AN ABSTRACT OF THE DISSERTATION OF

Marcia A. Vasquez Sandoval for the degree of Doctor of Philosophy in Wood Science presented on June 30, 2015.

Title: Life Cycle Assessment of Biomass for Generation of energy: Case Studies of Poplar Management in the Pacific Northwest of the U.S.A.

Abstract approved: ________________________________
Michael R. Milota

A Life Cycle Assessment (LCA) of the production of poplar biomass grown under four management conditions in the Pacific Northwest (PNW) of the U.S.A. was conducted. While the extraction of fossil fuels and the subsequent generation of energy have environmental impacts, the alternative of extracting poplar biomass also has impacts due to electricity for irrigation, fuels for machinery, chemical application, and water consumption. Two management conditions were short rotation and no irrigation (Site 1) or irrigation with river water (Site 2). The others were long rotation and irrigation with wastewater from a treatment facility (Site 3) or irrigation with landfill leachate (Site 4).

Questionnaires were used to obtain operating data for the production of cuttings and four processes in each site. These were land preparation, plantation management, harvesting, and land restoration. SimaPro v.8 and the USLCI and Ecoinvent v.3 databases were used to create a Life Cycle Inventory and the TRACI 2.1 v 1.01/US 2008 model was used to determine impact indicators. Biomass yield for future harvests was estimated using the 3-PG model.

Plantation management and harvesting had the greatest contributions to environmental impacts due to fuel consumption. Utilization of chemicals during land preparation and land restoration were also important contributors. Short rotations resulted in lower global warming potential (79.5 and 54.5 kg CO_2 eq· t^{-1}) and energy consumption (1381.8 and 877.4 MJ ·t^{-1}) than long rotations (93.1 and 81 kg CO_2 eq· t^{-1} and 1406.9 and 1343.5 MJ·

t^{-1}). This was mainly due to diesel use during plantation management. Higher planting density resulted in greater water consumption and electricity use due to irrigation when cuttings are produced. Site 2 had the lowest environmental impacts compared to the other sites due to a low planting density, no on-site irrigation, and low chemical and energy consumption. Chemical use, such as applying pesticides and herbicides, strongly affected ozone depletion and eutrophication while fuel consumption, such as diesel use, had strong effects on global warming, smog and acidification. Increasing biomass yield reduces impacts.

The biosolids applied in Site 3 reduced ozone depletion by 65% and other impacts by 19 to 24% compared to applying an equivalent amount of nitrogen fertilizer. The increased proportion of hydroelectricity in the PNW results a reduction in almost all impact categories compared to the typical electricity mix for the Western U.S. When the electricity was all from biomass, ozone depletion, smog and eutrophication increased.

This research provides the opportunity for environmental impacts to be considered when making decisions for plantation management.

LIFE CYCLE ASSESSMENT OF BIOMASS FOR GENERATION OF ENERGY: CASE STUDIES OF POPLAR MANAGEMENT IN THE PACIFIC NORTHWEST OF THE U.S.A.

by
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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Marcia A. Vasquez Sandoval, Author

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Chapter 1. INTRODUCTION

1.1 General context

Concern over national energy security, global increases in CO_2 emissions, and local and regional air and water pollution associated with fossil energy sources has promoted the development of sustainably produced biomass as a feedstock for bioenergy.

Globally the use of hydroelectricity and other grid-connected renewable energy sources are expected to increase from 10.6% in 2009 to 14.5% (a rate of 2.5% per year) until 2040 (EIA, 2014a). Most projections of global energy use predict that biomass will be an important component of this, contributing 10% to 45% of the total primary energy in the coming decades (Keoleian and Volk, 2005).

About 9.5% (2.71 EJ from hydropower and 7.1 EJ from all other sources of renewable fuels) of all energy consumed in the United States in 2013 was from renewable sources. Renewables accounted for about 12.9% of the nation's total energy production. In 2013, the distribution of U.S. renewable consumption by source was 28% hydropower, 23.5% biomass wood, 22% biomass biofuels, 17% wind, 5% biomass waste, 3% solar, and 2% geothermal. The contribution of renewable sources is expected to grow, spurred by State and Federal legislation including the Energy Independence and Security Act of 2007 (EIA, 2014a). In fact, about 12.4% (13.88 EJ) of the projected 112.15 EJ of energy consumption in 2040 is projected from renewable sources (EIA, 2014b). The increase of renewable sources in the State of Oregon is mandated by a Renewable Portfolio Standard (RPS) that requires the largest utilities to provide 25% of their retail sales of electricity from newer, clean, renewable sources of energy by 2025. Smaller utilities have similar, but lesser, obligations (ODOE, 2015)

The majority of biomass research shows that short rotation woody crops (SRWC) may be an important source of biomass (Berndes et al., 2003 cited by Keoleian and Volk, 2005). SRWC systems utilize genetically improved plant material grown on agricultural land with intensive site preparation, fertilization, and 3- to 4-year rotations, with multiple harvests from a single root stock. In 2014, consumption of energy from renewable sources was 10.07 EJ, of which 28% was from biomass (EIA, 2014a). A projection for 2025 shows an increment of 16.4% in total marketed renewable energy in the USA, where biomass will show an increment of 3.6%, based on 2012 data (EIA, 2014b). The cellulosic biomass consumption projected for 2035 is 2.32 EJ (Newell, 2011 based on EIA, 2014c).

1.2 Research question or problem definition

Woody biomass can be obtained from sources such as manufacturing residues, forest thinnings, forest residuals, and dedicated plantations. The latter source requires materials such as herbicides, fertilizer, and pesticides and fuels such as diesel and electricity for planting, managing, and harvesting. Hence, biomass from dedicated plantations with species such as poplar will have associated environmental impacts when it is used as a fuel or feedstock. Reducing the material and energy consumption at the plantation will make the biomass more competitive on both economic and environmental bases.

1.3 Potential alternatives to fossil fuel

Sources other than biomass can displace fossil fuels for producing energy. Renewable sources include hydro, solar, wind, geothermal, wave, and tidal energy (Demirel, 2012). Nuclear is a nonrenewable energy source. Each of these alternatives carries with it some environmental impact. Dams impact waterways, solar systems require large surface areas, wind turbines can have adverse impacts on birds, geothermal power plants can concentrate heavy metals in water, ocean-based energy devices can impact transportation and aquatic life, and nuclear power plants have disposal issues.

Using a waste material, even if not renewable, is desirable because it reduces the need for landfill space and creates a useful product. For example, electrical energy is often produced by combusting municipal solid waste (UCAUSA, 2015): Covanta Marion, Inc. in Marion County, Oregon has been producing electricity from municipal solid waste combustion since 1986 (ODOE, 2015). However, the concept of using a waste material does not have to be limited to directly converting the waste to energy. It is possible to use waste streams to displace some of the materials used at a plantation. This thesis will explore the life cycle impacts of using leachate from a landfill and biosolids from wastewater treatment to reduce the use of ground- or surface water for irrigation and offset fertilizer use. This also provides the potential for phytoremediation: allowing plants to uptake contaminates in the applied waste, reducing the hazard to the environment. As will be discussed in Chapter 2, poplar, willow, and some other species have been shown to be capable of this.

1.4 Summary of work

In this work, the material and energy consumption associated with poplar biomass grown under four management scenarios were determined. The four plantations, all located in OR, USA, included management with no irrigation, irrigation with river water, irrigation with water from a municipal water-treatment plant, and irrigation with leachate from a landfill. The environmental impact for each plantation was determined using life cycle assessment (LCA). The environmental burdens of materials, fuels, and electricity used in the plantations were based on the U.S. Life Cycle Inventory (USLCI) database, and the Ecoinvent v3 database. The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) was used for life-cycle impact assessment

(LCIA). The databases and TRACI were in the Simapro 8.0.3.14 simulation software (Prè Consultants, 2013).

Ozone depletion, global warming, smog, acidification, and eutrophication were compared among the four case studies. In addition to these comparisons, alternative methods of plantation management were also considered. This included electricity from hydroelectric power and biomass as alternatives to electricity from a grid. Finally, a comparison was also made in which the equivalent amount of nitrogen was applied with fertilizer rather than biosolids.

1.5 Research objective

1.5.1 General objective

Analyze the environmental impacts due to material and energy consumption for producing poplar biomass for energy under different plantation management systems in the Pacific Northwest of the United States.

1.5.2. Specific objectives

- Compare the material and energy consumption among the four irrigation scenarios for the production of poplar biomass.

- Use life cycle assessment to quantify the environmental impacts due to material and energy consumption for the production of poplar biomass without irrigation and with irrigation from one of three sources: river water, water discharged from a municipal wastewater treatment facility, and leachate collected from a landfill.

- Determine the changes in environmental impacts caused by changing the inputs to the poplar plantations. Input changes include the methods of electricity used and the replacement of biosolids with chemical fertilizer.

Chapter 2 LITERATURE REVIEW

2.1 Life Cycle Assessment

Life cycle assessment (LCA) is a detailed accounting from "cradle-to-grave" to document and study the environmental impact of products or processes. LCA can be also developed by "cradle-to-gate" (Curran, 2006; Crawford, 2008; PE International, 2010). LCA is an environmental tool that follows ISO 14040 guidelines (ISO, 2006a). The methodology includes four phases that are shown in Figure 2.1.

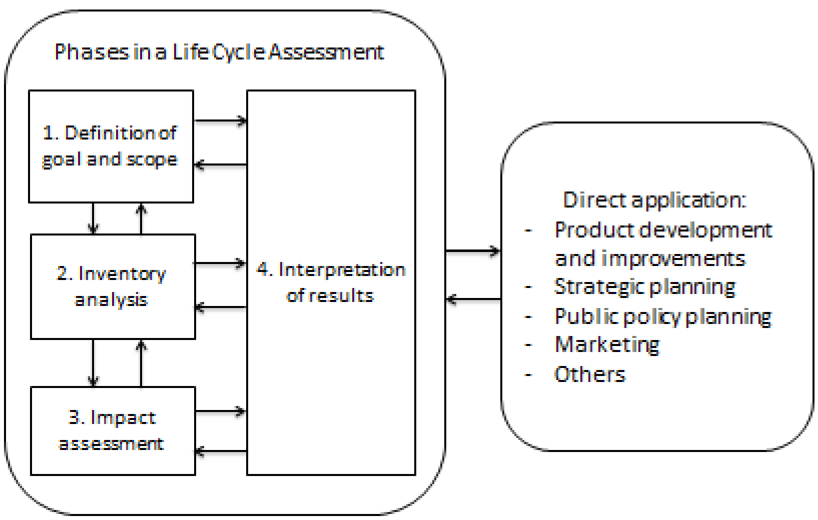

Figure 2.1 Phases in a Life Cycle Assessment (ISO, 2006a)

The LCA begins with defining the goal and scope of the study. The scope includes the system boundary and the level of detail for producing a product or service. These depend on the subject and the intended use of the LCA. Life cycle inventory (LCI) is an inventory of the materials and energy entering and leaving the system boundary. The balances often incorporate burdens associated with the manufacture of inputs, use of the product, and what happens at the end of life. Burdens of various inputs may be allocated among more than one product.

An LCA uses the information from an LCI and weighted impact factors to characterize the environmental impacts of the system. A complete LCA includes impact assessment and sensitivity analysis. The life cycle impact assessment (LCIA) should provide additional information to help assess a product system's LCI results and understand the magnitude and significance of its environmental impacts (Pré Consultants, 2013). Impacts can include categories such as toxicity, global warming potential (GWP), acidification, and carcinogenesis. A complete LCA that gives an accurate picture of the differences in environmental impact between different products or the same product at different times can be developed. The life cycle interpretation is the phase in which the results of an LCI, LCIA, or both are summarized and discussed as a basis for conclusions, recommendations, and decision-making in accordance with the goal and scope definition (Baumann and Tillman, 2004; ISO, 2006a).

According to methodological aspects of LCA there are six important decisions to make at the beginning of the LCA process, in order to use time and resources effectively (Curran, 2006):

1) Define the goal(s) of the project
2) Determine type of information needed to inform the decision-makers
3) Determine the required specificity
4) Determine how the data should be organized and the results displayed
5) Define the scope of the study
6) Determine the ground rules for performing the work

The primary goal of LCA is to identify the product, process, or service with the least effect on human health and the environment. Secondary goals of an LCA are diverse and depend on the specific purpose of the project. These might be to support broad environmental assessments, establish baseline information for a process, rank the relative contribution of individual steps or processes, identify gaps, support public policy, support product certification, provide information and direction to decision-makers, or guide product and process development.

2.1.1 Categories of LCA

The information collected depends on the decision-makers' specific purpose and are also defined by the parameters of the study. Recently, LCA has been classified into two types: attributional and consequential. Attributional LCA is applicable for understanding the environmental impacts directly associated with the life-cycle of a product, using average data for each unit process. Consequential LCA is used for describing the consequences of a decision, taking marginal data for analysis (Poeschl et al., 2012a).

The information ideally is site specific. However, if the product or service is common in the marketplace, data representing the common commercial practices may be more appropriate. The required level of data accuracy for the project depends on the use of the final results and the intended audience.

The organization of data (Decision 4) is based on a functional unit. The functional unit is a common basis of calculation used to compare different systems (Goglio and Owende, 2009). Four types of functional units have been identified for bioenergy systems: input unit related, output unit related, unit of agricultural land, and year (Cherubini and Strømman, 2011).

The scope (Decision 5) depends on the stage of a product or process life cycle. Stages include raw material acquisition, manufacturing, use, reuse, recycling, and disposal. An LCA for all stages is called cradle-to-grave or a full LCA. The goal of the study helps to define the stages that must be included in the LCA. In a process study, the scope will include the following items: product system to be studied, function of the product system, functional unit, system boundary, allocation procedure, impact categories selected and methodology of impact assessment, and its subsequent interpretation, data requirements, assumptions, limitations, and initial data quality requirement, among others (ISO, 2006a).

2.1.2 Allocation procedures

ISO 14040 defines allocation as partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems. The ISO standards propose that allocation should be avoided if possible either through the division of the whole process into sub-processes related to co-products or by expanding the system boundaries to include the additional functions related to the co-products; this is called the “system expansion approach” or the “substitution approach.” If allocation cannot be avoided, the environmental impacts can be partitioned according to a physical relationship, such as mass, energy, or exergy[1] content, or according to other relationships, including the economic value. However, the subdivision approach rarely avoids allocation completely because most multiple-function systems include processes that are common for some or all of its functional outputs (i.e., recovery of energy from waste or cogeneration of electricity and thermal energy), so some type of allocation will still be necessary. Finally, allocation procedures shall be uniformly applied to similar inputs and outputs throughout the system (Curran, 2007; ISO, 2006a; Siegl et al., 2011). Gonzalez-Garcia et al. (2013) described allocation as one of the most critical issues of LCA for the production of energy from biomass. Multi-output processes and more than one co-product require the selection of an allocation approach, which can have important effect on the results. Economic allocation was suggested when the main product and different co-products have large differences in market prices.

[1] Exergy is a measure of how large a part of a quantity of energy can be converted into mechanical work (World Energy Council, 2004).

2.1.3 Impact categories

There are two mandatory steps described in ISO 14044 for selecting impact categories. Step 1 is the classification of impact categories based on their impact pathway, impact indicator, and the elementary flows from the inventory, according to the substance contribution. Step 2 is the characterization of impact categories by quantitative models that report each impact in a common unit for all contributions within the impact category (e.g., kg CO_2-equivalents for greenhouse gases contributing to the climate change impact category; ISO, 2006a; ISO, 2006b).

Decision 6, determining the ground rules, means to decide how assumptions will be documented, what the procedures will be for quality assurance, and what the requirements are for reporting.

2.1.4 Environmental Impact Assessment methodologies

LCIA methodologies (e.g., CML 2002, Eco-indicator 99, EDIP97 and EDIP2003, EPS 2000, IMPACT 2002+, LIME, LUCAS, ReCiPe, Ecopoints 2006, TRACI, and MEEup) have been used to estimate midpoint and endpoint environmental impacts (ILCD, 2010). TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) is a midpoint method developed by the U.S. Environmental Protection Agency (EPA) in 1995 that represents environmental conditions in the U.S. (Bare et al., 2003). Ten impact categories are measured by TRACI; a description of each of them is presented below.

- Ozone depletion measures the potential to destroy ozone based on a chemical's reactivity and lifetime. It is measured in [kg CFC-11 eq] where CCl_3F or trichlorofluoromethane is the reference substance used to assess the importance of the effect produced by various gases. The global impact of zone depletion is increased ultraviolet radiation at the earth's surface.

- Global warming measures potential global warming based on chemical radiative forcing and lifetime. It is measured in [kg CO_2 eq] where CO_2 or carbon dioxide is the reference substance. The global impact of global warming is well documented.

- Acidification measures the potential to cause wet or dry acid deposition. It is measured in [kg SO_2 eq]. Acidification produces building corrosion and water body acidification, and it affects vegetation and soils. It is a regional impact.

- Eutrophication measures the potential for nutrients such as phosphorous and nitrogen to enter bodies of water. The impact is local and results in excessive plant growth and oxygen depletion. It is measured in [kg N eq].

- Smog formation measures potential to cause photochemical oxidation. It is measured in [kg O_3 eq]. Smog produces decreased visibility and results in eye irritation, respiratory tract and lung irritation, and vegetation damage. It is a regional impact.

- Cancer measures the potential of a chemical released into an evaluative environment to cause human cancer effects. It is measured in [CTUh] or comparative toxicity units for humans.

- The noncancer impact category is a measure of the potential for a chemical released into an evaluative environment to cause human (toxicological) noncancer effects. It is measured in [CTUh].

- The respiratory effects impact category is largely a measure of health effects due to particulate matter (PM). Particulate matter in the size range of 2.5 microns is able to travel deeply into the respiratory tract, reaching the lungs. Exposure to fine particles can cause short-term health effects such as eye, nose, throat, and lung irritation, coughing, sneezing, a runny nose, and shortness of breath. Long-term exposure to fine particulate matter may be associated with increased rates of chronic bronchitis, reduced lung function, and increased mortality from lung cancer and heart disease. It is measured in [kg $PM_{2.5}$ eq].

- Ecotoxicity measures the potential of a chemical released into an evaluative environment to cause ecological harm. It is measured in [CTUe] or comparative toxicity unit for environment.

- Fossil fuel use measures potential to lead to the reduction of the availability of low cost/energy fossil fuel supplies. It refers to a group of resources that contain hydrocarbons. The group includes gases such as methane, liquids such as petroleum, and solids such as coal. Fossil fuel depletion is measured in [MJ surplus].

2.1.5 Sensitivity analysis

A sensitivity analysis or perturbation analysis is used to identify the parameters that have the largest effects on the results of the study. It is a systematic procedure in which inputs and assumptions are changed independently to assess impact on the results (Richard, 2011). Huijbregts et al. (2001) suggest using a single standard sensitivity range (e.g., ±10%) for all parameters. It can be applied to the data, allocation methods, or calculation of category indicator results.

2.2 Biomass

Plant biomass is a product of photosynthesis. The components of biomass include cellulose, hemicelluloses, lignin, simple sugars, starches, water, and ash, among other compounds. The concentration of each class of compounds varies depending on species, type of plant tissue, stage of growth, and growing conditions. Due to the carbohydrate structure, biomass is highly oxygenated, compared to fossil fuels such as hydrocarbon liquids and coals. Typically, 30% to 40% of the dry weight of biomass is oxygen. The main constituent of biomass is carbon, making up from 30% to 60% of dry mass. Among organic components, hydrogen is the third major constituent, comprising typically 5% to 6% of the dry matter. Nitrogen, sulfur, and chlorine can also be found in small quantities, usually around 1%. Nitrogen is a macronutrient for plants and is critical to their growth. Inorganic compounds can be found as well. Potassium and silica constitute over 1% in wood and 10% to 15% of grains such as rice straw (Jenkins et al., 1998).
Biomass is derived from agriculture residues, short rotation crops (SRC) such as grasses, short rotation woody crops (SRWC), forest residues, forest thinnings, and byproducts from living organisms (Haefke, 2008).

2.2.1 Characteristics of biomass used for energy

Biomass is heterogeneous and usually has high moisture when it is collected. Higher moisture content (MC) increases the energy and cost to transport (McKendry, 2002). High MC reduces the energy value of biomass (Figure 2.2) by reducing the combustion temperature. Wet fuel also increases air emissions, due to incomplete combustion.

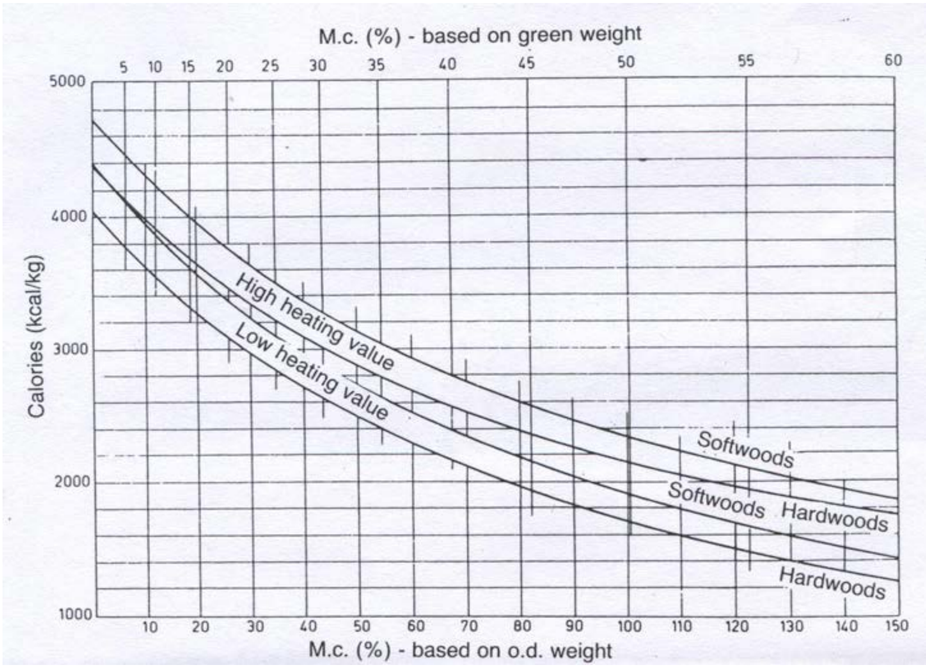

Figure 2.2 Relationship of heating value and moisture (Tsoumis, 1991). One kcal·kg^{-1} is equivalent to 4.187 kJ·kg^{-1}.

Klašnja et al. (2002), working with *P. deltoides* and *P. euroamericana*, determined the heating value to be between 16 and 24 MJ·kg^{-1}, where 2-year-old trees had a higher value than 1- or 12-year-old trees. Blankenhorn et al. (1985) measured small but significant differences in the higher heating value (HHV) (17.7 to 20.04 MJ·kg^{-1}) of seven hybrid poplar clones. However, Strong (1992) measured 19.4 to 19.9 MJ·kg^{-1} and detected no significant differences for nine *Populus* clones. Similar results were reported by Geyer et al. (2000) and Movessessian (2003). The later study further indicated that hybrid poplar clones grown on different sites had different energy contents. Maranan (2006) studied 78 hybrid poplars at different ages (4, 5, 10, and 15 years old), parentages (16), and growing sites (6) to show that age and growing sites had no significant effect on heating value; however, in some cases, parentage had a significant effect. A heating value of 18.5 MJ·kg^{-1} for poplar from short rotation woody crops was reported by AIEL (2008), which is between the values reported above.

Properties that affect the heating value of wood are physical composition (density, moisture content), chemical composition (lignin and extractives), anatomical composition (ratio of juvenile to mature wood), and species (softwood and hardwood) (Francescato et al., 2008; Jenkins et al., 1998; Klašnja et al., 2002; Maranan, 2006; Tsoumis, 1991; White, 1987).

There are two heating values, lower heating value (LHV) and higher heating value (HHV), also called gross heat of combustion (White, 1987). The HHV can be expressed as shown in the following equation:

$$HHV = 0.196\ FC + 14.119\ [MJ \cdot kg^{-1}]$$

where FC is fixed carbon, expressed in weight percent. The correlation coefficient heating value was 0.997, which was calculated using the equation above, and showed a mean difference of 2.2% (Demirbas, 1996)

Other correlations of HHV can be based on proximate analysis and ultimate analysis. Sheng and Azevedo (2005) reported a correlation for HHV based on proximate analysis

$$HHV = 19.914 - 0.2324\ Ash\ [MJ \cdot kg^{-1}] \text{ with a } R^2=0.625$$

$$HHV = -3.0368 + 0.2218\ VM + 0.2601\ FC\ [MJ \cdot kg^{-1}] \text{ with a } R^2=0.617$$

where Ash is the ash, VM is volatile matter, and FC is fixed carbon, all measured as a weight percent of the dry biomass.

The same authors reported a correlation HHV based on ultimate analysis is

$$HHV = 0.3259\ C + 3.4597\ [MJ \cdot kg^{-1}] \text{ with a } R^2 = 0.758$$

$$HHV = -1.365 + 0.3137\ C + 0.7009\ H + 0.03180\ O\ [MJ \cdot kg^{-1}] \text{ with a } R^2 = 0.834$$

where C is carbon, H is hydrogen, and O is oxygen expressed as a weight percent of the dry biomass.

2.2.2 Biomass production

SRWC is an intensive cultivation system with fast-growing species at high planting density and with an average rotation of less than 10 years (Rockwood et al., 2004). Poplar is one of the three species adopted for SRWC cultivation based on its great adaptability over a wide range of habitats.

2.2.2.1 Plantation establishment

Soil type, soil pH, water availability and drainage, microclimate, region of the state, pests and diseases, and availability of suitable poplar clonal material should be taken into account when deciding to establish a plantation. Some poplars perform better in periodically flooded soils and can be used as riparian site species. Planting a mosaic of poplar clones maintains diversity that can decrease plantation susceptibility to biological (pests and diseases) or physical (wind) effects (Isebrands, 2007). Getting the highest productivity with the lowest cost for management should be a goal.

Planting density is a key decision to ensure high production and high survival over time. A single-row arrangement has a row spacing of 3 m between rows and 0.5-0.6 m within the rows, for a planting density of 6600 ha^{-1}. Double row plantings typically have 3 m between twin-rows, 0.5 m between row-pairs, and 0.5 m along rows, for an average planting density of 9500 ha^{-1}. Triple-row plantings require 3 m between triple rows, 0.4 between the triple rows, and 0.5 m along rows, for an average planting density of 17100 ha^{-1} (Armstrong et al., 1999; Di Mateo et al., 2012; Klašnja et al., 2008; Spinelli et al., 2008; Tubby and Armstrong, 2002; Verani et al., 2008).

Rotation age is the age at harvest, commonly two years for willow. However, poplar reaches a maximum yield later than willow, at an age between three to four years, which may well represent the optimum rotation age (Kauter et al., 2003; Deckmyn et al., 2004 cited by Spinelli et al., 2011).

2.2.2.2 Agricultural processes

SRWC are more suited to agricultural cultivation than forest plantations. The steps include land preparation, plantation management, harvesting, and land restoration. Land preparation is important to create a suitable rooting environment (growth); levelling the land will facilitate future treatments that will have an impact in productivity (Keddy, 2012).

Plantation management occurs after planting. Weeds are managed with the application of herbicides until canopy closure at the end of the second or third year. Pesticides are applied to protect plants from insects and diseases (DOE, 2011). Fertilization and irrigation of poplar are required to maintain maximum productivity. The goal of fertilization is to maximize nutrient uptake by the poplar, while minimizing runoff (especially nitrogen and phosphorous) into streams or groundwater (Isebrands, 2007). Common N fertilizer doses are in the range of 56 to 150 $kg \cdot ha^{-1}$ (Gonzalez-Garcia et al., 2012; Isebrands, 2007; Heller et al., 2003; Pertu, 1993 cited by Dimitroui, 2005; Keoleian and Volk, 2005; Pontailler et al., 1999), with an average of 100 $kg \cdot ha^{-1}$. Adler et al. (2007) and Williams (2011) reported 5.48 kg of fertilizer applied per dry ton over a 10-year rotation and 0.056 kg $NPK \cdot tree^{-1}$ yr^{-1}.

Poplar has a high water requirement (Monclus et al., 2006; Gasol et al., 2009a) and performs best where soils are moist throughout the growing season and where the soil has a high moisture-holding capacity coupled with adequate drainage. Irrigation is beneficial where groundwater is below 10 feet. The quantity of water applied through irrigation depends upon soil texture, soil drainage, clone, tree age, and planting design. Dickmann et al. (2001) cited by Isebrands (2007) reported 11 to 15 L of water$\cdot$ $hr^{-1} \cdot tree^{-1}$ in mid-day, with overall estimated water use of 19 to 57 $L \cdot day^{-1} \cdot tree^{-1}$, depending upon tree size and environmental conditions. For example, an irrigation rate of 1,750 $m^3 \cdot ha^{-1}$ yr^{-1} of poplar was applied at Sonia, Spain (Gasol et al., 2009b), and only 400 m^3 ha^{-1} yr^{-1} in the Po Valley, Italy (Gonzalez-Garcia et al., 2012).

Dimitroui and Robinson et al. (2000), Nixon et al. (2001), and Hall et al. (1998), all cited by Aylott et al. (2008), reported that poplar and willow have a high tolerance to high toxicity and waterlogging, and that differences in water use between the species are negligible. Some flooding can be tolerated by poplar during the dormant season (Isebrands, 2007). A water deficit can be detrimental to biomass production (Felix et al., 2008). Water use efficiency (WUE) is defined as the amount of dry aboveground biomass produced per unit of evapotranspired (ET) water (Berndes, 2002). WUE varied significantly among 17 poplar clones, from 0.44 to 0.93 p/t x 10^{-1}, where p is dry matter production and t is unit transpiration (Blake et al., 1984). Evapotranspiration is a measure of total water loss from the coppice system, including evaporative losses from soil and plant surfaces and losses internally from the plant. Evapotranspiration in a short rotation (SR) willow plantation equates to approximately 5,000 $m^3 \cdot ha^{-1}$ during a growing season (Caslin et al., 2011). Average evapotranspiration of poplar is 588.3 $mm \cdot yr^{-1}$; or irrigated poplar uses 750 $mm \cdot yr^{-1}$ for optimal growth (Deckmyn et al., 2004). Daily water use for hybrid poplar can be as high as 14 mm per day. Average growing season water use for 3-year-old and older hybrid poplar is 11,362 $m^3 \cdot ha^{-1}$(Shock et al., 2013)

The harvest method must be chosen based on cost and safety. The best method depends on tree size, age, and planting density (DOE, 2011). A cut-and-chip system is common for very short rotation (VSR) and SR biomass (Spinelli et al., 2009; Spinelli et al., 2011). A modified forage harvester with a special SR head cuts, chips, and loads the biomass into trailers. This system has very high productivity, ranging from 10 to over 40 green tons per hour ($gt \cdot hr^{-1}$) with an average of 25 to 30 $gt \cdot hr^{-1}$. For longer rotations, a feller buncher is used to cut and delimb the trees. Debarking and chipping may also be done, or logs might be moved by a tracked harvester or grapple or cable skidder. These approaches vary greatly in cost and energy use (Isebrands, 2007).

Land restoration is done after a harvest or multiple harvests to prepare for another crop or to reestablish the plantation with new cuttings. Herbicide is used to kill stumps. The stumps may be removed with a bulldozer or they may be left if not problematic (Isebrands, 2007).

2.2.2.3 Alternative nutrients for woody biomass production

Municipalities and industries treat wastewater before discharging. Table 2.1 shows the allowable levels of contaminates wastewater (US EPA, 1972). Irrigation of nonfood crops, such as biomass, with urban wastewater reduces fertilizer use and reduces acidification and eutrophication due to runoff. It also can help abate the fossil energy and emissions associated with manufacturing fertilizers (Gonzalez-Garcia et al., 2012; Brentrup et al., 2000, cited by Gonzalez-Garcia et al., 2012; Di Candilo et al., 2010; Keoleian and Volk, 2005).

Table 2.1 Wastewater treatment requirement after secondary treatment

Characteristic of discharge	Units	Average monthly value	Average weekly value
BOD5	mg/l	30	45
Suspended solids	mg/l	30	45
Hydrogen ion concentration	pH	6.0-9.0	
CBOD5	mg/l	25	40

(Source: U.S. Environmental Protection Agency, Public Law 92-500, 40 CFR[2])

Poplar trees are very effective at taking up water for environmental remediation (Isebrands, 2007). However, Dimitriou and Aronsson (2005) showed that sewage sludge is not a balanced fertilizer and contains mainly organically bound nitrogen and high amounts of phosphorous, but very little potassium. Nevertheless, sewage sludge was suggested as an alternative for inorganic nitrogen fertilizers by Heller et al. (2003) and Pertu (1993), cited by Dimitroui (2005). Other environmental effects regarding nitrification and denitrification in fields were reported by Henry et al. (1999) and Wang et al. (2012).

[2] CFR: Code of Federal Regulation. Title 40. Protection of Environmental. Part 133. Secondary Treatment Regulation.

Biosolids are also a product from treating municipal wastewater. This product contains nutrients that promote plant growth (Table 2.2), making it attractive as a fertilizer for nonfood crops.

Table 2.2 Characteristics of representative sewage sludge biosolids from two New York municipalities (Heller et al., 2003)

	Syracuse, NY	Little Valley, NY
Calculated application rate* (tonnes ha^{-1})	6.9	5.6
Nutrients (g kg^{-1})		
NH_4-N	5.6	2
NO_3-N	0	0.05
Organic N	38.7	56.0
K	0.9	3.3
P	23.1	21
Trace metals (mg kg^{-1})		
Mercury	-	4
Arsenic	-	2
Cadmium	16	3.4
Chromium	63.8	22
Molybdenum	18.6	2.1
Lead	74.9	64
Nickel	20.9	22
Zinc	434	800
Copper	647	540
Magnesium	5.5	-
Calcium	33.4	-

* Calculated to provide 100 kg plant-available- N ha^{-1}

Plants with extensive perennial roots can effectively filter mineral nutrients and possibly control the flow of heavy metals in the system (Aronsson and Perttu, 2001, cited by Koeleian and Volk, 2005). Introducing organic matter to the soil can also increase soil carbon sequestration, which, along with a nitrogen source, can increase NO^{-}_{3} production (nitrification), resulting in higher ammonia volatilization (Beauchamp, 1997, cited by Koeleian and Volk, 2005).

Correlation between tree phytoremediation (soil contaminant levels) capability and tree productivity (tree yield by volume and biomass) was investigated by Zalesny and Bauer (2007c). *Populus* and *Salix* genotypes were irrigated for the last 12 weeks of the 18 weeks of study with landfill leachate (pH = 6.3) or municipal water (pH = 8.4 outside of optimal range of 5.0 to 7.5) and tested for differences in concentrations of elements (P, K, Ca, Mg, S, Zn, B, Mn, Fe, Cu, Al, and Na) and volume and dry mass of leaves, stems, and roots. The study showed negligible difference between irrigation treatments. However, the treatment × clone interaction exhibited a broad variability among and within genera (genera and clones within genera responded differently to leachate and water treatment), that shows a great potential for the identification and selection of specific genotypes with a combination of elevated phytoremediation capability and tree yield.

A sanitary landfill permanently stores solid waste in a manner that limits impact on the environment. A liquid effluent, leachate, from landfills is collected and recovered in a wastewater treatment plant. An alternative is to utilize it for irrigation of plantation crops that can survive in contaminated soil (Zaman, 2010). Previously aerated leachate has been used to irrigate SR willow coppice in Italy, Sweden, Belgium, United Kingdom, and USA (Dimitroui, 2005; Keoleian and Volk, 2005; Lauryenses et al., 2004; Licht and Isebrand, 2005). Poplar and willow have high evapotranspiration, which can reduce or eliminate conventional leachate processing.

Complex physical, chemical, and biological reactions occur within a landfill. Landfill leachate results from the percolation of water through, and the generation of water from, decomposing putrefiable and organic fractions in the landfill. The quality of the leachate produced is highly variable and depends on the composition of the solid waste, depth of waste, site hydrology, compaction, waste age, interaction of leachate with the environment, landfill design and operation, available oxygen, and temperature. Although landfill leachate contains a complex mixture of chemicals (Table 2.3), there are some general underlying pollutants common to all landfill effluents. These include high levels of BOD (biochemical oxygen demand), COD (chemical oxygen demand), NH_4^+, Na, and Cl (Nixon, 2002; Jones et al., 2006). The leachate quality is site specific and frequently varies even within a single landfill site. Variability of leachate components is also high; examples of such components that affect growth of vegetation are methane, chloride, and sodium (Ettala, 1988; Ettala and Lagerkvist, 1999; Dimitriou, 2005; Jones et al., 2006; Nagendran et al., 2006).

Table 2.3 Typical chemical compositions of landfill leachates

Parameter	Typical leachate range (Alker, 1999 cited by Dimitriou, 2005)	Leachate range (Jones et al., 2006)
pH	5.3- 8.5	6.5-7.5
COD (mg/l)	150-10,000	250-1,400
BOD_5 (mg/l)	100 – 90,000	20-128
TOC (mg/l)	10- 25,000	
NH_4-N (mg/l)	1-1,500	80 – 877 as NH_4^+
Total N (mg/l)	1-2,000	
Total P (mg/l)	0.1-30	0.7-1.6
Cl (mg/l)	30-4,000	65-2,080
Na (mg/l)	50-4,000	50-2,421

COD = chemical oxygen demand.
BOD_5 = biological oxygen demand after 5 days.

2.2.3 Phytoremediation as an alternative to conventional biomass production

Phytoextraction is the accumulation of contaminants from soil into harvestable plant tissue and their subsequent removal. It is a way to clean mildly contaminated soils that do not require quick remediation. Phytoremediation is a complex process that involves physical and chemical reactions among the soil contaminants and microorganisms (US

EPA, 2011). The difference between phytoextraction and phytoremediation is the retention and reduction of contaminants, respectively.

Some of the advantages and disadvantages of phytoremediation are described in Table 2.4. Phytoremediation can be practiced on land irrigated with contaminated water, such as biosolids from wastewater treatment or landfill leachate. Phytoremediation using vegetation filters (in-situ treatment) is a more advanced treatment to reduce soil toxicity in moderately contaminated sites caused by wastewater from landfills or heavy metals coming from industrial waste (French et al., 2006, Witters et al., 2009).

Table 2.4 Advantages and disadvantages of phytoremediation (Green and Hoffnagle, 2004)

Advantages	Disadvantages
Cost reduced over traditional methods	Long remediation time
Low secondary waste volume	Effective depth limited by plant roots
Improved aesthetics	Phytotoxicity limitations
Habitat creation, biodiversity	Fate of contaminants often unclear
Green technology	Climate dependent/ variable
More publicly accepted	Seasonal effectiveness
Provide erosion control	Potential transfer of contaminants (i.e., to animals or air)
Prevent runoff	Harvesting and disposal of metals in biomass as hazardous waste may be required, although generally not.
Reduce dust emission	Larger treatment footprint
Reduce risk of exposure to soil	
Less destructive impact (applied in-situ)	

Crop disposal is an important consideration following phytoremediation. Techniques include composting, compaction, incineration, ashing, pyrolysis, direct disposal, and liquid extraction. Among these, incineration (smelting) has been considered the most economical and environmentally sound (Green and Hoffnagle, 2004).

2.2.3.1 Phytoremediation sites in the U.S. Pacific Northwest

Municipal wastewater and landfill leachate are used to irrigate poplar plantations in the Pacific Northwest (PNW). In Oregon, companies are using from 15 to over 100 ha of poplar as a vegetative filter. For example, the Riverbend Landfill near McMinnville is irrigating 20 ha with landfill leachate, and the Municipal Waste Treatment Plant and Biosolids Management Facility near Eugene is irrigating 145 ha with water containing biosolids.

2.2.3.1 Species used in phytoremediation

2.2.3.1.1 Populus

Poplar cultures have been used in riparian buffers and as vegetative filters for phytoremediation. *Populus trichocarpa* x *P. deltoides, P. deltoides* x *P. deltoides, P. deltoides* x *P. maximowiczii, P. nigra* x *P. maximowiczii, P. deltoides* x *P. nigra,* and *P. deltoides,* with their genomic groups, have been tested for various phytoremediation needs (Zalesny and Bauer 2007c). A list of genomic groups of hybrid poplars with their clones has been developed for phytoremediation by the same authors.

Hybrid poplar have been used to uptake perchloroethylene (PCE), trichloroethylene (TCE), nitrogen, tritium, chlorinated solvents, petroleum hydrocarbons, heavy metals, and nitrates as contaminants (Rockwood et al., 2004). Poplar accumulates relatively high levels of Al, Cd, and Zn in leaves and bark and has potential for phytoextraction of Al, Cd, and Zn on slightly contaminated soils (Laureysens et al., 2004a; Laureysens et al., 2004b). Pitman (2006) found that Ca is the main element present in wood ash from poplar (Table 2.5) used in phytoremediation.

