total energy use for 126 odt/ha over 19 years and 6 rotations broken down by processes.

3.3 *Scenario and Sensitivity Analysis*

A sensitivity analysis was conducted on yield and a scenario analysis was conducted on willow cuttings being transported within Ontario.

3.3.1 Yield

The yield was changed from 7 odt/ha to 5 and 10 odt/ha to determine the effect on energy ratios. The results of the sensitivity analysis are shown in Table 3.1. In changing yields, it was assumed that there were no changes made to the fertilizer or pesticide inputs, or in the amount of fuel used to harvest the change in yields. However, it is clear that the yield data are important to the energy ratios. The energy ratio changes from 10 to 20 as the yield changes from 5 to 10 odt/ha.

Table 3.1 Sensitivity analysis based on changes in yield.

Starting yield	Total yield		Energy Input	Energy Input	Energy Ratio
odt/ha	GJ/ha	odt/ha	MJ/ha	MJ/ odt biomass	MJ out/MJ in
5	1,782	90	175,164	1,946	10
7	2,495	126	175,164	1,390	14
10	3,564	180	175,164	973	20

3.3.2 Willow Cutting Transport Distance

The distance travelled was changed from 3400 km to 100 km, representing transportation from Edmonton, Alberta to cuttings produced within Southern Ontario, respectively. GHG emissions and TEU results are presented in Table 3.2. GHG emissions and TEU from willow cutting transportation decreased by 30% as the distance decreased from 3400 to 100 km.

Table 3.2 Sensitivity analysis results for GHG emissions and total energy use as a result of changing willow cutting transportation distance.

	Distance traveled	**GHGs**	**TEU**
		kg CO_2e/126 odt	MJ/126 odt
Willow Cutting Transportation	100 km	145	1,541
	3400 km	4,929	52,382
Total Life Cycle	100 km	12,010	124,323
	3400 km	16,793	175,164

3.4 *Confirmation of LCA Screening Results*

In order to confirm the results of this screening study, the Heller et al. (2003) willow biomass study for a cradle to farm gate analysis was reviewed. The results from this study and the Heller et al. (2003) study are given in Table 3.3. The net GHGs for the Heller et al. (2003) study were 3,700 kg CO_2e/ha over a 23 year willow plantation life time, assuming 10 odt/ha and seven rotations. This resulted in 274 odt/ha yield over the lifetime of the plantation. Heller et al. (2003) GHG emissions included a credit for carbon sequestration and an emission for N_2O due to leaf litter decomposition. In this study, the total GHGs were 16,793 kg CO_2e/ha over a 19-year willow plantation life, assuming 7 odt/ha and 6 rotations. Assuming the same carbon sequestration rate and N_2O emissions as in the Heller et al. study, the net GHG emissions are 10,042 kg CO_2e/ha, or almost 3 times the emissions in Heller's study.

In terms of total energy use, the Heller study determined that 98,092 MJ/ha were used to produce 274 odt/ha, while in this study 175,164 MJ/ha were used to produce 126 odt/ha. In order to compare energy use based on yield, the energy ratio is used, which is the amount of energy produced from the willow biomass divided by the amount of energy used to produce the biomass. In Heller et al.'s study, the energy ratio was 55, or 55 units of renewable energy were produced for every unit of fossil fuel energy. This study yielded an energy ratio of 14, which is almost 4 times smaller than that in Heller et al.'s study.

One of the main reasons for these differences is the transport distance of the willow cuttings and the number of rotations. The following analysis discusses the implications of changing these inputs on the final GHG and TEU results.

Table 3.3 GHG emissions and energy parameters for this screening study and a willow biomass LCA by Heller et al. (2003).

Study	Starting yield	Rotations	Total yield		Energy Input	Energy Input	Energy Ratio	GHGs	Comment	
	odt/ha		GJ/ha	odt/ha	MJ/ha	MJ/ odt biomass	MJ out/MJ in	(kg CO2e/ha)		
Heller et al. 2003	10	7	5,430	274	98,092	358	55	3,700	Includes C sequestration and N2O emissions due to leaf litter fall	Cradle to farm gate; i N2O emissions due t
This study	7	6	2,495	126	175,164	1,390	14	16,793	No C sequestration	No below ground bio
								2,693	With C sequestration	Using Heller et al. 20 biomass of -14100 k
								9,973	With C sequestration and N2O emissions from leaf litter fall	Using N2O emission study

3.4.1 Adjusted emissions

Taking into consideration the sensitivity analysis, this study was adjusted for similar yield and rotations as the Heller et al. (2003) study (Table 3.4). The results for this study show an improvement in the energy ratio, from 14 to 22, and a decrease in the GHG emissions from 16,793 kg CO_2e/ha to 11,566 kg CO_2e/ha.

