QUANTIFYING ENVIRONMENTAL IMPACTS OF POPLAR BIOMASS PRODUCTION IN THE US PACIFIC NORTHWEST

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Abstract. The life cycle impacts were determined for poplar-managed four ways in the Pacific Northwest of the United States. Two sites had 3-yr rotations and either no irrigation (Site 1) or irrigation with river water (Site 2). The other sites had 12-yr rotations and irrigation with wastewater from a treatment facility (Site 3) or irrigation with landfill leachate (Site 4). Primary data for land preparation, plantation management, harvesting, and land restoration at each site and the production of cuttings at an additional facility were collected. A cradle to gate life cycle assessment was conducted using SimaPro PhD v8 based on the primary data and secondary data from the US life cycle inventory and ecoinvent v3 database to create a life cycle inventory. Impact indicators were provided by TRACI model. Short rotations resulted in lower global warming impact per unit output (79.5 and 54.5 kg CO_2 eq/t) and energy consumption (1381.8 and 877.4 MJ/t) than long rotations (93.1 and 81 kg CO_2 eq/t and 1406.9 and 1343.5 MJ/t) mainly due to reduced diesel use. Higher planting densities resulted in greater water and electrical consumption attributed to cuttings. Pesticide and herbicide use strongly affected ozone depletion and eutrophication, whereas fuel consumption had strong effects on global warming impact, smog, and acidification. Increasing biomass yield reduced impacts. When the electricity was all from biomass, global warming and acidification decreased; however, ozone depletion, smog, and eutrophication increased. The results suggested that both, herbicide application during plantation management and diesel consumed during harvesting at these sites should be optimized to decrease the environmental impacts.

Keywords: Short rotation woody crops, plantation management, irrigation systems, cuttings, life cycle assessment (LCA), environmental impacts.

INTRODUCTION

Biomass is considered to be a renewable alternative to conventional, nonrenewable sources of energy, such as crude oil. Biomass is promoted as an energy source for reasons that include concerns over national energy security, global increases in CO_2 emissions, and local and regional air and water pollution associated with fossil energy sources. Most projections of global energy use predict that biomass will be an important component of grid-connected renewable energy sources, contributing 10-45% of the total primary energy in the coming decades (Keoleian and Volk 2005).

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The consumption of renewable energy was 10.07 EJ in the United States in 2014, of which 28% was from biomass (EIA 2014a). A projection for 2025 shows an increase of 16.4% in the renewable energy market in the United States with the biomass portion of this increasing of 3.6%, based from 2012 (EIA 2014b).

Many studies on life cycle assessment (LCA) have shown biomass being less impactful to the environment as compared with fossil fuels (Heller et al 2003; Amponsah et al 2014; Fiala and Bacenetti 2012). Poplar (*Populus* spp.) is a hardwood species with multiple uses ranging from solid wood to bioenergy. Poplar plantations are highly productive and demonstrate a high degree of physiological adaptability (Di Matteo et al 2015). Poplar is often managed as a short rotation woody crop (SRWC). These forest plantations are managed for biomass production under agricultural practices, ie intensive regimes in comparison with usual forestry practices (Heller et al 2003). The woody biomass can be used for energy while sequestering CO_2 during biomass growth (Hinchee et al 2009).

Poplar plantations can have high yields, but requiring large amounts of water and nutrients due to extensive root systems and a high rate of transpiration. Poplars can survive in polluted soil and with contaminated irrigation water from a wastewater treatment plant or landfill leachate (Dimitriou 2005; Keoleian and Volk 2005; Zalesny et al 2007). Willow and poplar have been used for phytoremediation as a green filter to clean sources of water and soil, providing oxygen and capturing CO_2 (Zalesny and Bauer 2007). The environmental impacts of using different water quantities and quality in the production of poplar biomass have not been studied yet.

Poplar has low requirements for nutrients, herbicides, pesticides, and soil maintenance compared with annual crops (Balasus et al 2012). According to FAO (2006), oats, wheat, maize, and rice use 76, 116, 136, and 112 kg/ha of fertilizers, respectively, all greater than the poplar. Balasus et al (2012) indicate that the application of 75 kg N eq/ha/yr of fertilizer for poplar harvested after 2 yr caused an increase of 40 kg N/ha/yr for nitrate leaching and 0.2 kg N/ha/yr for nitrous oxide emissions and concluded that poplar could be produced over a 2-yr cycle in a more effectively and with less environmental impacts without mineral fertilization. However, fertilization can be important for yield. Strauss and Grado (1992) showed a 21% yield increase in the second rotation for poplar fertilized at rates recommended for corn production.

These plantations are often established using cuttings. Planting cuttings is a method of vegetative propagation in which a part of a plant, such as a stem, leaf, shoot, or twig is induced to form its own roots (FGC 2015). Genetic selection of poplar cuttings could reduce the use of fertilization while maintaining sustainable forest growth on poor sites (adapted from Werhahn-Mess et al 2011). The production of cuttings requires materials and energy, which become embodied and thus impacts the life cycle of the plantation, especially at high planting densities. However, there is limited information on the environmental impacts resulting from the production of poplar cuttings due to material and energy use (Bacenetti et al 2012).

The main objective of this study was to use life cycle analysis tools to compare and contrast environmental impacts of poplar biomass production under four different management regimes in the Pacific Northwest (PNW) region of the United States. More specifically, the objectives were the following:

1. To analyze the environmental impacts due to material and energy consumption from producing poplar biomass for energy grown under different conditions in the PNW.
2. To compare the material and energy consumption among four irrigation scenarios for the production of poplar biomass.
3. To determine the changes in environmental impacts caused by changing the electrical grid and replacing biosolids with chemical fertilizer.