Table 2.5 Element concentrations in wood ash from specified tree types in mg/kg (Pitman, 2006)

Species	Al	Ca	Fe	K	Mg	Mn	Na	P	S	Si
Populus tremuloides	1.4	212	2.6	112.5	35.5	1.4	0.6	11.8	7.0	1.1
Populus sp.	3.5	257	3.2	79.3	90.9	4.5	23.0	9.5	10.2	ND

2.2.3.1.2 Salix

Salix species propagate well, achieve high annual biomass production, and generally possess a high tolerance for metal pollution, all of which have resulted in their use for phytoremediation. Stabilization of soils and removal of contaminants from soils are main uses for *Salix* spp. *Salix pupurea, S. eriocephala, S. ericephala 28* x *S. eriocephala 24, S. interior* x *S. eriocephala, S. discolor, S.* x *dasyclados,* and *S. sachalinensis, and S. miyabeana,* with their genomic groups, have been tested for various phytoremediation needs (Zalesny and Bauer 2007c). Several studies have also demonstrated that many species or clones of *Salix* have the capacity to accumulate elevated levels of Cd and Zn in biomass above ground (Vysloužilová et al., 2003). In Sweden, *Salix* plantations have been shown to reduce the content of heavy metals in arable land, as the uptake of heavy metals in *Salix* shoots is normally much higher than in other crops. The uptake of Cd in *Salix* shoots is 35 to 70 times higher than in grass and straw (Abyhammar et al., 1993 cited by Börjesson, 1999). This suggests that *Salix* may be sufficiently tolerant to decrease the plant-available heavy metal load in contaminated soils, while still maintaining high yields in a phytoremediation system. The obtained biomass might be used for biofuel production (Meers et al., 2007).

2.2.3.1.3 Other species

Eucalyptus (E.grandis and *E. amplifolia), Juniperus, Betula, Alnus,* and *Acer* have also been reported to reduce contamination in soils polluted with heavy metals (Pulford and Watson, 2003; Rockwood et al., 2006; Gomes, 2012).

2.2.4 Biomass yield

Biomass yield is the mass produced per area per time (ton·ha^{-1}·yr^{-1}) and is the main economic criterion when investing in a plantation. Yield is affected by many factors, such as genetic background, geography, planting density, irrigation, fertilization, pest management, rotation time, weed control, diseases, and animal browse. The wood properties required in the final product are important and are also affected by plantation management. For example, a long rotation time is required to produce lumber, while a shorter rotation time is required for energy, fiber, environmental benefits (carbon storage, prevention of soil erosion), and social benefits (inmediate cash flow for farmers, jobs for rural workforce).

The growth profile of hybrid poplars with a rotation of 10 years at different planting densities was reported by Fang et al. (2007; Figure 3.3). This shows a sigmoid relation between biomass production and stand age, with yield at a maximum during years 3 and 4. Higher planting density resulted in greater yield prior to year 7.

Extensive research has been conducted to determine the yield of biomass from SRWC (Tables 2.6 and 2.7). The effect of clones is often confounded with other factors. Consistent with Fang et al. (2007), the highest biomass yield is not obtained in the first two years. If all conditions are equal (genetic material, planting density, and site), then biomass yield increases in the second rotation (Armstrong et al., 1999). Similar positive annual increments in yield are expected in the following rotations, with a peak that depends on genetic material, planting density, and site, among other factors. Moore (1997) and Watters (1997, cited by Mitchell et al., 1999) show that the assumption that yield increases after the first rotation is not borne out in over half of more than 100 data sets. Lower yields in a second rotation might be ascribed to physiological stress due to harvest, soil damage by harvesting machinery, timing of the harvest, poor establishment technique, poor clonal selection, susceptibility to disease, or frost intolerance. Finally, projections of yield from small experimental plots may be overly optimistic because of more intensive management than in commercial plantations and because pest damage was not adequately accounted for (Hansen, 1991, cited by Dickmann, 2006).

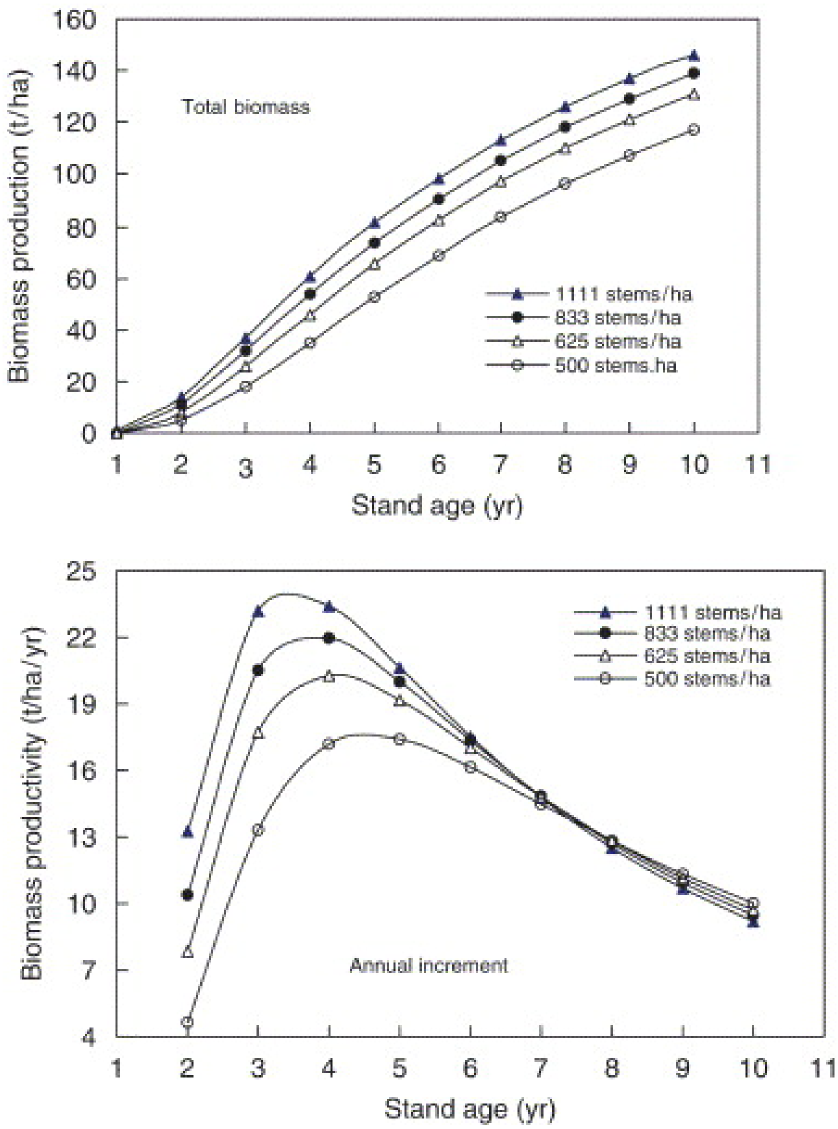

Figure 2.3 Dynamics of total biomass production and its annual increment at different planting densities (Fang et al., 2007)

Table 2.6 Yield of poplar cultivated at less than 5,000 cuttings per hectare

Source	Genetic material	Planting density (Cutting/ha)	Year of harvest	Yield (BDmT ha^{-1} yr^{-1}
Armstrong et al. (1999) UK	Beaupré Boelare Trichobel [a]	2500 (2m × 2m)	2/4	
Long Ashton (site 1) (wettest)				6.6 and 7.5 5.0 and 6.7 4.0 and 6.1
Mepal (site 2)				1.6 and 4.4; and 2.1 and 3.6
Alice Holt (site 3)				1.0 and 4.1 1.1and 3.9 1.2 and 4.1
DOE (2011), USA	-	726	8	8.65-14.68
Fang et al. (2007), Hanyuan Forestry Farm, Baoying County, Jiangsu Province, (33°08'N, 119°19'E) China	I-60 I-72 NL-8051 [b]	500 (4m × 5m) 625 (4m × 4m) 833 (3m × 4m) 1111 (3m × 3m	4/6/10	17.4/13.7/11.7 20.3/16.4/13.1 22/18/13.9 23.4/19.6/14.6
Miller and Bender (2012), USA	NM2 DN5 DN34 NM6 D105 NE222 [c]	2700 2700 2700 2200 2200 1900	5	7 5 2.84 7.52 3 3.6
Stanton, 2007 USA	-	-	6/10	13.5/10.1
James et al., 2010 USA	-	2720	10	8.4

[a] Three poplar clones: *Populus trichocarpa* x *P. deltoides* "Beaupré", *Populus trichocarpa* x *P.deltoides* "Boelare", and *Populus trichocarpa* "Trichobel".

[b] Three poplar clones: *Populus deltoides* Bartr.cv. "Lux" (I-69), *P.* x *euroamericana* (Dode) Guinier cv. "San Martino" (I-72), and *P.deltoides* Bartr.cv. "Lux" (I-69) x *P.deltoides* Bartr. Cv. "Havard" (I-63).

[c] Six hybrid poplar taxa or clones: one taxon of *Populus deltoides* (D105), three taxa of *P.* x *P.canadensis* (DN5, DN34, and NE222), and two taxa of *P.nigra* x *P. maximowiczii* (NM2 and NM6).

A high planting density is 5,000 to 20,000 cuttings or trees per hectare (Dickmann, 2006) and has been recommended for 1- to 5-year rotations for bioenergy feedstock production.

Table 2.7 Yield of poplar cultivated at more than 5,000 cuttings per hectare

Source	Planting density # ha^{-1} (planting design)	Year of harvest	Yield odt · ha^{-1} yr^{-1}	Genetic material
Armstrong et al. (1999) UK	10,000 (1m x 1m)	2/4		Beaupré Boelare Trichobel
Long Ashton (site 1)			9.6 and 8.5 8.2 and 7.9 7.4 and 6.1	
Mepal (site 2)			2.8 and 7.6; and 5.4 and 4.4	
Alice Holt (site 3)			1.7 and 7.2 2.4 and 7.3 3.9 and 8.1	
Pontailler et al. (1999), Orsay-France	15,625	2	19	Beaupre poplar species
Laureysens et al. (2005), Belgium in waste disposal site	10,000	2	9.7	*P.nigra* clone Wolterson
Klansja et al. (2008), Serbia	16,667	2	11.09 3.54	*P. deltoides* cl. B-229 *P. deltoides* cl. 181/81
Spinelli (2007), Lombardy region, Italy	6,000 to 7,000	2 (from 2nd rotation)	4.96 and 10.72	Pegaso (Alasia clone)
Manzone et al. (2009), western Po Valley, Italy	6,700 (3m x 0.4m)	2/4/6/8	10 every year	No published
Di Nasso et al. (2010), Pisa (43°40'N, 10°19'E), Italy	10,000 (2m x 0.5m)	3/6/9/12	24.6/19.3/16/7	*Populus deltoides* Bartr. (clone Lux)

Pontailler et al. (1999) reports a biomass yield ranging from 4.96 to 19 ton·ha^{-1}yr^{-1} with a maximum of 19 ton·ha^{-1}yr^{-1}, while 5-20 oven-dry tons (odt)·ha^{-1} yr^{-1} was reported by Dickmann (2006). Headlee et al. (2013) reported 4.4 to 13 odt·ha^{-1} yr^{-1} in Minnesota and Wisconsin. This agrees with 2.2-13.5 odt·ha^{-1} yr^{-1} given by Mitchell et al. (1995), cited by Mitchell et al. (1999) for data from seven countries, five genera, 88 different clones, and 23 planting densities.

The same variety grown on different sites resulted in different yields (Armstrong et al., 1999) (Table 2.8). The work of all of these authors indicates that matching species and variety to site conditions is essential to maximize growth. Harper Adams (wet site) showed an increase in yield in year 3 compared with Dunstall Court (dry site) in the East Midlands of England (Tubby and Armstrong, 2002).

Table 2.8 Comparison of poplar yield at two sites in the East Midlands of England after one 3-year cutting cycle (Tubby and Armstrong, 2002)

Variety	Site	Standing biomass (odt ha^{-1})		
		At year 1	At year 2	At year 3
'Trichobel'	Harper Adams	11.91	23.23	41.71
	Dunstall Court	4.90	11.60	23.68
'Beaupre'	Harper Adams	15.87	24.70	36.54
	Dunstall Court	7.29	12.24	21.31
'Ghoy'	Harper Adams	14.62	22.89	35.89
	Dunstall Court	7.48	13.91	23.76

The Riverbend Landfill in McMinnville, OR obtained a yield of 7.73 dry ton·ha^{-1}yr^{-1} from a thinned stand of 184-411 poplar clones irrigated with leachate. The yield from a 15-year-old stand of D-01 poplar clones was only 2.35 ton·ha^{-1}yr^{-1}. The concentration of boron in leaf tissue resulted in consequent yield decline.

2.2.5 Estimation of biomass yield

For a given site and climate, biomass yields are determined by genetically controlled physiological processes that regulate tree growth, site quality, and climate. Yield models include FOREST-BGC (Running and Coughlan, 1998; Running and Gower, 1991); BIOMASS (McMurtrie et al.1992); PnET (Aber and Federer, 1992); and TREGRO (Weinstein et al., 1991). These models are tools for predicting biomass yield (Landsberg and Waring, 1997). Recently, Wang et al. (2013) developed PEcAn-ED2 for similar purposes.

FOREST-BGC (BioGeochemical Cycles) is an ecosystem-process model that calculates carbon, water, and nitrogen cycles through a forest ecosystem. These elements can alter the leaf to root to stem allocation for dynamic annual carbon partitioning controlled by water and nitrogen limitations. This model has been used to simulate the annual hydrological balance and net primary production (NPP) of a hypothetical forest stand in different environments. The model includes the effect of fertilization in the determination of carbon and nitrogen budgets (Running and Coughlan, 1998; Running and Gower, 1991). The model does not include regrowth.

BIOMASS is a process-based model of forest growth that includes sub-models for radiation absorption, canopy photosynthesis, partitioning of assimilate between plant organs, litter fall, and stand water balance. This model includes an assumption that all crowns have identical dimensions, and this enhances its utility for long-term simulations. This model can be used for any species (softwood or hardwood), but does not account for plantation management and regrowth.

PnET is a set of models for estimating carbon, nitrogen, and water dynamics in forest ecosystems. It uses climate and site variables and has a land use classification map for New England. This includes grids of climate variables (e.g., monthly precipitation), and annual N and S (sulfur) atmospheric deposition. The model outputs generally include annual NPP, wood production, and runoff under current and climate change conditions.

Climate change predictions are presented as ratios of future to current values. This model does not include plantation management.

The TREGRO model evaluates the effects of air pollution stress on carbon allocation. It models growth based on the mechanisms by which plants regulate their carbon, water, and nutrient cycles to mitigate damage caused by pollutants such as ozone and acid rain (Weinstein and Beloin 1990, cited by Weinstein et al., 1991). The model can estimate the carbon allocation of an isolated tree. This model does not include plantation management.

The PEcAn-ED2 model (Predictive Ecosystem Analyzer, Ecosystem Demography 2) is a process-based modeling approach to estimate the yield and carbon sequestration potential of hybrid poplar for a given climate and soil (Wang et al., 2013). This model does not include regrowth.

The 3-PG (Physiological Principles in Predicting Growth) model uses solar radiation, temperature, and species-specific photosynthetic parameters to establish maximum potential productivity (Landsberg and Waring 1997). From this, actual productivity is estimated based on limiting factors, such as site fertility and water availability, and is allocated among the stem, foliage, and roots based on an allometric relationship (Headlee et al., 2013). The model can be applied over large regions and for multiple species, with few modifications of the model parameters. Hart et al. (2014) adapted the 3-PG model to SRWC, including coppicing by adding a component that allows for a growth contribution from root mass. Poplar species are propagated by cuttings or bare stems with the root balls well established by the time of coppicing. This allows resprouting from the residual root and stem biomass. The model specifies a relatively small contribution to aboveground growth from the accumulated root mass after coppicing in order to initiate the next cycle of production. It also incorporates root contribution, leaf area index target, root conversion efficiency, weather, and month of harvest in the growth estimate (The 3-PG Model, 2014). Categories and parameters of the 3-PG model are described in Appendix A.

2.3 LCA applications in forestry

Environmental impacts of producing biomass in plantations and the processing of forest products are explained in the following sections.

2.3.1 LCA of woody biomass

Life cycle assessment has been conducted for biomass from agricultural, forestry, and waste management systems. In a forestry system, dedicated biomass comes from areas grown primarily for energy, but may also produce non-energy by-products. Research on environmental impacts, listed in Table 2.9, shows that sources of CO_2 emissions exist in plantations and other greenhouse gases (GHG) such as NO_2 that also contribute to the net GWP.

Table 2.9 Biomass LCA research

#	Year	Author	Research location	Environment	Energy	Water
1	1992	Graham et al.	USA	X		
2	2003	Heller et al.	USA	x		
3	2003	Lettens et al.	Belgium	X	X	
4	2005	Keoleian and Volk	USA	x	X	
5	2007	Adler et al.	USA	X		
6	2007	Fang et al.	China	X		
7	2009a	Gasol et al.	Spain	X	X	X*
8	2009	Manzone et al.	Italy		X	
9	2010	Butnar et al.	Spain	X		
10	2010	Cherubini	Norway	X		
11	2010	Di Nasso et al.	Italy		X	
12	2011	Börjesson and Tufvesson	North Europe	X	X	
13	2011	Cherubini and Strφmman	Global	X	X	
14	2011	Djomo et al.	Belgium	X	X	
15	2012	Bacenetti et al.	Italy	X	X	
16	2012	Fiala and Bacenetti	Italy	X	X	
17	2012	Gonzalez-Garcia et al.	Italy	X	X	X
18	2013	Dillen et al.	Belgium		X	
19	2013	Gonzalez-Garcia et al.	UK	X		
20	2014	Amponsah et al.	UK	X		

* Water consumption, irrigated.

Gasol et al. (2009a) reported 1,166 and 1,318 kg CO_2 eq per ha for GWP, 152 and 155 mg CFC 11 eq per ha for ozone depletion, 8.78 and 10.03 kg SO_2 eq per ha for acidification, and 1.79 and 2.09 kg PO_4 eq per ha for eutrophication for packets of stems and chips, respectively. The poplar plantation yielded 13.5 $t \cdot ha^{-1} yr^{-1}$ from three 5-year rotations.

Bacenetti et al. (2012) reported GHG emissions for poplar for 2-year and 5-year rotations as 5.7 and 5.3 t CO_2 eq per ha, respectively, for a 10-year plantation life. These include emissions for chip production. However, a calculated proportion was fixed for biomass during its growth, which ended with a mitigation of GWP of 365.1 and 375.3 ton CO_2 eq per ha in each respective system. In this study, the main contributors of GHG emissions were mechanical weed control, fabrication of urea, harvesting, and biomass transport.

In a similar study for 2- and 5-year rotations, Gonzalez-Garcia et al. (2012) showed that 2-year rotations were favorable in all impact categories except ozone depletion (Table 2.10).

Table 2.10 LCIA results per ha of poplar plantation under 5-year and 2-year rotation scenarios and cumulative energy demand

Categories	Unit	5-year rotation	2-year rotation	% change, relative to 2-year rotation
Acidification	kg SO_2 eq	108.87	140.08	-22
Eutrophication	kg PO_4^{-3} eq	25.89	32.99	-21
Global warming	kg CO_2 eq	-433,865	-374,787	-16
Ozone depletion	kg CFC-11 eq	7.41×10^{-4}	7.13×10^{-4}	+4

Butnar et al. (2010) and Cherubini and Strφmman (2011) indicate that some impact categories decrease with yield. The intensity of farming operations, quantity of fertilizer, and use of irrigation, among others, increase productivity, but also increase GHG emissions, which challenges the goal of sustainable production. Butnar et al. (2010) found that GWP for poplar was 62% due to fertilizers, 3% to pesticides, 13% to harvesting, and 22% other sources. A similar distribution of impact contribution was observed for acidification, 65%, 3%, 15%, and 17%, respectively.

Heller et al. (2003) reported CO_2 emissions resulting from diesel fuel combustion for willow biomass production of approximately 11 kg CO_2 per ton of biomass. The NO_2 emissions, based on Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC, 1996), were 0.29 Mg CO_2 eq per ton of biomass. However, IPCC guidelines do not account for differences in fertilizer type, soil type/or drainage, or other site specific parameters.

A recent review of life-cycle GHG emissions from renewable energy sources (Amponsah et al., 2014) found potential to produce high GHG emissions. However, similar studies also found higher GHG emissions for fossil fuel heat and electricity.

Fiala and Bacenetii (2012) reported specific GHGs emissions in a harvesting operation for SR poplar plantations of from 15.7 to 18.2 kg CO_2/t_{dm}, with a yield of 60 t_{wb}/ha.

The production of electricity from woody crops has a small global warming potential (39-52 kg CO_2 eq per MWh electricity), depending on the conversion technology.

Mattews (2001) and Heller et al. (2003, cited by Volk et al., 2004) indicate net ratios from 1:29 to 1:55 for the energy to produce willow biomass, compared to that recovered.

Contrasts among environmental impact studies show that impacts are difficult to compare when the parameters involved in biomass production are different. For example, Bacenetti et al. (2012) reported higher GHG impact than the GWP reported by Gasol et al. (2009a), which could be attributed to different elements taken into account, such as timeframe of the plantations and growing conditions (weather and soil type), among others. Similarly, GWPs reported by Gasol et al. (2009a), Bacenetti et al. (2012), and Gonzalez-Garcia et al. (2012) were completely different among each other.

The preceding discussion is in complete agreement with Cherubini and Strømman (2011): “The use of different input data, functional units, allocation methods, reference systems and other assumptions complicates comparison of LCA bioenergy studies.”

2.3.2 LCA in the Forest Industry

The Consortium for Research on Renewable Industrial Materials (CORRIM) has measured the cradle-to-gate energy consumption for kiln-dried softwood lumber (Puettmann et al., 2010), plywood (Wilson and Sakimoto, 2005), laminated veneer lumber, LVL (Wilson and Dancer, 2005), oriented-strand board, OSB (Kline, 2005), particleboard, PB (Wilson, 2008a), and medium-density fiberboard, MDF (Wilson, 2008b; Figure 2.4). The production processes for these materials involve breaking down material, removing moisture, and, in some cases, reassembling with adhesives. The energy inputs are wood energy, electricity, and fossil fuels. Drying consumes 72% to 86% of the energy required to produce for kiln-dried lumber (Puettmann et al., 2010; Milota et al., 2005). Drying and sanding dominate energy consumption in glulam. Plywood and LVL require less energy than glulam because drying is highly correlated to the thickness of the member—more material equals more consumption of energy (Puettmann and Wilson, 2005)

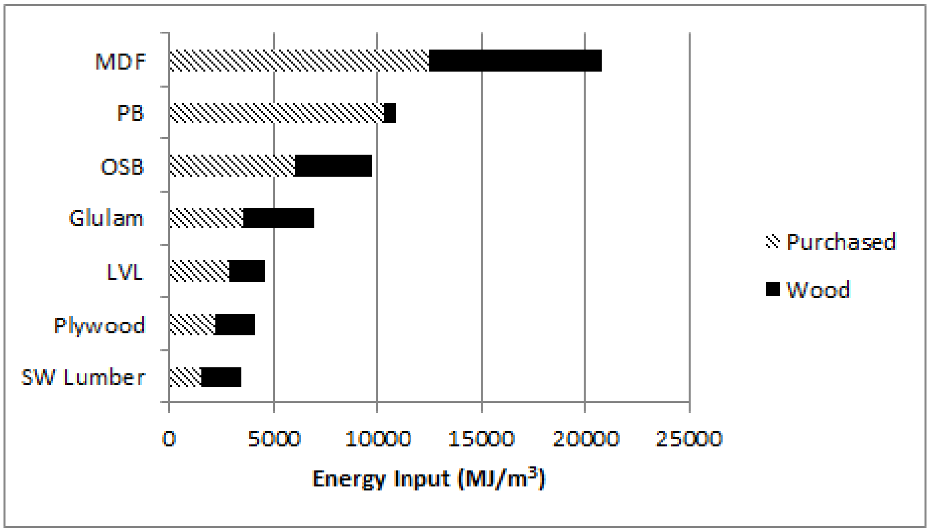

Figure 2.4 Cradle-to-gate energy consumption for various wood products (Puettmann, 2009).

2.3.3 LCA of energy production

Electricity production from biomass has lower environmental impacts than does production from current technologies based on fossil fuels (Mann and Spath, 1997). A GWP of 4.9 g CO_2 per kWh was reported from dedicated wood crops: 61.8% from the feedstock, 12% due to transportation, and 26.2% from the energy conversion at the power plant. Dinca et al. (2010) reported GWP for fossil fuels during their process of production. For extraction and treatment of hard coal, natural gas, and oil, g CO_2 eq per kWh was 10.8, 72, and 25.2, respectively. The feedstock production contributions were 2.7%, 24%, and 6.6% for coal, natural gas, and oil, respectively, of the total GWP for energy production. According to Curran (2013, cited by Amponsah et al., 2014) SR coppice wood chips produced GHG emissions of 60 to 270 g CO_2 eq per $kWh_{electricity}$.

Cogeneration is the simultaneous production of heat and electricity, commonly called combined heat and power (CHP). CHP is used for producing electricity and steam for dry kilns at sawmills. A biomass-fed, integrated-gasification combined cycle (IGCC) had a

GWP of 50 g CO_2 eq per kWh, compared to 1,020 g CO_2 eq per kWh for coal (Haefke, 2008). The biomass system had lower GWP because of the absorption of CO_2 during biomass growth. On the other hand, the direct-fired biomass system had a negative rate of GHG emissions due to the avoided methane generation associated with biomass biodegradation. IGCC with natural gas had the lowest GWP among fossil inputs due to higher efficiency.

2.3.4 LCA of energy and water consumption for biomass production

The fossil fuel energy consumption for growing, cutting, and transport of *Miscanthus* and willow was 935.8 GJ· ha^{-1} and 620.9 GJ· ha^{-1}, respectively, each reported for 100-year period, in order to make their performance comparable (Lettens et al., 2003).

An Ethiopian mustard (*Brassica carinata*) bioenergy system required 5.6 times more energy input (482 GJ · ha^{-1}), and a natural gas production and distribution system required 8.5 times more energy input (721.93 GJ · ha^{-1}) than a poplar bioenergy system (approximately 85 GJ· ha^{-1}), according to Gasol et al. (2009a). This increment in energy also contributed to their environmental impacts.

An analysis of the cumulative energy demand of poplar grown with 5-year (SR) and 2-year (VSR) rotations in a 10-year plantation time frame was performed that took into account the entire energy demand for production, use, and disposal (Gonzalez-Garcia et al., 2012). The demands were 3,700 GJ eq·ha^{-1} and 3,200 GJ eq·ha^{-1} for SR and VSR, respectively, with a poplar heating value of 18.5 GJ ·odt^{-1}. The value was 15.6% higher for the SRC than the VSRC because diesel consumption was different, due to technology used in harvesting and biomass extraction. A pincer connected to a tractor was used to harvest SRC and they were then chipped, which required 578.4 kg diesel. A combine harvester was used for the VSR, which required 440 kg diesel for operation.

The high difference of energy required among Lettens et al. (2003), Gasol et al. (2009), and Gonzalez-Garcia et al. (2012) is due to different feedstock, processes, and energy accountability.

Manzone et al. (2009) reported that about 7% of biomass energy production is based on cultivation and management of irrigated SR poplar; that is 14.2 GJ $\cdot ha^{-1}yr^{-1}$. The highest energy consumption is linked to plantation management (47%), followed by harvesting and transport to farm storage (16%).

Börjesson and Tufvesson (2011) reported a total energy of 7.5 GJ$\cdot ha^{-1}yr^{-1}$ for the production of willow biomass. Diesel fuel contributed 38.67%, fertilizer 53.34%, and other energy inputs 8%. The biomass yield was 180 GJ$\cdot ha^{-1}yr^{-1}$, and the willow heating value was 17.6 GJ$\cdot odt^{-1}$.

Bacenetti et al. (2012) reported the cumulative energy demand that represents the whole energy demand (valued as primary energy) related to the production, use, and disposal of an economic good. Poplar under VSR (2-year) and MRF (5-year cutting frequency) cultivations required 84.6 and 59.7 GJ per throughout the 10-year plantation, respectively. SR poplar had more energy demand, mainly due to the higher rate of fertilizer and the more rigorous cycle management in terms of harvesting, fertilizing, and pest-control events. The main contributions for energy demand were N fertilization, mechanical weed control, and wood chip harvesting.

Energy input depends on yield, annual use of the machines, and scheduling of operations, concluded Fiala and Bacenetti (2012) after their analysis of biennial poplar SR harvesting operations. Energy input of from 212 to 228 MJ per ton dry matter was reported for single- and twin-row poplar plantations at high planting density (over 5000 plants per hectare) during harvesting operations that yield 60 ton (wet basis) per hectare.

Dillen et al. (2013) reported a 16-year timeframe study of poplar growing on degraded land. They found that survival of a mixture of pure poplar species and hybrid *Populus* spp. clones suggested that pure species might perform better than hybrids under suboptimal growth conditions, such as those found for poplar established on degraded land with no irrigation, fertilization, and fungicides. That site, specifically, was a former waste disposal site moderately polluted with heavy metals. The average dry biomass yield during the fourth rotations and over the time frame of 16 years was 4.3 ± 3.4 ton·ha^{-1} yr^{-1}, which was low, compared to reported yields of 10-12 ton ·$ha^{-1}yr^{-1}$. Despite the relatively low yields, the investigated system on degraded land had a positive energy balance, producing 7.9 times more energy than it consumed from cradle to plant gate. Since low inputs imply smaller environmental impacts and lower net carbon dioxide emissions, the study poplar may be characterized by low environmental impacts and a small contribution to GHG emissions. The energy ratio from cradle to farm gate (ER_{farm}) was calculated by dividing the harvested biomass energy at the farm gate by the total energy consumed in biomass production. The poplar SRC system yielded an ER_{farm} of 29.8 that fit the range of 13 to 79 reported by Djomo et al. (2011) in a review on the energy ratios of these bioenergy plantations. Previous research developed by Keoleian and Volk (2005) reported an energy ratio of 16.6 at the farm gate for agricultural production of willow biomass after the first rotation. This ratio increases to 55.3 when output and consumption over the full seven rotations is considered; this means that 55 units of energy stored in biomass are produced with one unit of fossil energy.

An environmental disadvantage of poplar is the high consumption of water needed for its cultivation. For example, Gasol et al. (2009a) reported 28,000 m^3·ha^{-1} of water consumption for irrigation over a 16 year period of cultivation at Soria (Spain); with a mean rainfall of 30 mm per year, that is equivalent to 1,750 m^3·ha^{-1} yr^{-1}. However, only 400 m^3·ha^{-1} was applied during a 10-year rotation at Po Valley (Italy), with a mean rainfall of 745 mm per year (Gonzalez-Garcia et al., 2012), which is equivalent to 40 m^3·ha^{-1} yr^{-1}.

Chapter 3 METHODOLOGY

The environmental consequences of producing poplar woody biomass at four sites were determined by measuring the mass and energy inputs and outputs, and then applying life cycle assessment (LCA) methodology. The environmental impacts associated with the production of cuttings were determined and carried forward into the plantations. The intended application is to provide life cycle inventory (LCI) data related to biomass production for use in life cycle analysis (LCA) of heat or electricity generation from poplar biomass. The data also provides a useful comparison of the environmental impacts of biomass production for companies or farmers that have similar growing conditions for poplar. A second goal was to determine which LCA impact categories are most affected by different management scenarios.

The scope of the study covered the production of poplar biomass production in plantations that had different rotation ages, types of silvicultural management (irrigation and fertilization), and harvesting techniques. It also covered the production of cuttings in a nursery that were transported to and planted in plantations. The functional unit for the study was 1 BDmT (bone-dry metric ton) of biomass for energy.

3.1 Production of cuttings

All study sites used poplar cuttings from the GWR Boardman Tree Farm near Boardman, OR. This company is a major supplier of poplar cuttings in the Pacific Northwest. GWR operates a section of their Boardman plantation to produce cuttings. Cuttings are produced on a 3-year cycle that begins with site preparation. After three harvests, the stumps are removed and the land is cleared. Branches are removed during each of the three harvest years, bundled into units of approximately 50 branches, and transported a short distance to an on-site processing facility, where the branches are cut into 22-inch cuttings. The cuttings are then stored under refrigeration.

The poplar cuttings had a small-end diameter of 1.27-cm and a large-end diameter of 2.54-cm. They were 0.52 m long, with a volume of 0.00015 m^3 per cutting. The dry mass of the cutting was 0.0465 kg, based on a specific gravity of 0.31. The mass of a cutting with moisture was 0.093 kg, if 100% moisture content is assumed.

3.2 Case study sites

There were four case studies for this research project. The case study sites consisted of poplar plantations in Oregon, three in the Willamette Valley and one east of the Cascade Mountain range (Figure 3.1). Site 1 had no irrigation, Site 2 was irrigated with river water from the Columbia River, Site 3 was irrigated with treated water from a wastewater treatment plant, and Site 4 was irrigated with landfill leachate. There were other differences in management which are described in the following sections.

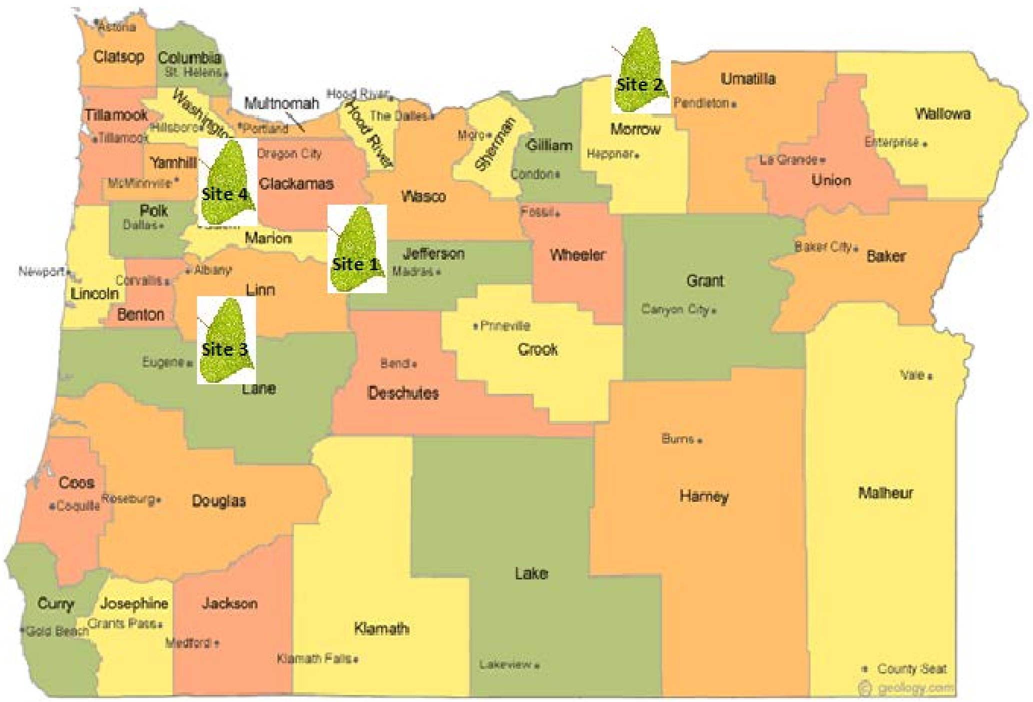

Figure 3.1 Locations of the four study sites. Map adapted from http://geology.com/county-map/oregon.shtml accessed May 25th, 2014.

3.2.1 Site 1: Poplar plantation without irrigation

Site 1 is a 34-ha (85-ac) demonstration farm located in the Willamette Valley near Jefferson, OR. It is leased as a test site for the Advanced Hardwood Biofuels (AHB) Northwest project, which is funded by the Agriculture and Food Research Initiative (AHB, 2014), and managed by the Greenwood Tree Farm Fund (GTFF). Site 1 represents the simplest situation among the four sites. It was planted in the spring of 2012, and no irrigation or fertilization has been used since its establishment (Figure 3.2). Site 1 receives 43 inches of precipitation per year, which is ample for good poplar growth. It contains 11 poplar clones planted in unequal amounts. The first harvesting operation was in September 2013 (Figure 3.3), while the trees retained their leaves. The harvested biomass was piled on the ground to compost.

The equipment used for land preparation consisted of a 3-wheel agricultural sprayer, a large tractor, and a mid-size tractor. The equipment used during plantation management included a semi-tractor trailer, a cooler/van, and a small tractor for applying herbicide. For harvesting, a Case New Holland FR 6080 forage harvester for cutting, tandem axle truck for off-loading, and a support truck were used. It is assumed that land restoration will be done with a large tractor and a 3-wheel agricultural sprayer.

Figure 3.2 Poplar in a demonstration site near Jefferson, OR. September 9th, 2013.

Figure 3.3 (a and b) Harvesting operation with New Holland Series 9080 forage harvester near Jefferson, OR on September 23, 2013; (c) stumps for regrowth; and (d) transportation of woody chips from poplar SRWC.

3.2.2 Site 2: Poplar plantation irrigated with river water

The Boardman Tree Farm, owned by GreenWood Resources (GWR), covers approximately 12,900 ha (31,800 ac) in the Columbia Basin in Oregon and Washington (Figure 3.4). The farm is divided into 16- and 28-ha (40- and 70-ac) plots separated by access roads. Site 2 is located in eastern Oregon, an area heavily influenced by the Cascade Mountains to the west. The site receives around 10 inches of annual rainfall, most of which occurs during the winter. The winter temperatures are slightly above freezing (BTF, 2011). Site 2 has the driest soil among the four sites and is irrigated with river water.

An inter-cropping strategy has been in development since 2011. The poplar for biomass is planted between rows of trees being grown for lumber. Hybrid poplar cuttings for this study were inter-planted in the spring of 2013 in open strips between saw log trees. The planting density is approximately 1,485 trees/ha (600 trees/ac). The intercropping project received financial incentives from the Farm Service Agency of the U.S. Department of Agriculture Biomass Crop Assistance Program (BCAP; USDA FSA, 2011).

Nine 1,000 motors powered pumps to bring 442,260 L/min (117,000 gal/min) of water from the Columbia River for irrigation (Mohamed, 2011). The use of chemical pesticides and herbicides is limited, as integrated pest management processes are employed. Sawdust, tops, branches, and foliage from harvesting are ground and applied to the soil, limiting the need for chemical fertilizers.

An average of approximately 63 truckloads per day are harvested and delivered to an adjacent mill. About 25 of these loads consist of sawlogs, 25 of chips produced during sawlog harvest, and the balance are chips from plantation from thinnings. A typical load is 35 to 40 net tons. The poplar lumber is marketed as Pacific Albus, a trademarked name that loosely means “Pacific whitewood.” Pacific Albus is a hybrid of four to five different poplars, cross strained for better yield, faster growth, straighter trees, and lower water needs. The trees take 10 to 12 years to reach maturity, after which they are harvested and processed into lumber for moldings and furniture parts and chips for paper manufacturing. Log residue is used for hog fuel. The sawdust and sander dust are compressed into bricks for fireplaces and wood stoves (http://www.amusingplanet.com/2013/09/boardman-tree-farm-of-greenwood.html accessed October 12th, 2013).

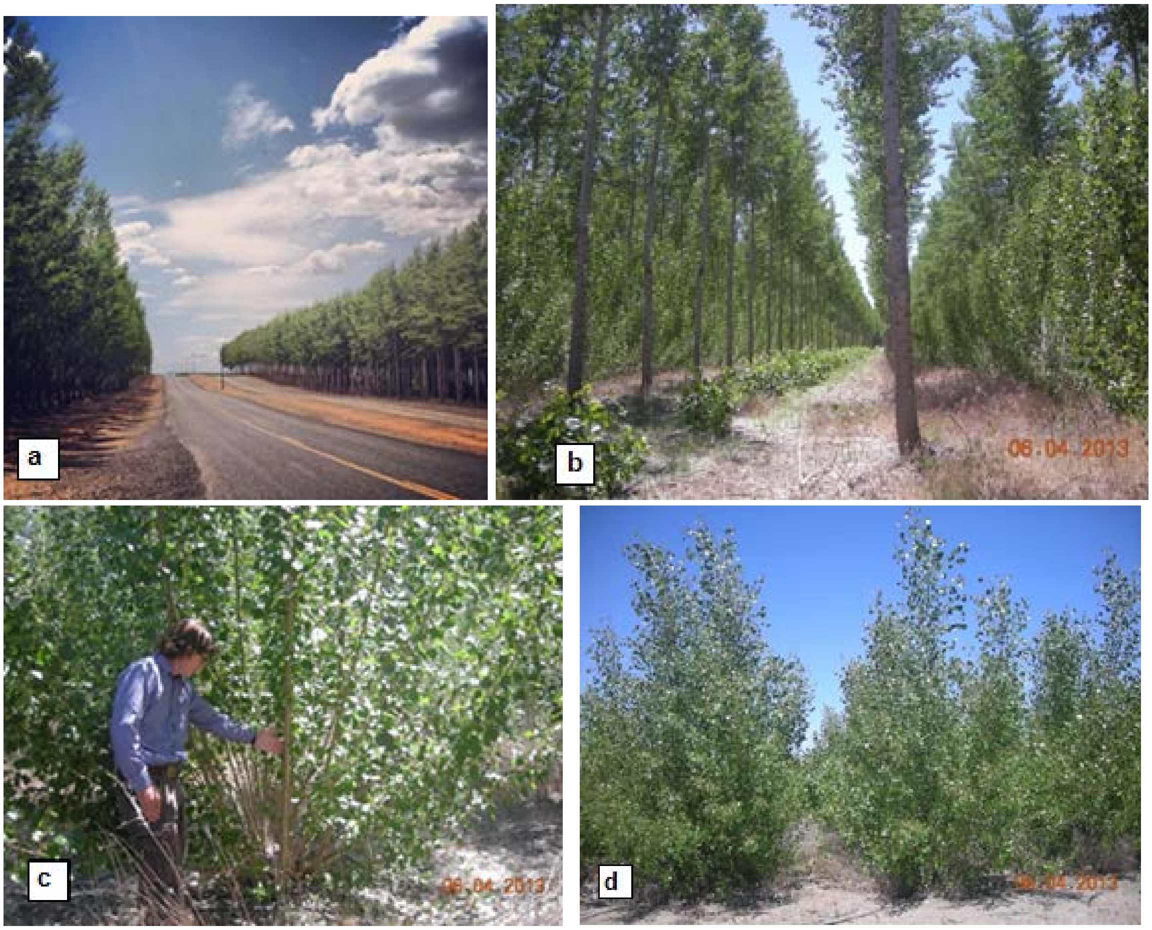

Figure 3.4 Boardman Tree Farm showing different forms of silvicultural management based on products: (a) and (b) show intercropping between trees for the production of lumber; (c) and (d) show a double-row poplar plantation with a high planting density for bioenergy purposes (June 4th 2013).