The remaining differences in energy use and GHGs may be attributed to the following:

1. The cuttings are still assumed to be produced in Alberta, which may have a higher electricity grid emission factor than the Heller et al. study. Once the information is available for crediting the cuttings produced in the Ontario system, these numbers should improve since the Ontario grid has an emission factor that is 3 to 4 times smaller than that of Alberta. This could reduce the total GHG emissions by about 1000 kg CO_2e/ha. Additionally, reducing transportation distance of the cuttings would result in a reduction in emissions by 4500 kg CO_2e/ha.
2. A N_2O emission factor of 0.017 kg N_2O-N/kg N applied was used for Ontario, based on a regionalization of N_2O emissions done by Rochette et al. (2008). Heller used the IPCC factor of 0.0125 kg N_2O-N/kg N. This results in a difference in GHG emissions of about 1000 kg CO_2e/ha.
3. Since Canadian emission factors were not available for the pesticides used in this study, a conservative approach was used. The highest values energy coefficients and GHG emission factors available for Canadian herbicides were used; these factors are about 3 times larger than those used by Heller et al.

Table 3.4 GHG emission and total energy use results adjusted for equivalent yield, rotations, and no transport of willow cuttings.

Study	Starting yield	Rotations	Total yield		Energy Input	Energy Ratio	GHGs
	odt/ha		GJ/ha	odt/ha	MJ/ha	MJ out/MJ in	(kg CO2e/ha)
Heller et al. 2003	10	7	5,430	274	98,092	55	3,700
This study	10	7	4,158	210	190,173	22	11,566

4 Conclusions and Recommendations

Screening LCAs can provide an understanding of the hot spots of a system by life cycle stage or processes. The study highlighted the importance of biomass yield on GHG emissions and TEU, as well as highlighting the importance of transportation to the environmental burden of biomass for energy production.

This study has shown several data gaps in activity levels for the Ontario willow plantation test site. These data can be collected as the pilot study progresses. The following are the key variables required for improving LCA results:

1. Actual yield based on a mature stand
2. Number of rotations
3. Soil N_2O emissions resulting from fertilizer application.
4. N_2O emissions resulting from leaf litter decomposition. This is important both from an emission standpoint and from a management standpoint, since N being added through leaf litter could reduce fertilizer use.
5. Activity levels for on-site cutting production. Particularly, data is required on how the cuttings are handled and stored, and the number of cuttings produced per hectare.

Once these data become available, the model can be refined and improved for more reliable LCA results. Uncertainty analysis should also be considered. Finally, this model could be used for creating a range of willow biomass for energy scenarios, including looking at management options for improving the environmental profile of willow.

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Appendix A

Detailed mass and energy life cycle inventory for willow cutting production. Activity levels are based on Heller et al. (2003) data. Canadian emission factors were used to determine greenhouse gas emissions and Canadian-based energy coefficients were applied for the total energy use analysis. The inputs from Heller et al. (2003) study produced 456,437 cuttings.

Input	Amount	Units	Comments	GHGs (upstream)	GHGs (nursery)	Energy use (upstream)	Energy use (nursery)
				kg CO2e	kg CO2e	MJ	MJ
Diesel oil	227	L		128	714	876	8,779
Liquified petroleum gas	30.2	kg	Assume propane				
	16,503	L	volume basis	9,285	25,460	103,472	421,315
Gasoline	757	L	Assume same as diesel precombustion	426	1,802	700	29,154
Electricity	9000	kWh	Assume Alberta grid, where cuttings originate	8,199	-	92,790	-
Heavy fuel oil (heat)	2271	L	Assume same GHGs as diesel production precombustion and same energy as light fuel oil precombustion	1,278	7,141	8,766	94,762
Wood (heat)	1296	kg	assume biogenic emissions only	-	-		23,328
Carbaryl (insecticide)	6.53	kg a.i.	assume worst case with Achieve X Gold	208	-	4,568	-
Glyphosate (herbicide)	3.63	kg a.i.	Assume Roundup	63	-		-

Input	Amount	Units	Comments	GHGs (upstream)	GHGs (nursery)	Energy use (upstream)	Energy use (nursery)
						1,354	
Granular mixed fertilizer (15-15-15)	3289	kg	assume ammonium nitrate as N (34%), P as MAP P2O5, K as K2O	2,411	-	41,116	-
Ammonium Sulfate fertilizer	249	kg	assume 21% ai and same GHGs as UAN (30%)	745	-	14,459	-
Urea fertilizer	249	kg	Assume 46% N	1,021	-	17,649	-
Soil emissions			Assume Rochette et al. 2008 emission factor for Ontario = 1.7 % N2O/kgN		3,344		-
Output of planting stock	456437	units					
Total GHGs					62,225		
Total Energy use							863,088