4. To quantify the environmental impacts associated with producing cuttings by conducting a case study of the main producer located in PNW.

MATERIALS AND METHODS

The objectives of this study are achieved through case studies at four poplar plantations located in the PNW of the United States. Sites 1, 3, and 4 were located in the Willamette Valley of Oregon, whereas Site 2 was located on the east side of the Cascade Mountain range in Oregon. A general description of the sites is provided in Table 1. These sites differed in the way they were irrigated. Site 1 had no irrigation, Site 2 was irrigated with river water, Site 3 with wastewater from a sewage treatment plant, and Site 4 with diluted landfill leachate. Apart from irrigation, the sites also differed in the rotation period of the crops. Sites 1 and 2 had 3-yr rotations, whereas Sites 3 and 4 had 12-yr rotations. All sites planted poplar cuttings produced within Site 2, but with a different process than biomass. This plantation is the major supplier of poplar cuttings in the PNW.

A cradle-to-gate LCA was conducted according to ISO 14040 (ISO 2006a). All four sites were analyzed by means of case study to fulfill the first three objectives of this study. The functional unit was one-bone dry metric ton of biomass.

Figure 1 shows the production system, including all inputs to the processes, from land preparation to land restoration for the production of biomass. The mass and energy inputs and outputs for Sites 1 and 2 were reported for the first rotation and estimated for future rotations using the 3-PG (Physiological Principles in Predicting Growth) model for forest growth. This model uses solar radiation, temperature, and species-specific photosynthetic parameters to establish maximum potential productivity (Landsberg and Waring 1997). This model has been used extensively by Haedlee et al (2013), Amichev et al (2011), and Rodriguez-Suarez et al (2010), among others. Hart et al (2014) adapted the 3-PG model to SRWC, including coppicing by adding component that allows for a growth contribution from root mass. Estimation of material and energy inputs for future rotations were based on the estimates of the biomass produced. Neither machine fabrication nor transportation of biomass from the sites was accounted for in this study.

The Netherlands SimaPro PhD v.8 software along with the US Life Cycle Inventory (USLCI) and European ecoinvent v.3 databases were used to create a life cycle inventory (LCI). Primary data for each site were obtained by questionnaires that were answered by the respective field managers. Operating data for land preparation, plantation management, harvesting, and land restoration at each biomass site and for the production of cuttings were collected from September 2012 to July 2014. In addition, secondary data were obtained from scientific literature.

The inputs associated with each process and for every site are summarized in Table 2. Pollutant emissions associated with the inputs are

Table 1. General site description.

Parameters (units)	Site 1	Site 2	Site 3	Site 4
Latitude/longitude	44°41′ N, 122°57′ W	45°44′ N, 119°32′ W	44°7′ N, 123°11′ W	45°9′ N, 123°15′ W
Plantation surface (ha)	28.63	315	21.05	4.45
Planting density (#/ha)	3586	1485	553	1375
Number of clones	11	3	3	1
Rotation (years)	2 (1st rotation) 3 (2nd and 3rd rotations)	3	10	12
Number of harvest cycles	4	4	1	1
Plantation lifetime (years)	11	12	10	12
Soil type	Clay	Sandy	Clay	Clay
Rainfall (mm/year)	1000	200	1000	1058

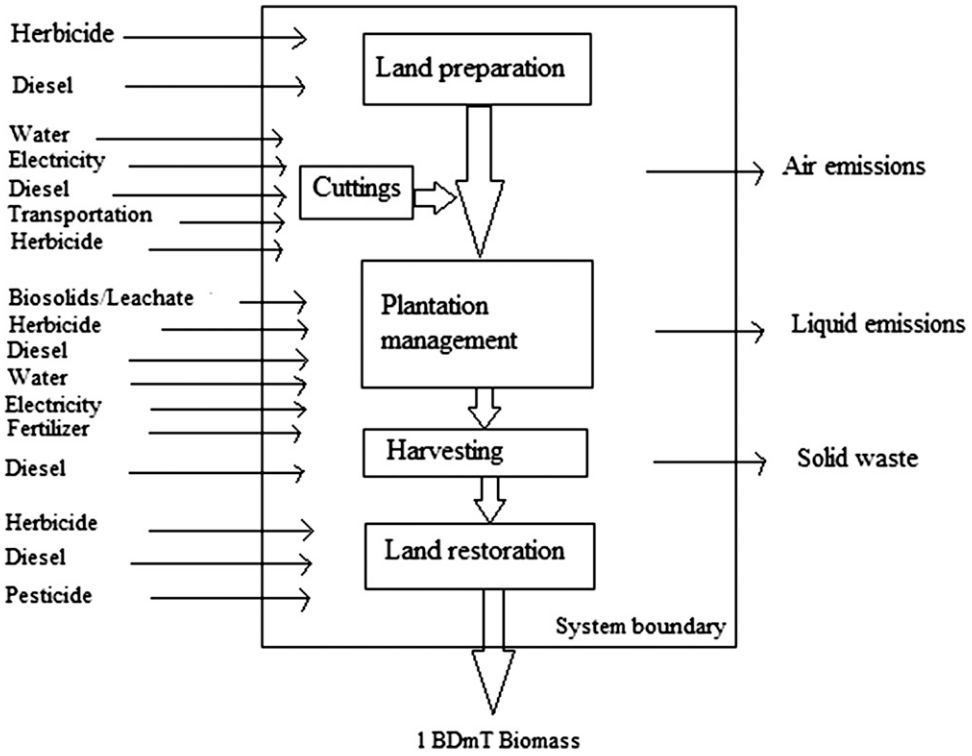

Figure 1. General system boundary for the production of 1 ton of biomass.

quantified from USLCI (NREL 2012) and ecoinvent databases. The process model biomass production was done in SimaPro PhD v.8.0.3.14 (Pré Consultants 2013).