3.2.3 Site 3: Poplar plantation irrigated with treated wastewater

The Metropolitan Wastewater Management Commission (MWMC) owns a water treatment plant located near Eugene, OR. It receives wastewater from more than 220,000 Eugene and Springfield, OR inhabitants and can process $6.7x\ 10^{10}\ L\cdot yr^{-1}$. Biosolids generated from the biological treatment of wastewater are pumped from the treatment plant to lagoons at the Biosolids Management Facility (BMF) where, over time, natural decomposition further stabilizes the materials and reduces pathogens. Once fully treated, the biosolids are dried using mechanical dewatering and an air-drying process. The end result is biosolids, which are safe for the environment and contain a high concentration of essential plant nutrients (P and N), organic matter, and metals. The solids are recycled as fertilizer and soil amendment. The majority of the biosolids are applied to agricultural lands and a small amount composted for urban use (MWMC, 2014).

The biosolids are also applied on the Biocycle Tree Farm (BTF), a poplar plantation under the same ownership located on approximately 243 ha of agricultural land just west of the BMF. Poplar trees grow very rapidly and consume the nutrients provided by the biosolids, making the BTF cost-effective for recycling biosolids (MWMC, 2014).

Nearly 162 ha (400 ac) of poplar were planted in three phases, managed as an agricultural crop, and irrigated with treated wastewater from municipal sewage (Figure 3.5). Multiple varieties of poplar were planted to increase the stand’s resistance to disease, pests, and climatic conditions. Seven non-proprietary varieties of poplar were planted on BTF in phase 1 in the spring of 2004 (Miller, 2011; MWMC, 2014). Site 3 is a 21-ha (52-ac) area of this containing 12,700 10-year-old poplar trees and was harvested during the summer of 2013 (Figure 3.6), after 10 growing seasons. The trees still retained their leaves.

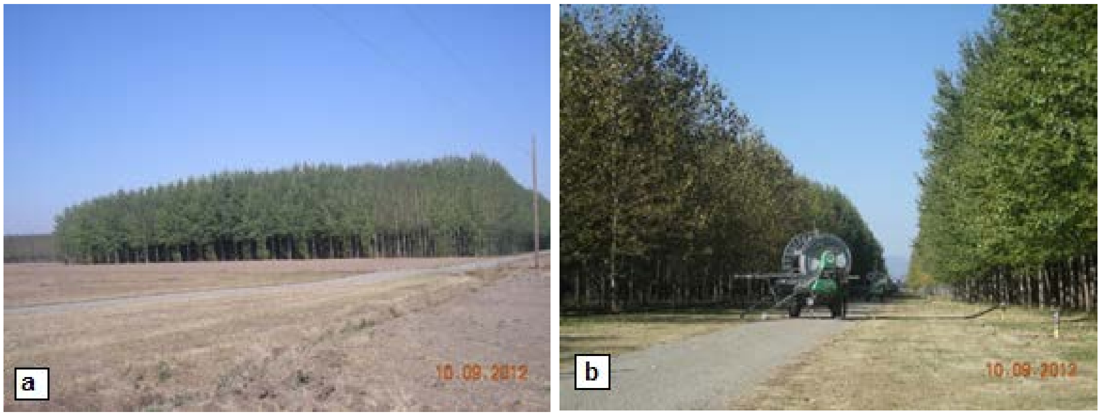

Figure 3.5 (a) Biocycle Farm on October 9, 2012, showing (b) the technique for irrigation.

Land preparation, harvesting, and land restoration were performed by a third party. A small tractor (Kubota B2920), two medium tractors (Case IH DX45), and a large truck (TerraGator 8104) were used in land preparation. During plantation management two medium tractors (John Deere 7420) were used to relocate biosolids, move hose reels, and add chemical fertilizer. A large truck (Sterling LT 9500's) was also used to haul dried biosolids.

Lane Forest Products Company used a 20 FB Hydro-ax tree shear mounted on a size 200 John Deere excavator during harvesting to shear the trees and lay them down in rows. A front-end loader with log forks was used to gather logs and transport them to the stockpiling area. From the stockpile area, Lane Forest Products used a DDC 5000 G Peterson flail chipper harvester that de-limbs, de-barks, and chips the trees. At the same time, an excavator with a brush rake was used to pull stumps, pick up any loose brush, and smooth out the dirt. The chips were used in paper manufacturing. Some material was ground for hog fuel and burned to generate electricity. The chips were temporarily stored in one of the air-drying beds at the BMF prior to hauling.

3.2.4 Site 4: Poplar plantation irrigated with landfill leachate

Riverbend Landfill is a municipal solid-waste management site owned by Waste Management Inc. (WM) and located in Yamhill County near McMinnville, OR. Riverbend Landfill accepts waste from Oregon and Washington. The landfill produces electricity from biogas.

Rain infiltrates the landfill, producing leachate (landfill wastewater). This liquid contains relatively high concentrations of solutes and suspended solids extracted from the solid waste. The landfill site has a 76,000,000 L (20,000,000 gal) lined storage pond where the leachate is collected year-round (Figure 3.7). Since 1992, some of the leachate generated by decomposition and rainfall has been applied to a poplar plantation (DEQ Solid Waste permit #345, 1999). Since 2001, a drip irrigation system has delivered landfill leachate and river water to the tree roots during the summer months. The daily irrigation ranges from 0.07 to 0.29 inches, depending on weather conditions and soil moisture (WM Website, 2014, Riverbend Annual Report, 2012). The river water is needed to control salinity in the soil.

There are 18 ha (45 ac) of poplar, with 1,375 trees/ha (556 trees/ac). Riverbend harvests and replants a few hectares with fast-growing trees every year (Figure 3.8). The biomass is used in the pulp and paper industry. Site 4 is the 4.45-ha (approx. 10 ac) north field harvest site (Figures 3.7 to 3.10). A medium-sized tractor was used for land preparation. This plus a large tractor were used during plantation management to distribute fertilizer. The harvesting was done by a third party with a feller-buncher, large grapple skidder, flail chipper, truck, and grinder. A large tractor with 3-wheel agricultural sprayer was used to apply herbicide during land restoration.

Figure 3.6 Biocycle Farm harvesting activities on the southeast section of Management Unit I on September 19, 2013: stumps (a) and their removal (b); chipping (c); and transportation system (d).

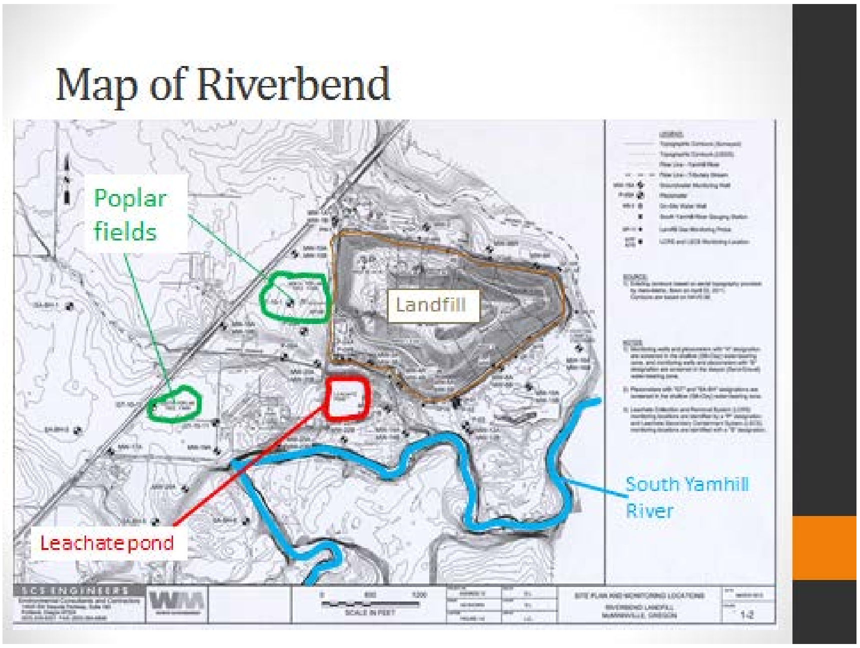

Figure 3.7 Map of Riverbend Landfill. (Source: Waste Management Annual Report, 2012)

Figure 3.8 Poplar cultivation at Riverbend Landfill. (Source: http://riverbend.wm.com/environmental-protection/index.jsp)

Figure 3.9 Landscape view from the hump top at Riverbend Landfill on May 8th, 2014

Figure 3.10 Harvesting on the north field at Riverbend Landfill on May 8th, 2014. A wind barrier with 12-year-old poplar trees is on the right and some products from site restoration are in the foreground

3.2.5 Summary of site descriptions

A summary of main characteristics of each site is presented in Table 3.1. A high variability in yield was expected among sites due to factors such as genetic variation, soil type, weather, and management. Attributes for each case study were used in analyzing the biomass yield.

Table 3.1 Summary of growing condition on the four different study sites

General attributes		Site 1	Site 2	Site 3	Site 4
Genotypes variables	Surface area (ha)	28.63	315	21.05	4.45
	Planting density (trees/ha)	3586	470	553	1375
	Lifespan (years) [a]	11	12	10	12
	Rotation (years)	2, 3, 3, 3	3,3,3,3	10	12
	Final diameter (mm)	75-130		255	
	Number of clones	11[b]	3[c]	3[d]	1[e]
Environmental variables	Soil	Clay	Sandy	Clay	Clay
	Average rainfall (mm)	1,000	200	1,000	1,058
Irrigation		No	Yes	Yes	Yes
Harvesting operation		NH Forage Harvester	NH Forage Harvester	Feller buncher	Feller buncher

[a] The plantations time frames were ≤ 12 years because agricultural activities under this period of time are regulated with different taxes than forest activities that require longer growth periods.
[b] *Populus trichocarpa* x *P. maximowiczii* (Clone 1157); *P. trichocarpa x P. deltoides* (Clones 1428, 5077); *P. deltoides x P. trichocarpa* (Clone 4491); and *P. deltoides* x *P. maximowiczii* (Clones 6294, 6320, 6323, 6329, 7388, and 8019)
[c] Clones BC78, BC79, and PC4
[d] Clones OP-367, 184-411, and others. Total clones planted = 8, but only 3 clones were harvested on 2013.
[e] Clone OP-367. Total clones planted = 5, but only 1 clone was harvested on 2013.

3.3 Data collection

Qualitative and quantitative data to be used in LCI analysis was collected for each site, using the forms in Appendix B. Data collected included the following:

- Types of clones and their respective planting densities
- Machinery used for the preparation of soil, planting, and chemical treatments
- Consumption of diesel or gasoline for each machine
- Type and amount of water applied
- System for irrigation and its energy consumption (electricity used)
- Amount of biomass produced
- Type and amount of emissions (liquid, air, and solid) and waste
- Herbicides and pesticides used

These were collected for all phases of the plantations, from land preparation to land restoration, with the exception of Site 2, on which no harvesting and land restoration had occurred. Missing information was estimated from similar activities at other sites, calculated based on machine hours, or estimated from the literature. Harvested biomass estimates for Site 2, as well as future harvested biomass in Site 1 were modeled. There were no cut-off criteria for the initial inclusion of inputs because all data were assumed to have an important contribution to energy consumption and environmental impacts.

Data was collected from September 2012 to July 2014. The collection methods included field trips, examination of published documents from sites, examination of operating permits, and surveys. Surveys were followed up with e-mail and telephone conversations to clarify some responses. In general, sites had difficulty reporting some inputs, such as diesel use, because a third party was either contracted to manage some aspects of the plantation or was hired to do work for a fee. For example, site preparation or harvesting might be contracted out rather than done by the plantation owner. Therefore, some sites were unable to specify the concentrations of chemicals such as herbicides. These were taken from the literature based on the concentrations recommended by the manufacturer. In other cases, the information was deduced from secondary data collected at the site. For example, diesel use was calculated from equipment horsepower and run time or estimated from a similar operation at another site. Also, no emissions to air or water were reported from any site.

In general, each site had records of poplar clones used and plantation management, including the use of chemicals and equipment and the dates of site preparation and harvests. However, rotation ages and plantation life spans varied among the four sites. Site 1, for example, had only one rotation after two growing seasons because it was an experiment plot rather than a commercial venture. Site preparation and land restoration would have a greater effect on the life cycle impact in this case, compared to a longer plantation life, for example, 12 years. To make comparisons more valid among the sites, the number of rotations was increased for Sites 1 and 2 to extend the lives of the plantations. The biomass yields of future harvests at these sites were estimated, using the 3-PG Model (Hart et al. 2014). Because of its experimental nature, Site 1 did, however, have excellent information for LCI development, which was obtained from its AFRI Sustainability Report at the University of Washington, with the collaboration of GreenWood Resources (GWR).

The water quality also differed among the sites, and this may have affected the biomass yield (See section 2.2.4 Chapter 2). However, this was not a factor that could be quantified through the limited case studies in this project. It would require a controlled experiment.

Common inputs to the four sites were commodities such as diesel fuel burned in machinery or used for on-site transport and electricity. These commodities have the same embodied energy because they are derived from similar sources using similar methods of production. Some of these common inputs were primary data provided by the plantations and some were secondary data obtained from the literature. Sites 1 and 2 provided information from which the fuel consumption could be estimated, and Sites 3 and 4 reported the amount of diesel used. Inputs in Site 4 were compared with the WM Annual Report (2012) and Smesrud et al. (2012). These reports described in details the utilization of landfill leachate, other materials, and energy for poplar biomass production. All sites reported the amount of electricity used.

Poplar cuttings were also a common input because all sites obtained cuttings from the Boardman Tree Farm of GWR. The cutting clones varied among and within the sites; however, the same basic process was used by GWR to produce cuttings regardless of the clone.

3.4 System boundaries

The cradle-to-gate system boundary for the production of a cutting includes the materials and processes shown in Figure 3.11. The processes within the system boundary occurred on the plantation site. All inputs were primary data supplied by GWR, except the electricity for processing. The data were divided among four phases, as depicted in the figure. Inputs to land preparation included diesel for machines and chemical application for weed control. Inputs to plantation management included water for irrigation; electricity for irrigation pumps, processing, and refrigeration; and diesel for machinery. Inputs to land restoration included diesel for machines and chemicals for weed control. GWR also supplied other information vital to the LCA, including the planting density, yield of branches, and the on-site transportation distance for branches.

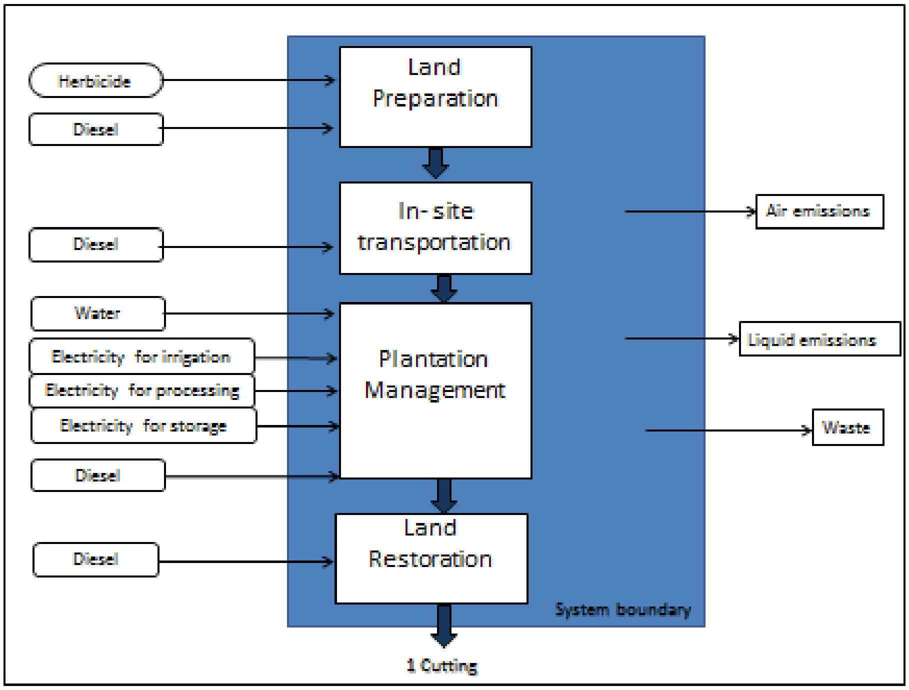

Figure 3.11 Cradle-to-gate system boundary for production of one cutting

The system boundaries for the plantations at each site are shown in Figures 3.12 to 3.15. The analyses are cradle to gate, and they account for the burdens carried by the inputs. The life of the product and its disposal are not within the system boundary. The system boundary for a site may not include the entire plantation, only a harvested area.

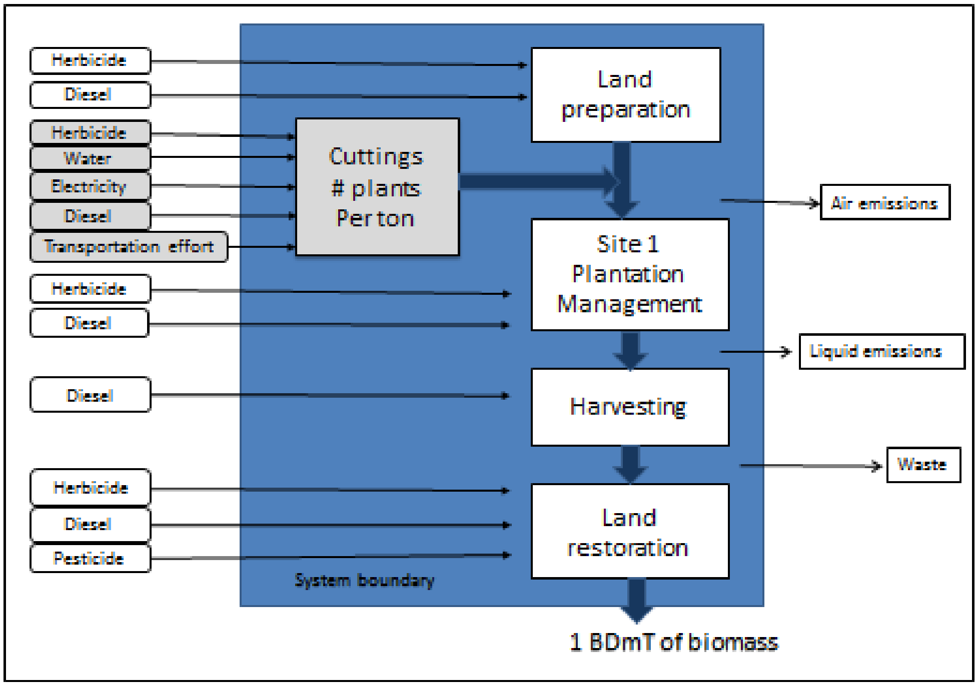

Figure 3.12 Cradle-to-gate system boundary for biomass production at site 1. Shaded inputs and cuttings are common to all sites

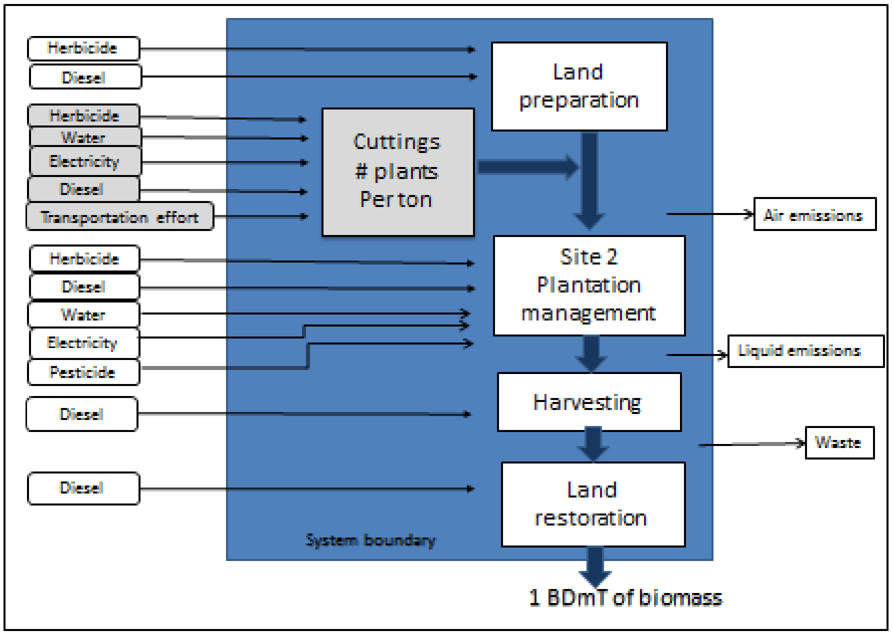

Figure 3.13 Cradle-to-gate system boundary for biomass production at site 2. Shaded inputs and cuttings are common to all sites

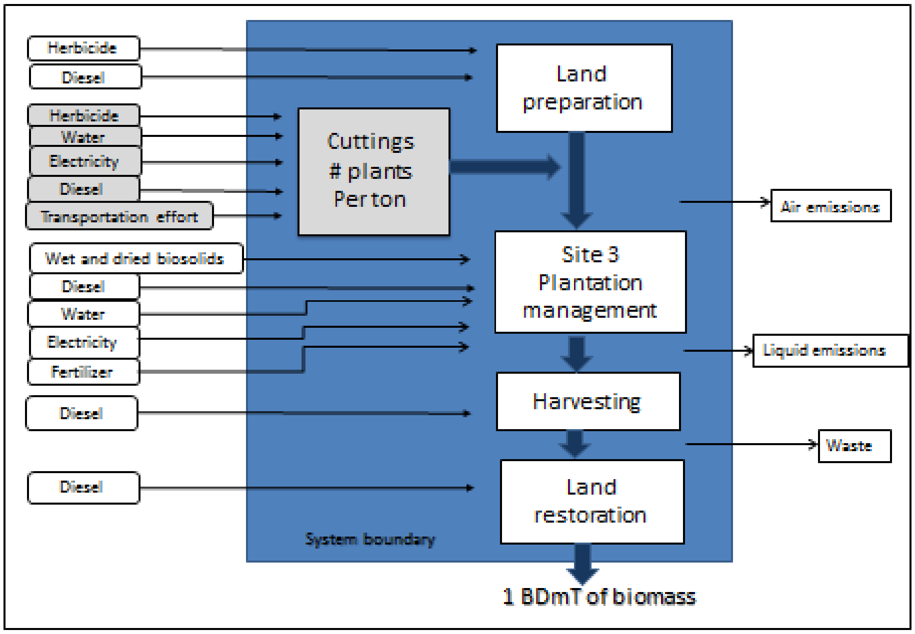

Figure 3.14 Cradle-to-gate system boundary for biomass production at site 3. Shaded inputs and cuttings are common to all sites

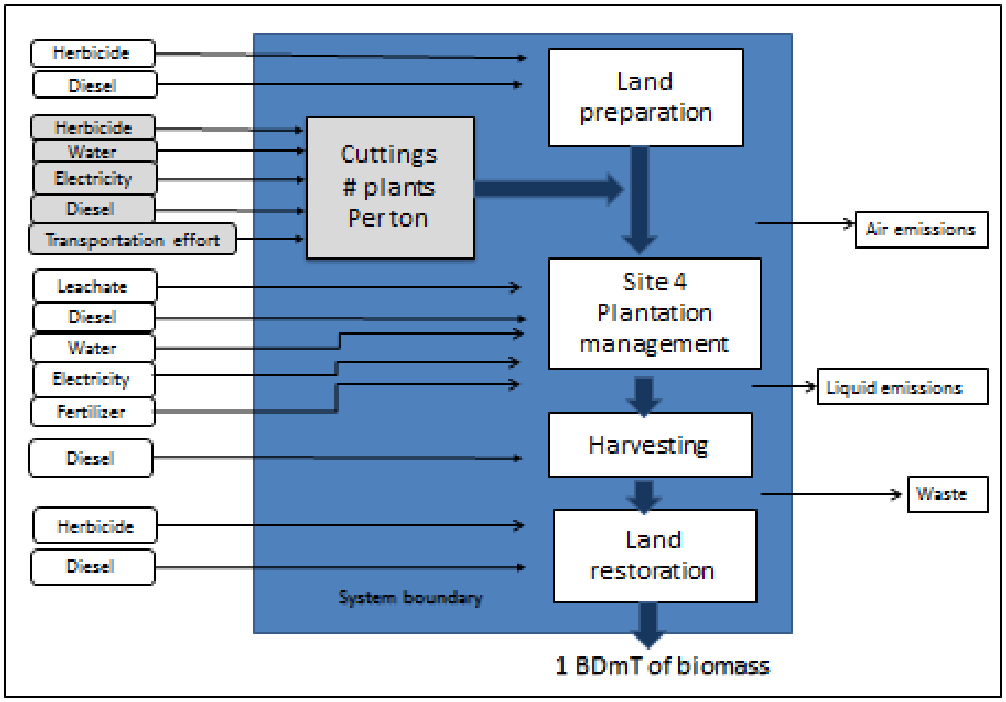

Figure 3.15 Cradle-to-gate system boundary for biomass production at site 4. Shaded inputs and cuttings are common to all sites

3.4.1 Allocation

Biomass was the only product from Sites 1 and 2, so no allocation was required. Residues obtained by land restoration, at the end of the plantation and after multiple harvests, were used in the same site to provide organic matter. In Site 3 and Site 4, the allocation between biomass and compost was based on dry mass.

3.4.2 Assumptions

The planting density was assumed to be constant throughout the plantation life; that is, no thinnings occurred and subsequent rotations had similar spacing. While all plantations had some harvested area and provided yield data, not all rotations in the growing cycle had occurred for Sites 1 and 2. The first harvest on Site 1 occurred after 2 years, and it was assumed that future harvests would be every 3 years for three rotations. For Site 2, the first harvest was assumed to be after 3 years, and future harvests were assumed to occur every 3 years for three rotations. For these cases, an estimate of biomass yield in future harvests was made using 3PG simulation software (see section 3.2.5).

Missing data was collected from related literature, such as fertilization doses or fuel consumption for some specific machines.

3.5 Life cycle inventory analysis

The information collected was input into SimaPro 8.0.3.14 simulation software to develop the LCI. The US LCI (2012) and EcoInvent v.3 databases were used to provide information on production processes for inputs such as fertilizers and herbicides, agricultural systems (material, energy use, and emissions of machinery), and data related to the production, distribution, and consumption of fuels.

The cradle-to-gate energy and water consumptions were determined by inventories for the contribution of each process, provided by the SimaPro model for each poplar plantation site. The LCIA phase used the inventory data to obtain indicators for the impact categories listed in section 4.3, which together represent the LCIA profile for the product system.

3.6 Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) was developed using the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts, TRACI 2 V 4.00, a model developed by the U.S. Environmental Protection Agency (EPA) in 2008.. TRACI, a mid-point method, was selected because it represents the environmental conditions in the USA. Acidification, eutrophication, and smog formation are determined for impacts throughout North America. Global impacts include ozone depletion and global warming (EU, 2010). A description of TRACI as an impact assessment method can be found in section 2.1.1.3.

These five of ten TRACI environmental impacts were reported for each site. The impact contribution criterion was defined as 5% to designate environmental impacts.
Ozone depletion (kg CFC-11$_{eq}$), global warming (kg $CO_{2\ eq}$), smog (kg $O_{3\ eq}$), acidification (kg SO_2 eq), eutrophication (kg N $_{eq}$) are reported. Health-related impacts, carcinogenic (CTU h), non-carcinogenic (CTU h), respiratory effects (kg PM $_{2.5\ eq}$), ecotoxicity (CTU e) are not reported. Although fossil-fuel depletion (MJ surplus) is an environmental issue, it is not reported. It is indirectly included in the energy consumption calculations. A further description of each impact category can be found in section 2.1.4.

3.7 Interpretation

3.7.1 Sensitivity analysis

A sensitivity analysis was performed on inputs contributing more than 5% to impacts by systematically changing their values by ±10% (Table 3.2).

Table 3.2 Summary of inputs tested for their effect on impact indicators

Site #	Parameter
1	Chemical
	Diesel
2	Chemicals
	Diesel, at harvesting
	Herbicide, at plantation management
3	Diesel, at harvesting, at plantation management
4	Chemical
	Fertilizer
	Diesel, at harvesting
All sites	Biomass yield

Material and energy inputs were tested individually to assess the influence of each on the overall results. However, specific sensitivity analysis was performed for harvesting and plantation management because high environmental contributions were reported for some sites. Yield was also changed by ± 10% and the effects on impact indicators reported.

3.7.2 Energy and water consumption determination

Overall electrical energy consumption was calculated from that used on site and that required to produce the inputs. The latter came from the SimaPro databases. This was reported by raw sources, such as coal, oil, and natural gas. This data should provide useful information for comparing energy efficiency among sites.

Similarly, water consumption was calculated for irrigated sites. This included water used directly on the site and water used to make inputs, for example cuttings. Water use for off-site processes came from the SimaPro databases. This was reported by water source, for example surface or ground. These data should provide useful information for comparing water efficiency among sites.

3.8 Alternative methodological aspects investigated

Alternative sources for fertilizer and electricity were studied to analyze their effects on the results.

3.8.1 Source of nutrients

Fertilizer was substituted for biosolids at Site 3. The site provided a nitrogen analysis (Kjeldahl nitrogen, ammonia nitrogen, and nitrate plus nitrite nitrogen) for biosolids, applied to the plantation. An amount of synthetic fertilizer that would provide the same amount of nitrogen was substituted as an input to the LCI in place of biosolids. The impacts are reported.

3.8.2 Source of electricity generation

Electric energy was utilized for the irrigation of cuttings and for irrigation in Sites 2, 3 and 4. The Western Electricity Coordinating Council (WECC) electricity mix from the U.S. LCI Database was used as a base case. This represents a region from Canada to northern Mexico, near the Pacific Ocean. The WECC mix consists mainly of coal and natural gas. The first alternative source was a mix for the Pacific Northwest in which the hydro component was greater. The second alternative was electricity from biomass only. A new SimaPro process was developed for the PNW. Existing processes “Electricity from a turbine using steam from wood boiler, US_PNW” and “Wood combusted, at boiler, at mill, kg, PNW/US v1.2”, found in the U.S. LCI Database were used for biomass.

Chapter 4 RESULTS AND DISCUSSIONS

The main goal of the study was to assess the environmental impacts associated with the production of biomass from the sites, based on the materials and energy used by the sites, including cuttings, and the outputs from the sites. The environmental impacts associated with the production of cuttings were carried forward into the plantations. The intended application is to provide life cycle inventory (LCI) data related to biomass production for use in life cycle analysis (LCA) of heat or electricity generation from poplar biomass. The data also will provide a useful comparison of the environmental impacts of biomass production for companies or farmers that have similar growing conditions for poplar. A second goal was to determine which LCA impact categories are most affected by different management scenarios.

4.1 Production of cuttings

4.1.1 Life cycle inventory – Cuttings

The planting density was 470 initial cuttings per hectare[3]. After plantation management, each initial cutting yielded four cuttings during the first year, six during the second, and nine during third and final year[4]. This resulted in 8930 cutting/ha over the 3-year life of the plantation.

$$470\,\frac{\text{initial cuttings}}{\text{ha}}\ \text{x}\ 19\,\frac{\text{cuttings}}{\text{initial cuttings}} = 8930\,\frac{\text{cuttings}}{\text{ha}}$$

[3] Personal communication with Maynard-GWR, 2014
[4] Personal communication with Carlos Gantz, 2014

Chemicals were applied to kill weeds during land preparation. Two types of herbicides were used: glyphosate and flumioxazin (SureGuard ™). The amounts were calculated as follows:

$$1.17\ \frac{\text{liters of glyphosate}}{\text{ha}}\ \text{x}\ 0.48\ \frac{\text{kg}}{\text{liter}} = 0.56\ \frac{\text{kg}}{\text{ha}}\text{, then}$$

$$\frac{0.56\ \frac{\text{kg}}{\text{ha}}}{8930\ \frac{\text{cuttings}}{\text{ha}}} = 0.00006\ \frac{\text{kg Glyphosate}}{\text{cutting}}$$

and

$$0.05\ \frac{\text{kg of SureGuard}}{\text{ha}}\text{, then}$$

$$\frac{0.05\ \frac{\text{kg}}{\text{ha}}}{8930\ \frac{\text{cuttings}}{\text{ha}}} = 0.000006\ \frac{\text{kg SureGuard}}{\text{cutting}}$$

Diesel used was 9.25 $L{\cdot}ha^{-1}$ for land preparation[5], 216 $L{\cdot}ha^{-1}$ for plantation management[6], and 17.05 $L{\cdot}ha^{-1}$ for land restoration

$$\frac{9.25\ \frac{\text{liter}}{\text{ha}}}{8930\ \frac{\text{cuttings}}{\text{ha}}} = 0.001\ \frac{\text{liter}}{\text{cutting}}$$

$$\frac{216\ \frac{\text{liter}}{\text{ha}}}{8930\ \frac{\text{cuttings}}{\text{ha}}} = 0.024\ \frac{\text{liter}}{\text{cutting}}$$

[5] AHB-AFRI Project report, 2014
[6] Personal communication with Brian Stanton and Ric Stonex- GWR, 2014

$$\frac{17.05\ \frac{\text{liter}}{\text{ha}}}{8930\ \frac{\text{cuttings}}{\text{ha}}} = 0.0019\ \frac{\text{liter}}{\text{cutting}}$$

The branches were cut with loppers and transported by tractor. The mass of a branch was estimated to be 0.00035 green ton. This was obtained from 2,250 branches per ha (45 bundles of 50 branches), volume of each branch (0.00056 m^3), wood basic density (310 kg/m^3), and MC (100%). The transportation distance in-site was reported as 4.83 km from where the trees were grown to the processing facility. The diesel consumption per ton of branches was then calculated as

$$0.00035\ \text{green ton x } 4.83\ \text{km x } 2{,}250\ \frac{\text{branches}}{\text{ha}} = 3.80\ \frac{\text{green ton km}}{\text{ha}}\text{, then}$$

$$\frac{3.80\ \frac{\text{green ton km}}{\text{ha}}}{8{,}930\ \frac{\text{cuttings}}{\text{ha}}} = 0.0004\ \frac{\text{ton} \cdot \text{km}}{\text{cutting}}$$

The stumps were not actually cleared, but were mulched, which explains why this value is low[7].

Water use from the Columbia River was reported as 1.829 m, 45.7, 61.0, and 76.2 cm in the first, second, and third years, respectively[1]. The consumption of water was then calculated as

$$1.829\ \text{m x }\ \text{x } 10{,}000\frac{\text{m}^2}{\text{ha}}\ \text{x } 1{,}000\frac{\text{l}}{\text{m}^3} = 18{,}290{,}000\ \frac{\text{l}}{\text{ha}}\text{, then}$$

$$\frac{18{,}290{,}000\ \frac{\text{l}}{\text{ha}}}{8{,}930\ \frac{\text{cuttings}}{\text{ha}}} = 2{,}048.15\ \frac{\text{l}}{\text{cutting}}$$

[7] Personal communication with Maynard-GWR, 2014

Electricity was used for irrigation, processing, and storage. The cost for pumping river water to the site was reported as 260 $\$\cdot ha^{-1}\cdot yr^{-1}$, with an electrical cost of 0.0415 $\$\cdot kWh^{-1}$. From this, the consumption of electricity was calculated as

$$\frac{260\,\frac{\$/ha}{year}}{0.0415\,\frac{\$}{kWh}} \text{ x } 9 \text{ years } = 56{,}385.5\ \frac{kWh}{ha}, \text{ then}$$

$$\frac{56{,}385.5\ \frac{kWh}{ha}}{(8{,}930\ \frac{cutting}{ha\cdot rotation} \text{ x } 3 \text{ rotations})} = 2.10\ \frac{kWh}{cutting}$$

Electricity used to operate a band saw to produce cuttings from branches was estimated from machine horsepower (1.5 hp) and processing time. The machine horsepower was determined from catalogs. The number of bundles processed was

$$\frac{8{,}930\ \frac{cutting}{ha}}{200\ \frac{cutting}{bundles}} = \text{approx.}\ 45\ \frac{bundles}{ha}$$

Each bundle produced approximately 200 cuttings, and it was assumed that each bundle required 2 minutes of machine time. Therefore, the energy required was

$$45\ \frac{bundles}{ha} \text{ x } 2\ \frac{minutes}{bundle} \text{ x } \frac{1\ hr}{60\ min} \text{ x } 1.5 \text{ hp x } \frac{0.746\ kW}{hp} = 1.68\ \frac{kWh}{ha}, \text{ then}$$

$$\frac{1.67\ \frac{kWh}{ha}}{8{,}930\ \frac{cuttings}{ha}} = 0.00019\ \frac{kWh}{cutting}$$

This is a very small amount, compared to 2.10 kWh per cutting for irrigation, so the assumptions made are not critical to the overall LCI.

Secondary data was utilized to determine the electricity consumption for storing the cuttings. The cuttings were refrigerated for approximately 3.5 months, and the electrical consumption was 14,000 kWh per month. The storage occurred in each of the three harvest years, and material from 315 ha was stored. Thus, the electrical consumption was

$$\frac{14{,}000\ \frac{\text{kWh}}{\text{month}}\ \text{x}\ 3.5\ \frac{\text{months}}{\text{yr}}}{315\ \text{ha}}\ \text{x}\ 3\text{yr}\ = 467\ \frac{\text{kWh}}{\text{ha}}\text{, then}$$

$$\frac{467\ \frac{\text{kWh}}{\text{ha}}}{8{,}930\ \frac{\text{cuttings}}{\text{ha}}} = 0.052\ \frac{\text{kWh}}{\text{cutting}}$$

No fertilizer or fungicides were applied during the plantation management phase. A summary of the final input values for the production of cuttings is shown in Table 4.1.

Table 4.1 Inputs for the production of one cutting

Processes	Inputs	Unit	Amount	Source*	SimaPro process
Land preparation	Herbicide	kg	0.000066	P	Glyphosate {RER}/production with US electricity/Alloc Def, U
	Diesel	l	0.001	P	Diesel, combusted in industrial equipment/US
Transportation	Diesel	tkm	0.00040	P	Transport, single unit truck, diesel powered, US
Plantation management	Water	l	2,070	P	Water, river, US
	Electricity for irrigation	kWh	2.12	p	Electricity, at grid, WECC, 2008/RNA U
	Electricity for processing	kWh	0.00019	S	Electricity, at grid, WECC, 2008/RNA U
	Electricity for storage	kWh	0.050	P	Electricity, at grid, WECC, 2008/RNA U
	Diesel	l	0.024	P	Diesel, combusted in industrial equipment/US
Land restoration	Diesel	l	0.0019	P	Diesel, combusted in industrial equipment/US

*P means primary data and S means secondary data.

4.1.2 Life cycle impact assessment – Cuttings

The LCIA (Table 4.2) shows that the use of electricity was the greatest contributor in four of five impact categories, with a contribution of 61% to 91%. The main utilization of electrical energy was for irrigation. The electricity source was modeled on the basis of Western Electricity Coordinating Council (WECC) data, which included electricity that is 32.25% from coal and 31.8% from natural gas. Other electricity came from hydro (22.24%), nuclear (9.4%), wind (2.35%), geothermal (1.93%), biomass (0.75%), and solar (0.11%) energy sources. A GWP of 1.30 kg CO_2 eq was reported for the production of each cutting. Smog (0.10 kg O_3 eq), acidification (0.012 kg SO_2 eq), and eutrophication (0.00021 kg N eq) produced per cutting were mainly due to electricity for irrigation. The utilization of chemical herbicide was the main contributor to ozone depletion.

Figure 4.1 shows this result in a network provided by SimaPro. The viewer can visualize the relative contributions of each material and process based on line width. The network shows that electricity contributes 14 times more to global warming than diesel does. The utilization of bituminous coal and natural gas are the main contributors to global warming potential.

Few researchers have reported the environmental impacts for the production of cuttings. Bacenetti et al. (2012) reported values of 1.06 or 4.70 kg CO_2 eq per cutting for 2- and 5-year rotations, respectively. The planting densities were 5560 and 1150 ha^{-1}, respectively. The values included planting, pest control, fertilization with nitrogen, and mechanical operations. The GWP in the present study, 1.30 kg CO_2 eq per cutting, fell within this range, but cannot be compared exactly because GWR used a 3-year rotation and a planting density of 8930 ha^{-1}. Network diagrams for other impact categories for the production of one cutting are shown in Figures E 1.1 to E 1.5 in Appendix E.