The TRACI 2.1 v 1.01/US 2008 (Bare 2011) impact category model was used to provide the critical environmental impacts. A few key impact categories were ozone depletion, global warming, smog, acidification, and eutrophication. Woody biomass yield for future harvests was estimated using the 3-PG model. The potential environmental impacts of poplar woody biomass production were evaluated by measuring the mass and energy inputs and outputs, applying the LCA method, and then using Life Cycle Inventory Analysis (LCIA) within the framework defined in ISO 14044 (ISO 2006b). The LCIA was performed using the TRACI method. Applying a LCIA to LCI results will result in a LCA that will help the industry to prioritize areas for environmental action and, at the same time, get the best return on investment by reducing operational environmental impact.

The environmental impacts are affected by how electricity is generated off-site. Significant amounts of electricity are used to pump water for irrigation. Therefore, three methods of generating electricity were considered to determine the changes in environmental impacts caused by changing the composition of the electrical grid. Data were taken for the default method, which was a mix of electrical sources specified by the Western Electricity Coordination Council (WECC). An alternative source was the PNW grid, where 68.3% of total electricity is hydroelectricity. The other alternative was the hypothetical scenario of using only electricity produced from biomass. When replacing biosolids with chemical fertilizer in Site 3, the comparison of natural (biosolids) and synthetic (nitrogen) was based on its equivalent nitrogen application. The LCIA method utilized was the same as earlier.

Table 2. Inputs for production of 1 ton of poplar biomass.

Processes input	Unit	Site 1	Site 2	Site 3	Site 4
Land preparation					
Herbicide	kg	0.021	0.008		
Diesel	L	0.21	1.24	0.30	0.012
Stock for initial planting					
Cuttings	#	33.42	3.08	4.39	9.05
Transportation	t·km	1.12		0.18	0.27
Plantation management					
Herbicide	kg	0.44	0.19		
Diesel	L	1.36	1.01	12.5	7.98
Water	L		47,235	66,938	54,000
Electricity	kWh		14.88	9.25	17.04
Biosolids	ton			0.78	
Leachate	ton				130
Fertilizer	kg N			0.36	6.39
Pesticide	kg		0.11		
Harvest					
Diesel	L	7.91	10.18	11.44	13.71
Land restoration					
Herbicide	kg	0.021			0.008
Diesel	L	0.15	0.11	4.9	0.05
Pesticide	kg	0.023			
Biomass yield	t/ha/yr	9.76	12.70	12.60	12.66

Blanks indicate the material was not used.

To quantify the embodied energy and environmental consequences of cutting production for poplar plantations at different planting densities, only the Greenwood Resources Boardman Tree Farm near Boardman, Oregon (Site 2), was considered. This site is a major supplier of poplar cuttings in the PNW. It is a large plantation, much of which is managed as SRWCs with a small section devoted to cuttings. The cuttings are both used on-site and sold to external parties. The 3-yr production cycle begins with site preparation. Branches are removed during each of the three subsequent years, bundled into units of approximately 50, and transported a short distance to an on-site processing facility where the branches are cut into 560-mm (22-inch) cuttings. The cuttings are then stored under refrigeration until sold. The poplar cuttings had a small-end diameter of 1.27 cm and a large-end diameter of 2.54 cm. They typically are 0.52 m long with a volume of 0.00015 m^3 and dry mass of 0.0465 kg, based on a basic specific gravity of 0.31. The average mass of cutting in green condition was 93 g. The stumps are removed and the land is cleared after the third harvest. The functional unit for this analysis was a cutting. Figure 2 shows the system boundary of cutting production and Table 3 shows the inputs for the production of one cutting. The information was collected from field manager of Site 2. The life cycle impact assessment method used was the same as earlier.

RESULTS AND DISCUSSION

Environmental Impacts Due to Material and Energy Consumption

LCA was used to assess the potential environmental impacts associated with the production of biomass in PNW poplar plantations for bioenergy. The results are summarized in Tables 4-7 for four different sites per ton of woody biomass produced. In general, plantation management and harvesting had the greatest contributions to environmental impacts due to fuel consumption associated with these operations. Use of chemicals during land preparation and land restoration were also important contributors. Chemical use, such as applying pesticides and herbicides,

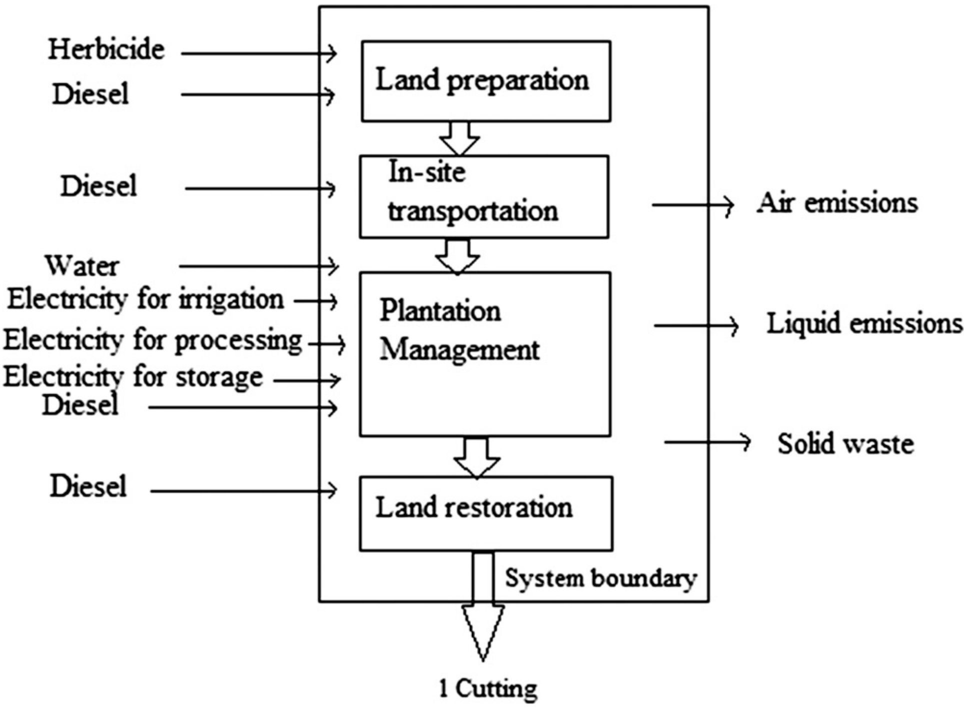

Figure 2. Cradle-to-gate system boundary for production of one cutting.

strongly affected ozone depletion and eutrophication, whereas fuel consumption, such as diesel use, had strong effects on global warming, smog, and acidification. Increasing biomass yield (Table 2) reduces impacts based on comparing Site 1 to Sites 2, 3, and 4.

The impact categories for the four sites per ton of woody biomass are presented in Tables 4-7. Considering biomass production, Site 1 resulted in the highest level of ozone depletion among the sites. This was attributed to the use of herbicide applied during plantation management process, which accounts for 88.6% of the associated impacts. Application of herbicide has been previously shown to have similar effect on forest plantations (González-García et al 2012; Morales et al 2015). Similarly, the use of herbicide at Site 1 for plantation management accounts for 59.0% of the eutrophication value

Table 3. Inputs for the production of one cutting.

Processes	Inputs	Unit	Amount
Land preparation	Herbicide	kg	0.000066
	Diesel	L	0.001
Transportation	Diesel	t km	0.00040
Plantation management	Water	L	2070
	Electricity for irrigation	kWh	2.12
	Electricity for processing	kWh	0.00019
	Electricity for storage	kWh	0.050
	Diesel	L	0.024
Land restoration	Diesel	L	0.0019
Energy	From fossil fuel (80.4%)	MJ	24.6

Table 4. Environmental impact categories in Site 1 with its respective main inputs and process contributors. Values are per dry ton of woody biomass produced.

Impact category	Unit (kg)	Total	%	Caused by
Ozone depletion	CFC-11 eq	1.18E-06	88.6	Herbicide in plantation management
Global warming	CO_2 eq	79.55	54.4	Cutting
Smog	O_3 eq	17.13	64.0	Diesel in harvesting
Acidification	SO_2 eq	0.85	45.9	Cutting
Eutrophication	N eq	0.092	58.8	Herbicide in plantation management

(Table 4). Sites 2 and 3 had similar eutrophication values (0.061 and 0.070 kg N eq, respectively). This was unexpected as land preparation and plantation management between sites were completely different in regard to the use of chemicals. Site 2, eg used herbicide, whereas Site 3 did not. On the other hand, Site 3 used biosolids and fertilizer during plantation management as opposed to Site 2. This analysis did not, however, consider any interactions. For example, if the chemical application had been optimized to maximize yield in the base case, any change would reduce yield and further increase the unit impact.

Biomass from Site 2 had the lowest global warming impact among the sites where diesel consumption in plantation management and harvesting accounted for 73% of the value. The lowest global warming impact compared with other sites was due to a low planting density, short rotation, and low chemical and energy consumption. Higher planting density carried the burdens of greater water and electrical consumption associated with irrigation. Biomass from Site 2 had the highest smog value. The main contributor to smog value was consumption of diesel during harvesting, which contributed toward 77% of the total smog (Table 5).

The diesel used in the plantation management and harvesting processes of Site 3 were the main contributors to all the impact categories with contributing ratios higher than 64% (Table 6). In contrast, the acidification of all other sites was lower than Site 3. In case of Site 4, the consumption of diesel in the harvesting process produces the highest global warming impacts that represent the 47% of its contribution. However, short rotations at Sites 1 and 2 resulted in both lower global warming impact per unit output (79.6 and 54.8 kg CO_2 eq/t, respectively) and energy consumption (1381.8 and 877.4 MJ/t, respectively) than long rotations at Sites 3 and 4 for global warming impact per unit output (93.1 and 81.0 kg CO_2 eq/t, respectively) and energy consumption (1406.9 and 1343.5 MJ/t, respectively) mainly due to reduced diesel use as a summation of all diesel consumed in the different processes. Hence, there are indications that shorter rotations lead to lower global warming impact. However, capture of carbon due to longer rotation of trees could contribute positively to reduce global warming impact by apportioning of diesel.

Sites 1 and 4 had similar global warming impacts (Tables 4 and 7). Within the resolution of the LCA conducted, it cannot be conclusively discerned as to which was lower. The main contributor to the global warming impacts were cutting and diesel

Table 5. Environmental impact categories in Site 2 with its respective main inputs and process contributors. Values are per dry ton of woody biomass produced.