Table 4.2 Results of LCIA showing environmental impacts for the production of one cutting

Impact category	Unit (kg)	Total	Land preparation (%)		Transport in-site (%)	Plantation management (%)					Land restoration (%)
						Diesel	Electricity (%) used for				
			Herbicide	Diesel			Irrigation	Processing	Storage		Diesel
Ozone depletion	CFC-11 eq	1.73E-10	**89.6**	0.08	0.00	1.80	**8.19**	0.00	0.19		0.14
Global warming	CO_2 eq	1.30	0.06	0.24	0.00	**5.84**	**91.2**	0.01	2.15		0.46
Smog	O_3 eq	0.10	0.05	1.36	0.01	**32.7**	**61.9**	0.01	1.46		2.59
Acidification	SO_2 eq	0.012	0.04	0.38	0.00	**9.02**	**87.8**	0.01	2.07		0.71
Eutrophication	N eq	0.00021	3.78	1.24	0.01	**29.7**	**61.5**	0.01	1.45		2.35

Bold numbers mean that the input contribution was ≥5% in each impact category

LCIA results are reported with a maximum of 3 significant figures

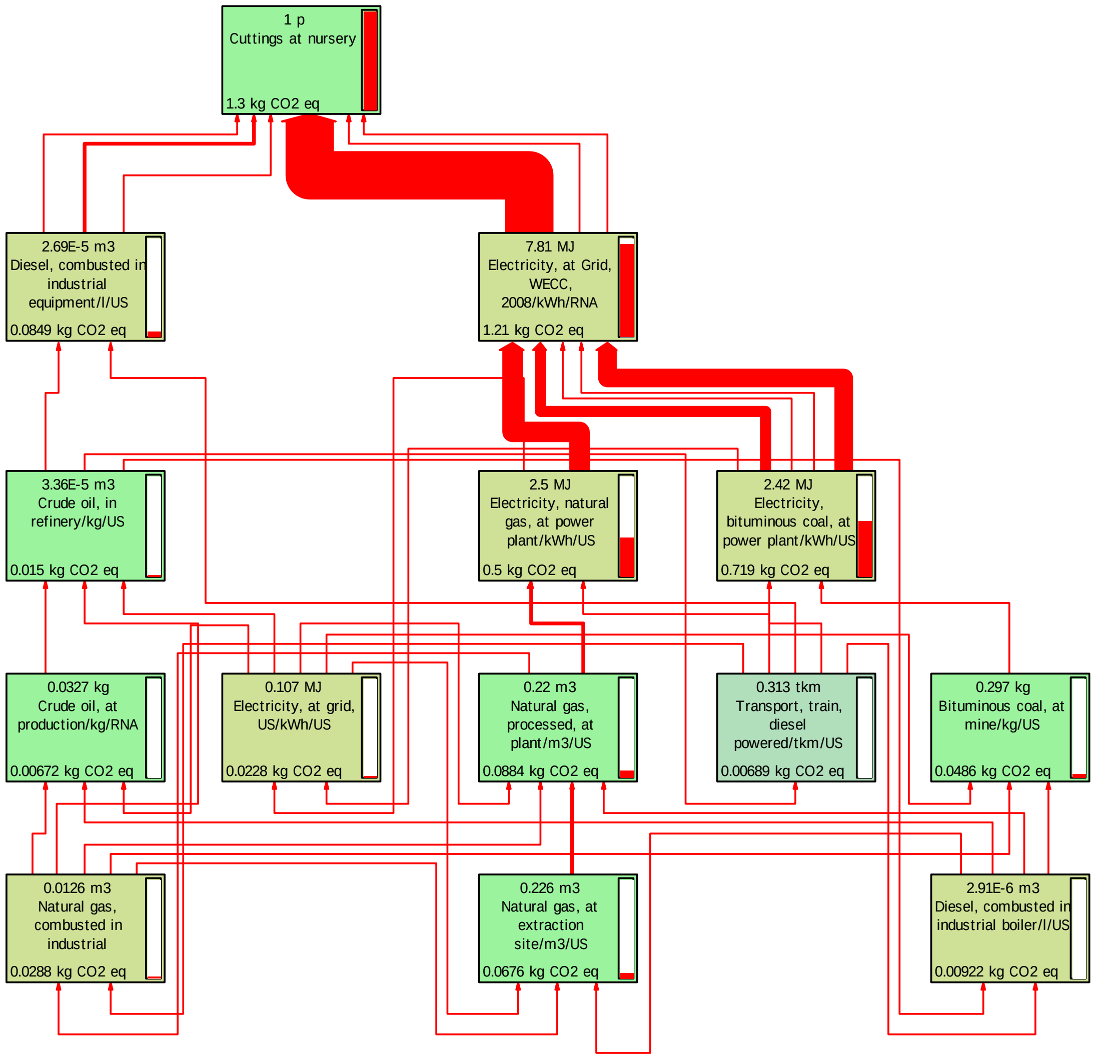

Figure 4.1 Network of global warming with characterization indicators for cuttings at nursery

4.1.3 Life cycle interpretation

Life cycle interpretation is a phase of LCA in which the findings of either the inventory analysis or the impact assessment or both are evaluated in relation to the defined goal and scope in order to reach conclusions and make recommendations (ISO, 2006a). The sensitivity analysis of cuttings was not part of the cutting interpretation because it was assumed that their growing condition was independent of each site, based on planting design, density, and silvicultural practices used in plantation management.

4.1.4 Energy use and water consumption

The energy needed to produce one cutting was 24.6 MJ (Table 4.3) or 264 MJ per kg of green cutting. According to the LCIA networks, coal and natural gas were used to produce electricity, and oil was used in the production of diesel combusted in industrial equipment.

Table 4.3 Breakdown of the energy sources for producing cuttings in nursery. Values reported per cutting.

	Fuel	HHV MJ· $Unit^{-1}$	MJ	%
Fossil fuel				
Coal	0.35 kg	27.8	9.63	39.1
Natural gas	0.23 m^3	38.4	8.69	35.3
Oil	0.03 kg	45.3	1.48	6.03
Fossil fuel - from Dummy process				
Petroleum			0.022	0.087
Tire-derived fuel			0.0002	0.0008
Unspecified			0.0007	0.0029
Non-fossil fuel				
Uranium	6.96E-06 kg	3.81E+05	2.65	10.8
Non-fossil fuel - from Dummy process				
Biomass			0.04	0.15
Wind			0.18	0.75
Geothermal			0.15	0.62
Hydropower			1.75	7.10
Solar			0.009	0.036
Photovoltaic			0.00002	0.0001
Total			**24.6**	100.00

The oil contribution was low 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 80.48% of energy consumed. Approximately 93% of raw energy contributions went to electricity for irrigation. This is evident in Table 4.2, where irrigation shows the largest contribution in four of five impact categories.

The water consumption was 2.07 $m^3 \cdot cutting^{-1}$ where 99.9% was provided from river.

4.1.5 Conclusions

The main contributor to the global warming impact indicator for the production of cuttings was the use of fossil fuel to produce electricity to operate pumps for irrigation. The environmental impacts and energy and water consumption to produce one cutting is important because the burdens will be carried forward to the plantations in which the cuttings are used. Each of the four sites in this study uses a different planting density, and the embodied energy and impacts categories reported for the production of cuttings will affect the biomass production in the following sections of this research.

4.2 Production of biomass in Site 1

The first two growing seasons at Site 1 produced a yield of 6.78 $BDmT \cdot ha^{-1}yr^{-1}$, assuming 100% moisture content (MC). The next harvest is scheduled for 2016. An assumption was made that additional harvests will occur in 2019 and 2022, after which the plantation's life will end. Future productivity was estimated by 3PG biomass simulator software. These assumptions and the model projections allow the plantation life span to be similar to Sites 3 and 4.

4.2.1 Life cycle inventory

Information for this site was obtained from the AHB-AFRI project[8] for data up to July, 2014. Data for the environmental consequences of materials input to the site were included in the libraries of SimaPro software (PhD version 8.0.3.14). A detailed accounting of data collected in a spreadsheet of Site 1 is shown in Appendix C1.

4.2.2 Biomass production

The amount of biomass harvested in 2013 (after 2 growing season), 13.56 $t{\cdot}ha^{-1}$, was provided by GWR. The biomass in future harvests (2016, 2019, 2022) was estimated using the 3-PG model (see Section 3.2.5), with the Jefferson area weather conditions (Figure 4.2a) and soil type. Profiles of stem mass and root mass are shown in Figure 4.2b and 4.2c, respectively. The yield for the three future harvests was obtained from the mass of stems (Figure 4.2 b) without foliage and is reported in Table 4.4.

[8] Advanced Hardwood Biofuels Northwest (AHB), USDA Agriculture and Food Research Initiative (http://hardwoodbiofuels.org)

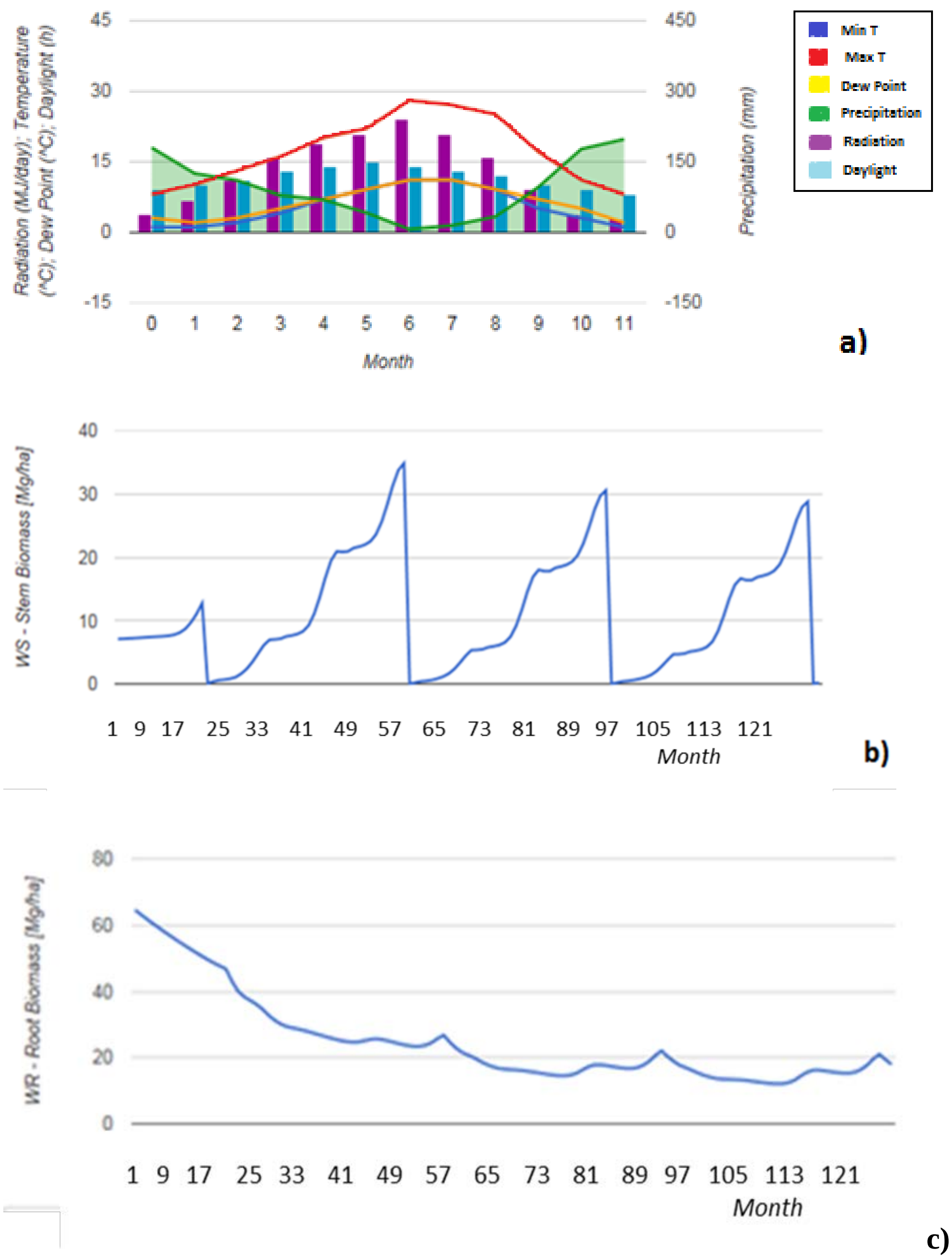

Figure 4.2 (a) Jefferson weather, (b) mass of stem, and (c) mass of roots variation at Site 1 (1 Mg = 1 ton).

Table 4.4 Yield of stem biomass estimated from 3-PG model

Year	Rotation years	Production Dry Ton ha^{-1}	Yield Dry Ton ha^{-1} yr^{-1}	Amount relative to 2013
2013	2	12.84	6.42	1
2016	3	34.95	11.65	1.82
2019	3	30.66	10.22	1.59
2022	3	28.86	9.62	1.50

The stem and foliage biomass yields estimated by 3PG after the first harvest are 6.42 and 2.40 $t{\cdot}ha^{-1}yr^{-1}$, respectively, or 8.82 $t{\cdot}ha^{-1}yr^{-1}$ combined. This is 30% greater than the 6.78 $t{\cdot}ha^{-1}{\cdot}yr^{-1}$ biomass yield (Stanton et al. 2013) of stem and foliage measured during 2 years of growth. Without foliage biomass, the biomass yield estimated by the model is 6.42, or 5.3% less than the measured biomass. Usually, the biomass for energy conversion utilized only stem wood, not foliage, and future estimation of biomass considered only stem wood. Also, the 3PG model estimate is for a single clone, which may not represent those in the plantation. The 11 clones in the plantation were selected to survive with minimum plantation management and no irrigation. Another factor that could be part of the uncertainty in the harvested amount is the estimated MC. The harvest was weighed green, and a higher estimate of MC could result in a lower estimate for dry biomass.

The mass of roots removed after the last harvest was 17.98 tons per hectare, based on the 3-PG model (Figure 4.2 c). This is 0.17 ton of roots per BDmT of stem biomass, based on 107.31 BDmT/ha harvested over the life of the plantation.

Off-site emissions were obtained from the SimaPro libraries to create a cradle-to-gate life cycle inventory. These included the USA Input Output Database System Expansion, USLCI, and an adapted database of Ecoinvent 3 and Ecoinvent.

4.2.3 Material and energy inputs

The materials and fuels required to produce 1 BDmT of biomass in Site 1 are shown by process in Table 4.5. No other on-site outputs were reported. Similarly, the plantation reported no emissions to air, water, or land.

Table 4.5 Inputs for production and SimaPro simulation of biomass in site 1. Values are per ton of biomass produced

Processes	Inputs	Unit	Amount	Source*	SimaPro process
Land preparation	Herbicide	kg	0.021	S	Glyphosate {RER}/production with US electricity/Alloc Def, U
	Diesel	l	0.21	P	Diesel, combusted in industrial equipment/US
Cutting	Cutting	p	33.42	P	
Transport from Boardman to Jefferson	Transportation	tkm	1.12	P	Transport, combination truck, diesel powered/US
Plantation management	Herbicide	kg	0.44	P	Glyphosate {RER}/production with US electricity/Alloc Def, U
	Diesel	l	1.36	S	Diesel, combusted in industrial equipment/US
Harvesting	Diesel	l	7.91	S	Diesel, combusted in industrial equipment/US
Land restoration	Herbicide	kg	0.021	P	Glyphosate {RER}/production with US electricity/Alloc Def, U
	Diesel	l	0.15	P	Diesel, combusted in industrial equipment/US
	Pesticide	kg	0.023	P	Pesticide, unspecified {RER}/production with US electricity/ Alloc Def, U

*P means primary data and S means secondary data.

The original values of the plantation are reported in Table C 1 in Appendix C1; however, some conversion was necessary to obtain the values shown in Table 4.5.

The plantation reported 2.24 kg of glyphosate and 0.04 $kg \cdot ha^{-1}$ of Oust applied during land preparation. This was converted as

$$\frac{2.24\ \frac{kg\ \ Glyphosate}{ha} + 0.04\frac{kg\ Ous}{ha}}{107.31\ \frac{BDmT}{ha}} = 0.021\ \frac{kg}{BDmT}$$

The plantation reported 22.7 $l \cdot ha^{-1}$ of diesel used in equipment during land preparation. This was converted as

$$\frac{22.70\frac{\mathrm{l}}{\mathrm{ha}}}{107.31\frac{\mathrm{BDmT}}{\mathrm{ha}}} = 0.21\ \frac{\mathrm{l}}{\mathrm{BDmT}}$$

The planting density was 3586 ha^{-1}. This was put on a biomass basis as follows:

$$\frac{3586\ \frac{\text{cuttings}}{\text{ha}}}{107.31\ \frac{\text{BDmT}}{\text{ha}}} = 33.42\ \frac{\text{cuttings}}{\text{BDmT}}$$

The distance from Boardman, where the cuttings were produced, to the plantation site was 360 km. In section 4.1.1, the green mass of a cutting was determined to be 0.093 kg, or 0.000093 tons. Transportation of cuttings was then determined to be

$$0.000093\ \frac{\text{GTon}}{\text{cutting}}\ \text{x}\ 33.42\ \frac{\text{trees}}{\text{BDmT}}\ \text{x}\ 360\ \text{km}\ = 1.12\ \frac{\text{tkm}}{\text{BDmT}}$$

Glyphosate was applied at a rate of 4.49 $kg \cdot ha^{-1}$ during year 1 and 2.24 $kg \cdot ha^{-1}$ during year 2. It was assumed that it would be applied at a rate of 4.49 $kg \cdot ha^{-1}$ for the remainder of the plantation's life, because this application rate most closely matches that recommended by the manufacturer. Oust was applied in year 3 at a rate of 0.04 $kg \cdot ha^{-1}$, and it was assumed that it would be applied in subsequent non-harvest years at the same rate. The amount applied during plantation management, on a basis of biomass produced, was then

$$(4.49\text{x}10 + 2.24)\frac{\text{kg Glyphosate}}{\text{ha}} + (0.04\text{ x }6)\frac{\text{kg Oust}}{\text{ha}} = 47.38\ \frac{\text{kg}}{\text{ha}}$$

$$\frac{47.38\ \frac{\text{kg}}{\text{BDmT}}}{107.31\ \frac{\text{BDmT}}{\text{ha}}} = 0.44\ \frac{\text{kg}}{\text{BDmT}}$$

The diesel consumption for plantation management was reported to be 6.48 $\text{l}\cdot\text{ha}^{-1}$ for the first year, 14.06 $\text{L}\cdot\text{ha}^{-1}$ for the second year, and 13.88 $\text{l}\cdot\text{ha}^{-1}$ for the third year. It was assumed for future years that 14.06 $\text{L}\cdot\text{ha}^{-1}$ had been consumed during the three harvest years due to the utilization of a mid-size tractor and 3-wheel agricultural sprayer, and that 13.88 $\text{L}\cdot\text{ha}^{-1}$ was consumed during growing periods, due to the utilization of a mid-size tractor and small tractor reported by the AFRI project.[9]. Thus, diesel consumption for plantation management was calculated as

$$(6.48 + 14.06\text{ x }3 + 13.88\text{ x }7) = 145.82\ \frac{\text{l}}{\text{ha}}$$

$$\frac{145.82\ \frac{\text{l}}{\text{ha}}}{107.31\ \frac{\text{BDmT}}{\text{ha}}} = 1.36\ \frac{\text{l}}{\text{BDmT}}$$

Diesel consumption for harvesting was reported as 143.61 L for the first harvest. This was 0.36 $\text{L}\cdot\text{t}^{-1}$ of biomass. It was assumed that a proportional amount of diesel would be required per ton of biomass in future harvests. This proportionality is obtained by the amount relative to 2013 shown in Table 4.4, so that

[9] Personal communication with Rich Schuren, GWR at September 23th, 2014.

$$(143.61 + 261.37 + 228.34 + 215.42) = 848.74\ \frac{\mathrm{l}}{\mathrm{ha}}$$

would be required for the four harvests during the plantation's life. On a basis of biomass, this is

$$\frac{848.74\ \frac{\mathrm{l}}{\mathrm{ha}}}{107.31\ \frac{\mathrm{BDmT}}{\mathrm{ha}}} = 7.91\ \frac{\mathrm{l}}{\mathrm{BDmT}}$$

It was assumed that 2.24 kg·ha^{-1} of herbicide was applied during land restoration. This assumption was based on the application frequency reported by the AFRI. Herbicide utilized in land restoration was calculated as follows:

$$\frac{2.24\ \frac{\mathrm{kg\ Glyphosate}}{\mathrm{ha}}}{107.31\ \frac{\mathrm{BDmT}}{\mathrm{ha}}} = 0.021\ \frac{\mathrm{kg\ Gly}}{\mathrm{BDmT}}$$

Based on information from the AFRI project, it was assumed that a large tractor and 3-wheel agricultural sprayer were used during land restoration. The AFRI project estimate for diesel was 16.28 l·ha^{-1}. Diesel consumption was then calculated as

$$\frac{16.28\ \frac{\mathrm{l}}{\mathrm{ha}}}{107.31\ \frac{\mathrm{BDmT}}{\mathrm{ha}}} = 0.15\ \frac{\mathrm{l}}{\mathrm{BDmT}}$$

Similarly, AFRI estimated pesticide use for land restoration at 2.51 kg of 2,4,D per ha, and pesticide use was calculated as follows:

$$\frac{2.51\ \frac{\mathrm{kg\ 2,4\ D}}{\mathrm{ha}}}{107.31\ \frac{\mathrm{BDmT}}{\mathrm{ha}}} = 0.023\ \frac{\mathrm{kg\ 2,4\ D}}{\mathrm{BDmT}}$$

The certainty of the data up to the July 2014 report during year 3 of the plantation life is high because detailed information was provided by AFRI. Future years are projected, however. Details of inputs to SimaPro are shown in Figure D1in Appendix D.

4.2.4 Life cycle impact assessment

Inputs were analyzed to identify unusual quantities that were not physically impossible or technically implausible. Results of LCI were also checked in quality and quantity to provide accurate information for the LCIA system analysis. In some cases inputs were compared with data in reported papers and in other cases inputs were compared with data from case studies. This analysis was developed to meet the goal and scope of the study.

The environmental impacts estimated using TRACI2.1 v1.01/US 2008 are shown in the Table 4.6. A 5% or greater contribution within an impact category is in bold.

Land preparation makes a minimal contribution to the impact indicators relative to the other processes. Similarly, the relative impacts of land restoration are small, except for ozone depletion due to herbicide use. Their small relative contributions are partly attributable to the processes being one time occurrences over the 11-year plantation life.

The production of cuttings has a large effect on most of the impact indicators, relative to the other processes. This is mainly due to the electricity used to pump water for irrigation. Acidification is also mainly attributable to electricity used to produce cuttings. The transportation of cuttings to the plantation also makes minimal relative contributions to the impacts (see inputs that affect LCIA network Figure E 2.2 in Appendix E).

Plantation management is the main contributor to ozone depletion and eutrophication, due to the distribution of chemicals in the site. The 88.6% contribution of plantation management to the ozone depletion impact indicator only indicates its relative contribution, not whether the value is of large or small magnitude (see network Figures E 2.1 and E 2.4 in Appendix E).

Harvesting has the largest contribution to the smog indicators, due to high diesel consumption (7.91 L per BDmT) compared with other processes. Similar to the herbicide contribution to ozone depletion, the 64% contribution of harvesting to the smog impact indicator only shows its relative contribution, not whether the value is of large or small magnitude (see network Figure E 2.3 in Appendix E).

4.2.5 Life cycle interpretation

Land preparation, plantation management, harvesting, and land restoration are under the control of management at Site 1. These on-site operations could be manipulated to minimize the environmental impacts. The steps to reduce the impact will vary by process. Production of cuttings and transportation are off-site and are not under the control of management.

The application of chemicals and consumption of diesel are the main on-site activities that produce environmental impacts in Site 1. A sensitivity analysis was applied to estimate the effects of changing the amounts used. To do this, chemicals and diesel use were changed, one at a time, by increasing or decreasing them by 10% in all processes in system boundary. The responses of the impact indicators are reported Table 4.7.

Table 4.6 Environmental impacts from Site 1

	Site processes		Land preparation (%)		Cutting (%)	Transport (%)	Plantation management (%)		Harvesting (%)	Land restoration (%)		
Impact category	Unit (kg)	Total	Herbicide	Diesel	Cutting	Transport	Herbicide	Diesel	Diesel	Herbicide	Diesel	Pesticide
Ozone depletion	CFC-11 eq	1.18E-06	4.23	0.00	0.49	0.00	**88.6**	0.01	0.09	4.23	0.00	2.29
Global warming	CO_2 eq	79.6	0.31	0.83	**54.4**	0.13	**6.48**	**5.39**	**31.4**	0.31	0.59	0.15
Smog	O_3 eq	17.1	0.09	1.70	**19.9**	0.10	1.90	**11.00**	**64.0**	0.09	1.21	0.04
Acidification	SO_2 eq	0.85	0.19	1.08	**45.9**	0.07	3.89	**7.02**	**40.8**	0.19	0.77	0.08
Eutrophication	N eq	0.092	2.81	0.60	**7.69**	0.04	**58.78**	3.87	**22.5**	2.81	0.43	0.48

Bold number means that input contribution is ≥ 5% in each impact category
LCIA results are reported with a maximum of 3 significant figures

Table 4.7 Percent change in impact indicators given a ±10% change in chemical application or diesel use in all on-site processes in Site 1

Input	Ozone depletion	Global warming	Smog	Acidification	Eutrophication
Herbicide and pesticide	**9.06** **-9.06**	0.66 -0.66	0.19 -0.19	0.40 -0.40	**5.92** **-5.92**
Diesel	0.61 -0.59	3.58 -3.8	**7.78** **-7.83**	4.98 -3.04	4.98 -2.45

Ozone depletion is very dependent on the amount of chemicals applied. Eutrophication follows a similar pattern. This analysis does not consider any interactions. For example, if the chemical application had been optimized to maximize yield in the base case, then any change, more or less, would affect yield. This would result in a greater increase in ozone depletion with an increase in chemical use and a smaller decrease in ozone depletion with a decrease in chemical use.

Changes to the amounts of chemicals did not greatly alter results of global warming, smog, and acidification. Changing the diesel use had the greatest effect on smog. Global warming, acidification, and eutrophication were also affected. Changing diesel use had a small effect on ozone depletion. Usually, machinery with high diesel efficiency is operated by trained personnel, so reducing diesel use in practice may be challenging.

The effect of biomass yield was analyzed by increasing and reducing biomass yield by 10%. The production was multiplying by 1.1 or 0.9. Table 4.8 shows that impact categories had behavior that was similar, but not the same. A 10% yield increase resulted in an average reduction of 9.08% in the impact indicators, and a 10% decrease in yield an average increase of 11.15% in the impact indicators. A higher sensitivity effect is produced by variation of biomass yield, and this had an important effect on apportioning environmental impacts.

Table 4.8 Response of impact indicators when biomass yield is changed by ±10%. Sensitivity analysis of biomass yield in Site 1

Impact category	Unit	Original	+10%	-10%
Ozone depletion	kg CFC-11 eq	1.18E-06	1.08E-06	1.32E-06
Global warming	kg CO_2 eq	79.55	72.34	88.40
Smog	kg O_3 eq	17.13	15.58	19.03
Acidification	kg SO_2 eq	0.85	0.77	0.94
Eutrophication	kg N eq	0.092	0.083	0.102
Percentage of change in category impact				
Ozone depletion	%		-9.12	11.24
Global warming			-9.07	11.11
Smog			-9.05	11.11
Acidification			-9.07	11.11
Eutrophication			-9.10	11.18
Average	%		**-9.08**	**11.15**

Impact categories do not perform the same with changes in inputs. These have been demonstrated by the greater effect of chemicals on ozone depletion and eutrophication than on other impact categories. Conversely, the variation of biomass yield modified the amount of diesel that affected global warming, smog, and acidification more than ozone and eutrophication. These reasons can explain why a sensitivity analysis of biomass yield does not act exactly the same in every category.

The sensitivity analysis of chemicals and diesel for site 1 are reported in Tables G 1.1 and G 2.2 in Appendix G.

4.2.6 Energy use and water consumption

Energy consumption in Site 1 is 1.38 GJ·BDmT^{-1}. This energy represents a consumption of 13.5 GJ·ha^{-1} yr^{-1} to produce 107.3 BDmT·ha^{-1} during 11 years of management. It is also important to emphasize that 87.5% of the energy comes from fossil fuels: 51.5% of natural gas and coal is used for electricity generation, 42% of oil is used for diesel that is combusted in machines such as tractors, and 6.5% of fossil fuels are used for the production of chemicals.

Table 4.9 Breakdown of the energy sources for Site 1. Values are per ton of biomass.

	Amount	HHV MJ·Unit^{-1}	MJ	%
Fossil fuel				
Coal	13.9 kg	27.8	387.8	28.1
Natural gas	8.91 m^3	38.4	341.9	24.7
Oil	10.6 kg	45.3	479.0	34.7
Fossil fuel - from Dummy process				
Petroleum			0.72	0.052
Tire derived fuel			0.0068	0.0005
Unspecified			0.063	0.0045
Non-fossil fuels				
Uranium	2.64E-04 kg	3.81E+05	100	7.29
Non-fossil fuel - from Dummy process				
Biomass			1.24	0.09
Wind			6.15	0.45
Geothermal			5.08	0.37
Hydropower			58.79	4.25
Solar			0.30	0.021
Photovoltaic			0.0017	0.0001
Total			**1,382**	100.00

The water consumption was 69.97 m^3·BDmT^{-1}, essentially all of which (99.96%) was river water for irrigating cuttings. Site 1 was not irrigated, making the percentage near

100%. To put the amount into perspective, it would be the equivalent of applying 7 cm of water per year to the plantation over its 11-year life. The electricity used to pump this water was 93.4% of the electricity used (obtained from global warming network for cuttings, Figure E 1.2, Appendix E) of the energy shown in Table 4.6.

4.2.7 Conclusions and recommendations

The production of cuttings that were placed on the site, plantation management, and harvesting produced greater environmental impacts compared to other operations. Cuttings were a major contributor to GWP and acidification because of the electricity for irrigation and the use of chemicals. Herbicide was a greater contributor to ozone depletion and eutrophication. Diesel contributed to smog during plantation management and harvesting. Harvesting accounted for 60% of the smog impact.
Sensitivity analysis showed that reducing chemical consumption and diesel use can reduce the environmental impacts significantly. A greater biomass yield reduces all impacts. Thus, more research is recommended to develop poplar clones that have a higher yield with less utilization of chemicals (herbicides and pesticides) and can be processed with less diesel.

4.3 Production of biomass in Site 2

The planting configuration used in Site 2 (Figure 4.3), using alternating inter-row distances and closer row spacing, could reduce canopy closure for this plantation and prolonged exposure to light would increase productivity in the earlier stages of growth after coppicing (Hant et al. 2014)

The application of herbicide during land preparation was done with a medium-sized tractor, and a large tractor was used for tilling. A tractor was used to apply herbicide and pesticide during plantation management. The New Holland 6080 forage harvester was used for the harvest and the land was restored by grinding the stumps and spreading for mulch.

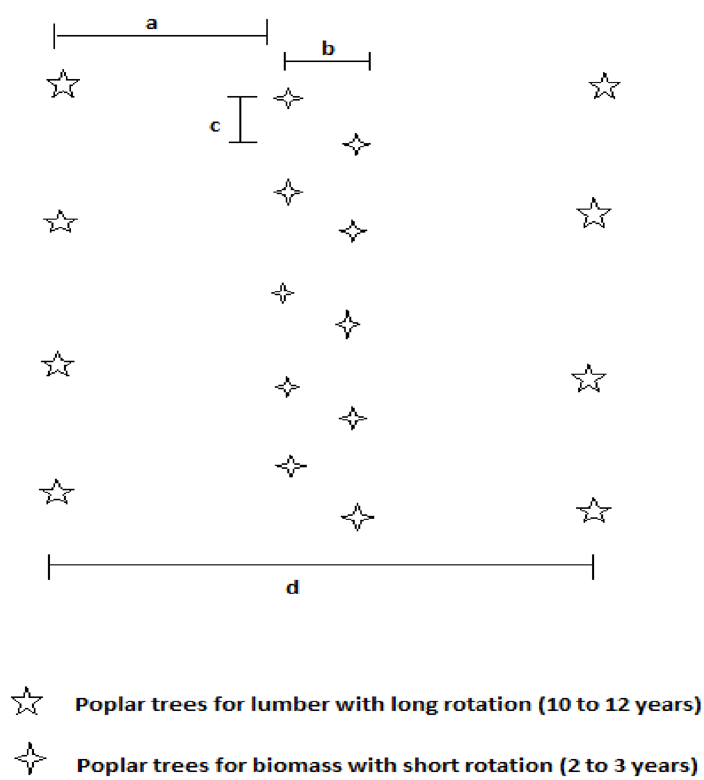

Figure 4.3 Planting design of cutting inter-cropping, site 2. The distances are: a = 3m, b = 0.3m, c = 1m, 1.1m, or 1.2m depending on the field, and d = 6m.

4.3.1 Life cycle inventory

Information for this site was obtained directly from the manager of GWR-Boardman. Data for the environmental consequences of materials input to the site were included from processes in the libraries of SimaPro (PhD version 8.0.3.14). The summary of collected data is shown in Table C 2 in Appendix C.

4.3.2 Biomass production

The first biomass harvest on Site 2 will occur in 2015 after three growing seasons. Rotations of three years were assumed for the next three harvests (2018, 2021, and 2024).

The site productivity and biomass growth were estimated with the 3-PG model (see Section 3.2.3) with the Boardman weather conditions (Figure 4.4 a) and soil type. The profile of stem mass is shown in Figure 4.4 b. Determination of yield from each harvest is reported in Table 4.10. The lifetime productivity of Site 2 was 152.43 BDmT·ha^{-1}, with a yield of 12.7 BDmT·ha^{-1}yr^{-1}.

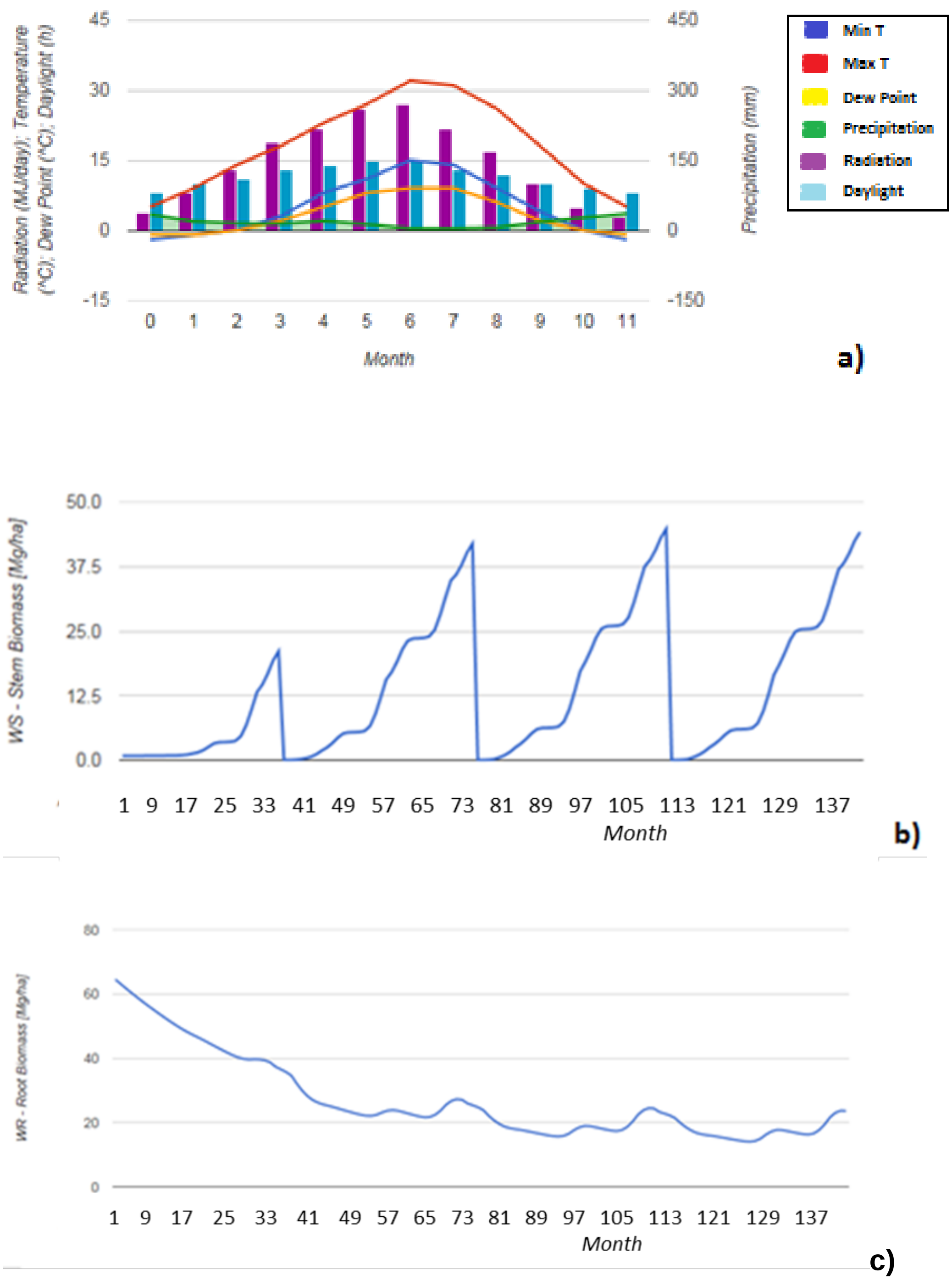

Figure 4.4 (a) Boardman weather, (b) Mass of stem, and (c) Mass of root variation at Site 2 (1 Mg = 1 ton).

Table 4.10 Biomass yield estimated by 3-PG model

Year	Rotation years	Production Dry Ton ha^{-1}	Yield Dry Ton ha^{-1} yr^{-1}	Amount relative to 2015
2015	3	21.21	7.07	1
2018	3	42.04	14.01	1.98
2021	3	44.89	14.96	2.11
2024	3	44.29	14.76	2.08

4.3.3 Material and energy inputs

The material and energy inputs entered into SimaPro are shown in Table 4.11. An image of the SimaPro model screen for Site 2 is shown in Figure D 3 in Appendix D.

Table 4.11 Inputs of biomass per bone dry ton produced in Site 2

Processes	Inputs	Unit	Amount	Source*	SimaPro process
Land preparation	Herbicide	kg	0.008	P	Glyphosate {RER}/production with US electricity/Alloc Def, U
	Diesel	l	1.24	P	Diesel, combusted in industrial equipment/US
Cutting	Cutting	p	3.08	P	
Plantation management	Electricity	kWh	14.88	S	Electricity, at Grid, WECC, 2008/RNA U
	Herbicide	kg	0.19	S	Glyphosate {RER}/production with US electricity/Alloc Def, U
	Water	l	472350	S	Water, river, US
	Diesel	l	1.01	S	Diesel, combusted in industrial equipment/US
	Pesticide	kg	0.11	S	2,4-diclhlorophenol {RER}/production/Allo c Def, U
Harvesting	Diesel	l	10.18	S	Diesel, combusted in industrial equipment/US
Land restoration	Diesel	l	0.11	P	Diesel, combusted in industrial equipment/US

*P means primary data and S means secondary data.

The original values obtained for Site 2 are reported in Appendix C, Figure C 2. Material and energy consumptions in future years were estimated based on the first year of plantation management. The SimaPro inputs shown in Table 4.11 were calculated as shown bellow.