Impact category	Unit (kg)	Total	%	Caused by
Ozone depletion	CFC-11 eq	6.05E-07	75.0	Herbicide in plantation management
Global warming	CO_2 eq	54.74	58.7	Diesel in harvesting
Smog	O_3 eq	18.32	77.0	Diesel in harvesting
Acidification	SO_2 eq	0.67	66.1	Diesel in harvesting
Eutrophication	N eq	0.061	43.8	Diesel in harvesting

Table 6. Environmental impact categories in Site 3 with its respective main inputs and process contributors.

Impact category	Unit (kg)	Total	%	Caused by
Ozone depletion	CFC-11 eq	4.40E-09	33.2	Diesel in plantation management
			30.4	Diesel in harvesting
Global warming	CO_2 eq	93.14	38.1	Diesel in plantation management
			34.9	Diesel in harvesting
Smog	O_3 eq	37.00	42.1	Diesel in plantation management
			38.6	Diesel in harvesting
Acidification	SO_2 eq	1.24	39.7	Diesel in plantation management
			36.3	Diesel in harvesting
Eutrophication	N eq	0.070	42.0	Diesel in plantation management
			38.5	Diesel in harvesting

in harvesting in Sites 1 and 4, respectively. Site 3 had the highest global warming impact (93.14 kg CO_2 eq), which is attributed to diesel consumed in land preparation and land restoration. Site 2 is the site with the lowest global warming potential (54.74 kg CO_2 eq) due to diesel in harvesting.

On the other hand, Site 4 is the only site which the impact category of acidification was associated with the amount of fertilizer applied during plantation management. The differences in fertilizer doses between sites are related to the differences in soil and water qualities.

Effect of Irrigation, Diesel and Herbicides, Electrical Grid, and Biosolid Replacement

Irrigation level and method depend on environmental factors and the resource allocation decided by management. Sites 1, 3, and 4 were in a wetter climate than Site 2. Irrigation may not have been needed, but Sites 3 and 4 were irrigated to dispose of either wastewater from a treatment plant or landfill leachate. Site 1 was not irrigated which may partially contribute to its lower yield (Table 2). Site 2 was in a dry climate and irrigation was needed. The water was pumped a considerable distance in this case resulting in the high electricity consumption (Table 2). Site 4 with a relatively high irrigation level had an extra process of diluting the landfill leachate and both contributed to high electrical use during plantation management (Table 2). High electricity use can increase impacts such as global warming and acidification.

Similarly, management affects other inputs which, in turn, affect the environmental impacts. During land preparation, significant weed control occurred at Site 1 resulting in 2.6 times more herbicide use than Site 2. This high consumption of chemicals in Site 1 produced the highest eutrophication among sites.

The most diesel for land preparation was used at Site 2 compared with the other sites which had better soil. For example, 5.9 times more diesel was used for land preparation compared with Site 1 (Table 2), which had previously been tilled for agricultural. Site 4 had low diesel consumption for both harvest and restoration due to use of different technology for 12-yr rotations

Table 7. Environmental impact categories in Site 4 with its respective main inputs and process contributors. Values are per dry ton of woody biomass produced.

Impact category	Unit (kg)	Total	%	Caused by
Ozone depletion	CFC-11 eq	2.47E-08	68.0	Herbicide in plantation management
Global warming	CO_2 eq	80.98	47.3	Diesel in harvesting
Smog	O_3 eq	3.69	46.0	Diesel in harvesting
Acidification	SO_2 eq	0.42	26.9	Fertilizer in plantation management
			22.1	Cutting
Eutrophication	N eq	0.011	43.5	Diesel in harvesting

poplar plantation than that of 3-yr rotations poplar plantation. Sites 1 and 2 with short rotations had lower diesel lower consumption than Sites 3 and 4 due to different technology used in these types of plantations.

All LCIA results in this article are based on WECC data, which include electricity that is 32.3% from coal, 31.8% from natural gas, 22.2% from hydropower, 9.4% from nuclear, and the balance from wind, geothermal, biomass, and solar. Compared with the WECC data, a greater proportion, 68%, of the electricity for the PNW is from hydropower resulting in reductions in global warming, smog, acidification, and eutrophication impacts (Fig 3). The effect in Site 1

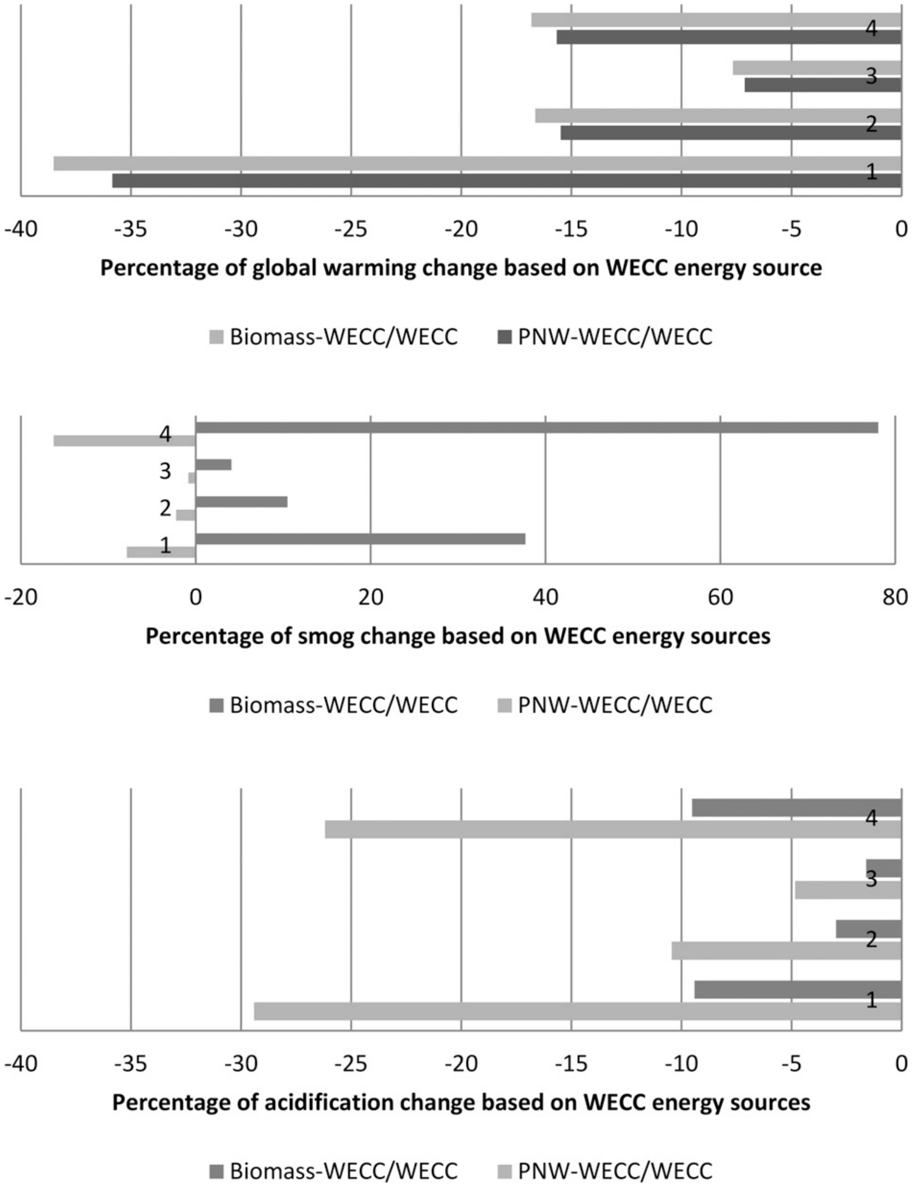

Figure 3. Percentage change in impact categories in each site due to the use of alternative sources of electricity.

was due to off-site consumption when cuttings are produced. When the electricity was all from biomass, global warming, and acidification were reduced; however, ozone depletion, smog, and eutrophication increased. The source of increased smog derived from the particular matter emitted from woody biomass combustion.

The biosolids (natural fertilizer, equivalent to nitrogen application) applied to Site 3 resulted in reductions of 65% for ozone depletion, 24% for global warming, 23% for acidification, and 19% for smog and eutrophication, compared with applying an equivalent amount of nitrogen fertilizer. This is due to the burdens associated with manufacturing fertilizer, compared with biosolids, which are considered to be a waste product and carry no burdens.

Case Study on Production of Cuttings

Site 2, being the largest US producer and supplier of poplar cuttings, was chosen for a case study to quantify the material and energy use and environmental impacts associated with their production. The process inputs to produce cuttings are shown in Table 3. There are some differences in the harvest method and frequency of harvest as well as some on-site transportation and refrigeration that are included in Table 3 compared with four biomass sites in Table 2. Diesel consumption is highest during plantation management (Table 3). There is minimal herbicide used while no fertilizers or pesticides are used. Irrigation during plantation management dominated electrical use.

The results of LCIA to produce one cutting are presented in Table 8. The use of electricity was the main contributor to four of the five impact categories, with contributions ranging from 61 to 91%. A global warming impact of 1.30 kg CO_2 eq was reported for the production of each cutting. This result is within the range of 1.06 or 4.70 kg CO_2 eq for 2- and 5-yr rotations, respectively, as reported by Bacenetti et al (2012). The cuttings produced were 5560 and 1150/ha, respectively, compared with 8390/ha in this study. Thus, an exact comparison is difficult. Their values included planting, pest control, fertilization with nitrogen, and mechanical operations. A network diagram (Fig 4) shows that electricity contributes 14 times more than diesel to global warming impact with bituminous coal and natural gas being the main contributors. Smog (0.10 kg O_3 eq), acidification (0.012 kg SO_2 eq), and eutrophication (0.00021 kg N eq) were mainly due to electricity for irrigation. The use of chemical herbicide was the main contributor to ozone depletion.

The raw energy needed to produce one cutting was 24.6 or 264 MJ per kilogram of green cutting (Table 3), mostly attributed to the coal and natural gas used to produce electricity. Approximately 93% of raw energy was for electricity for irrigation. Diesel combusted in industrial equipment accounted for 6%. This is small because many of the operations during plantation management were done manually, such as cutting branches with loppers, and no fertilizer and fungicides were applied. Energy produced from fossil fuels accounted for 80.5% of energy consumed.

CONCLUSIONS

Selecting processes to grow biomass are key factors that affect the associated environmental

Table 8. Environmental impacts for the production of one cutting. Values are per dry ton of woody biomass produced.