Glyphosate (Credit Extra™) and SureGaurd™ were applied during land preparation. The total amount on a biomass basis was expressed as

$$\frac{1.17\ \frac{\text{kg Glyphosate}}{\text{ha}} + 0.05\ \frac{\text{kg SureGuard}}{\text{ha}}}{152.43\ \frac{\text{BDmT}}{\text{ha}}} = 0.008\ \frac{\text{kg}}{\text{BDmT}}$$

The plantation reported 189.5 $\text{l}\cdot\text{ha}^{-1}$ of diesel used in equipment during land preparation. This is converted to a biomass basis as

$$\frac{189.5\ \frac{\text{l diesel}}{\text{ha}}}{152.43\ \frac{\text{BDmT}}{\text{ha}}} = 1.24\ \frac{\text{l}}{\text{BDmT}}$$

The planting density reported was 470 cuttings per ha. This is converted in biomass basis as follows:

$$\frac{470\ \frac{\text{cutting}}{\text{ha}}}{152.43\ \frac{\text{BDmT}}{\text{ha}}} = 3.08\ \frac{\text{cuttings}}{\text{BDmT}}$$

Electricity was used to pump water from the river for irrigation. The site reported that the cost of electricity was \$260 $\text{ha}^{-1}\ \text{yr}^{-1}$ at a rate of \$0.0415 kWh^{-1}. From this, the consumption of electricity was calculated as

$$\frac{260\ \frac{\$}{\text{ha}\cdot\text{yr}}}{0.0415\ \frac{\$}{\text{kWh}}} = 6265\ \frac{\text{kWh}}{\text{ha}\cdot\text{yr}}$$

The system boundary included 315 ha within the 10,438.68 ha plantation or 3.02% of total surface. Therefore, the annual electricity consumption was 189.05 $\text{kWh}\cdot\text{ha}^{-1}\ \text{yr}^{-1}$. This was converted to biomass as follows:

$$\frac{189.05\ \frac{\text{kWh}}{\text{ha}\cdot\text{yr}}\ \text{x}\ 12\ \text{yr}}{152.43\ \frac{\text{BDmT}}{\text{ha}}} = 14.88\ \frac{\text{kWh}}{\text{BDmT}}$$

Glyphosate was applied during plantation management as a rate of 3.38 kg·ha^{-1} during the first year and 2.25 kg·ha^{-1} during the second and third years of each harvest cycle. It was assumed that this pattern would continue for the 12-year plantation life except for the last year, when only 1.13 kg·ha^{-1} would be applied due to proximity of the final harvest[10]. The amount applied on a biomass basis produced was then,

$$(3.38\ \text{x}\ 4 + 2.25\ \text{x}\ 7 + 1.13)\frac{\text{kg Glyphosate}}{\text{ha}} = 30.4\ \frac{\text{kg Glyphosate}}{\text{ha}}$$

$$\frac{30.4\ \frac{\text{kg Glyphosate}}{\text{ha}}}{152.43\ \frac{\text{BDmT}}{\text{ha}}} = 0.20\ \frac{\text{kg}}{\text{BDmT}}$$

Based on data obtained by the company, three years of coppice requires approximately 1800 mm of water or 0.6 meter water per year. This amount was placed on a biomass basis as follows:

$$0.6\ \frac{\text{m}}{\text{yr}}\text{x}\ 10{,}000\ \frac{\text{m}^2}{\text{ha}}\ \text{x}\ 12\ \text{yr} = 72{,}000\ \frac{\text{m}^3}{\text{ha}}$$

$$\frac{72000\ \frac{\text{m}^3}{\text{ha}}}{152.43\ \frac{\text{BDmT}}{\text{ha}}} = 472.35\ \frac{\text{m}^3}{\text{BDmT}}\ \text{or}\ 472{,}350\ \frac{\text{l}}{\text{BDmT}}$$

The diesel consumption for plantation management was estimated to be 13.88 l·ha^{-1} for the first 11 years, and 1.48 l·ha^{-1} for the last year when the final harvested was planned, based on AHB-AFRI Sustainability Metric Spreadsheet (2014)[11]. An even diesel

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[10] Personal communication with Brian Stanton-Chief Science Officer and Carlos Gantz -Tree improvement and nurseries and managing Director, Biological Research Group of GWR. Email contact on October 1st, 2014.

[11] Personal communication with Rich Schuren, GWR. Email contact on September 23th, 2014

consumption was assumed during a long period, due to the utilization of a mid-size tractor and a small tractor, as reported by the AFRI project. Then, diesel consumption for management was calculated as

$$(13.88 \text{ x } 11 + 1.48)\frac{\text{l}}{\text{ha}} = 154.16 \frac{\text{l}}{\text{ha}}$$

$$\frac{154.16 \frac{\text{l}}{\text{ha}}}{152.43 \frac{\text{BDmT}}{\text{ha}}} = 1.01 \frac{\text{l}}{\text{BDmT}}$$

Pesticide, 2,4 D, was utilized during plantation management, and the estimated amount was obtained by AFRI project. This was 1.87 $kg_{2,4\,D}$ ha^{-1} during the first year and 1.24 kg 2,4 D·ha^{-1} during the second and third year of growth. It was assumed at 0.62 kg 2,4 D·ha^{-1} during the year of final harvest. The pesticide application on a biomass basis was calculated as follows:

$$(1.87 \text{ x } 4 + 1.24 \text{ x } 7 + 0.62)\frac{\text{kg}_{2,4\text{ D}}}{\text{ha}} = 16.78 \frac{\text{kg}_{2,4\text{ D}}}{\text{ha}}$$

$$\frac{16.78 \frac{\text{kg}_{2,4\text{ D}}}{\text{ha}}}{152.43 \frac{\text{BDmT}}{\text{ha}}} = 0.11 \frac{\text{kg}_{2,4\text{ D}}}{\text{BDmT}}$$

Diesel consumption for the first harvest was estimated as 216.03 l·ha^{-1}, and a proportional relation between the amount of biomass harvested and diesel consumption was assumed for future harvests. This proportionality is obtained by the amount relative to 2015 shown in Table 4.10. Then,

$$(216.03 + 428.19 + 457.22 + 451.12)\frac{\text{l}}{\text{ha}} = 1552.56 \frac{\text{l}}{\text{ha}}$$

would be required for the four harvests during the plantation life. On a biomass basis the consumption of diesel would be

$$\frac{1552.56\ \frac{\mathrm{l}}{\mathrm{ha}}}{152.43\ \frac{\mathrm{BDmT}}{\mathrm{ha}}} = 10.18\ \frac{\mathrm{l}}{\mathrm{BDmT}}$$

Finally, the diesel consumption for grinding stumps during land restoration was estimated to be 17.03 $\mathrm{l \cdot ha^{-1}}$. This estimate was based on data reported by the site manager[12]. On a biomass basis, this would be

$$\frac{17.03\ \frac{\mathrm{l}}{\mathrm{ha}}}{152.43\ \frac{\mathrm{BDmT}}{\mathrm{ha}}} = 0.11\ \frac{\mathrm{l}}{\mathrm{BDmT}}$$

4.3.4 Life cycle impact assessment

The results were checked and the environmental impacts (Table 4.12) estimated in a manner similar to that described in section 4.2.4 for Site 1. Environmental impacts data are reported in Table F 2, Appendix F.\

Harvesting is the process with the highest contribution to environmental impact. It makes up 43% to 77% of the contribution to global warming, smog, acidification, and eutrophication (Table 4.12). Consumption of diesel is the main reason for this behavior.

Land preparation has a lesser effect on the impact indicators due to lower diesel consumption. Herbicide use makes minimal contributions. However, herbicide has the highest relative impact in ozone depletion in plantation management.

[12] Personal communication with Mr. Luke Maynar, GWR. Email June 1st, 2014

Table 4.12 Environmental impacts from Site 2

Site processes			Land preparation (%)		Cutting (%)	Plantation management (%)				Harvest-ing (%)	Land restoration (%)
Impact category	Unit (kg)	Total	Herbi-cide	Diesel	Cuttings	Electricity	Herbi-cide	Diesel	Pesti-cide	Diesel	Diesel
Ozone depletion	CFC-11 eq	6.05E-07	3.16	0.03	0.09	0.02	**75.00**	0.02	**21.5**	0.22	0.00
Global warming	CO2 eq	54.7	0.17	**7.15**	**7.29**	**15.2**	4.07	**5.82**	1.05	**58.7**	0.63
Smog	O3 eq	18.3	0.03	**9.38**	1.71	2.41	0.77	**7.64**	0.20	**77.0**	0.83
Acidification	SO2 eq	0.67	0.09	**8.05**	**5.32**	**10.6**	2.11	**6.55**	0.46	**66.1**	0.71
Eutrophication	N eq	0.061	1.62	**5.34**	1.07	1.50	**38.4**	4.35	3.49	**43.8**	0.47

Bold numbers mean that input contribution is ≥ 5% in each impact category

LCIA results are reported with a maximum of 3 significant figures

In plantation management, electricity also has a high relative contribution to global warming and acidification impact categories, due to the use of fossil fuels in its generation (see network in Figures E 3.1, E 3.2 and E 3.4 in Appendix E). Land restoration makes minimal contributions to the impacts indicators relative to the other processes.

4.3.5 Life cycle interpretation

Land preparation, plantation management, harvesting, and land restoration are under the control of the manager at Site 2. These on-site operations could be manipulated to minimize the environmental impacts. The steps to reduce impacts will vary by process. The production of cuttings is developed at this site, and is also under control of the site manager.

The application of chemicals and consumption of diesel are the main activities that produce environmental impacts at Site 2. Sensitivity analyses for the impact responses to these factors were done four ways. First, chemical amounts were increased or decreased by 10% in all processes (Line 1 in Table 4.13). Second, herbicide was increased or decreased by 10% for plantation management only (Line 2, Table 4.13).Third, diesel consumption was increased or decreased by 10% in all processes (Line 3, Table 4.13). Finally, diesel consumption was increased or decreased by 10% for only the harvesting process.

Table 4.13 Percent change in impact indicators given a ±10% change of chemical application or diesel use in on-site in Site 2

Input	Ozone depletion	Global warming	Smog	Acidification	Eutrophication
Herbicide and pesticide in all processes	**10.16** **-10.35**	0.54 -0.55	0.10 -0.10	0.27 -0.27	4.52 -4.55
Herbicide in plantation management	**7.89** **-7.89**	0.43 -0.43	0.08 -0.08	0.22 -0.22	4.04 -4.04
Diesel in all processes	0.03 -0.03	**7.20** **-7.21**	**9.46** **-9.47**	**8.11** **-8.12**	**5.38** **-5.39**
Diesel in harvesting	0.02 -0.02	**5.88** **-5.88**	**7.72** **-7.72**	**6.62** **-6.62**	4.39 -4.39

Changes in chemical application had more impact on ozone depletion and eutrophication than global warming, smog, and acidification. The changes in the chemical and diesel inputs directly affected each impact category; that may help to make the decision to reduce chemical and diesel use to improve environmental impacts. This would be beneficial not only for the environmental aspects.

The effect of ± 10% change in biomass yield on the impacts was also analyzed. A change in biomass yield produced new inputs that were included in the SimaPro model in order to determine their effect on the environmental impacts. An increase in biomass yield resulted in an average reduction of 8.2% in the impact indicators and a decrease of 12.07%.

Table 4.14 Response of impact indicators when biomass yield is changed by ±10%. Sensitivity analysis of biomass yield in Site 2

Impact category	Unit	Original	+10%	-10%
Ozone depletion	kg CFC-11 eq	6.05E-07	5.66E-07	6.90E-07
Global warming	kg CO_2 eq	54.74	49.88	60.92
Smog	kg O_3 eq	18.32	16.67	20.35
Acidification	kg SO_2 eq	0.67	0.61	0.75
Eutrophication	kg N eq	0.06	0.06	0.07
Determination of category impact effects				
Ozone depletion	%		-6.33	14.03
Global warming			-8.88	11.28
Smog			-8.99	11.12
Acidification			-8.95	11.19
Eutrophication			-7.63	12.75
Average	%		**-8.16**	**12.07**

The sensitivity analyses of chemicals and diesel for Site 2 are reported in Tables G 2.1 to G 2.4 in Appendix G.

4.3.6 Energy and water consumption

The raw energy consumption is shown in Table 4.15. Energy produced from fossil fuels accounted for 93.41% of energy consumed. Energy consumption for Site 2 was 0.88 GJ per BDmT; and 11.05 $GJ \cdot ha^{-1}yr^{-1}$ for 152.43 BDmT per ha produced during 12 years. Energy was used for production of cuttings, irrigation of river water during plantation management, and harvesting.

Table 4.15 Breakdown of the energy sources for site 2. Values are per ton of biomass.

	Amount	HHV MJ ·Unit^{-1}	MJ	%
Fossil fuel				
Coal	5.01 kg	27.8	139	15.9
Natural gas	3.32 m^3	38.4	127	14.5
Oil	12.2 kg	45.3	552	63.0
Fossil fuel - from Dummy process				
Petroleum			0.21	0.024
Tire derived fuel			0.0020	0.0002
Unspecified			0.088	0.0101
Non-fossil fuel				
Uranium	9.38E-05 kg	3.81E+05	35.75	4.07
Non-fossil fuel - from Dummy process				
Biomass			0.37	0.04
Wind			1.84	0.21
Geothermal			1.53	0.17
Hydropower			17.9	2.04
Solar			0.09	0.010
Photovoltaic			0.0015	0.0002
Total			**877**	100.00

The water consumption (478.67 $m^3 \cdot BDmT^{-1}$) was determined from the inventory analysis provided by SimaPro. This is equivalent to 600 mm per year of rainfall. The on-site water consumption was 472.28 $m^3 \cdot BDmT^{-1}$, 98.67% of the total water use, 99.99% of this for irrigation. The balance, 6.38 $m^3 \cdot BDmT^{-1}$ (1.33%) was off-site.

There was particular interest in knowing the energy and water consumption at Site 2 for drip irrigation, given that it is one of the biggest poplar plantations in the Pacific Northwest.

4.3.7 Conclusions and recommendation

Poplar biomass at Site 2 produced environmental impacts mainly due to diesel consumption in the harvesting process. This accounted for 77% of the smog impact indicator. Electricity consumption contributed to GWP and acidification during plantation management.

Based on a sensitivity analysis, lower diesel consumption and higher biomass yield could reduce the environmental impacts significantly. A greater biomass yield reduces all impacts. More research is recommended to develop high-yield poplar clones that thrive with lower herbicide and pesticide uses and that might be processed with less diesel in order to reduce GWP to less than 50 kg CO_2 eq per ton.

4.4 Production of biomass in Site 3

4.4.1 Life cycle inventory

On-site data was obtained from the Metropolitan Wastewater Management Commission (MWMC) site manager. Off-site environmental burdens were obtained from the libraries of SimaPro software (PhD version 8.0.3.14). The data is shown in Table C 3, Appendix C.

4.4.2 Biomass production

The amount of biomass harvested in 2013 was 12.60 $t \cdot ha^{-1}$. Chips from stems, hog fuel from branches and foliage, and compost from stumps were produced. The chips and hog fuel totaled 125.97 BDmT per ha. This was 90% of the site's production, 46% as chips and 44% as hog fuel. Stumps removal produced 13.29 BDmT per ha, that was 10% of the site's production.

4.4.3 Material and energy inputs

All inputs of Site 3 are reported in Table 4.16. The SimaPro screen is reproduced in Figure D 4, Appendix D. Site 3 is different from the other sites in that biosolids were used as a partial substitute for inorganic fertilizer. The biosolids inputs were modeled as dummy processes because they were by-products of wastewater treatment plant that had not burdens. The amount of water reported in Table 4.16 is half of the total amount reported in Table C3, Appendix C because half of water was removed to obtain dried biosolids.

Table 4.16 Inputs for production of biomass in site 3. Amounts are per ton of biomass produced.

Processes	Inputs	Unit	Amount	Source*	SimaPro process
Land preparation	Diesel	l	0.31	P	Diesel, combusted in industrial equipment/US
Cutting	Cutting	p	4.39	P	
Transport from Boardman to Eugene	Transportation	tkm	0.18	P	Transport, combination truck, diesel powered/ US
Plantation management	Wet biosolids	ton	0.39	P	Wet biosolids-Dummy process
	Dry biosolids	ton	0.39	P	Dried biosolids-Dummy process
	Water	l	66937.91	P	Water, river, US
	Electricity	kWh	9.25	P	Electricity, at Grid, WECC, 2008/RNA U
	Inorganic fertilizer	kg	0.36	P	Nitrogen fertilizer, production mix, at plant/US
	Diesel	l	12.5	P	Diesel, combusted in industrial equipment/US
Harvesting	Diesel	l	11.44	S	Diesel, combusted in industrial equipment/US
Land restoration	Diesel	l	4.9	S	Diesel, combusted in industrial equipment/US

*P means primary data and S means secondary data.

The original values of the plantation are reported in Appendix C3. To convert inputs in biomass basis needed some calculations that are shown bellow

The plantation reported diesel consumption of 38.80 $l \cdot ha^{-1}$ for land preparation. Expressing this value in biomass basis was

$$\frac{38.80\ \frac{\mathrm{l}}{\mathrm{ha}}}{125.97\ \frac{\mathrm{BDmT}}{\mathrm{ha}}} = 0.31\ \frac{\mathrm{l}}{\mathrm{BDmT}}$$

The reported planting density was 553 cutting per ha. Then

$$\frac{553\ \frac{\mathrm{cuttings}}{\mathrm{ha}}}{125.97\ \frac{\mathrm{BDmT}}{\mathrm{ha}}} = 4.39\ \frac{\mathrm{cuttings}}{\mathrm{BDmT}}$$

The distance from the nursery site to Site 3 was 436 km. The green mass of each cutting was 0.000093 tons. Transportation of cuttings was determined as

$$0.000093\ \frac{\mathrm{green\ Ton}}{\mathrm{cutting}} \mathrm{x}\ 4.39\ \frac{\mathrm{cuttings}}{\mathrm{BDmT}}\ \mathrm{x}\ 436\ \mathrm{km} = 0.18\ \frac{\mathrm{t} \cdot \mathrm{km}}{\mathrm{BDmT}}$$

Biosolids amounts applied were applied irregularly during the plantation's life: 44.60 t in 2004, 534.6 t in 2006, 502.1 t in 2007, 481.00 t in 2008, 349.5 t in 2010, 51 t in 2012, and 108.00 t in 2001. The total applied on a biomass basis was

$$\frac{(44.60 + 534.60 + 502.10 + 481.00 + 349.50 + 51.00 + 108.00)\ \mathrm{dry\ ton}}{21.05\ \mathrm{ha}} = 98.37\ \frac{\mathrm{dry\ ton}}{\mathrm{ha}}$$

$$\frac{98.37\ \frac{\mathrm{dry\ ton}}{\mathrm{ha}}}{125.97\ \frac{\mathrm{BDmT}}{\mathrm{ha}}} = 0.78\ \frac{\mathrm{dry\ ton}}{\mathrm{BDmT}}$$

The biosolids were applied in both wet and dried states and the assumption was made that this was done in equal parts so that 0.39 $t \cdot BDmT^{-1}$ were applied at 3.5% solids.

Water was added to the other half of the biosolids to change its solids content from 3.5% to 0.5%. The amount of water used to dilute the biosolids was

$$(3{,}822{,}857 + 45{,}822{,}857\ 43{,}037{,}143 + 41{,}228{,}571 + 29{,}957{,}143 + 4{,}371{,}429 + 19{,}257{,}143)\ \mathrm{l} = 354{,}994{,}285.7\ \mathrm{l}$$

$$\frac{177{,}497{,}143\ \mathrm{l}}{21.05\ \mathrm{ha}} = 8{,}432{,}168\ \frac{\mathrm{l}}{\mathrm{ha}}$$

$$\frac{16{,}864{,}336.61\ \frac{\mathrm{l}}{\mathrm{ha}}}{125.97\ \frac{\mathrm{BDmT}}{\mathrm{ha}}} = 66{,}938\ \frac{\mathrm{l}}{\mathrm{BDmT}}$$

Electricity to pump biosolids was obtained on the basis of operating two 75 hp pumps for 1,050 hr per season, which means 368.15 kWh · ha^{-1} for the whole plantation. The distributions of biosolid and water over 7 years were based on their total amount applied per year. The total electricity was then

$$(25.10 + 300.81 + 282.53 + 270.65 + 196.66 + 28.70 + 60.77)\frac{\mathrm{kWh}}{\mathrm{ha}} = 1165.22\ \frac{\mathrm{kWh}}{\mathrm{ha}}$$

$$\frac{1165.22\ \frac{\mathrm{kWh}}{\mathrm{ha}}}{125.97\ \frac{\mathrm{BDmT}}{\mathrm{ha}}} = 9.25\ \frac{\mathrm{kWh}}{\mathrm{BDmT}}$$

Application of fertilizer was reported as nitrogen. It was applied in 2006, 2007, 2008, 2009, 2012, and 2013 in the amounts appearing in the following equation. The amounts were placed on a biomass basis as follows

$$(1.60 + 15.68 + 2.46 + 4.59 + 12.67 + 9.01)\frac{\mathrm{kg\ N}}{\mathrm{ha}} = 46.01\frac{\mathrm{kg\ N}}{\mathrm{ha}}$$

$$\frac{46.01\frac{\mathrm{kg\ N}}{\mathrm{ha}}}{125.97\ \frac{\mathrm{BDmT}}{\mathrm{ha}}} = 0.36\ \frac{\mathrm{kg\ N}}{\mathrm{BDmT}}$$

The diesel consumption for plantation management was reported to be 5074.96 l in 2004, 6481.28 L in 2006, 3485.23 L in 2007, 4708.08 L in 2008, 4096.66 L in 2010, 4035.49 L in 2012, and 5258.39 L in 2013. It was converted to a biomass basis as

$$\frac{33{,}140.09\ \text{L}}{21.05\ \text{ha}} = 1{,}574.35\ \frac{\text{L}}{\text{ha}}$$

$$\frac{1{,}574.35\ \frac{\text{L}}{\text{ha}}}{125.97\ \frac{\text{BDmT}}{\text{ha}}} = 12.5\ \frac{\text{L}}{\text{BDmT}}$$

Diesel use of 43,350.06 L was reported for harvesting and land restoration. It was assumed that the harvesting accounted for 70% and land restoration 30% of the reported value. The diesel use for harvesting was

$$(43{,}350.06\ \text{x}\ 0.7)\text{L} = 30{,}345.04\ \text{L}$$

$$\frac{30{,}345.04\ \text{L}}{21.05\ \text{ha}} = 1{,}441.56\ \frac{\text{L}}{\text{ha}}$$

$$\frac{1{,}441.56\ \frac{\text{L}}{\text{ha}}}{125.97\ \frac{\text{BDmT}}{\text{ha}}} = 11.44\ \frac{\text{L}}{\text{BDmT}}$$

Similarly, diesel consumption for land restoration was

$$(43{,}350.06\ \text{x}\ 0.3)\text{L} = 13{,}005.02\ \text{L}$$

$$\frac{13{,}005.02\ \text{L}}{21.05\ \text{ha}} = 617\ \frac{\text{L}}{\text{ha}}$$

$$\frac{617\ \frac{\text{L}}{\text{ha}}}{125.97\ \frac{\text{BDmT}}{\text{ha}}} = 4.9\ \frac{\text{L}}{\text{BDmT}}$$

The biosolids nutrient concentration (MWMC, 2001) was used to estimate the amount of nitrogen in biosolids. The sum of the total Kjeldahl nitrogen, and nitrate + nitrite nitrogen was 4.85% of the biosolids dry weight, where 3.15% corresponded to organic nitrogen

From the total amount of nitrogen calculated applied (46.01 kg $\text{N}\cdot\text{ha}^{-1}$) and the total amount of biosolids applied (98.38 ton $\cdot\text{ha}^{-1}$), the total amount of nitrogen applied over 10 years was

$$98.38\ \frac{\text{dry ton}_{\text{Biosolids}}}{\text{ha}}\ \text{x}\ 0.0315\ \frac{\text{ton N}}{\text{dry ton}_{\text{Biosolids}}} = 3.098\ \frac{\text{ton N}}{\text{ha}}\ \text{or}\ 3{,}098\ \frac{\text{kg N}}{\text{ha}}$$

$$(3{,}098 + 46.01)\frac{\text{kg N}}{\text{ha}} = 3{,}144\ \frac{\text{kg N}}{\text{ha}}$$

$$\frac{3{,}144\,\frac{\text{kg N}}{\text{ha}}}{125.97\ \frac{\text{BDmT}}{\text{ha}}} = 24.96\ \frac{\text{kg N}}{\text{BDmT}}$$

MWMC reported that the nutrient content of the biosolids remained reasonably constant, but frequent monitoring is important to determine the nutrient content for land application loading calculations.

4.4.4 Life cycle impact assessment

The LCIA results are shown for each impact category in Table 4.17. Complete data is reported in Table F 4, Appendix F.

Diesel consumption during plantation management, harvesting and land restoration has the largest effect in all impact categories. The most affected is smog due to due to high diesel consumption of 12.5, 11.44, and 4.9 l·BDmT^{-1}, respectively (Figure E 4.3, Appendix E).

Land preparation and transportation process make minimal contributions to the environmental impacts, relative to the other processes. Their small relative contributions are partly attributable to the fact that they are one-time occurrences over the 10-year plantation lifespan.

The production of cuttings accounts for 15.6% of the ozone depletion due to the application of herbicide during land preparation. The application of fertilizer in plantation management processes accounted for 5.7%. However, like smog, diesel consumed during plantation management, harvesting, and land restoration affect this ozone most, mainly due to fuel burned on machinery (Figure E 4.1, Appendix E).

4.4.5 Life cycle interpretation

Land preparation, plantation management, harvesting, and land restoration are under the control of management at Site 3. These on-site operations could be manipulated to minimize the environmental impacts. The steps needed to reduce the impact will vary by process. The production of cuttings and transportation are off-site and not under the control of the manager.

Diesel consumption is the main on-site activity that produces environmental impacts. Sensitivity analyses were done to estimate the effects of increasing or decreasing the amount of diesel used in different processes by10% on the impacts. This was first done for diesel in all processes (line 1 in Table 4.18). It was then done for plantation management only (line 2), and finally for harvesting only (line 3). Sensitivity analysis calculations of diesel are reported in Tables G 3.1, G 3.2, and G 3.3 in Appendix G.

Table 4.17 Environmental impacts from Site 3

			Land preparation (%)	Cutting (%)	Transport (%)	Plantation management (%)			Harvesting (%)	Land restoration (%)
Impact category	Unit (kg)	Total	Diesel	Cuttings	Transport	Electricity	Fertilizer	Diesel	Diesel	Diesel
Ozone depletion	CFC-11 eq	4.40E-09	0.80	**15.6**	0.01	1.27	**5.69**	**33.2**	**30.4**	**13.0**
Global warming	CO2 eq	93.1	0.91	**5.50**	0.02	4.98	0.68	**38.1**	**34.9**	**14.9**
Smog	O3 eq	37.0	1.01	1.09	0.01	0.67	0.02	**42.1**	**38.6**	**16.5**
Acidification	SO2 eq	1.24	0.95	3.71	0.01	3.24	0.52	**39.7**	**36.3**	**15.6**
Eutrophication	N eq	0.070	1.01	1.19	0.01	0.73	0.09	**42.0**	**38.5**	**16.5**

Bold numbers mean that input contribution is ≥ 5% in each impact category

LCIA results are reported with a maximum of 3 significant figures

Table 4.18 Percent change in impact indicators given a ±10% change in diesel use in all on-site processes in Site 3.

Inputs	Ozone depletion	Global warming	Smog	Acidification	Eutrophication
Diesel in all processes	**8.33** **-8.31**	**8.92** **-8.83**	**9.81** **-9.80**	**9.27** **-9.21**	**9.79** **-9.77**
Diesel for Plantation Management	3.59 -3.57	3.85 -3.77	4.22 -4.20	4.00 -3.94	4.21 -4.20
Diesel for harvesting	3.27 -3.25	3.52 -3.43	3.85 -3.84	3.65 -3.59	3.84 -3.83

Impact categories are very dependent on the amount of diesel consumed when all processes are considered, and less so when the amount was changed in individual processes. Based on these results, it is recommended that machinery utilized during the processes be carefully chosen, so that it is fuel efficient to minimize diesel use.

The effect of biomass yield was analyzed by increasing and reducing biomass yield by 10%. Change in biomass yield started with the modification of inputs in the spreadsheet that contains inputs of Site 3 (Table C 3, Appendix C). Increasing production 10% produced more apportioning of inputs, and then lower inputs contributed to a reduction of environmental impacts. Similarly, a reduction of production, with its effect on biomass yield, increased the apportioning of inputs negatively, and that showed an increment of environmental impacts. These changes in impact categories are shown in Table 4.19.

Table 4.19 Response of impact indicators when biomass yield is changed by ±10%. Sensitivity analysis of biomass yield in Site 3.

Impact category	Unit	Original	+10%	-10%
Ozone depletion	kg CFC-11 eq	4.40E-09	4.00E-09	4.90E-09
Global warming	kg CO_2 eq	93.14	84.71	103.58
Smog	kg O_3 eq	37.00	33.65	41.14
Acidification	kg SO_2 eq	1.24	1.12	1.38
Eutrophication	kg N eq	0.07	0.06	0.08
Percentage of change in category impact				
Ozone depletion	%		-9.03	11.34
Global warming			-9.06	11.20
Smog			-9.06	11.19
Acidification			-9.06	11.20
Eutrophication			-9.06	11.19
Average	%		**-9.05**	**11.22**

4.4.6 Energy and water consumption

The sources of raw energy to produce a ton of biomass at Site 3 are shown in Table 4.20. Total energy consumption is 1.4 GJ/BDmT or 17.6 GJ/ha-year, based on 126 BDmT/ha after 10 years of management. Over 97% of the energy was from fossil fuels. The water consumption was 68.3 $m^3 \cdot BDmT^{-1}$. Of this, 66.9 $m^3 \cdot BDmT^{-1}$ was used on site for diluting biosolids. The balance was used mostly to irrigate cuttings during their production; cutting irrigation water was essentially 99.99% river water.

Table 4.20 Breakdown of the energy sources for Site 3. Values are per ton of biomass.

	Amount	HHV MJ·Unit^{-1}	MJ	%
Fossil fuel				
Coal	4.01 kg	27.8	112	7.93
Natural gas	3.44 m^3	38.4	132	9.39
Oil	24.8 kg	45.3	1,127	80.1
Fossil fuel - from Dummy process				
Petroleum			0.17	0.012
Tire derived fuel			0.0016	0.00011
Unspecified			0.24	0.017
Non-fossil fuel				
Uranium	8.54E-05 kg	3.81E+05	32.5	2.31
Non-fossil fuel - from Dummy process				
Biomass			0.29	0.020
Wind			1.45	0.10
Geothermal			1.24	0.088
Hydropower			0.0030	0.00021
Solar			0.069	0.0049
Photovoltaic			0.0030	0.00021
MSW			0.022	0.0015
TOTAL			**1,407**	100.00

4.4.7 Conclusions and recommendations

Diesel consumption during plantation management, harvesting, and land restoration produced environmental impacts. The use of diesel in plantation management contributed to smog and eutrophication. High diesel consumption during plantation management and harvesting caused almost 97% of the raw energy to be from fossil sources. A sensitivity analysis showed that lower diesel consumption and higher biomass yield can reduce the environmental impacts significantly.

It is recommended to review the technology used for plantation management, harvesting, and land restoration in order to reduce the diesel consumption at Site 3.

4.5 Production of biomass in Site 4

4.5.1 Life cycle inventory

Most on-site inputs for this site were obtained from the site manager and publicly accessible documents. The leachate amounts and water consumption were provided by the protection specialist[13] of Waste Management of Oregon. Data for the environmental consequences of materials input to the site were from SimaPro process libraries (PhD version 8.0.3.14). A summary of collected data is shown in Appendix C4.

4.5.2 Biomass production

The amount of biomass harvested in 2013, 151.91 BDmT per ha of chips and 18.23BDmT per ha of compost, was provided by the third party that did the harvesting. Diesel consumption was provided by AHB-Sustainability. The site's production was 88% chips and 12% compost. The chip biomass yield was 12.66 BDmT·ha^{-1} yr^{-1}.

4.5.3 Material and energy inputs

The materials and fuels consumed at Site 4 (Table 4.21) were calculated from the original values (Table C 4, Appendix C) as shown below. The SimaPro model is shown in Figure D 4, Appendix D.

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[13] Personal communication with Mr. Jeff O'Leary. Contact by mails between July 22nd to August 26th, 2014.

Table 4.21 Inputs for production and SimaPro process of biomass in Site 4. Values are per ton of biomass produced.

Processes	Inputs	Unit	Amount	Source*	SimaPro process
Land preparation	Diesel	l	0.012	P	Diesel, combusted in industrial equipment/US
Cutting	Cutting	p	9.05	P	
Transport from Boardman to McMinnville	Transportation	tkm	0.27	P	Transport, combination truck, diesel powered/ US
Plantation management	Leachate	ton	130	P	Leachate from MSWP-Dummy process
	Water	l	54,000	P	Water, river, US
	Electricity	kWh	17.04	P	Electricity, at Grid, WECC, 2008/RNA U
	Inorganic fertilizer	kg	6.39	P	Nitrogen fertilizer, production mix, at plant/US
	Diesel	l	4.56	P	Diesel, combusted in industrial equipment/US
Harvesting	Diesel	l	13.71	S	Diesel, combusted in industrial equipment/US
Land restoration	Herbicide	kg	0.008	P	Glyphosate {RER}/production with US electricity/Alloc Def, U
	Diesel	l	0.05	S	Diesel, combusted in industrial equipment/US

*P means primary data and S means secondary data

Diesel consumption for land preparation was 8.54 liters. On an area basis, this was

$$\frac{8.54\ \mathrm{l}}{4.45\ \mathrm{ha}} = 1.92\ \frac{\mathrm{l}}{\mathrm{ha}}$$

On a basis of the biomass produced the diesel consumption becomes

$$\frac{1.92\ \frac{\mathrm{l}}{\mathrm{ha}}}{151.91\ \frac{\mathrm{BDmT}}{\mathrm{ha}}} = 0.012\ \frac{\mathrm{l}}{\mathrm{BDmT}}$$

The planting density of Site 4 was 1,375 cuttings per ha. This was put on a biomass basis as follows:

$$\frac{1{,}375\ \frac{\mathrm{cutting}}{\mathrm{ha}}}{151.91\ \frac{\mathrm{BDmT}}{\mathrm{ha}}} = 9.05\ \frac{\mathrm{cuttings}}{\mathrm{ha}}$$

The distance from the nursery to McMinnville was 323 km. The green weight of a cutting was 0.000093 ton. Transportation of cuttings was determined to be

$$0.000093\ \frac{\mathrm{green\ ton}}{\mathrm{cutting}}\ \mathrm{x}\ 9.05\ \frac{\mathrm{cuttings}}{\mathrm{ha}}\ \mathrm{x}\ 323\ \mathrm{km} = 0.27\ \mathrm{t}\cdot\mathrm{km}$$

The site was irrigated with landfill leachate during plantation management. This was reported for the whole plantation (17.41 ha). The harvested area was 4.45 ha, so 25.58% of the reported values were used. The values added in the following equation are the amounts applied from 2002 to 2012.

(30.20 + 25.70 + 36.22 + 32.47 + 35.62 + 28.20 + 37.36 + 45.72 + 27.33 + 36.68 + 9.88)

= 345.38 Ml

adjusting for the percent of the plantation harvested gives

$$345.38\ \mathrm{Ml}\ \mathrm{x}\ 0.2558 = 88.35\ \mathrm{Ml}.$$

On a biomass basis this becomes

$$\frac{88.35\ \mathrm{Ml}}{4.45\ \mathrm{ha}} = 19.85\ \frac{\mathrm{Ml}}{\mathrm{ha}}$$

$$\frac{19.85\ \frac{\text{Ml}}{\text{ha}}}{151.91\ \frac{\text{BDmT}}{\text{ha}}} = 0.13\ \frac{\text{Ml}}{\text{BDmT}}$$

It was assumed that the leachate density was the same as water, so that 0.13 Ml·BDmT^{-1} is 130 ton·BDmT^{-1}.

The water consumption from 2002 to 2012 were added to get a total for the plantation.

$$(12.75 + 10.86 + 15.55 + 13.70 + 16.88 + 16.92 + 19.91 + 15.97 + 11.16 + 5.94 + 4.24) = 143.88\ \text{Ml}$$

Adjusting for the percent of the plantation harvested gives

$$143.88\ \text{Ml x}\ 0.2558 = 36.8\ \text{Ml}$$

On a biomass basis this becomes

$$\frac{36.80\ \text{Million liters}}{4.45\ \text{ha}} = 8.27\ \frac{\text{Ml}}{\text{ha}}$$

$$\frac{8.27\ \frac{\text{Ml}}{\text{ha}}}{151.91\ \frac{\text{BDmT}}{\text{ha}}} = 0.054\ \frac{\text{Ml}}{\text{BDmT}}\ \text{or}\ 54{,}000\ \frac{\text{l}}{\text{BDmT}}$$

Similarly, electricity used for leachate irrigation was reported for the whole plantation. The amount of electricity consumed for the study area from 2002 to 2012 was

$$(889.82\ +\ 757.13 + 1067.11 + 956.72 + 1087.46 + 934.57 + 1187.03 + 1277.98 + 797.37 + 882.83 + 292.45)\frac{\text{kWh}}{\text{ha}}\ \text{x}\ 0.2558 = 2{,}591.36\frac{\text{kWh}}{\text{ha}}$$

On a biomass basis this becomes

$$\frac{2{,}591.36\ \frac{\text{kWh}}{\text{ha}}}{151.91\ \frac{\text{BDmT}}{\text{ha}}} = 17.04\ \frac{\text{kWh}}{\text{BDmT}}$$

Fertilizer was reported as nitrogen and was applied at a rate of 124.36 kg·ha^{-1} in 2003, 219.6 kg·ha^{-1} in 2004, 379.8 kg·ha^{-1} in 2005 and 399.8 kg·ha^{-1} in 2006 to 2012, and 268.9 kg·ha^{-1} in 2013. It was calculated on a biomass basis as follows

$$(124.36 + 219.60 + 379.8 + 399.8 \text{ x } 7 + 268.89)\text{x } 0.2558\frac{\text{kg N}}{\text{ha}} = 970.12\frac{\text{kg N}}{\text{ha}}$$

$$\frac{970.12\frac{\text{kg N}}{\text{ha}}}{151.91\ \frac{\text{BDmT}}{\text{ha}}} = 6.39\ \frac{\text{kg N}}{\text{BDmT}}$$

Diesel for plantation management was assumed to be constant during the first 11 years. A 90-hp mid-size tractor was used with a diesel consumption of 267.83 L·yr^{-1}. During the 12$^{\text{th}}$ year, diesel use was assumed to halve because of the harvest. The total amount of diesel consumed at Site 4 was calculated as follows

$$11.5 \text{ years x } 267.83\ \frac{l}{year} = 3{,}080.04 \text{ l}$$

$$\frac{3{,}080.04 \text{ liters}}{4.45 \text{ ha}} = 692.14\ \frac{\text{l}}{\text{ha}}$$

$$\frac{692.14\ \frac{\text{l}}{\text{ha}}}{151.91\ \frac{\text{BDmT}}{\text{ha}}} = 4.56\frac{\text{l}}{\text{BDmT}}$$

As reported, the diesel consumption for harvesting included 1% for a residual grinder. This was subtracted, and diesel used was calculated as follows

$$9{,}369.77\ \mathrm{l}\ \ \mathrm{x}\ \ 0.99 = 9{,}276.07\ \mathrm{l}$$

$$\frac{9{,}276.07\ \mathrm{l}}{4.45\ \mathrm{ha}} = 2{,}084.51\frac{\mathrm{l}}{\mathrm{ha}}$$

$$\frac{2{,}084.51\ \frac{\mathrm{l}}{\mathrm{ha}}}{151.91\ \frac{\mathrm{BDmT}}{\mathrm{ha}}} = 13.71\ \frac{\mathrm{l}}{\mathrm{BDmT}}$$

Glyphosate herbicide was applied during land restoration. This was calculated as follows

$$\frac{1.26\ \frac{\mathrm{kg\ Glyphosate}}{\mathrm{ha}}}{151.91\ \frac{\mathrm{BDmT}}{\mathrm{ha}}} = 0.008\ \frac{\mathrm{kg\ Glyphosate}}{\mathrm{BDmT}}$$

Finally, diesel consumption for land restoration was calculated as follows

$$\frac{37.02\ \mathrm{l}}{4.45\ \mathrm{ha}} = 8.32\frac{\mathrm{l}}{\mathrm{ha}}$$

$$\frac{8.32\ \frac{\mathrm{l}}{\mathrm{ha}}}{151.91\ \frac{\mathrm{BDmT}}{\mathrm{ha}}} = 0.05\ \frac{\mathrm{l}}{\mathrm{BDmT}}$$

The high variability in leachate components was described in Section 2.3.1. However nutrient composition was measured at the pump station in 2011 (Table 4.22) and a profile of nitrogen distribution was developed based on WM Annual Report, 2012 (Table 4.23).

Table 4.22 Leachate nutrient composition in mg per l (DEQ, 2011)

Parameter	06/15	06/23	07/01	07/14	07/21	08/10	08/18	08/23	08/24	08/26	08/30	09/02	09/09
Nitrate as N	58	98	120	130	130	120	140	100	30	ND	ND	ND	ND
Nitrite as N	27	ND	ND	10	14	28	19	28	87	ND	ND	ND	ND
Ammonia as N	170	140	130	98	100	68	63	49	41	36	NA	44	61
Total Kjeldahl Nitrogen	180	180	110	73	110	65	60	58	51	48	NA	61	73
Total	435	418	360	311	354	281	282	235	209	84		105	134
Average													246.77

Table 4.23 Profile of nitrogen distribution (range of NH4-N mg/l equal to 1-1500)

Year	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Nitrogen mg/l	435	435	435	435	435	435	84	84	247	247	0	0

In Table 4.23 the average nitrogen from year 2002 to 2013 is equal to 272.67 mg· l^{-1}. This average is in the range of 1 to1500 mg NH_4-N per liter (Alker, 1999 cited by Dimitriou, 2005) and the range of 80 to 877 mg NH_{4+} per liter (Jones et al. 2006).

The applied nitrogen was calculated from the leachate applied, 130 tons per ton of biomass, and its concentration 272.67 mg·l^{-1} as follows.

$$130{,}000 \frac{l_{\text{Leachate}}}{\text{ton}_{\text{Biomass}}} \text{ x } 272.67 \frac{\text{mg}}{l_{\text{Leachate}}} \text{ x } \frac{\text{kg}}{1 \text{ x } 10^6 \text{ mg}} = 35.44 \frac{\text{kg N}}{\text{ton}_{\text{biomass}}}$$

This amount of natural fertilizer provided by landfill leachate might be beneficial for growing plants (Isebrands, 2007).

4.5.4 Life cycle impact assessment

The environmental impacts associated with biomass production are presented Table 4.24. Details of inputs are reported in Appendix F, Table F 5.

Diesel consumption in the plantation management and harvesting processes had a large effect on the impacts relative to the other processes, especially land preparation and restoration which had minimum impacts. However, ozone depletion due to diesel use during plantation management was low (2.10%).