Impact category	Unit (kg)	Total	%	Caused by
Ozone depletion	CFC-11 eq	1.73E-10	89.6	Herbicide in land preparation
Global warming	CO_2 eq	1.30	91.2	Irrigation in plantation management
Smog	O_3 eq	0.10	61.9	Irrigation in plantation management
Acidification	SO_2 eq	0.012	87.8	Irrigation in plantation management
Eutrophication	N eq	0.00021	61.5	Irrigation in plantation management

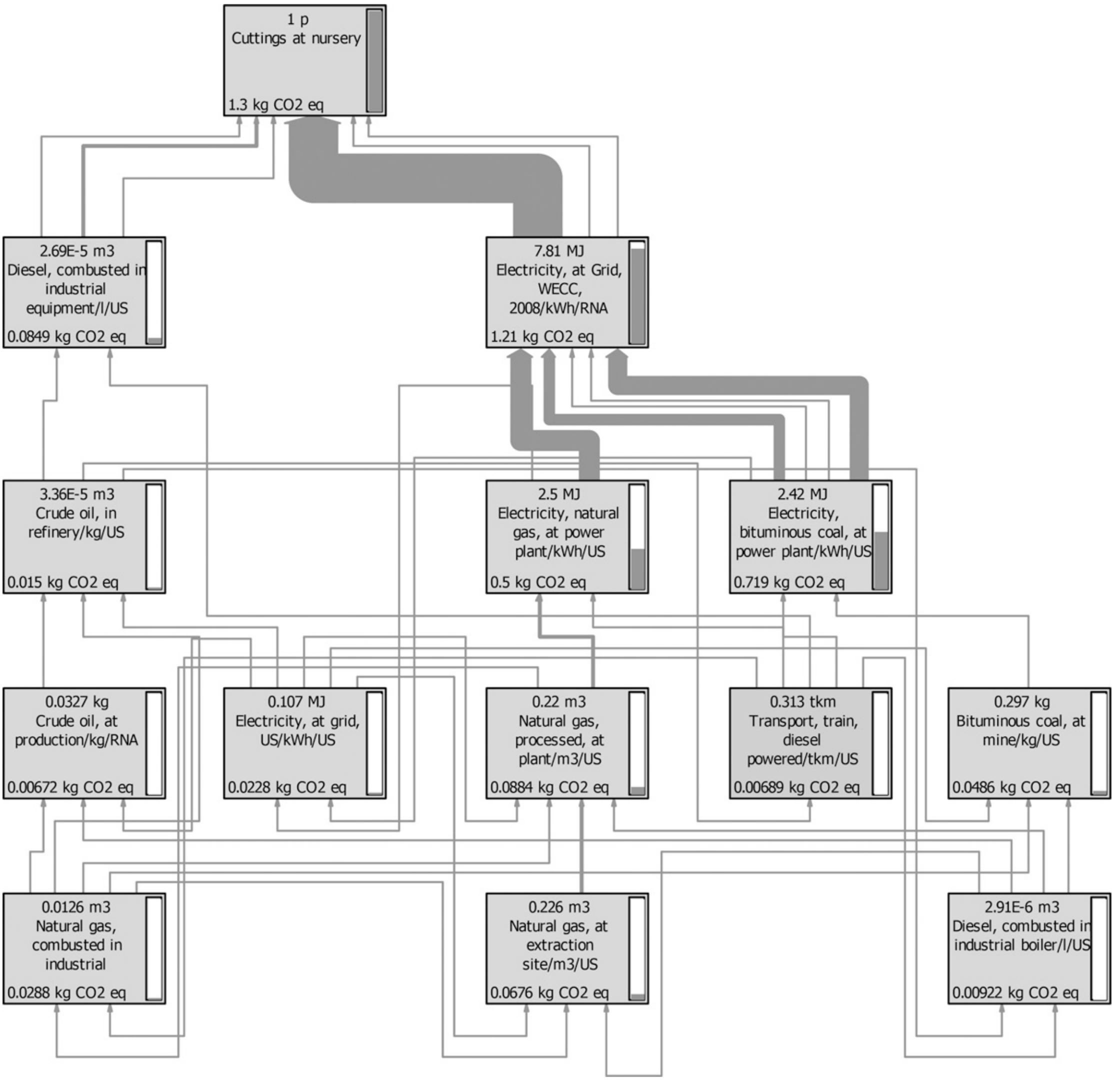

Figure 4. Network of global warming impact for cuttings at nursery. Line width is indicative of the relative contribution.

impacts. In this study, plantation management and harvesting had strong influence on global warming, smog, and acidification due to fuel consumption. The use of chemicals during land preparation and restoration were important contributors to ozone depletion and eutrophication.

There were indications that a shorter rotation period for crops may lead to lower global warming impact and energy consumption. It is important to highlight that Sites 1 and 2 had 2.3 times lower diesel consumption (9.6 and 12.5 L/t, respectively) than Sites 3 and 4 (29.1 and 21.7 L/t, respectively). Sites 1 and 2 were mainly short rotation plantations, which produced less global warming impact. At the same time, Sites 1 and 2 had lower energy consumption (1381.8 and 877.4 MJ/t, respectively) compared with Sites 3 and 4 (1406.9 and 1343.5 MJ/t, respectively). The irrigation on-site did not have much impact on associated environmental impacts. However, the electricity used for irrigation did influence some of the environmental impact categories, namely global warming impact and acidification during the production of cutting.

Substitution of the electricity mix for the western United States (62% from fossil) with an electricity mix representing the PNW (68% from hydropower) reduces environmental impacts. If the substitution is 100% from biomass, the global warming and acidification were decreased, but smog, ozone depletion, and eutrophication were increased. Biosolid application compared with use of nitrogen fertilizer in Site 3, resulted in a significant reduction, 65%, in ozone depletion and a reduction of 20% for the other environmental impacts. These were mostly due to the avoided emissions derived from the fertilizer production (such as nitrogen). Finally, cuttings produced off-site have environmental impacts due to the energy used for irrigation. This had a significant environmental contribution to almost all the impact categories studied.