Harvesting had the highest contribution to the global warming impact, followed by smog and eutrophication. The reason for this behavior is fossil fuel for the production of diesel, (Figure E 6.2 in Appendix E).

The production of cuttings affected all impact categories, especially acidification due to utilization of electricity (Figure E 6.4 in Appendix E). Transportation of cuttings had minimal contribution to the impacts indicators, relative to the other processes.

Table 4.24 Environmental impact from Site 4

			Land preparation (%)	Cuttings (%)	Transport (%)	Plantation management (%)			Harvesting (%)	Land restoration (%)	
Impact category	Unit (kg)	Total	Diesel	Cuttings	Transport	Electricity	Fertilizer	Diesel	Diesel	Herbicide	Diesel
Ozone depletion	CFC-11 eq	2.47E-08	0.01	**5.57**	0.00	0.41	**17.6**	2.10	**6.34**	**68.0**	0.02
Global warming	CO2 eq	81	0.04	**12.7**	0.03	**10.3**	**13.6**	**15.7**	**47.3**	0.10	0.17
Smog	O3 eq	3.69	0.40	**22.0**	0.10	**12.1**	3.99	**15.2**	**46.0**	0.14	0.17
Acidification	SO2 eq	0.42	0.11	**22.1**	0.03	**17.2**	**26.9**	**8.32**	**25.1**	0.13	0.09
Eutrophication	N eq	0.011	0.25	**15.3**	0.07	**8.35**	**10.2**	**14.4**	**43.5**	**7.85**	0.16

Bold numbers mean that input contribution is ≥ 5% in each impact category

LCIA results are reported with a maximum of 3 significant digits

Application of fertilizer during plantation management had a high effect on acidification, followed by ozone depletion, global warming, and eutrophication. Herbicide applied in land restoration produces the highest effect on ozone depletion, and some small effect on eutrophication. Reasons for this behavior are based on the utilization of fossil fuel (natural gas) in the production of nitrogen as chemical fertilizer and utilization of glyphosate as herbicide (Figures E.6.1 and E.6.5, Appendix E).

4.5.5 Life cycle interpretation

The application of chemicals and diesel consumption are the main on-site activities that produce environmental impacts. The sensitivity of the impact indicators to these were assessed. First, this was done by changing chemicals inputs in all processes by ±10% (line 1 in Table 4.25). Fertilizer in plantation management only (line 2) was then changed similarly. Then for herbicide in land restoration only (line 3) was tested. And finally, diesel in all processes (line 4), and for harvesting only (line 5) were tested.

Table 4.25 Percent change in impact indicators given a ±10% change in chemical or diesel use in all on-site processes in Site 4

Input	Ozone depletion	Global warming	Smog	Acidification	Eutrophication
Chemical	**8.56** **-8.56**	1.37 -1.37	0.41 -0.41	2.70 -2.70	1.80 -1.80
Fertilizer for Plant. Manag.	1.76 -1.76	1.36 -1.36	0.4 -0.4	2.69 -2.69	1.02 -1.02
Herbicide land restoration	**6.8** **-6.8**	0.01 -0.01	0.01 -0.01	0.01 -0.01	0.79 -0.79
Diesel	0.84 -0.84	**6.30** **-6.30**	**6.15** **-6.15**	3.35 -3.35	**5.81** **-5.81**
Diesel at harvesting	0.63 -0.63	4.73 -4.73	4.59 -4.59	2.51 -2.51	4.35 -4.35

The impact categories do not perform the same with change of inputs. Changes in chemicals, and specifically herbicide in land restoration, had greater effect on ozone depletion relative to the other impact categories. However, changes in diesel had more effect on global warming, smog, and eutrophication, compared with other impact categories. Results of the sensitivity analysis calculations for chemical and diesel for Site 4 are reported in Tables G 4.1 to G 4.4 in Appendix G.

The effect of biomass yield was analyzed by increasing and reducing biomass yield 10%. An increment of biomass yield reduced the inputs, and this positively affected the impact categories, reducing their amount. Conversely, a reduction of biomass yield increased the inputs, and this negatively affected the impact categories, obtaining higher amounts than for the original scenario.

Table 4.26 Sensitivity analysis of biomass yield in Site 4

Impact category	Unit	Original	+10%	-10%
Ozone depletion	kg CFC-11 eq	2.47E-08	2.32E-08	2.83E-08
Global warming	kg CO_2 eq	80.98	73.69	90.04
Smog	kg O_3 eq	3.69	3.36	4.11
Acidification	kg SO_2 eq	0.42	0.38	0.47
Eutrophication	kg N eq	0.011	0.010	0.012
Determination of category impact effects				
Ozone depletion	%		-6.29	14.62
Global warming			-9.01	11.18
Smog			-8.99	11.22
Acidification			-9.01	11.20
Eutrophication			-8.69	11.59
Average	%		**-8.40**	**11.96**

For a biomass yield of 13.93 BDmT $\cdot ha^{-1}\ yr^{-1}$ the GWP was 73.7 kg CO_2 eq per ton (optimistic scenario). For 11.39 BDmT$\cdot$ $ha^{-1}\ yr^{-1}$ the GWP was 90.0 kg CO_2 eq per ton (pessimistic scenario). A consistent variation in results, based on sensitivity analysis of main inputs tested in the overall processes and specific ones, shows the results' reliability.

4.5.6 Energy and water consumption

The sources of raw energy to produce a ton of biomass at Site 4 are shown in Table 4.27. Energy consumption was 1.34 GJ $\cdot BDmT^{-1}$ or 17 GJ$\cdot ha^{-1}\ yr^{-1}$, based on total productivity of 151.91 BDmT$\cdot ha^{-1}$ and 12 years of management. The raw energy inputs are over 94% attributable to fossil fuel.

The total water consumption was 60.3 $m^3 \cdot BDmT^{-1}$, with 99.99% of which was river water. Irrigation of cutting consumed 31% and 69% was used to reduce the concentration of the landfill leachate.

Table 4.27 Breakdown of the raw energy sources for Site 4. Values are per ton of biomass

	Amount	HHV MJ · Unit $^{-1}$	MJ	%
Fossil fuel				
Coal	6.19 kg	27.8	172	12.8
Natural gas	9.99 m^3	38.4	383	28.5
Oil	15.6 kg	45.3	706	52.5
Fossil fuel - from Dummy process				
Petroleum			0.32	0.024
Tire derived fuel			0.0030	0.0002
Unspecified			0.088	0.0065
Non fossil fuel				
Uranium	1.27E-04 kg	3.81E+05	48.3	3.60
Non-fossil fuel - from Dummy process				
Biomass			0.55	0.04
Wind			2.75	0.20
Geothermal			2.30	0.17
Hydropower			26.8	2.00
Solar			0.13	0.010
Photovoltaic			0.0024	0.0002
Other fuels, unspecified			0.46	0.0341
Total			**1,343**	100.00

4.5.7 Conclusions and recommendations

The production of poplar biomass produced environmental impacts due to cuttings, plantation management, harvesting, and land restoration.

Plantation management produced the highest relative contributions to acidification due to electricity use, ozone depletion due to fertilizer use, and GWP due to diesel use. Cuttings also contributed to acidification. Harvesting produced a high relative contribution to

GWP and smog due to diesel consumption. Land restoration had the highest contribution in ozone depletion due to herbicide utilization.

Sensitivity analysis showed that a 10% reduction in chemical and diesel use in all processes will produce the highest mitigation of ozone depletion and global warming, respectively, compared with specific reductions in processes. The utilization of poplar clones with higher biomass yield is recommended, due to the significant reduction in environmental impacts.

4.6 Comparison among sites

There are many differences among the four sites that limit how well they can be compared and what conclusions can be drawn. Nevertheless, this section compares the inputs used by the sites and the effects of these inputs on the impacts.

4.6.1 Comparison of inputs among sites

Water was used to produce cuttings that were planted in all sites (Table 4.28). It was also used for irrigation during plantation management at sites 2, 3, and 4. The differences among sites can also be observed in Figure 4.9.

The planting density clearly impacts water use. Site 1, with a planting density of 3,586 ha^{-1} had the highest water consumption due to cuttings while Site 2, with a planting density of 470 ha^{-1} had the lowest. The other sites were in between and the water use due to cuttings varied proportionally.

Table 4.28 Comparison of water consumption among sites

	Units	Site 1	Site 2	Site 3	Site 4
Cuttings	Liters per BDmT	69,174	6,383	9,087	18,736
	% contribution	100.0%	1.35%	13.58%	34.70%
Irrigation	Liters per BDmT	0.00	465,967	57,851	35,264
	% contribution	0.00%	98.65%	86.42%	65.30%
Total	Liters per BDmT	69,174	472,350	66,938	54,000

On-site water consumption, mainly for irrigation, was the highest at Site 2 which is located in north central Oregon where dry and hot summers resulted in lowest rainfall among the sites. In contrast, Site 2 had zero on-site water utilization during plantation management because of ample rainfall, 200 mm during the wet season, and soil that retained the water well. Like Site 2, Sites 3 and 4 were in the Willamette Valley with adequate rainfall and good soil; however, they were irrigated for other purposes (Figure 4.5).

The biosolids concentration at Site 3 was reduced to maintain soil quality. At Site 4, water was used in addition to leachate to avoid percolation of non-desired components in the groundwater.

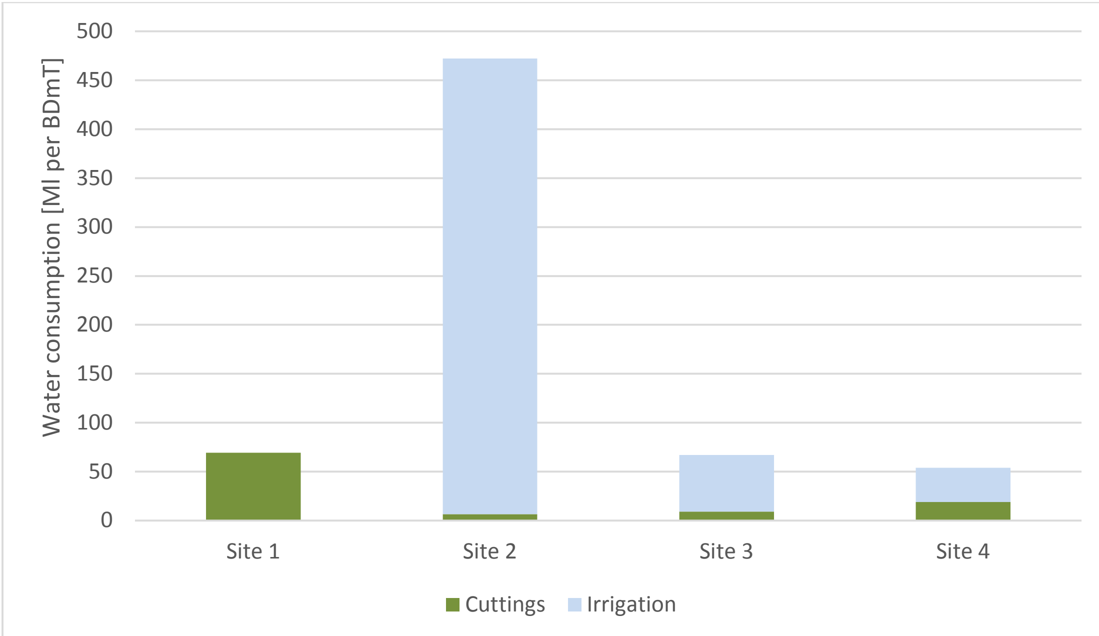


Figure 4.5 Water consumption among sites

Despite significant irrigation, on-site electrical consumption for Site 2 was similar to sites 3 and 4 (Table 4.29). The water for Site 2 was applied by drip irrigation which may partially account for this. Also, there are multiple pump stations at Site 2, which made pumping more energy efficient. In addition, the river water at Site 2 has lower viscosity and density than the water with biosolids or leachate.

Table 4.29 Comparison of on-site electricity consumption in kWh· $BDmT^{-1}$

	Site 1	Site 2	Site 3	Site 4
Electricity consumption	0.00	14.9	9.25	17.0

Site 1 had the lowest on-site diesel consumption and no on-site electricity use, resulting in the lowest on-site energy use among the sites (Table 4.30). However, Site 1 had the highest off-site energy due to the high planting density and energy associated with cuttings. At Site 1, coal accounted for 28% of the Site 1 more than at the other sites (8%

to 16%) (Table H6 in Appendix H). Meanwhile, oil 35% for Site 1 accounted for a smaller portion of raw energy than for other sites (52% to 80%).

Table 4.30 Comparison of energy consumption among sites in MJ $\cdot$BDmT^{-1}

		Site 1	Site 2	Site 3	Site 4
Total energy		1,382	877	1,407	1,343
On-site energy	Diesel [(1)]	346	451	687.3	782
	Electricity	0.0	53.6	33.3	61.3
Off-site energy		1,036	372.4	326.2	499.7

[(1)] conversion of l$\cdot$BDmT^{-1} to MJ$\cdot$BDmT^{-1} was developed with a LHV of U.S. conventional diesel of 42.79 MJ$\cdot$kg^{-1} and density of 836.7 g$\cdot$l^{-1}. Accessed from http://cta.ornl.gov/bedb/appendix_a/Lower_and_Higher_Heating_Values_of_Gas_Liquid_and_Solid_Fuels.pdf on May 19th, 2015

Manzone et al. (2009) reported an energy consumption of 14.2 GJ$\cdot$ha^{-1} yr^{-1} for eight years of cultivation and management of irrigated, short-rotation poplar. This was about 7% of the biomass energy production (about 188 GJ $\cdot$ ha^{-1} yr^{-1}). This compares to 2.4% to 6.1% at the sites in the present study.

The utilization of biosolids and landfill leachate in Sites 3 and 4, respectively, provide some beneficial and non-beneficial components for plant growth. Fertilizer was used at these sites to balance the additives, was approximately six times higher at Site 4 than the largest dose reported by Isebrand (2007) of 1.1 kg N per BDmT. This unusual amount of fertilizer in Site 4 is to avoid negative effect on biomass yield from irrigation with landfill leachate. The high level of fertilizer applied was effective because biomass yield was similar to irrigated other sites.

A comparative analysis of environmental impacts among sites (Table 4.31) shows that the impacts from Site 2 are less than Site 1, even with both under short-rotation management. The lower herbicide during land preparation and herbicide and pesticide use during land restoration (Table 4.32) at Site 2 contributes to this. The environmental impacts, except ozone depletion, are lower for Site 4 compared to Site 3. Both have long-rotations.

The global warming, acidification, and eutrophication impacts are more similar among the sites than the ozone depletion. The smog impact is much lower in Site 4 compared to the other sites and the plantation management method might be useful in a location where smog is one of the main operational restrictions.

Table 4.31 Comparison of environmental impacts among sites

Impact category	Unit · $BDmT^{-1}$	Site 1	Site 2	Site 3	Site 4
Ozone depletion	kg CFC-11 eq	1.18E-06	6.05E-07	4.40E-09	2.47E-08
Global warming	kg CO_2 eq	79.6	54.7	93.1	81.0
Smog	kg O_3 eq	17.1	18.3	37.0	3.69
Acidification	kg SO_2 eq	0.85	0.67	1.24	0.42
Eutrophication	kg N eq	0.092	0.061	0.070	0.011

Sites 2 and 3 had similar planting density but different rotation times. Site 2, with the short rotation, showed lower environmental impacts except for ozone depletion. This is partly due to a higher yield. Site 3 had the lower ozone depletion impact by a factor of 10 because only a small amount of fertilizer was used.

Table 4.32 Comparison of chemical consumption among sites in kg·$BDmT^{-1}$

		Site 1	Site 2	Site 3	Site 4
Chemicals	Herbicide	0.48	0.20	0.00	0.008
	Pesticide	0.023	0.11	0.00	0.00
	Fertilizer	0.00	0.00	0.36	6.39
Total		0.50	0.31	0.36	6.40

Haefke (2008) reported a global warming impact of 2,066 kg CO_2 eq per ton for the production and combustion of biomass. The global warming impact for the production of biomass in Sites 1-4 showed 54.7 to 93.1 kg CO_2 eq per ton, 3.8% to 4.5% of the impact reported by Haefke.

The GWP impact reported by Gasol et al. (2009) was 35.23 kg CO_2 eq per BDmT for poplar biomass transported as a packet of stems. This was 1.5 to 2.6 times lower than for sites in the present study because the technology used was different. For example, a brush hog was used to remove existing vegetation during site preparation, chemicals were dispersed by spreaders, plantation management was done with rototiller and planter, harvesting was done with a rake, the biomass collection with a trailer, and land restoration was by stump kill down that consumed much fuel (49.2 l/ha-yr). The productivity, 216 BDmT ·ha^{-1}, was higher than for Sites 1-4.

Fiala and Bacenetti (2012) reported GHG emissions in biomass production to be 5,660.5 kg CO_2 eq per ha or 33.59 kg CO_2 eq per BDmT for poplar with five harvests on 2-year rotations using a self-propelled forage combine harvester equipped with a special biomass-header. They reported 30.67 kg CO_2 eq per BDmT for two harvests on a 5-year rotation using a self-propelled harvester (felling operation), a tractor coupled with a trailer equipped with pincers (whole tree transported from field to chipping place), and a fixed wood chipper. In other research with willow, the reported GHG emission was 12.58 kg CO_2 eq per BDmT of biomass produced (Heller et al. (2003). Fiala and Bacenetti (2012) and Heller et al. (2003) report GHG emissions, not a GWP indicator.

The calculated amounts of CO_2 eq for the sites in this study are higher than values reported in literature. The differences in emissions can be explained by factors such as clone, yield, management style, and technology used. However, the accountability of emissions could be a base line to improve the management styles in poplar plantations in the PNW.

4.6.2 Fertilizer analysis in Site 3

The effect of using fertilizer rather than biosolids was considered. The hypothetical site with fertilizer is called Site 3a, and the inputs to the site are shown in Table 4.33. The amount of fertilizer was set at 50 kg $N \cdot ha^{-1}\ yr^{-1}$, the amount recommended for poplar plantations by Adler et al. 2007 and Isebrand, 2007. This appears in the table as 3.97 $kg_N \cdot BmDT^{-1}\ yr^{-1}$. This table can be compared to Table 4.16 for Site 3.

Table 4.33 Inputs for production of 1 BDmT of biomass in Site 3a

Site process	Inputs	Unit	Amount	SimaPro process
Land preparation	Diesel	l	0.31	Diesel, combusted in industrial equipment/US
Cutting	Cutting	p	4.39	
Transport Boardman to Eugene	Transportation	tkm	0.18	Transport, combination truck, diesel powered/ US
Plantation management	Water	l	43059.68	Water, river, US
	Electricity	kWh	9.74	Electricity, at Grid, WECC, 2008/RNA U
	Inorganic fertilizer	kg	3.97	Nitrogen fertilizer, production mix, at plant/US
	Diesel	l	18.0	Diesel, combusted in industrial equipment/US
	Diesel	l	11.44	Diesel, combusted in industrial equipment/US
Land restoration	Diesel	l	4.9	Diesel, combusted in industrial equipment/US

The amount of water was reduced for Site 3a because the water in Site 3 was used to dilute the biosolids and was not needed with the fertilizer. The life cycle impacts for Site 3a are shown in Table 4.34.

Table 4.34 Life cycle impact assessment of Site 3a

Processes			Land prep. (%)	Cutting (%)	Transport (%)	Plantation management (%)			Harvesting (%)	Land rest. (%)
Impact category	Unit (kg)	Total	Diesel	Cutting	Transport	Nitrogen	Electricity	Diesel	Diesel	Diesel
Ozone depletion	CFC-11 eq	7.25E-09	0.48	**5.18**	0.01	**38.1**	0.81	**29.0**	**18.5**	**7.91**
Global warming	CO_2 eq	115	0.74	4.40	0.01	**6.06**	4.24	**44.3**	**28.2**	**12.1**
Smog	O_3 eq	44.0	0.85	0.91	0.01	0.21	0.59	**51.1**	**32.5**	**13.9**
Acidification	SO_2 eq	1.52	0.78	3.00	0.01	4.70	2.77	**46.5**	**29.6**	**12.7**
Eutrophication	N eq	0.083	0.84	0.99	0.01	0.85	0.64	**50.7**	**32.2**	**13.8**

Bold numbers mean that input contribution is ≥ 5% in each impact category
LCIA results are reported with a maximum of 3 significant digits

4.6.2.1 Comparison of impact indicators between Sites 3 and 3a

Ozone depletion is the impact category most sensitive to the use of chemical fertilizer (Table 4.35 and Figure 4.6) and its substitution with biosolids reduced ozone depletion 65%. Similarly, reductions of 24% occurred for global warming potential, 19% for smog, 23% for acidification, and 19% for eutrophication. These impacts increase because of the burdens associated with the manufacturing of fertilizer compared to biosolids which are considered to be a waste product and carry no burdens.

Table 4.35 Percentage of difference between impact categories in Site 3 and 3a

Impact category	Units	Site 3	Site 3a	% difference
Ozone depletion	kg CFC-11 eq	4.40E-09	7.25E-09	65%
Global warming	kg CO_2 eq	93.1	115	24%
Smog	kg O_3 eq	37.0	44.0	19%
Acidification	kg SO_2 eq	1.24	1.52	23%
Eutrophication	kg N eq	0.07	0.083	19%

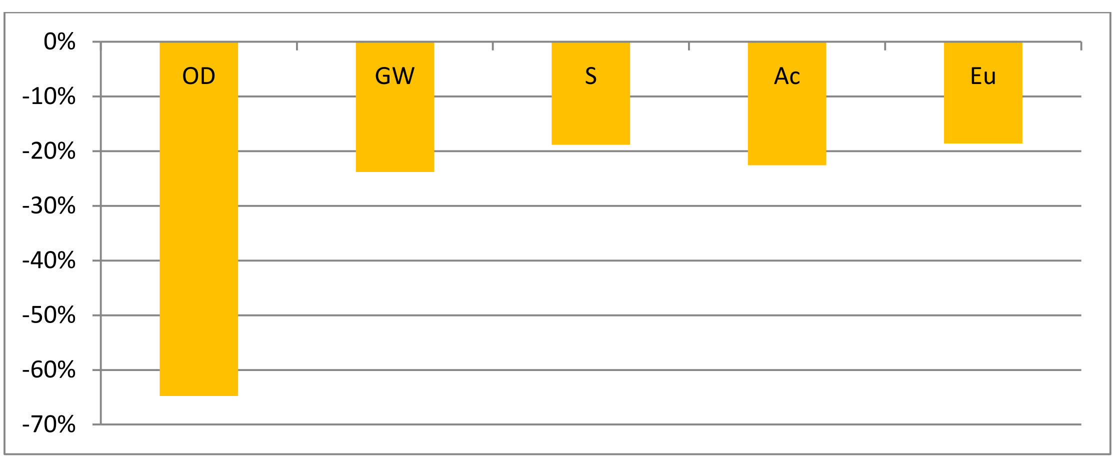


Figure 4.6 Percentage of impact category reduction with utilization of biosolids

4.6.2.2 Energy and water consumption in site 3a

A 27.3% increase in energy consumption occurred due to the application of nitrogen fertilizer in Site 3a (Table 4.36) compared to fertilization with biosolids in Site 3 (Table 4.20).

Table 4.36 Comparative energy consumption in Sites 3 and 3a

Source of energy	Energy, MJ		% change
	Site 3	Site 3a	
Fossil fuel			
Coal	112	124	11.4
Natural gas	132	272	106.2
Oil	1,127	1,341	18.9
Fossil fuel - from Dummy process			
Petroleum	0.17	0.17	0.0
Tire derived fuel	0.0016	0.0016	0.0
Unspecified	0.24	0.14	-41.6
Non –fossil fuel			
Uranium	32.5	36.3	11.6
Non-fossil fuel - from Dummy process			
Biomass	0.29	0.30	3.5
Wind	1.45	1.50	3.5
Geothermal heat	1.24	1.29	0.0
Hydroelectric	0.0030	15.5	516,567
Solar energy	0.069	0.071	2.9
Photovoltaic (Solar)	0.0030	0.0038	26.7
MSW	0.022	0.022	0.00
Ocean	0.00	0.00	0.00
TOTAL	1,407	1,791	**27.3**

In contrast to energy consumption, a reduction of 31% occurred for water consumption in Site 3a (Table 4.37) compared with Site 3 (Table 4.20) because water was not needed to apply biosolids in a liquid state or to reduce the salinity of the biosolids.

Table 4.37 Water consumption in Site 3a

	m^3	kg	Conversion	%
Source of water - Site 3a				
Water, lake	1.30E-07			0.0000003
Water, river	46.9			99.99
Water, unspecified natural origin	2.75E-06			0.0000059
Water, well, in ground	4.70E-06			0.000010
Water discharge	-6.50E-08	-6.50E-05	0.001	0.00
Water, completely softened	1.64E-07	0.00016	0.001	0.00
Water, decarbonised	6.23E-06	0.0062	0.001	0.00001
Water, deoinized	7.07E-07	0.00071	0.001	0.00
Water, ultrapure	1.68E-08	1.68E-05	0.001	3.57E-08
Total	**46.9**			100.00

In conclusion, the use of synthetic fertilizer in Site 3a produced an increase in all impact categories and energy consumption, but did reduce water consumption. From the environmental point of view, it is better to apply natural fertilizer (Site 3) than synthetic fertilizer (Site 3a). Another positive contribution is the utilization of waste from the wastewater treatment plant.

4.7 Analysis of electricity generation substitution

The environmental impacts are affected by how electricity is generated off site. This is most significant when cuttings are produced and during plantation management because electricity is used to pump water for irrigation. Three methods of generating electricity

(Table 4.38) were considered. The default method, used for all prior work, was the mix of electrical sources specified by the Western Electricity Coordination Council (WECC). It represents a large portion of the western U.S. (Figure 4.16), western Canada, and a small portion of Mexico.

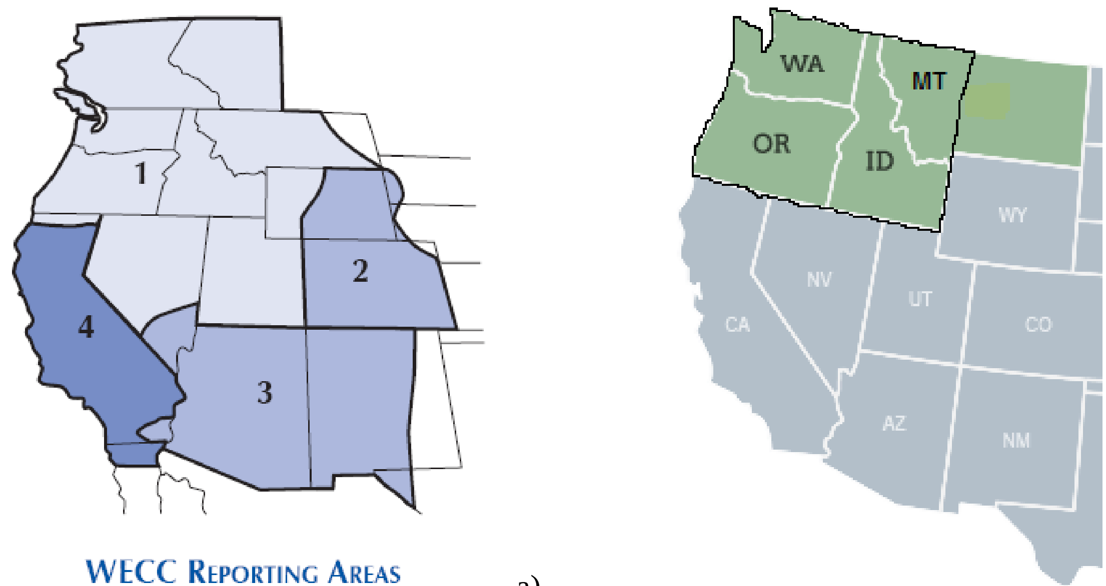
Table 4.38 Percentage of source composition of alternative electric energy

Electricity Sources	WECC[A] (default)	PNW[B] (alternative 1)	Woody Biomass[C] (alternative 2)
Bituminous coal	**30.25%**	9.26%	
Diesel	0.041%		
Petroleum pumped	0.013%	0.23%	
Petroleum storage	0.26%	0.02	
Natural gas	**31.80%**	8.80%	0.01%
Other gas		0.18%	
Nuclear	9.4%	4.22%	
Hydroelectric	22.24%	**68.35%**	
Wood or solid biomass	0.75%	1.10%	**99.99%**
Liquid biomass	0.11%		
Gas biomass	0.60%		
Other biomass		0.25%	
Wind	2.35%	7.28%	
Solar or Photovoltaic	0.11%	0.003%	
Geothermal	1.93%	0.045%	
MSW	0.036%		
Other fuels	0.09%		

[A] original sources of electricity available in USLCI database in SimpaPro v. 8.0.3
[B] Electric power industry generation by primary energy source. 2012. From http://www.nwenergy.org/wp-content/uploads/randstudy.pdf. Accessed on Nov. 20th, 2014
[C] CORRIM Database

The first alternative was a mix more specific to the Pacific Northwest states (PNW, Table 4.38, Figure 4.7b) and used by CORRIM. It contains more hydro and less fossil electricity than the base case.

The second alternative was electricity from a biomass boiler process developed by CORRIM. It is based on survey data from mills operating wood boilers in lumber and plywood facilities in the PNW and the southern U.S. In the model, 0.195 kg of wood is required to produced 1 kg of steam. The steam then passes through a turbine, and 1.95 kg of steam is required to produce 1 kW·hr of electricity. It was assumed that the biomass was transported 20 km.



a) b)

Figure 4.7 (a) Map of WECC and (b) Map of PNW of USA from the energy point of view (from http://www.pnaa.org accessed January 31st, 2015)

4.7.1 Site 1

The lowest consumption of electricity is expected in Site 1 because there is no irrigation. However, electric energy is embodied in cuttings and Site 1 has the highest planting density among the sites. Using electricity based on PNW sources results in a reduction on global warming, smog, acidification, and eutrophication impacts (Table 4.39). This is due to a greater proportion from hydroelectric power and less from natural gas. Using electricity from biomass results in a 38% reduction of global warming compared to WECC. However, the smog is 38% higher than for WECC and 49% higher than for PNW sources due to particulate matter.

Using electricity from WECC or PNW resulted in the same level of ozone depletion. It increased 9% with biomass. In the case of eutrophication, a 3% reduction was observed for PNW and a 20% increase with biomass compared to WECC.

Table 4.39 Environmental impacts for Site 1 with alternative sources of electricity

Impact Category	Unit per BDmT	Amount per BDmT		
		WECC (default)	PNW (alternative 1)	Biomass (alternative 2)
Ozone depletion	kg CFC-11 eq	1.18E-06	1.18E-06	1.29E-06
Global warming	kg CO_2 eq	79.5	51.0	48.9
Smog	kg O_3 eq	17.1	15.8	23.6
Acidification	kg SO_2 eq	0.85	0.60	0.77
Eutrophication	kg N eq	0.092	0.089	0.11

4.7.2 Site 2

In Site 2, 14.88 kWh per ton are utilized for on-site irrigation and 2.17 kWh are embodied in each cutting. The total was 243.73 MJ per ton of biomass (Table 4.40).

Changing the electricity mix from WECC to PNW reduces global warming potential by 15.5% (Table 4.40). This is due to more hydroelectricity and less natural gas. The other impacts are unchanged of slightly less. Changing to electricity from biomass reduces global warming potential by 16.6% and, similar to Site 1, smog increases 10.5% due to increased particulate matter, and there was little effect on ozone depletion because only 5% of increment was observed with biomass, compared with WECC and PNW.

Table 4.40 Environmental impacts for Site 2 with alternative sources of electricity

Impact category	Unit per BDmT	Total amount		
		WECC (default)	PNW (alternative 1)	Biomass (alternative 2)
Ozone depletion	kg CFC-11 eq	6.05E-07	6.05E-07	6.36E-07
Global warming	kg CO_2 eq	54.7	46.3	45.6
Smog	kg O_3 eq	18.3	17.9	20.2
Acidification	kg SO_2 eq	0.67	0.60	0.65
Eutrophication	kg N eq	0.061	0.060	0.065

4.7.3 Site 3

Site 3 has higher global warming and smog impacts compared to Sites 1 and 2 due to factors other than just electricity use. On-site irrigation requires 9.25 kWh per ton, and 2.17 kWh are embodied in each cutting. The total electricity consumption was 390.82 kWh per ton of biomass (Table 4.41). When the electrical source at this site was changed from WECC to PNW or biomass, ozone depletion changed by +2% and -35%, respectively (Table 4.41). However, the absolute change is miniscule compared to Sites 1 and 2. Global warming was reduced 7% and 7.7%, and acidification 5% and 2% respectively. Smog and eutrophication change slightly.

Table 4.41 Environmental impacts for Site 3 with alternative sources of electricity

Impact category	Unit per BDmT	Total amount		
		WECC (default)	PNW (alternative 1)	Biomass (alternative 2)
Ozone depletion	kg CFC-11 eq	4.40E-09	4.32E-09	2.87E-08
Global warming	kg CO_2 eq	93.1	86.5	86.0
Smog	kg O_3 eq	37.0	36.7	38.5
Acidification	kg SO_2 eq	1.24	1.18	1.22
Eutrophication	kg N eq	0.070	0.069	0.073

4.7.4. Site 4

In Site 4, 17.04 kWh per ton was used on site for irrigation, and 2.17 kWh is embodied in each cutting. The total electrical consumption was 373.21 kWh per ton of biomass. When the electrical source at this site was changed from WECC to PNW or biomass, global warming decreased 15.7% and 16.8%, respectively. The smog impact more than doubled from biomass (Table 4.42).

Table 4.42 Environmental impacts for Site 4 with alternative sources of electricity

Impact category	Unit	Total amount		
		WECC (default)	PNW (alternative 1)	Biomass (alternative 2)
Ozone depletion	kg CFC-11 eq	2.47E-08	2.46E-08	7.11E-08
Global warming	kg CO_2 eq	81.0	68.3	67.4
Smog	kg O_3 eq	3.69	3.09	6.57
Acidification	kg SO_2 eq	0.42	0.31	0.38
Eutrophication	kg N eq	0.011	0.01	0.018

Each of the four sites had a higher level of smog for electricity from biomass. Wood combustion produces oxides of nitrogen (NO, NO_2) at temperatures over 1000 K. Oxides of nitrogen affect smog, visibility, acid rain, and human health (irritation in lungs that can cause chronic obstructive pulmonary disease).

Alternative 1 with 68.5% hydroelectricity has the lowest environmental impacts at all sites. In the LCA, electricity from hydropower has no impacts because there are no fuel inputs.

Figures 4.8 to 4.11 show comparative impacts for alternatives sources of electric energy (PNW and biomass) compared to WECC. Ozone depletion (Figure 4.17) nearly unchanged for the PNW alternative. The change from WECC to biomass increased ozone depletion at Sites 3 and 4. Sites 1 and 2 were much less affected because they utilize less chemicals.

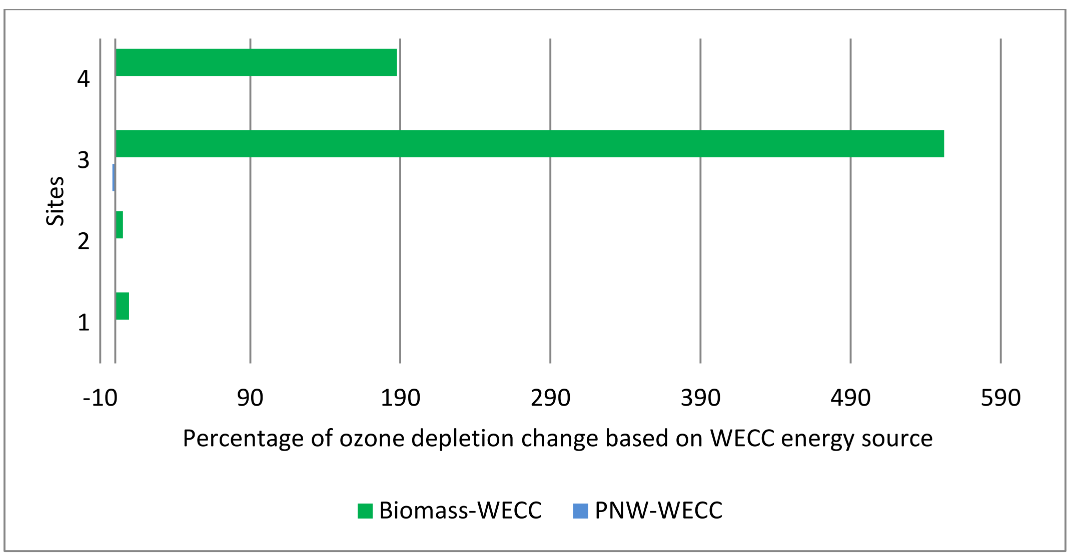


Figure 4.8 Percentage of variation of ozone depletion in each site due to alternative sources of electricity

Global warming potential (Figure 4.9) is reduced in all sites when either PNW or biomass electricity is substituted for WECC. For the PNW electricity, this is largely because hydro is subtituted fro natural gas. The reduction are least in Site 2 because it has the lowest electrical use due to no on-site irrigation.Processes with higher contribution to this effect were cuttings at a nursery that use biomass from Site 2, because this site provided the vegetative material to all sites, and electricity from a turbine using steam from the wood boiler.

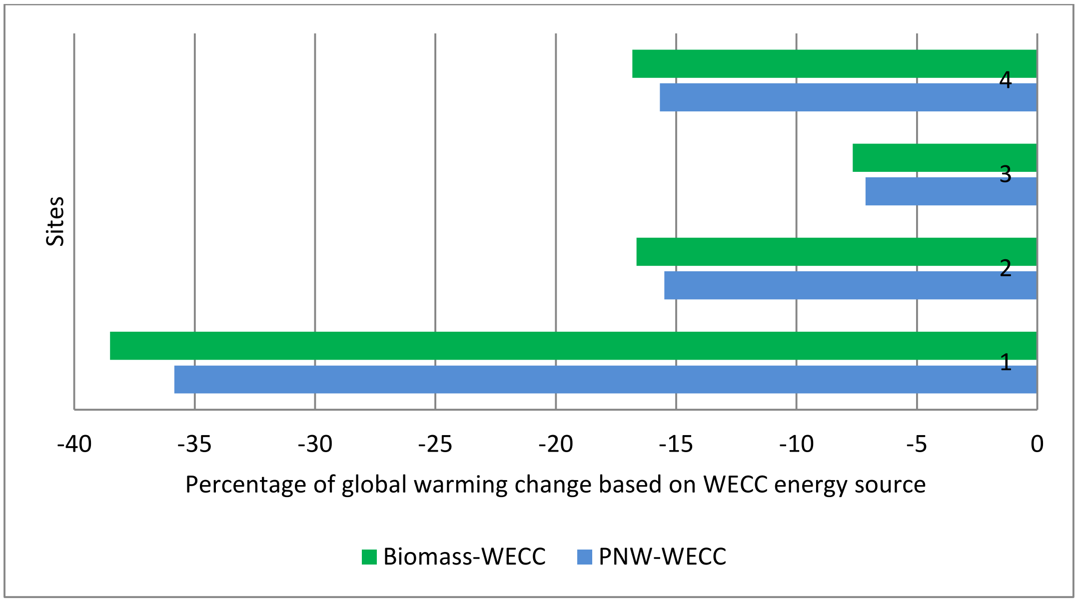


Figure 4.9 Percentage of variation of global warming for each site due to alternative sources of electricity

Smog (Figure 4.10) is reduced in all sites when PNW electricity is substitud for WECC and increased when biomass is substituted. The reduction for the PNW mix is because less fossil fuels are burned. The increase for biomass is because of the particulate emissions associated with wood combustion. The effects are largest in Site 4 because higher electricity consumption (17.04 kWh) than other sites (9.25 and 14.88 kWh) and the embodied energy for the production of fertilizer that was also the highest in Site 4 than other sites.

Acidification (Figure 4.11) is reduced more when the PNW mix is substituted for the WECC mix than when the biomass is substituted. This is because of the increased hydroelectric component in the PNW mix. The reduction for biomass is because of non-fossil fuels sources of energy. The effect at Site 1 is largest because of embodied electrical energy associated to extra inputs, such as herbicide and pesticide in land restoration and higher amount of cuttings that required electrical energy for irrigation.