REFERENCES

Amichev B, Johnston M, Van Rees K (2011) A novel approach to stimulate growth of multi-stem willow in bioenergy production systems with a simple process-based model (3-PG). Biomass Bioenerg 35:473-488.

Amponsah N, Troldborg M, Kington B, Aalders I, Hough R (2014) Greenhouse gas emissions from renewable energy sources: A review of lifecycle considerations. Renew Sustain Energy Rev 39:461-475.

Bacenetti J, Gonzalez-Garcia S, Mena A, Fiala M (2012) Life cycle assessment: An application to poplar for energy cultivated in Italy. J Agr Eng 43:72-78.

Balasus A, Bischoff W-A, Schawrz A, Scholz V, Kern J (2012) Nitrogen fluxes during the initial stage of willows and poplars in short-rotation coppices. J Plant Nutr Soil Sci 175(5):729-738.

Bare J (2011) TRACI 2.0: The tools for the reduction and assessment of chemical and other environmental impacts 2.0. Clean Technol Environ Policy 13:687-696.

Di Matteo G, Nardi P, Verani S, Speradino G (2015) Physiological adaptability of Poplar clones selected for bioenergy purposes under non-irrigated and suboptimal site conditions: A case study in central Italy. Biomass Bioenerg 81:183-189.

Dimitriou I (2005) Performance and sustainability of short-rotation energy crops treated with municipal and industrial residues. Dissertation, Swedish University of Agricultural Sciences. Uppsala, Sweden, 38 pp.

EIA (Energy Information Administration) (2014a) U.S. Renewables consumption. http://www.eia.gov/renewable/ (7 April 2015).

EIA (2014b) Annual energy outlook. Renewable energy consumption by sector and source. U.S. Department of Energy, Washington DC, U.S.A. Table A17. 2 pp.

FAO (2006) Statistics on fertilizer use by crop *in* Fertilizer use by crop. FAO Fertilizer and Plant Nutrition, Rome, Italy. Bulletin Number 17. 124 pp.

FGC (Forest Genetic Council of British Columbia) Glossary of Forest Genetic Terms. http://www.fgcouncil.bc.ca/doc-glos.html (26 November 2015).

Fiala M, Bacenetti J (2012) Economic, energetic and environmental impact in short rotation coppice harvesting operations. Biomass Bioenerg 42:107-113.

González-García S, Bacenetti J, Murphy R, Fiala M (2012) Present and future environmental impact of poplar cultivation in the Po Valley (Italy) under different crop management systems. J Clean Prod 26:56-66.

Haedlee W, Zalesny R Jr, Donner D, Hall R (2013) Using a process-based model (3-PG) to predict and map hybrid poplar biomass productivity in Minnesota and Wisconsin, USA. Bioenerg. Res. 6:196-210.

Hart Q, Prilepova O, Merz J, Badura V, Jenkins B (2014) Modeling poplar growth as a short rotation woody crop for biofuels. 25 pages. https://escholarship.org/uc/item/1cc1p27b (18 August 2014).

Heller M, Keoleian G, Volk T (2003) Life cycle assessment of a willow bioenergy cropping system. Biomass Bioenerg 25:-165.

Hinchee M, Rottmann W, Mullinax L, Zhang C, Chang S, Cunningham M, Pearson L, Nehra N (2009) Short-rotation woody crops for bioenergy and biofuels applications. In Vitro Cell Dev Biol Plant 45(6):619-629.

ISO (2006a) Environmental management—Life cycle assessment—Principles and framework. ISO 14040, 1st ed 2006-06-31. International Organization for Standardization, Geneva, Switzerland. 32 pp.

ISO (2006b) Environmental management—Life cycle assessment—Requirements and guidelines. ISO 14044, 1st ed 2006-07-01. International Organization for Standardization, Geneva, Switzerland. 46 pp.

Keoleian G, Volk T (2005) Renewable energy from willow biomass crops: Life cycle energy, environmental and economic performance. Crit Rev Plant Sci 24:385-406.

Landsberg J, Waring R (1997) A generalized model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. For Ecol Mgmt 95:209-228.

Morales M, Aroca G, Rubilar R, Acuña E, Mola-Yudego B, González-García S (2015) Cradle-to-gate life cycle assessment of *Eucalyptus globulus* short rotation plantations in Chile. J Clean Prod 99:239-249.

NREL (National Renewable Energy Laboratory) (2012) U.S. Life Cycle Inventory Database. http:www.nrel.gov/lci/ (15 March 2013).

Pré Consultants (2013) SimaPro Life Cycle assessment software package, version 8.0.3. 2014. Amersfoort, The Netherlands. http:www.pre.nl (1 January 2014).

Rodriguez-Suarez J, Soto B, Iglesias M, Diaz-Ferroz F (2010) Application of the 3PG forest growth model to a eucalyptus plantation in northwest Spain. Eur J For Res 129:573-583.

Strauss C, Grado S (1992) Input-output-analysis of energy-requirements for short rotation, intensive culture, woody biomass. Sol Energy 48(1):45-51.

Werhahn-Mess W, Palosuo T, Garcia-Gonzalo J, Roser D, Linder M (2011) Sustainability impact assessment of increasing resource use intensity in forest bioenergy production chains. Glob Change Biol 3(2):91-106.

Zalesny R, Bauer E (2007) Selecting and utilizing populus and salix for landfill covers: Implications for leachate irrigation. Int J Phytoremediation 9:497-511.

Zalesny J, Zalesny R Jr, Coyle D, Hall R (2007) Growth and biomass of populus irrigated with landfill leachate. For Ecol Mgmt 248:143-152.