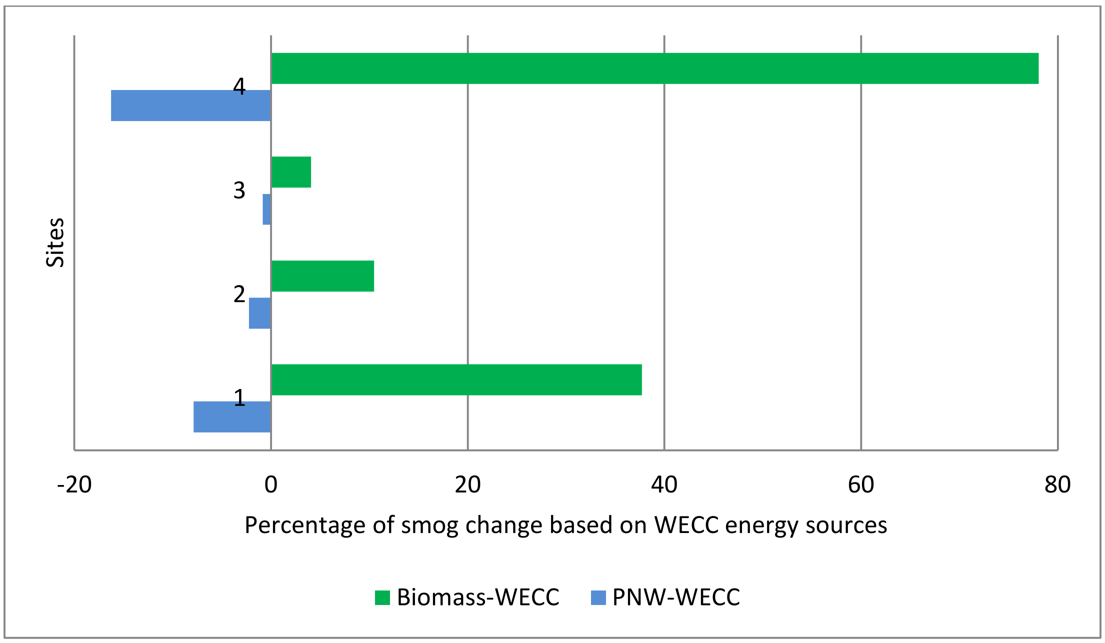


Figure 4.10 Percentage of variation of smog in each site due to alternative sources of electricity

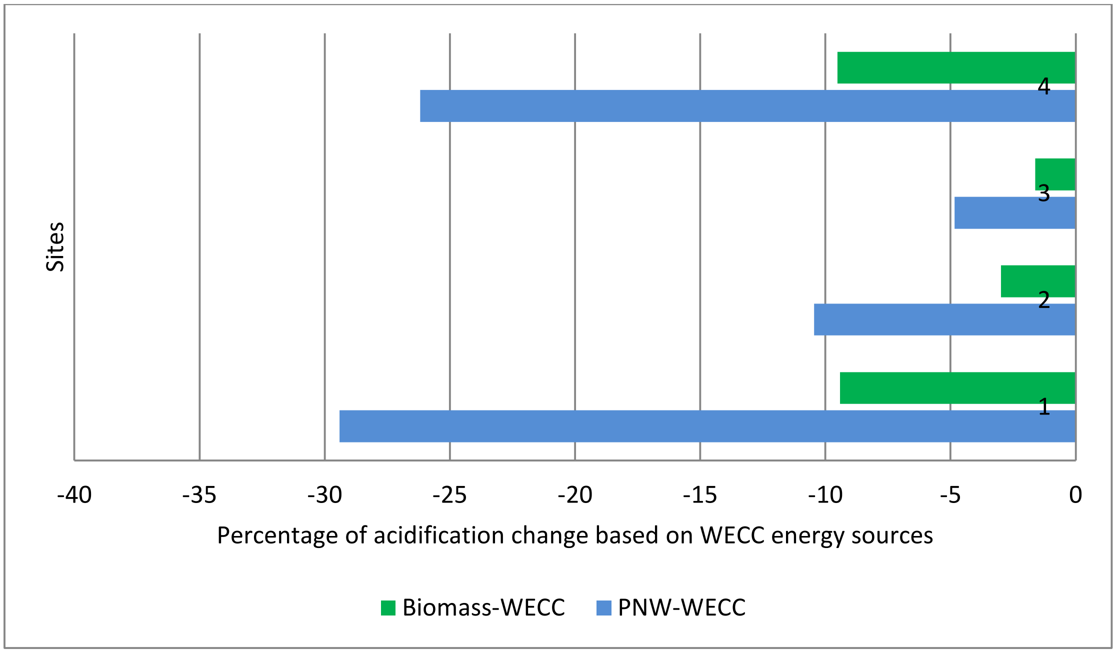


Figure 4.11 Percentage of variation of acidification in each site due to alternative sources of electricity

Eutrophication (Figure 4.12) is reduced in all sites when PNW electricity is substituted for WECC and increased when biomass is substituted. The reduction for the PNW mix is because less fossil are burned. The increase for biomass is because of nutrients required to growth forest plantation that result in excesive plant gowth and oxygen depletion in wter bodies. The effects are the largest in Site 4 because of the highest fertilizer amount (6.39 kg per ton of biomass).

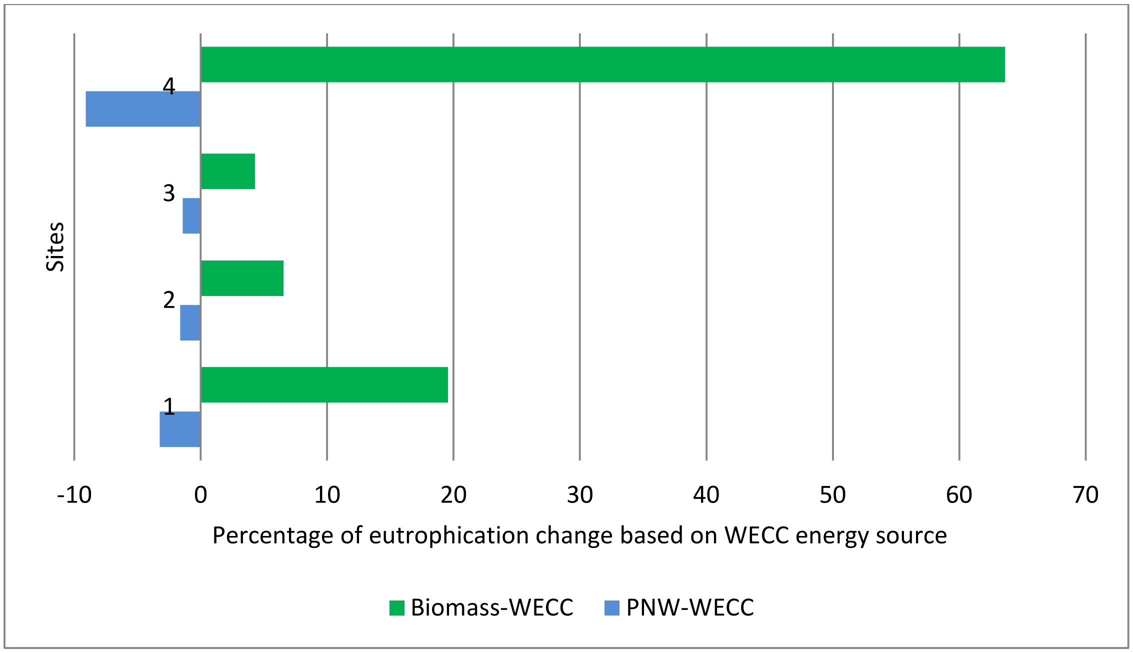


Figure 4.12 Percentage of variation of eutrophication in each site due to alternative sources of electricity

Global warming and acidification impacts were reduced in all sites with alternative sources of electricity (PNW and biomass); however, all impact categories were reduced by the utilization of PNW.

Complete results of environmental impacts for original and alternative sources of electricity are shown in Tables J 1 to J 3 at Appendix J. A main effect is the reduction in global warming potential due to lower fossil fuel use for both PNW and biomass when substituted for WECC. A second main effect is an increase in smog when biomass is substituted due to particulate emissions.

Chapter 5 CONCLUSIONS

The methods used for land preparation, management, harvesting, and land restoration when producing poplar biomass affect the environmental impacts. The application of herbicides and pesticides during land preparation and restoration contribute strongly to the ozone depletion and eutrophication impacts. The selection of machinery and the application of fertilizer are the most important contributors to environmental impacts during plantation management. Shorter rotations resulted in less diesel consumption during plantation management; however, there were also differences in irrigation methods and fertilization that may confound this conclusion.

There are both off-site and on-site environmental impacts from irrigation. The off-site impacts embodied in cuttings are increased when planting density is increased. For example, Site 1, with a planting density of 3586 ha^{-1}, had a higher global warming potential than Site 2, with 470 ha^{-1}. The electricity for irrigation is the main contributor to the impacts during the production of cuttings, especially global warming potential.

Environmental impacts decrease as yield increases. For example, the lowest energy consumption and global warming potential occurred in Site 2, concurrent with the highest yield. A sensitivity analysis demonstrated this effect for the all sites.

Different environmental impacts show different sensitivities among the sites. The difference is attributed to materials used and energy consumed in each site. Global warming due to consumption of diesel varied more in Site 3 (±8.3%) than in Site 1 (±3.8%). But, the sensitivity of ozone depletion due to utilization of chemicals does not vary as much among sites, for example, ± 8.6% in Site 4 and ± 10.2% in Site 2.

The inclusion of other impact categories, such as ozone depletion and eutrophication that are not directly related with energy consumption, needs to be considered to have a better understanding of environmental impacts. The utilization of chemicals was the main contributor to these impact categories. For example, in Site 1, which used herbicides in land preparation, plantation management, and land restoration, ozone depletion and eutrophication were the highest compared with other sites.

The application of biosolids can reduce environmental impacts compared to applying nitrogen fertilizer. The biosolids applied in Site 3 reduced ozone depletion by 65%, global warming by 24%, acidification by 23%, and smog and eutrophication each by 19%. A benefit not factored into the impacts is reduced fuel use because the biosolids are not transported off site.

Substitution of the electricity mix for the western U.S. (62% from fossil) with an electricity mix representing the PNW (68% from hydro) reduces environmental impacts due to increased hydroelectric power in the mix. Substituting electricity that is produced 100% from biomass decreases global warming potential and acidification, but increases smog due to particulate emissions, ozone depletion, and eutrophication.

The biosolids and landfill leachate were assumed to be waste products and have no embodied environmental consequences. If demand for these wastes becomes high enough in the future, then this assumption may not be valid. In this case, it is recommended that LCIs and LCAs for the treatment facility and landfill be developed with allocation to biosolids and leachate as coproducts, so the embodied burdens can be incorporated into the estimate of the environmental impacts of biomass production.

Presently the biomass from sites fertilized with biosolids or irrigated with wastewater or leachate is sold and used in the marketplace in the same way as biomass irrigated with river water. It is strongly recommended that the chemical composition of the biomass from phytoremediation processes be determined. This information will be essential to determine biomass suitability for processes such as pulp and paper, composites, and bioenergy. It is expected that a total analysis of inorganic components (Gavlak et al., 1994), plasma optical emission spectroscopy (Ventura et al., 2014), high-performance liquid chromatography (HPLC), nuclear magnetic resonance spectroscopy, or a combination of gas chromatography with mass spectrometry (GC-MS) would be adequate tools to determine the composition.

The analysis in this study was a cradle-to-gate analysis for biomass production. Future work should extend this to a cradle-to-grave analysis by including the environmental impacts of combustion. In addition to what is already published in this area, the combustion of biomass from phytoremediation sites should be studied. At present, it is only hypothesized that concentrations of inorganic components are small and do not pose processing problems, environmental impacts, or health risks

BIBLIOGRAPHY

Aber, J. and C., Federer. 1992. A generalized, lumped-parameter model of photosynthesis, evapotranspiration and net primary production in temperate and boreal forest ecosystems. Oecologia. 92:463-474.

AHB (Advanced Hardwood Biofuels Northwest). 2014. USDA Agriculture and Food Research Initiative. From http://hardwoodbiofuels.org accessed on July 22nd, 2014.

AIEL (Italian Agroforestry Energy Association). 2008. Wood Fuels Handbook: Production, quality requirements, trading. 83 pages.

Alder, P., S. Del Grosso, and W. Parton. 2007. Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems. Ecological Applications. 17: 675-691.

Amponsah, N., M. Troldborg, B. Kington, I. Aalders, and R. Hough. 2014. Greenhouse gas emissions from renewable energy sources: A review of lifecycle considerations. Renewable and Sustainable Energy Reviews. 39:461-475.

Armstrong, A., C. Johns, and I. Tubby. 1999. Effects of spacing and cutting cycle on the yield of poplar grown as an energy crop. Biomass and Bioenergy. 17:305-314.

Aylott, M., E. Casella, I. Tubby, N. Street, P. Smith, G. Taylor. 2008. Yield of spatial of bioenergy poplar and willow short-rotation coppice in the UK. New Phytol. 178:358-370.

Bacenetti, J., S. Gonzalez-Garcia, A. Mena, and M. Fiala. 2012. Life cycle assessment: an application to poplar for energy cultivated in Italy. Journal of Agricultural Engineering. (XLIII: e11):72-78.

Bare, J., G. Norris, D. Pennington, and T. McKone. 2003. TRACI -The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts. Journal of Industrial Ecology. 6(3-4): 49-78.

Baumann, H. and AM. Tillman. 2004. Interpretation and presentation of results in Chapter 6 of The HitchHiker's guide to LCA: An orientation in life cycle assessment. Methodology and Application. 28 pages.

Berndes, G. 2002. Bioenergy and water - the implications of large scale bioenergy production for water use and supply. Global Environmental Change. 12:253-271.

Blake, T., T. Tschaplinski, and A. Eastham. 1984. Stomatal control of water use efficiency in poplar clones and hybrids. Can. J. Bot. 62:1344-1351.

Blankenhorn, P., T. Bowersox, K. Kuklewski, and G. Stimely. 1985. Effects of rotation, site and clone on the chemical composition of populus hybrids. Wood and Fiber Science. 17 (3): 351-360

Börjesson, P. 1999. Environmental effects of energy crop cultivation in Sweden-I: Identification and quantification. Biomass and Bioenergy. 16:137-154.

Börjesson, P., and L. Tufvesson. 2011. Agricultural crop-based biofuels resources efficiency and environmental performance including direct land use changes. J. Clean Prod. 19:108-120.

BTF (Boardman Tree Farm), 2011. Management Plan Public Summary. 8 pages

Butnar, I. J. Rodrigo, C. Gasol, and F. Castells. 2010. Life-cycle assessment of electricity from biomass: Case studies of two biocrops in Spain. Biomass and Bioenergy. 34:1780-1788.

Caslin, B., J. Finnan, and A. McCracken. 2011. Short rotation coppice willow. Best practice guidelines. Teagasc & AFBI Report. 72 pages.

Cherubini, F. 2010. GHG balances of bioenergy systems – Overview of key steps in the production chain and methodological concerns. Renewable energy. 35:1565-1573.

Cherubini, F. and Strφmman, A. 2011. Life cycle assessment of bioenergy systems: State of art and future challenges. Bioresource Technlogy. 102: 437-451.

Crawford, R. 2008. Validation of a hybrid life-cycle inventory analysis method. Journal of Environmental Management. 88(3): 496-506.

Curran, MA. 2006. Life cycle assessment: Principles and Practice. Report EPA/600/R-06/060, U.S. EPA, Cincinati, OH, Available from: http://www.epa.gov/nrmrl/lcaccess/pdfs/600r06060.pdf accessed November 21rst, 2011.

Curran, MA. 2007. Co-product and input allocation approaches for creating Life Cycle Inventory data: A literature review. Int. J. LCA 12 (Special Issue 1): 65-78.

Deckmyn, G., I. Laureysens, J. Garcia, B. Muys, and R. Ceulemans. 2004. Poplar growth and yield in short rotation coppice: model simulations using the process model SECRETS. Biomass and Bioenergy. 26: 221-227.

Demirel, Y. 2012. Energy and energy types *in* Energy Production, Conversion, Storage, and Coupling-Chapter 2. 70 p. ISBN: 978-1-4471-2371-2.

Demirbas, A. 1996. Calculation of higher heating value of biomass fuel. Fuel 76 (5): 431-434.

Dickmann, D. 2006. Silviculture and biology of short-rotation woody crops in temperate regions: Then and now. Biomass and Bioenergy. 30: 696-705.

Dillen, S., S. Djomo, N. Al Afas, S. Vanbeveren, and R. Ceulemans. 2013. Biomass yield and energy balance of a short-rotation poplar coppice with multiple clones on degraded land during 16 years. Biomass and Bioenergy. 56:157-165.

Dimitriou, I. 2005. Performance and Sustainability of Short-Rotation Energy Crops Treated with Municipal and Industrial Residues. Doctoral thesis. Swedish University of Agricultural Sciences. Uppsala. 38 Pages.

Dimitriou, I and P. Aronsson. 2005. Willows for energy and phytoremediation in Sweden. Unasylva 221(56):47-50

Di Candilo, M., Ceotto, E., Librenti, I., Faeti, V. 2010. Manure fertilization on dedicated energy crops: productivity, energy and carbon cycle implications. In: Procedings of the 14th Ramiran International Conference of the FAO ESCOR-ENA Network on the Recycling of Agricultural, Municipal and Industrial Residues in agriculture, pp. 4

Di Mateo, G., G. Sperandio, and S. Verani. 2012. Field performance of poplar for bioenergy in southern Europe after two coppicing rotations: effects of clone and planting density. iForest-Biogeosciences and Forestry 5:224-229

Di Nasso, N., Guidi, W., Ragaglini, G., Tozzini, C., and Bonari, E. 2010. Biomass production and energy balance of a 12-year-old short-rotation coppice poplar stand under different cutting cycles. Global Change Biology Bioenergy. 2: 89-87.

Djomo, S., Kasmioui, O., and Ceulemans, R. 2011. Energy and greenhouse gas balance of bioenergy production from poplar and willow: a review. Glob. Change Biol. Bioenergy. 3:181-197.

DOE (Department of Energy). 2011. U.S. Billion-Ton Update Biomass supply for a bioenergy and bioproducts industry. Study Report under contract DE-AC05-00OR22725. 228 pages.

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

EIA, 2014b. Annual Energy Outlook. Renewable energy consumption by sector and source. Table A17. 2 pages.

EIA, 2014. Annual Energy Outlook. From http://www.eia.gov/analysis/projection-data.cfm#annualproj accessed February 10th, 2015.

Ettala, M. 1988. Short-rotation tree plantations at sanitary landfills. Waste Management & Research. 6, 291-302.

Ettala, M. and A. Lagerkvist. 1999. Effects of leachate irrigation on landfill vegetation and subsequent methane emissions. Water, air, and soil pollution. 113:203-216.

EU (European Union), 2010. ILCD (International Reference Life Cycle Data System) Handbook. General guide for life cycle assessment- Detailed guidance EUR 24708 EN. Luxembourg. 417 pages.

Fang, S., J. Xue, and L. Tang. 2007. Biomass production and carbon sequestration potential in poplar plantations with different management patterns. Journal of Environmental Management. 85:672-679.

Felix, E., D. Tilley, G. Felton, and E. Flamino. 2008. Biomass production of hybrid poplar (Populus sp.) grown on deep-trenched municipal biosolids. Ecological Engineering. 33:8-14.

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

Francescato, V., E. Antonini, and L. Zuccoli. 2008. Wood fuels handbook. Production, Quality requirements, Tradding. AIEL- Italian Agriforestry Energy Association. 83 pages.

French, C., N. Dickinson, and Ph. Putwain. 2006. Woody biomass phytoremediation of contaminated brownfield land. Environmental pollution 141: 387-395.

Gasol, C., X. Gabarrell, A. Anton, M. Rigola, J. Carrasco, P. Ciria, and J. Rieradevall. 2009a. LCA of poplar bioenergy system compared with *Brassica carinata* energy crop and natural gas in regional scenario. Biomass and Bioenergy 33:1119-129.

Gasol, C., S. Martinez, M. Rigola, J. Rieradevall, A, Anton, J. Carrasco. 2009b. Feasability assessment of poplar bioenergy systems in the Southern Europe. Renew. Sustainable Energy Rev. 13(4):801-12.

Gavlak, R., D. Horneck, R. Miller, and J. Kotuby-Amacher. 2003. Soil, Plant and Water Reference Methods for the Western Region. WREP-125. 2nd Edition. WCC-103 Publication.

Geyer, W., J. DeWyke, W. Walawender. 2000. Biomass and gasification properties of young *populus* clones. Wood and Fiber Science. 32(3): 375-384

Goglio, P. and P. Owende. 2009. A screening LCA of short rotation coppice willow (Salix sp.) feedstock production system for small-scale electricity generation. Biosystems engineering. 103:389-394.

Gomes, H. 2012. Phytoremediation for bioenergy: challenges and opportunities. Environmental Technology Reviews. 1(1): 59-66.

Gonzalez-Garcia, S., J. Bacenetti, R. Murphy, and M. Fiala.2012. Present and future environmental impact of poplar cultivation in the Po Valley (Italy) under different crop management systems. Journal of cleaner production. 26:56-66.

Gonzalez-Garcia, S., B. Mola-Yudego, and R. Murphy. 2013. Life cycle assessment of potential energy uses for short rotation willow biomass in Sweden. International Journal Life Cycle Assessment. 18: 783-795.

Graham, R., L. Wright, and A. Turhollow. 1992. The potential for short-rotation woody crops to reduce U.S. CO_2 emissions. Climatic Change. 22:223-238.

Green, C. and A. Hoffnagle. 2004. Phytoremediation field studies database for chlorinated solvents, pesticides, explosives, and metals. U.S. Environmental Protection Agency, Washington, DC.www.clu-in.org accessed June 15th, 2013.

Haefke, C. 2008. Biomass combined heat and power (CHP) systems: The concept. Presented at Forever energy biomass for sustainable energy solutions. Duduque, Iowa. July 17th. 40 slides.

Hart, Q., O. Prilepova, J., Merz, V., Bandura, and B. Jenkins. 2014. Modeling poplar growth as a short rotation woody crop for biofuels. 25 pages. Accessed by Permalink https://escholarship.org/uc/item/1cc1p27b on August 18th, 2014.

Headlee, W., R. Zalesny Jr., D. Donner, and R. Hall, 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.

Heller, M., G. Keoleian, and T. Volk. 2003. Life cycle assessment of a willow bioenergy cropping system. Biomass and Bioenergy. 25:147-165.

Henry, Ch., D. Sullivan, R., Rynk, K., Dorsey, and C., Cogger. 1999. Managing nitrogen from biosolids. NW Biosolids Management Association. 75 pages.

Huijbregts, M., G. Norris, R. Bretz, A. Ciroth, B. Maurice, B. von Bahr, B. Weidema, and A. de Beaufort. 2001. Framework for modelling data uncertainty in life cycle inventories. Int. J. LCA. 6(3):127-132.

ILCB (International Reference Life Cycle Data System) handbook. 2010. Analysis of existing environmental impact assessment methodologies for use in Life Cycle Assessment. 105 pages.

IPCC (Intergovernmental Panel on Climate Change), 1996. Guidelines for national greenhouse gas inventories: Workbook. Module 5. Land-use change & Forestry. 56 pages.

Isebrands, J.2007. Best management practices poplar manual for agroforestry applications in Minnesota. USDA North Central Region Sustainable Agriculture Research. 56 pages.

ISO, 2006a. ISO 14040. Environmental management – life cycle assessment- principles and framework. Geneva, Switzerland. 20 pages

ISO, 2006b. ISO 14040. Environmental management-Life cycle assessment-Requirement and guidelines. Geneva, Switzerland. 46 pages.

James, L., S., Swinton, and K. Thelen. 2010. Profitability analysis of cellulosic energy crops compared with corn. Agronomy Journal. 102(2): 675-687.

Jenkins, B., L. Baxter, T. Miles Jr., and T. Miles. 1998. Combustion properties of biomass. Fuel Processing Technology. 54:17-46.

Jones, D., K. Williamson, and A. Owen. 2006. Phytoremediation of landfill leachate. Waste Management. 26: 825-837.

Kauter, D., I. Lewandowski, and W. Claupein. 2003. Quantity and quality of harvestable biomass from Populus short rotation coppice for solid fuel use – a review of the physiological basis and management influences. Biomass and Bioenergy. 24: 411-427.

Keddy, T. 2012. Short rotation woody crops for energy production-An overview. Canadian Forest Service. 18 slides.

Keller, C., C. Ludwig, F. Davoli, and J. Wochele. 2005. Thermal treatment of metal-enriched biomass produced from heavy metal phytoextraction. Environmental Science & Technology. 39:3359-3367.

Keoleian, G. and T. Volk. 2005. Renewable energy from willow biomass crops: Life cycle energy, environmental and economic performance. Critical Review in Plant Sciences. 24:385-406.

Klašnja, B., S. Kopitovic, S. Orlovic. 2002. Wood and bark of some poplar and willow clones as fuelwood. Biomass and Energy. 23: 427-432.

Klašnja, B., S. Orlović, Z. Galić, M. Drekić, V. Vasić, and A. Pilipović. 2008. Poplar biomass of high density short rotation plantations as raw material for energy production. Wood research. 53(2): 27-38.

Kline, E. 2005. Gate-to-gate life-cycle inventory of oriented strandboard production. Wood and Fiber Science. 37: 74-83.

Landsberg, J. and R. Waring. 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. Forest Ecology and Management 95:209-228.

Laureysens, I., R. Blust, L. De Temmerman, C. Lemmens, and R. Ceulemans. 2004a. Clonal variation in heavy metal accumulation and biomass production in a poplar coppice culture: I. Seasonal variation in leaf, wood and bark concentrations. Environmental Pollution. 131: 485-494.

Laureysens, I., L. De Temmerman, T. Hastir, M. Van Gysel, and R. Ceulemans. 2004b. Clonal variation in heavy metal accumulation and biomass production in a poplar coppice culture: II.Vertical distribution and phytoextraction potential. Environmental Pollution. 133: 541-551.

Laureysens, I., J. Bogaert, R. Blust, and R. Ceulemans. 2004c. Biomass production of 17 poplar clones in a short-rotation coppice culture on a waste disposal site and its relation to soil characteristics. Forest Ecology and Management. 187:295-309.

Laureysens, I., A., Pellis, J., Willen, and R., Ceulemans. 2005. Growth and production of a short rotation coppice culture of poplar. III. Second rotation results. Biomass and Bioenergy. 29:10-21.

Lettens, S., B. Muys, R. Ceulemans, E. Moons, J. Garcia, and P. Coppin. 2003. Energy budget and greenhouse gas balance evaluation of sustainable coppice systems for electricity production. Biomass and Bioenergy. 24: 179-197.

Licht, L. and J., Isebrand. 2005. Linking phtoremediated pollutant removal to biomass economic opportunities. Biomass and Bioenergy. 28(2):203-218.

Mann, M. and P. Spath. 1997. Life cycle assessment of a biomass gasification combined-cycle system. National Research Energy Lab. (NREL). 160 pages.

Manzone, M., G. Airoldi, and P. Balsari. 2009. Energetic and economic evaluation of a poplar cultivation for the biomass production in Italy. Biomass and Bioenergy. 33:1258-1264.

Maranan, M. 2006. Rapid assessment of chemical composition, calorific value and specific gravity of hybrid poplar using near infrared spectroscopy. Thesis of Master of Science in Mechanical Engineering at Washington State University. 85 pages.

McKenry, P. 2001. Energy production from biomass (part 1): Overview of biomass. Bioresource Technology. 83: 37-46.

McMurtrie, R., H. Comins, M. Kirschbaum, and Y-P Wang. 1992. Modifying existing forest growth models to take account of effects of elevated CO_2. Aust. J. Bot. 40:657-677.

Meers, E., B. Vandecasteele, A. Ruttens, J. Vangrnsveld, and F. Tack. 2007. Potential of five willow species (*Salix* spp.) for phytoremediation of heavy metals. Environmental and Experimental Botany. 60: 57-68.

Milota, M., C. West, and I. Hartley. 2005. Gate to gate life cycle inventory of softwood lumber production. Wood and Fiber Science, 37 CORRIM Special Issue. 47-57.

Miller, R. and B., Bender. 2012. Proceedings from Sun Grant national conference for biomass feedstock production and utilization. New Orleans, LA. From http://sungrant.tenneessee.edu/NatConference/ Accessed on November 23th, 2013.

Mitchell, C., E. Stevens, and M. Watters. 1999. Short-rotation forestry- operations, productivity and cost based on experience gained in the UK. Forest Ecology and Management. 121: 123-136.

Mohamed, N. 2011. Interaction of advanced scientific irrigation management (ASIM) with I-SCADA system for efficient and sustainable production of fiber on 10,360 hectares.http://digitool.library.colostate.edu/R/?func=dbin-jump-full&object_id=208878 accessed December 7th, 2013.

Monclus, R., E. Dreyer, M. Villar, F.M. Delmonte, D. Delay, J-M Petit, C. Barbaroux, D. Le Thiec, C. Brechet, and F. Brignolas. 2006. Impact of drought on productivity and water use efficiency in 29 genotypes of *Populus deltoides* x *Populus nigra*. New Phytol. 169: 765-777.

Movessessian, G. 2003. Wood biomass of fast growing poplar plantations as an alternative source of energy. Final report. Institute of Botany of Armenia.

MWMC (Metropolitan Wastewater Management Commission). 2001. Section 5 Biosolids characteristics *in* Biosolids management plan for the metropolitan wastewater management commission. Document No. Res-00449N. 32 pages

MWMC. 2014. Website www.mwmcpartners.org accessed February 21st, 2014.

Nagendran, R., A. Selvam, K. Joseph, and C. Chiemchaisri. 2006. Phytoremediation and rehabilitation of municipal solid waste landfills and dumpsites: A brief review. Waste Management 26: 1357-1369.

Nixon, P. 2002. Use of landfill leachate to supply water and nutrients for short rotation coppice. Report for WREN. Waste Recycling Environmental Limited. Norwich, UK.

ODOE (Oregon Department of Energy), wd. Renewable energy. From http://www.oregon.gov/energy/RENEW/Pages/RPS_home.aspx) accessed February 10th, 2015.

PE International, 2010. Handbook for Life Cycle Assessment (LCA). Using the GaBi education software package. 66 pages.

Pitman, R. 2006. Wood ash used in forestry- a review of the environmental impacts. Forestry 9(5): 563-588.

PnET. 2014. http://daac.ornl.gov/MODELS/guides/pnet_guide.html, Accessed June 10th, 2014

Poeschl, M., S. Ward, and P. Owende. 2012. Environmental impacts of biogas deployment – Part I: Life cycle inventory for evaluation of production process emissions to air. Journal of Cleaner Production. 24:168-183.

Pontailler, J., R. Ceulemans, and J. Guittet. 1999. Biomass yield of poplar after five 2-year coppice rotations. Forestry. 72(2):157-163.

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

Puettmman, M. and J. Wilson. 2005. Gate-to-gate life cycle inventory of glued-laminated timbers production. Wood and fiber science, 37:99-113. CORRIM Special Issue.

Puettmann, M. 2009. Cradle-to-gate LCI comparison of US wood products manufacturing. Forest Product Society Meeting. Boise, ID.

Puettmann, M., F. Wagner, and L. Johnson. 2010. Life cycle inventory of softwood lumber from the inland northwest U.S. Wood and fiber science. 42: 52-66

Pulford, I. and C. Watson. 2003. Phytoremediation of heavy metal-contaminated land by trees—a review. Environment International. 29:529-540.

Rafaschieri, A., M. Rapaccini, and G. Manfrida. 1999. Life cycle assessment of electricity production from poplar energy crops compared with conventional fossil fuels. Energy conversion and management. 40:1477-1493.

Richard, P. 2011. An assessment of UK bioenergy production, resource availability, biomass gasification, and life cycle environmental impacts. PhD thesis. Department of Mechanical Engineering, University of Bath. U.K. 314 pages.

Rockwood, D., C. Naidu, D. Carter, M. Rahmani, T. Spriggs, C. Lin, G. Alker, J. Isebrands, and S. Segrest. 2004. Short-rotation woody crops and phytoremediation: Opportunities for agroforestry? Agroforestry Systems. 61:51-63.

Rockwood, D., D. Carter, M. Langholtz, and J. Stricker. 2006. Eucaliptus and Populus short rotation woody crops for phosphate mined lands in Florida, USA. Biomass and Bioenergy. 30: 728-734.

Running, S., and J. Coughlan. 1998. A general model of forest ecosystem processes for regional applications. I. Hydrologic balance, canopy gas exchange and primary production processes. Ecological Modelling. 42: 125-154.

Running, S., and S. Gower. 1991. FOREST-BGC, a general model of forest ecosystem processes for regional applications. II. Dynamic carbon allocation and nitrogen budgets. Tree Physiology. 9:147-160.

Shock, C., R. Flock, E. Feibert, A. Pereira, and M. O'Neill. 2013. Drip irrigation guide for growers of hybrid poplar. Sustainable Agriculture Technique. EM 8902. 7 pages. Oregon State University, Extension Services.

Sheng, C. and J. Azevedo. 2005. Estimating the higher heating value of biomass fuels from basic analysis data. Biomass and Bioenergy. 28(5):499-507.

Siegl, S., M. Laaber, and P. Holubar. 2011. Green electricity from biomass, Part II: Environmental impacts considering avoided burdens from replacing the conventional provision of additional functions. Waste Biomass Valor. 21 pages. DOI 10.1007/s12649-011-9091-5.

SimaPro 8. 2013. From http://www.pre-sustainability.com/simapro. Accessed on January 2nd, 2013.

Smesrud, J., G. Duvendack, J. Obereiner, J. Jordahl, and M. Madison. 2012. Practical salinity management for leachate irrigation to poplar trees. International Journal of Phytoremediation. 14(S1):26-46.

Spinelli, R. 2007.Short rotation coppice (SRC) production in Italy. From http://www.sswm.info/sites/default/files/reference_attachments/SPINELLI%202006%20Short%20Rotation%20Coppice%20Production%20in%20Italy.pdf. Accessed on May 22nd, 2014.

Spinelli, R., C. Nati, and N. Magagnotti. 2008b. Harvesting short-rotation poplar plantations for biomass production. Croat. J. For. Eng. 29(2):129-139.

Spinelli, R., C. Nati, and N. Magagnotti. 2009. Using modified foragers to harvest short-rotation poplar plantations. Biomass and Bioenergy. 33:817-821.

Spinelli, R., N. Magagnotti, G. Picchi, C. Lombardini, and C. Nati. 2011. Upsized harvesting technology for coping with the new trends in short-rotation coppice. Applied Engineering in Agriculture. 27(4):1-7.

Stanton, B. 2007. Hybrid poplar feedstock production: Economic opportunity for renewable energy in North America. TAPPI International Conference on Renewable Energy. Atlanta, Georgia. 18 slides

Stanton, B., R. Shuren, R. Stonex, and B. Summers. 2013. Growing green energy: Poplar as a short rotation bioenergy crop. Webinar AHB-GWR at November 26th, 2013.

Strong, T. 1992. Energy values of nine *populus* clones. North Central Forest Experiment Station. Forest Service U.S.D.A. Research note NC-257

The 3-PG Model. 2014. http://goo.gl/xlQLNA Accessed June 10th, 2014

TRACI. 2008. The Tools for the Reduction and Assessment of Chemical and Other Environmental Impacts. Journal of Industrial Ecology. 6(3-4): 49-78.

Tsoumis, G. 1991. Thermal properties *in* Science and Technology of Wood. Structure, Properties, Utilization. Chapman & Hall. Page 201.

Tubby,I. and A. Armstrong. 2002.Establishment and management of short rotation coppice. Forestry Commision Practice Note (FCPN007). http://www.forestry.gov.uk accessed March 12th, 2014.

UCS USA (Union of Concerned Scientists) Science for a healthy planet and safer world, 2015. Environmental impacts of renewable energy technologies. http://www.ucsusa.org/clean_energy/our-energy-choices/renewable-energy/environmental-impacts-of.html#.VQxrJLB0y70 accessed March 2nd. 2015.

U.S. EPA (Environmental Protection Agency), 1972. Public Law 92-500. Water Quality Act. Secondary Treatment Regulation Code of Federal Regulations 40 CFD. Part 133. 88 pages.

U.S. EPA. 2011. Phytoremediation definitions. From http://toxics.usgs.gov/definitions/phytoremediation.html. Accessed on November 23th, 2013

U.S. LCI (Life Cycle Inventory Database). 2012. National Renewable Energy Laboratory. From https://www.lca.commons.gov/nrel/search accessed on May 13th, 2014.

USDA FSA (Farm Service Agency of US Department of Agriculture). 2011. Biomass Crop assistance program. From http://www.fsa.usda.gov/programs-and-services/energy-programs/index. Accessed on October 12th, 2013.

Ventura, L., B. Amaral, K. Wanderley, J. Godoy, and A. Gioda. 2014. Validation method to determine metals in atmospheric particulate matter by inductively coupled plasma optical emission spectrometry. J. Braz. Chem. Soc. 25(9): 1571-1582.

Verani, S., G. Sperandio, R. Picchio, R. Spinelli, and G. Picchi. 2008. Field handbook-Poplar Harvesting. International Poplar Commission thematic papers. Forestry department FAO. Working paper IPC/8. 60 pages.

Vysloužilová, M., P.Tlustoš, J. Száková, and D. Pavlíková. 2003. As, Cd, Pb and Zn uptake by *Salix spp*. Clones grown in soils enriched by high loads of these elements. Plant soil environ. 49:191-196.

Wang, Z., J. Dunn, and M. Wang. 2012. GREET model short rotation woody crops (SRWC) parameter development. Center for Transportation Research. Argonne National Laboratory. 19 pages.

Wang, D., D. LeBauer, and M. Dietze. 2013. Predicting yields of short-rotation hybrid poplar (*Populus spp*.) for the United States through model-data synthesis. Ecological Applications. 23(4): 944-958.

Weinstein, D., R. Belion, and R. Yanai.1991. Modeling changes in red spruce carbon balance and allocation in response to interacting ozone and nutrient stresses. Tree Physiology. 9:127-146.

White, R. 1987. Effect of lignin content and extractives on the higher heating value of wood. Wood and Fiber Science. 19(4): 446-452.

Williams, M. 2011. An analysis of supplemental biomass production through the establishment of short rotation woody crops (SRWC) in the Roaring Fork Valley. Flux Farm Foundation Report. 17 pages.

Wilson, J. and E. Dancer. 2005. Gate-to-gate life-cycle inventory of laminated veneer lumber production. Wood and fiber science. 37: 114-127

Wilson, J. and E. Sakimoto. 2005. Gate-to-gate life-cycle inventory of softwood plywood production. Wood and fiber science. 37: 58-73.

Wilson, J. 2008a. Particleboard: A life-cycle inventory of manufacturing panels from resource through product. Phase II. Final report. Module F, CORRIM. 57pages

Wilson, J. 2008b. Medium Density Fiberboard: A Life-Cycle Inventory of Manufacturing Panels from Resource through Product. Final Report Phase II – CORRIM. 60 pages

Witters, N., S. Van Slycken, A. Ruttens, K. Adriaensen, E. Meers, L. Meiresonne, F. Tack, T. Thewys, E. Laes, and J. Vangronsveld. 2009. Short-rotation coppice of willow for phytoremediation of a metal-contaminated agricultural area: a sustainability assessment. Bioenergy Res. 2: 144-152.

WM (Water Management) Annual Report. 2012. 2011 Leachate irrigation monitoring report. Drip irrigated poplar tree farm. Riverbend landfill. Yamhill County, Oregon. 100 pages.

Waste Management website. 2014. From http://riberbend.wm.com/ Accessed on February 10th, 2013.

World Energy Council, 2004. Comparison of energy systems using life cycle assessment. http://www.worldenergy.org/documents/lca2.pdf. Accessed April 22nd, 2012.

Zalesny, R. and E. Bauer. 2007. Selecting and utilizing *Populus* and *Salix* for Landfill covers: Implications for leachate irrigation. International Journal of Phytoremediation. 9: 497-511.

Zaman, A. 2010. Comparative study of municipal solid waste treatment technologies using life cycle assessment method. Int. J. Environ. Sci. Tech. 7(2): 225-234.

APPENDICES

Appendix A: Parameters used to estimate biomass yield with 3-PG model in Sites 1 and 2

Table A 1. List of categories and parameters of 3-PG model

Categories	Parameter	Sub parameters	Units	Site 1	Site 2
Tree	K		unitless	0.5	0.5
	fullCanAge		y	1.5	1.5
	kG		KPa^{-1}	0.5	0.5
	alpha		Kg/mol	0.08	0.08
	fT	mn	C	0	0
		opt		20	20
		mx		50	50
	BLcond			0.04	0.04
	fAge	f0		1	1
		f1	yr	0	0
		tm		47.5	47.5
		n		3.5	3.5
	fN0			0.26	0.26
	SLA	f0		19	19
		f1		10.8	10.8
		tm		5	5
		n		2	2
	Conductance	mn		0.0001	0.0001
		mx		0.2	0.2
		lai	m^2/m^2	2.6	2.6
	Intcptn	mn		0	0
		mx		0.24	0.24
		lai	m^2/m^2	7.3	7.3
	y			0.47	0.47
	pfs	stemCnt		2.8	2.8
		stemC	cm^{-1}	0.18	0.18
		stemP		2.4	2.4

		pfsMx		2	2
		pfsP		-0.772	-0.772
		pfsC	cm^{-1}	1.3	1.3
	pR	mn		0.17	0.17
		mx		0.7	0.7
		m0		0.5	0.5
		turnover	$month^{-1}$	0.02	0.02
	rootP	frac	$month^{-1}$	0.2	0.2
		LAITarget	m^2/m^2	10	10
		efficiency	kg/kg	0.7	0.7
	litterfall	f0		0.0015	0.0015
		f1		0.03	0.03
		tm	yr	2	2
		n		2.5	2.5
Plantation	type				
	StockingDensity		Tress/ha	3587	**470**
	SeedlingMass		kg	**0.02**	**0.02**
	pS		unitless	0.1	0.1
	pF		unitless	0	0
	pR		unitless	0.9	0.9
Soil	maxaws			-1	-1
	swpower			-1	-1
	swconst			-1	-1
Weather	Location			Jefferson	Boardman
	month		month		
	tmin		ºC		
	tmax		ºC		
	tdmean		ºC		
	ppt		mm		
	rad		MJ/day		
	daylight		h		
Constants	days_per_mo		days/mo	30.4	30.4

	nth				
	e20		Vp/t	2.2	2.2
	rhoAir		Kg/m^3	1.2	1.2
	lambda		J/kg	2460000	2460000
	VPDconv			0.000622	0.000622
	Qa		W/m^2	-90	-90
	Qb		unitless	0.8	0.8
	gDM_mol		g/mol(ºC)	24	24
	molPAR_MJ		mol(ºC)/MJ	2.3	2.3
Manage	irrigFrac			**0**	1
	fertility			**0.5**	0.7
	DatePlanted		date	**05/01/2012**	**05/01/2013**
	DateCoppiced		date	**09/24/2013**	**11/01/2015**
	CoppiceInterval		years	3	3
	DateFinalHarvest		date	**11/01/2022**	**11/01/2024**

Bold numbers mean specific data from sites

Source from: http://poplarmodel.org. Accessed on September 10th, 2014

Description of categories

Tree - Crop management parameters

Plantation - Greenwood PG values (default)

Soil - Soil information based on current location

Weather - Select location to set average weather data

Constants - These are constants used in the model

Manage - Crop management parameters

Description of parameters and Sub-parameters

From Tree category

K - Radiation extinction coefficient

fullCanAge - Year where tree reaches full canopy cover

kG – Determines the response of the canopy conductance to the vapor pressure deficit

alpha – Canopy quantum efficiency

fT – Specifies the parameters affecting temperature modifier, fT. A graph of how these parameters affect the temperature modifier is found here: https://www.desmos.com/calculator/69iwqntl28

mn – Specifies the minimum temperature of respiration

opt – Specifies the optimum temperature of respiration

mx – Specifies the maximum temperature of respiration

BLcond – Canopy boundary layer conductance. Used in the calculation of transpiration

fAge – Specifies the growth limiter as a function of the tree age. This is a time dependency parameter. The graph of the function is available at: https://www.desmos.com/calculator/wa0qih18h

f0 – Value at initial time

f1 – Value at infinite time

tm – Time in years where value is the average of f0 and f1

n - >=1; Parameter specifying the rate of change around tm. n=1 is approximately a linear change, as n increases, change becomes more localized around tm.

fN0 – Used in the calculation of the nutritional modifier, fNutr. fNutr ranges from (fN0,1) based on the fertility index which ranges from 0 to 1. When fN0=1 indicates fNUtr is 1

SLA – Specifies the specific leaf area as a function of the tree age. This is a time dependency parameter. Used in the calculation of LAI. The graph of the function is available at: https://www.desmos.com/calculator/wa0q2ih18h

f0 – Value at initial time

f1 – Value at infinite time

tm – Time in years where value is the average of f0 and f1

n - >=1; parameter specifying the rate of change around tm. n=1 is approximately a linear change, as n increases, change becomes more localized around tm.

Conductance – Along with a physiological modifier, specifies the canopy conductance. Used in calculation of transpiration.

mn – Minimum value, when lai=0

mx – Maximum value

lai – Leaf area index where parameter reaches a maximum value

Intcptn – Rainfall interception fraction. A linear function w.r.t. LAI

mn – Minimum value, when lai=0

mx – Maximum value

lai – Leaf area index where parameter reaches a maximum value

y – Assimilation use efficiency. Used in calculation of the NPP

pfs – This define the foliage to stem (WF/WS) fraction in allocating aboveground biomass of the tree. This is calculated with a pair of allometric power equations. The first relates basal diameter, (DOB) to total woody biomass, while the second relates DOB to pfs. The parameterization of the relationship between DOB and woody biomass is inverted to determine the DOB from the modeled woody fraction. The model allocates the appropriate fraction of wood based on the stocking density of the plantation. DOB rather than DBH is used for comparison of trees with a high stemCnt and rapid coppicing value.

stemCnt – Average number os stems per stump

stemC – Constant in relation of DOB to woody biomass

stemP – Power in relation of DOB to woody biomass

pfsMx – Maximum possible pfs value allowed

pfsP – Power in relation of DOB to pfs

pfsC – Constant in relation of DOB to pfs

pR – Along with a physiological parameter, specifies the amount of new growth allocated to the root system, and the turnover rate.

mn–Minimum allocation to the root, when the physiological parameter is1 mx – Maximum allocation to the root, when m0

m0 – Dependance of the fertility index. 0 indicates full dependence on fertility, 1 indicates a constant allocation, independent of fertility.

Turnover – Specifies the monthly root turnover rate.

rootP – These parameters specify root allocation to growth after coppicing.

frac – Specifies the factional amount of rrot biomass that exceeds the aboveground requirements that can be supplied in a given month.

LAITarget – Specifies a target LAI rate. The target LAI included in the calculation of a target NPP, based on weather parameters. Below this target, the roots will contribute biomass if the below ground root mass exceeds the requirements of the aboveground biomass. The target is specified in LAI to time root contributions to period of growth.

Efficiency – Specifies the efficiency in converting root biomass into aboveground biomass.

litterfall – Specifies the fractional monthly loss of foliage. This is a time dependency parameter. The graph of the function is available at: https://www.desmos.com/calculator/6iq9ppdqs7

f0 – Value at initial time

f1 – Value at infinite time

tm – Time in years where value is the average of f0 and f1

n - >=1; parameter specifying the rate of change around tm. n=1 is approximately a linear change, as n increases, change becomes more localized around tm.

From plantation category

Type –

StockingDensity – Number of trees planted per hectare

SeedlingMass – Mass of the seedling

pS – Proportion of seedling mass going into stem pF – Proportion of seedling mass going into foliage

pR – Proportion of seedling mass going into root

From soil category

maxaws – Maximum available soil water

swpower – Power parameter based on clay content of soil

swconst – Constant parameter based on clay content soil

From weather category

From constants category

days_per_month – Number of Days in an average month

e20 – Rate of change of saturated VP with T at 20C

rhoAir – Density of air

lambda – Latent heat of vapourisation of H_2O

VPDconv – Convert VPD to saturation deficit = 18/29/1000

Qa – Intercept of net radiation versus solar radiation relationship

Qb – slope of net vs solar radiation relationship

gDM_mol – Molecular weight of dry matter

molPAR_MJ – Conversion of solar radiation to PAR

From manage category

irrigFrac – irrigation fraction: 1=fully irrigated, 0=no irrigation. Any values between 0 and 1 are acceptable

fertility – Soil fertility

DatePlanted – Date the crop was planted

DateCoppiced – Date of the first coppice

CoppiceInterval – How after the crop is coppiced after the first coppice

DateFinalHarvest – Date when the crop is completely harvested

Appendix B: Primary data from questionnaires

Site 1: Jefferson

When was the plantation established, 2011 or 2012? (I understand that the poplar was harvested after two growing seasons)

Will the poplar clones remain the same during future cultivations (2014-2022)? I ask this because 6 of 11 poplar clones were very productive compared to the other five.

What will be the rotation age for future plantings?

What type and amount of herbicide and in what concentration was applied?

Were any air emissions measured or estimated for the time period from site preparation to harvest? If so, what were the types and amounts? The following are of the greatest interest.

Compound	Amount released	Units	How was this measured or estimated?
PM10			
PM2.5			
CO_2			
CO			
SO_x			
NO_x			
N_20			
CH_4			
VOC			

Were any liquid effluents emitted (and measured or estimated) for the time period from site preparation to harvest? If so, what were the types and amounts?

What was released?	How much was released?	Units	What was the concentration?	Units	How was this measured or estimated?

Were any materials sent to landfill (and measured or estimated) for the time period from site preparation to harvest? If so, what were the types and amounts?

What was landfilled?	How much was landfilled?	Units	How was this measured or estimated?

How much electricity (if any) was purchased or used from the beginning of site preparation until the end of the harvest?

How much gasoline (if any) was purchased or used from the beginning of site preparation until the end of the harvest?

Regarding diesel use –

A. How much diesel was purchased or used for site preparation?

B. How much diesel was purchased or used after site preparation until the start of the harvest?

C. I have values for the amount of diesel consumed during the harvest.

In the future, when the productivity of the planted clones decreases, will the stumps be removed?

A. What technologies would be used for stump removal and land clearing?

B. How much diesel would you expect to consumption of diesel for each activity?

Site 2: Boardman Tree Farm

How many hectares of poplar are planted to produce biomass for bioenergy in the BTF? What is the planting density of poplar for bioenergy?

Which poplar clones were utilized to produce bioenergy?

For each harvest of biomass for energy from 2009 to 2014

A. How many hectares of poplar were harvested?

B. What was the age of the poplar at the time of harvest?

C. How many tons of bone dry poplar biomass was obtained?

D. What was the moisture content of the biomass?

E. How much water was consumed while growing this?

F. What type, amount, and concentration of herbicides (if any) was applied for site preparation?

G. What types of fertilizer and fungicides and in what amounts and concentrations were applied after site preparation until the end of the harvest?

H. How much diesel was purchased or used for site preparation?

I. How much diesel was purchased or used after site preparation until the end of the harvest?

J. Were other fuels used? What quantities?

K. How much electricity was purchased or used for site preparation?

L. How much electricity was purchased or used after site preparation until the end of the harvest

Were any air emissions measured or estimated for the time period from 2009 to 2013? The following are of the greatest interest.

Compound	Amount released					Units	How was this measured or estimated?
	2009	2010	2011	2012	2013		
PM_{10}							
$PM_{2.5}$							
CO_2							
CO							
SO_x							
NO_x							
N_20							
CH_4							
VOC							
Others							

Were any liquid effluents measured or estimated for the time period from 2009 to 2013? Is so, what were the types, amounts and concentrations?

What was released?	How much was released? And What was the concentration?					Units	How was this measured or estimated?
	2009	2010	2011	2012	2013		

Were any materials sent to landfill (and measured or estimated) for the time period from 2009 to 2013? If so, what were the types and amounts?

What was landfilled?	How much was landfilled?					Units	How was this measured or estimated?
	2009	2010	2011	2012	2013		

For future harvests of biomass from the site

A. What would be the rotation age for future plantings of poplar for bioenergy?

B. What would be the expected yield from each rotation?

C. What technology would be used and how much would be the estimated consumption of diesel used for stump removing and land clearing after the final rotation is harvested?

Site 3: Biocycle Tree Farm (Eugene/Springfield)

These questions are for the site preparation, planting, and growing of 400 acres of Biocycle Tree Farm.

A. When this plantation was pruned and thinned during its growing? And how much biomass was collected each time?

B. If site preparation was a contracted service, would it be possible to get the contact information for the contractor to ask the following questions (if you don't know them)?

B1. What type, amount, and concentration of herbicides was applied?

B2. How much diesel, gasoline and other fuels were purchased or used?

C. If you have to determine the energy consumption for the poplar plantation (without site preparation), what would be the best number (average data) for the following sources: diesel, gasoline, and electricity.

D. You indicated that you don't know the annual fuel usage for the plantation. Would it be possible to provide fuel use for the facility and estimate the part that is used for the plantation? Alternatively, can fuel consumption be estimated from motor horsepower and run time?

These questions are for the harvesting, stump removal, and site restoration of the Phase 1 (52 acres) that was harvested in September 2013. Would it be OK for us to contact Todd Miller to learn more about the harvest

The questions we have are:

E. How many green tons of poplar was harvested?

F. What was the harvested material used for (biomass for energy, chips for pulp, other wood products)? And in what amounts?

G. What was the moisture content of the harvested material?

H. How much was the haul distance for the harvested material? Or where was the harvested material utilized?

H. How much diesel and/or gasoline were purchased or used for harvesting?

I. Were other fuels used for harvesting? What quantities?

J. How much electricity was purchased or used for harvesting?

K. How much diesel were purchased or used for stump removal and site restoration?

L. Were other fuels used for stump removal and site preparation? What quantities?

M. How much electricity was purchased or used for stump removal and site restoration?

Eugene/Springfield Water Pollution Control Facility has an Air Quality Permit # 202537. Does this permit cover the plantation? Are there other permits for the Biosolids Management facility and the Biocycle Tree Farm?

Were any additional or special environmental permits required for the 2013 harvest?

Were any materials sent to landfill (and measured or estimated) for the time period from site preparation to harvest? If so, what were the types and amounts?

What was landfilled?	How much was landfilled?	Units	How was this measured or estimated?

These questions are related with production of biosolids.

A. What polymer was used in the mechanical dewatering and in what amount?

B. How much electricity was used to transform sludge in dry biosolids?

C. Of the total liquid biosolids from the lagoons, what percent

C1. was applied to the Biocycle tree farm?

C2. was applied to the Beneficial Reuse Site

C3. went to the mechanical dewatering process?

D. How much electrical energy is required to pump to the Bicycle tree farm compared to the Beneficial Reuse Site? Alternatively, how much horsepower is each pump and how long does it run annually?

What are the compositions of dry and liquid biosolids? Do you have this published anywhere we can access? The following are of the greatest interest.

Compound	Dry Solids		Liquid Solids	
	Amount or range	Units	Amount or range	Units
Nutrients				
NH_4-N				
NO_3-N				
Organic N				
K				
P				
Trace elements				
Mercury				
Arsenic				
Cadmium				
Chromium				
Lead				
Nickel				
Zinc				

Copper				
Magnesium				
Calcium				
Other…				

The following questions are for the annual emissions during production of biosolids.

Were any materials sent to landfill (and measured or estimated) from the process of converting sludge to biosolids each year? If so, what were the types and amounts?

What was landfilled?	How much was landfilled?	Units	How was this measured or estimated?

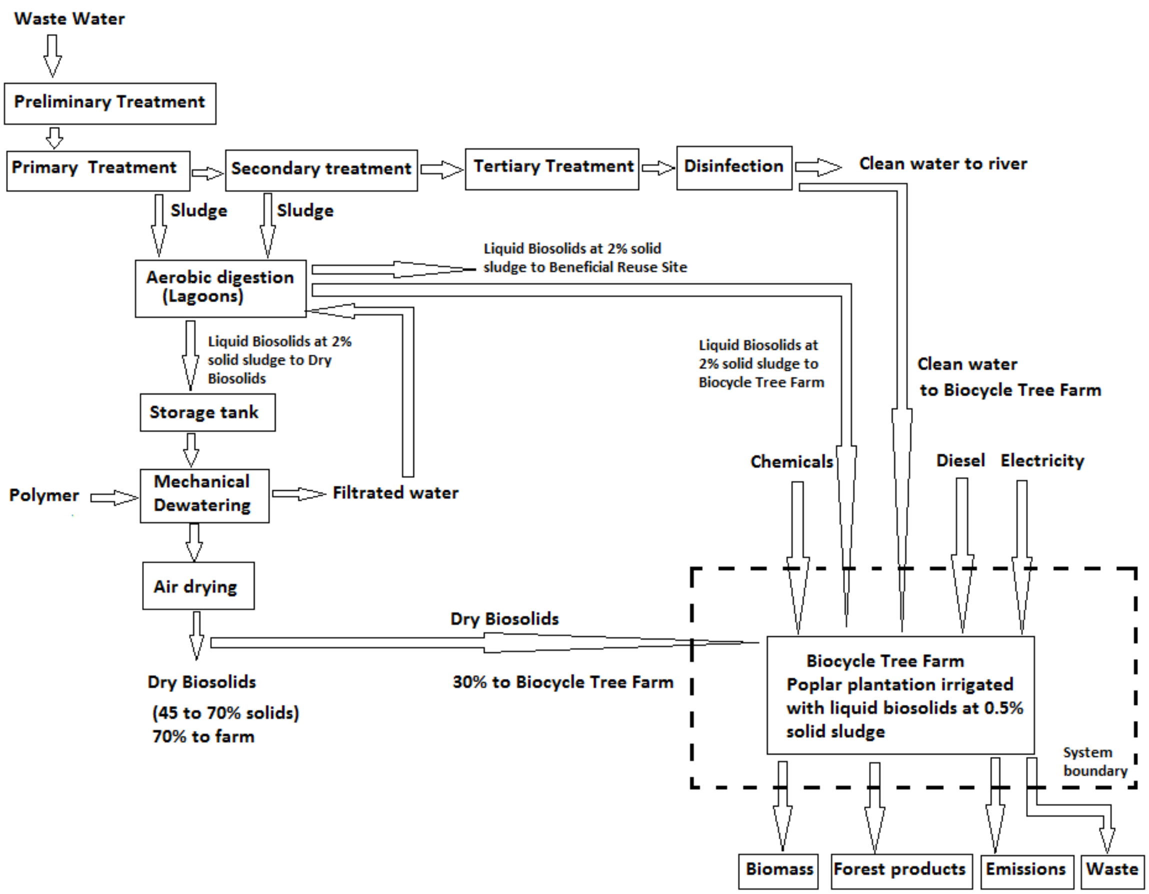


Figure B 1. Process flow diagram of Biocycle Tree Farm

Site 4: Riverbend Landfill (McMinnville)

The following questions are related to the two sites with drip irrigation (South and North Fields consisting of 45-acre total).

Part 1

A. When was the poplar planted?

B. What type, amount, and concentration of chemicals (if any, herbicides, fertilizer, fungicide, etc.) were applied for poplar tree farm?

C. How much pond leachate was used for drip irrigation of poplar tree farm?

D. How much freshwater was consumed during poplar growing?

E. How much energy (diesel, electricity, other) was used for the growing of poplar under drip irrigation?

F. When was the poplar pruned, thinned, or harvested?

Year	Mark the activity			Amount (green tons)	Moisture content (%)
	Thin	Prune	Harvest		

G. What will be the rotation age for future plantings?

H. From the point of view of environmental impacts, there are permits for air, water and solid emissions for the leachate management. However, these permits do not mention the poplar plantation. Could you tell us, if there is (are) additional permit(s) for emissions from the plantation?

Part 2

The following questions are related with landfill leachate utilization.

A. Was the leachate storage pond built specifically for irrigation of the poplar tree farm? If no, what would it be used for without poplar tree farm? Without the poplar farm, where would the effluent from the storage pond go?

B. How much energy (diesel, electricity, other) was used to transport (pump) leachate from the storage pond into sites with drip irrigation?

C. For the leachate from the landfill

How much was produced annually?

How much went to the storage pond?

How much was trucked off site?

What was the average haul distance?

What was the fate of the leachate hauled off site?

D. For the storage pond

Was landfill leachate the only input to the pond?

How much ponded leached was applied to the 45-acre South and North Sites?

How much was trucked off site?

What was the average haul distance?

What was the fate of the leachate hauled off site?

How much ponded leached was applied to the Spray Site?

Was ponded leachate disposed of in any other way? Where? How much?

E. Was the application of ponded leachate a seasonal activity? If so, during which months did this occur?
F. How old is the landfill leachate pond?

We have the report "2011 Leachate Irrigation Monitoring Report. Drip irrigated poplar tree farm. Riverbend Landfill. Yamhill County, Oregon". This was published on March 2012. Is this the best data for the composition of the landfill leachate? If not, what is a general composition of ponded leachate?

Parameter	Units	Range	Average
Bicarbonate Alkalinity	mg/L		
Carbonate Alkalinity	mg/L		
Total Alkalinity	mg/L		
Calcium, Dissolved	mg/L		
Chemical Oxygen Demand (COD)	mg/L		
Chloride	mg/L		
Hardness, as $CaCO_3$	mg/L		
Ammonia as N	mg/L		
Nitrate as N	mg/L		
pH adj. to 25 deg C	SU		
Silicon	µg/L		
Specific Conductance	umhos/cm		
Sulfate	mg/L		
Total Anions	meq/L		
Total Cations	meq/L		
Total Dissolved Solids	mg/L		
Total Kjeldahl Nitrogen	mg/L		
Total Organic Carbon- Average	mg/L		
Total Suspended Solids	mg/L		
Antimony	µg/L		
Arsenic	µg/L		
Barium	µg/L		
Boron	µg/L		
Cadmium	µg/L		
Chromium	µg/L		
Cobalt	µg/L		
Copper	µg/L		

Iron, Dissolved	µg/L		
Lead	µg/L		
Magnesium, Dissolved	µg/L		
Manganese, Dissolved	µg/L		
Nickel	µg/L		
Potassium, Dissolved	µg/L		
Sodium, Dissolved	µg/L		
Vanadium	µg/L		
Zinc	µg/L		
Others (Mercury, Silver, etc.)			

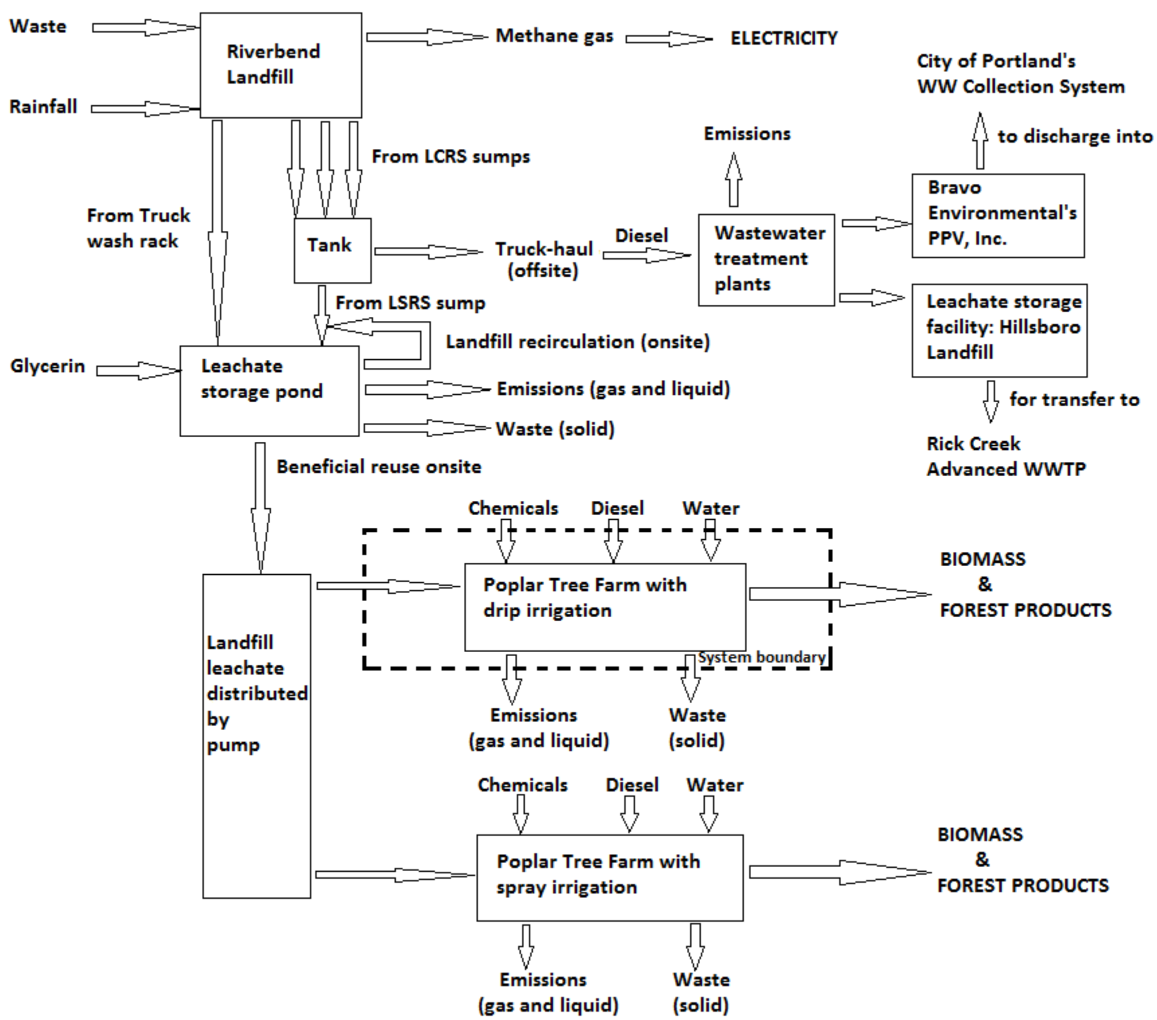


Figure B 2. Process flow diagram of Riverbend Landfill

INPUTS

Fuel required to produce 1 BDmT of biomass

Activity	Fuel consumption (L/h)	Machines (Power)
Site preparation		
Cultivation		
Harvesting		
Stump removal		
Transportation		
TOTAL		

Supplies required to produce 1 BDmT of biomass

Activity	Inputs	Unit	Amount	Concentration (mg/L)
Cultivation	Fertilizer *			
	N	Kg/ha-year		
	P	Kg/ha-year		
	K	Kg/ha-year		
	Herbicides*	Kg/ha-year		
	Insecticides *	Kg/ha-year		
	Water	L/ha-year		
	Electricity	KWh		
TOTAL				

*: Chemicals have to include type and concentration

Composition of treated wastewater and leachate used for irrigation

Element	Amount (mg)	Concentration (mg/L)
NH_4+		
NH_3-N		
NO_3-N		
P		
SO_4 2-		
Cl		
K		
Ca		
Mg		
Na		
Fe		

Mn		
Cu		
Cd		
Pb		
Hg		
Zn		
B		
Cl		
Other		
EC		
COD		
TDS		
TKN		
pH		
BOD_5		
$CBOD_5$		

Where: EC= Electrical conductivity, COD= chemical oxygen demand, TDS=Total dissolved solid, TKN=total Kjeldahl nitrogen, BOD_5=Biochemical oxygen demand after 5 days and $CBOD_5$= carbonaceous BOD_5

OUTPUTS

Emissions to land, water and air due to the production of 1 BDmT of biomass

	Unit	Amount	References (*)
Solid waste			
Residues			
Waterborne emissions			
BOD_5			
Suspended solids			
Hydrogen ion concentration			
$CBOD_5$			
Other (Total N levels, heavy metal and non-metals)			
Atmospheric emissions			
SOx			
NOx			
CO			
PM10			
NH4			

VOC			
CO_2			

(*) Mainly from databases (NREL USLCI and EcoInvent from SimaPro)

Appendix C. Spreadsheet with inputs for each site

Table C 1. Inputs for Site 1

Site 1: Without irrigation	(Jefferson)		Surface harvested on 2013		28.63	ha		RxSy: Root at x year and Steem at y year											
Database																			
Rotation years:	2	(two growing seasons in first harvest)				Assumption: continue the SRWC plantation for 2 more cycles													
		R2S2			R5S3			R8S3			R11S3								
INPUTS		Turnover 1			Turnover 2			Turnover 3			Last harvesting		Unit reported	Convertion	MC (%)		SI unit		Unit to SimaPro
	2012 (Year 1)	2013 (Year 2)	2014 (Year 3)	2015 (Year 4)	2016 (Year 5)	2017 (Year 6)	2018 (Year 7)	2019 (Year 8)	2020 (Year 9)	2021 (Year 10)	2022 (Year 11)	Total		to SI units					
Cuttings	2.25											2.25	Ton	1.00		0.08	Ton/ha	0.00073	Ton/BDmT
Cutting amount	3586											3586	p/ha					33.42	p/BDmT
Chemicals																			
Herbicides in land preparation																			
Glyphosate	2.24											2.24	kg/ha	1.00		2.24	kg/ha	0.021	kg/BDmT
Oust	0.04											0.04	kg/ha	1.00		0.04	kg/ha	0.00038	kg/BDmT
Herbicide in growing																			
Glyphosate	4.49	2.24	4.49	4.49	4.49	4.49	4.49	4.49	4.49	4.49	4.49	47.11	kg/ha	1.00		47.11	kg/ha	0.44	kg/BDmT
Oust			0.04	0.04		0.04	0.04		0.04	0.04		0.25	kg/ha	1.00		0.25	kg/ha	0.0023	kg/BDmT
Herbicide in land restoration																			
Glyphosate											2.24	2.24	kg/ha	1.00		2.24	kg/ha	0.021	kg/BDmT
Pesticide in land restoration																			
2-4 D											2.51	2.51	kg/ha	1.00		2.51	kg/ha	0.023	kg/BDmT
Water																			
Cultivation	0	0	0	0	0	0	0	0	0	0	0	0	Gallons	3.79		0.00	Liters		
Diesel																			
Land preparation	22.70											22.70	Liters/ha	1.00		22.70	Liters/ha	0.21	Liter/BDmT
Plantation management	6.48	14.06	13.88	13.88	13.88	14.06	13.88	13.88	14.06	13.88	13.88	145.79	Liters/ha	1.00		145.79	Liters/ha	1.36	Liter/BDmT
Harvesting (1/1.82/1.59/1.5)		143.61			261.37			228.34			215.42	848.74	Liters/ha	1.00		848.74	Liters/ha	7.91	Liter/BDmT
Land restoration											16.28	16.28	Liters/ha	1.00		16.28	Liters/ha	0.15	Liter/BDmT
Electricity																			
Cultivation	0	0	0	0	0	0	0	0	0	0	0	0	KWh	1.00		0.00	KWh/ha		
OUTPUTS: 1 BDmT of biomass													Unit reported	Convertion	MC (%)		SI units		
Estimated biomass by 3PG model		367.6092			1000.6185			877.7958			826.2618	3072.2853	Dry Ton			107.31	BDmT/ha		
Estimated biomass yield by 3PG		6.42			11.65			10.22			9.62	9.76				9.76	BDmT/ha/year		

Table C 2. Inputs for Site 2

Site 2: With irrigation		Boardman			315	ha		RxSy:Root at x year and Steem at y year													
					Assumption: The plantation is extended in three growing rotations																
				R3S3			R6S3			R9S3			R12S3								
													Last harvesting								
INPUTS	Land Prep	Plantation		1st turnover			2nd turnover			3rd turnover			4th turnover			Convertion					
	2012 (Year 0)	2013 (Year 1)	2014 (Year 2)	2015 (Year 3)	2016 (Year 4)	2017 (Year 5)	2018 (Year 6)	2019 (Year 7)	2020 (Year 8)	2021 (Year 9)	2022 (Year 10)	2023 (Year 11)	2024 (Year 12)	Total	Unit reported	to SI units			SI Unit		Unit to SimaPro
Cuttings		3.61												3.61	Dry Ton	1.00	3.61	0.01	BDmT/ha	7.51798E-05	BDmT/BDmT
Cutting amount		470.00												470.00	trees/ha					3.08	trees/BDmT
Chemicals																					
Herbicides for Land prep																					
Glyphosate (Credit extra)	1.17													1.17	kg/ha	1.00				0.01	kg/BDmT
SureGuard (pre-emergent)	0.05													0.05	kg/ha	1.00				0.00	kg/BDmT
Herbicide for growing																					
Glyphosate		3.38	2.25	2.25	3.38	2.25	2.25	3.38	2.25	2.25	3.38	2.25	1.13	30.41	kg/ha	1.00				0.20	kg/BDmT
Pesticide for growing																					
2,4- D		1.87	1.24	1.24	1.87	1.24	1.24	1.87	1.24	1.24	1.87	1.24	0.62	16.80	kg/ha	1.00				0.11	kg/BDmT
Fertilizers																					
N																					
P																					
K																					
Fungicides																					
Water																					
Growing		600.00	600.00	600.00	600.00	600.00	600.00	600.00	600.00	600.00	600.00	600.00	600.00	7200.00	mm	0.001	7.20	72000.00	m3/ha	472347.96	L/BDmT
Diesel																					
Land preparation	50.00													50.00	Gallons/ha	3.79	189.25	189.25	L/ha	1.24	L/BDmT
Plantation																					
Plantation management	1.11	13.88	13.88	13.88	13.88	13.88	13.88	13.88	13.88	13.88	13.88	13.88	1.48	155.27	liter/ha	1.00	155.27	155.27	l/ha	1.02	L/BDmT
Harvesting				57.00			112.98			120.64			119.03	409.64	Gallons/ha	3.79	1550.50	1550.50	L/ha	10.17	L/BDmT
Land restoration (*)													4.50	4.50	Gallons/ha	3.79	17.03	17.03	L/ha	0.11	L/BDmT
Electricity																					
Growing		189.05	189.05	189.05	189.05	189.05	189.05	189.05	189.05	189.05	189.05	189.05	189.05	2268.65	KWh/ha	1.00	2268.65	2268.65	KWh/ha	14.88	KWh/BDmT
(*) Mulch stump is developed in land restoration																					
OUTPUTS				1rst Turnover			2nd Turnover			3rd turnover			4th and last turnover		Unit reported	Convertion			SI units		
	0	1	2	3	4	5	6	7	8	9				Total		to SI units					
Biomass				6681.15			13242.60			14140.35			13951.35	48015.45	Dry Ton	1	48015.45	152.43	BDmT/ha		
Biomass yield				7.07			14.01			14.96			14.76	12.70	BDmT/ha/yr			12.70	BDmT/ha/yr		

Table C 3. Inputs for Site 3

Site 3: Wastewater irrigation (Eugene/Springfield) 21.05 ha equal to 52 acres

Rotation years: 10 Phase 1 includes 156 acres and only 52 acres were harvested on September 2013 33.33 % of phase 1 13.20 % of total biocycle farm

INPUTS	Land Prep&Plantat									**R10S10**		Unit reported	Convertion				Final unit		Unit reported
	2003 (Year 0)	2004 (Year 1)	2005 (Year 2)	2006 (Year 3)	2007 (Year 4)	2008 (Year 5)	2009 (Year 6)	2010 (Year 7)	2011 (Year 8)	2012 (Year 9)	2013 (Year 10)	Total		to SI units						in SimaPro
Biomass	553.28											553.28	trees/ha	1	553.28		553.28	trees/ha	4.392	BDmT/BDmT
Chemicals																				
Herbicides																				
Fertilizers																				
N				1.43	14	2.2	4.1			11.3	8.04	41.07	lbs/acre	1.120392	46.0145		46.01	kg/ha	0.365	kg/BDmT
P																				
K																				
Fungicides																				
Biosolids	0	44.60	0	534.60	502.10	481.00	0	349.50	0	51.00	108.00	2070.80	Dry metric ton				98.38	t/ha	0.78	t/BDmT
Water	0	7645714.29	0	91645714.29	86074285.71	82457142.86	0	59914285.71	0	8742857.14	18514285.71	354994285.71	Liters				16864336.61	l/ha	133875.82	l/BDmT
average water consumption		37386666.67																		
Proportion of used water		0.20450377		2.45	2.30	2.21		1.60		0.23	0.50									
Diesel																				
Land preparation	215.8											215.8	Gallons	3.785	816.803		38.80	l/ha	0.31	l/BDmT
Plantation		0																		
Plantation management		1340.81		1712.36	920.80	1243.88		1082.34		1066.18	1389.27	8755.64	Gallons	3.785	33140.09	Liters	1574.35	l/ha	12.50	l/BDmT
Harvesting											11453.12	8017.18	Gallons	3.785	30345.04	Liters	1441.57	l/ha	11.44	l/BDmT
Land restoration (*)												3435.94	Gallons	3.785	13005.02	Liters	617.82	l/ha	4.90	l/BDmT
Electricity																				
Growing		25.10		300.81	282.53	270.65		196.66		28.70	60.77	1165.21	kWh/ha	1	1165.214	kWh/ha	1165.21	kWh/ha	9.25	kWh/BDmT
				Only Phase 1	Phases 1&2	Phases 1&2		Phases 1&2&3		Phases 1&2&3										

(*) it includes stump removal and land clearing. Land restoration diesel consumption is already included in harvesting.

OUTPUTS													Unit reported	Convertion				SI units		
Biomass																				
Chips (46%)											26.00	26	BDT/acre	2.47	64.22		64.22	BDmT/ha		
Hog fuel (44%)											25.00	25	BDT/acre	2.47	61.75		61.75	BDmT/ha	125.97	
Stump (10%)											5.38	5.38	BDT/acre	2.47	13.29		13.29	BDmT/ha		

Table C 3a. Inputs for Site 3a

Site 3a: Irrigation and fertilization	(Eugene/Springfield)				21.05	ha	equal to 52 acres													
Database																				
Rotation years:	10	Phase 1 includes 156 acres and only 52 acres were harvested on September 2013						33.33	% of phase 1	13.20	% of total biocycle farm									
INPUTS	Land Prep&Plantat										**R10S10**		Unit reported	Convertion				Final unit		Unit reported
	2003 (Year 0)	2004 (Year 1)	2005 (Year 2)	2006 (Year 3)	2007 (Year 4)	2008 (Year 5)	2009 (Year 6)	2010 (Year 7)	2011 (Year 8)	2012 (Year 9)	2013 (Year 10)	Total		to SI units						in SimaPro
Biomass	553.28											553.28	trees/ha	1	553.28		553.28	trees/ha	4.392	BDmT/BDmT
Chemicals																				
Herbicides																				
Fertilizers																				
N (Alternative process)		50	50	50	50	50	50	50	50	50	50	500	kg/ha				500.00	kg/ha	3.97	kg/BDmT
P																				
K																				
Fungicides																				
Water (Alternative process)		11418328.35	11418328.35	11418328.35	11418328.35	11418328.35	11418328.35	11418328.35	11418328.35	11418328.35	11418328.35	114183283.50	Liters				5424384.01	l/ha	43060.92	l/BDmT
Diesel																				
Land preparation	215.8											215.8	Gallons	3.785	816.803		38.80	l/ha	0.31	l/BDmT
Plantation		0																		
Growing (Alternative process)		1261.40	1261.40	1261.40	1261.40	1261.40	1261.40	1261.40	1261.40	1261.40	1261.40	12614.00	Gallons	3.785	47743.99	Liters	2268.12	l/ha	18.01	l/BDmT
Harvesting											11453.12	8017.18	Gallons	3.785	30345.04	Liters	1441.57	l/ha	11.44	l/BDmT
Land restoration (*)												3435.94	Gallons	3.785	13005.02	Liters	617.82	l/ha	4.90	l/BDmT
Electricity																				
Growing (Alternative process)		122.72	122.72	122.72	122.72	122.72	122.72	122.72	122.72	122.72	122.72	1227.16	kWh/ha	1	1227.16	kWh/ha	1227.16	kWh/ha	9.74	kWh/BDmT
				Only Phase 1	Phases 1&2	Phases 1&2		Phases 1&2&3		Phases 1&2&3										

(*) it includes stump removal and land clearing. Land restoration diesel consumption is already included in harvesting.

OUTPUTS													Unit reported	Convertion				SI units	
Biomass																			
Chips (46%)											26.00	26	BDT/acre	2.47	64.22		64.22	BDmT/ha	
Hog fuel (44%)											25.00	25	BDT/acre	2.47	61.75		61.75	BDmT/ha	125.97
Stump (10%)											5.38	5.38	BDT/acre	2.47	13.29		13.29	BDmT/ha	

Table C 4. Inputs for Site 4

Site 4: Irrigated with leachate from landfill (McMinnville) 17.41 ha 43 acres The biomass produced was irrigated with leachate by drip system From [2]

Surface harvested on 2013 4.45 ha 11 acres 25.58 % land was harvested in 2013

Database

Rotation years: 12 From [3]

INPUTS	Land Prep&Plant 2001 (Year 0)	2002 (Year 1)	2003 (Year 2)	2004 (Year 3)	2005 (Year 4)	2006 (Year 5)	2007 (Year 6)	2008 (Year 7)	2009 (Year 8)	2010 (Year 9)	2011 (Year 10)	2012 (Year 11)	R12S12 2013 (Year 12)	Total	Unit reported	Convertion to SI units	MC (%)		Final unit		SimaPro unit
Biomass	1375.00													1375.00	Trees/ha			1375.00	Trees/ha	9.05171	Trees/BDmT
Chemicals																					
Herbicides													1.13	1.1300	lb/acre	1.120392		1.266043	kg/ha	0.00833	kg/BDmT
Fertilizers																					
N (268 to 371)			111.00	196.00	339.00	357.00	357.00	357.00	357.00	357.00	357.00	357.00	240.00	865.93	lb N /acres	1.120392		970.18	kg/ha	6.39	Kg/BDmT
P																					
K																					
Fungicides															kg/ha			0	kg/ha	0	kg/BDmT
Growing																					
Water		3.37	2.87	4.04	3.62	4.46	4.47	5.26	4.22	2.95	1.57	1.12	0	9.71	Million gallons	3.785		8.25	ML/ha	0.0543	ML/BDmT
Leachate		7.98	6.79	9.57	8.58	9.41	7.45	9.88	12.08	7.22	9.69	2.61	0	23.35	Million gallons	3.785		19.84	ML/ha	0.131	ML/BDmT
Total solution		11.35	9.66	13.61	12.20	13.87	11.92	15.14	16.30	10.17	11.26	3.73	0								
Solution average		11.75														3.785					
Diesel																					
Land preparation	2.2572													2.2572	Gallons	3.785		1.92	l/ha	0.0126	l/BDmT
Plantation															Gallons						
Plantation management		70.76	70.76	70.76	70.76	70.76	70.76	70.76	70.76	70.76	70.76	70.76	35.38	813.78	Gallons	3.785		691.63	l/ha	4.5531	l/BDmT
Harvesting (+ residual grinder)													2475.5	2450.745	Gallons	3.785		2082.90	l/ha	13.71	l/BDmT
Land restoration (*)													9.7812	9.7812	Gallons	3.785		8.31	l/ha	0.05	l/BDmT
Electricity																					
Growing		889.82	757.13	1067.11	956.72	1087.46	934.57	1187.03	1277.98	797.37	882.83	292.45	0.00	2591.52	KWh/ha	1		2591.52	KWh/ha	17.06	KWh/BDmT

(*) It includes stump removal and land clearing

OUTPUTS															Unit reported	Convertion	MC (%)		SI units
Biomass													1353.00		Green ton	1	100	151.91	BDmT/ha
Residual biomass in site													162.36		Green ton		100	18.23	BDmT/ha

Appendix D. Screens of SimaPro for cutting at nursery and each site

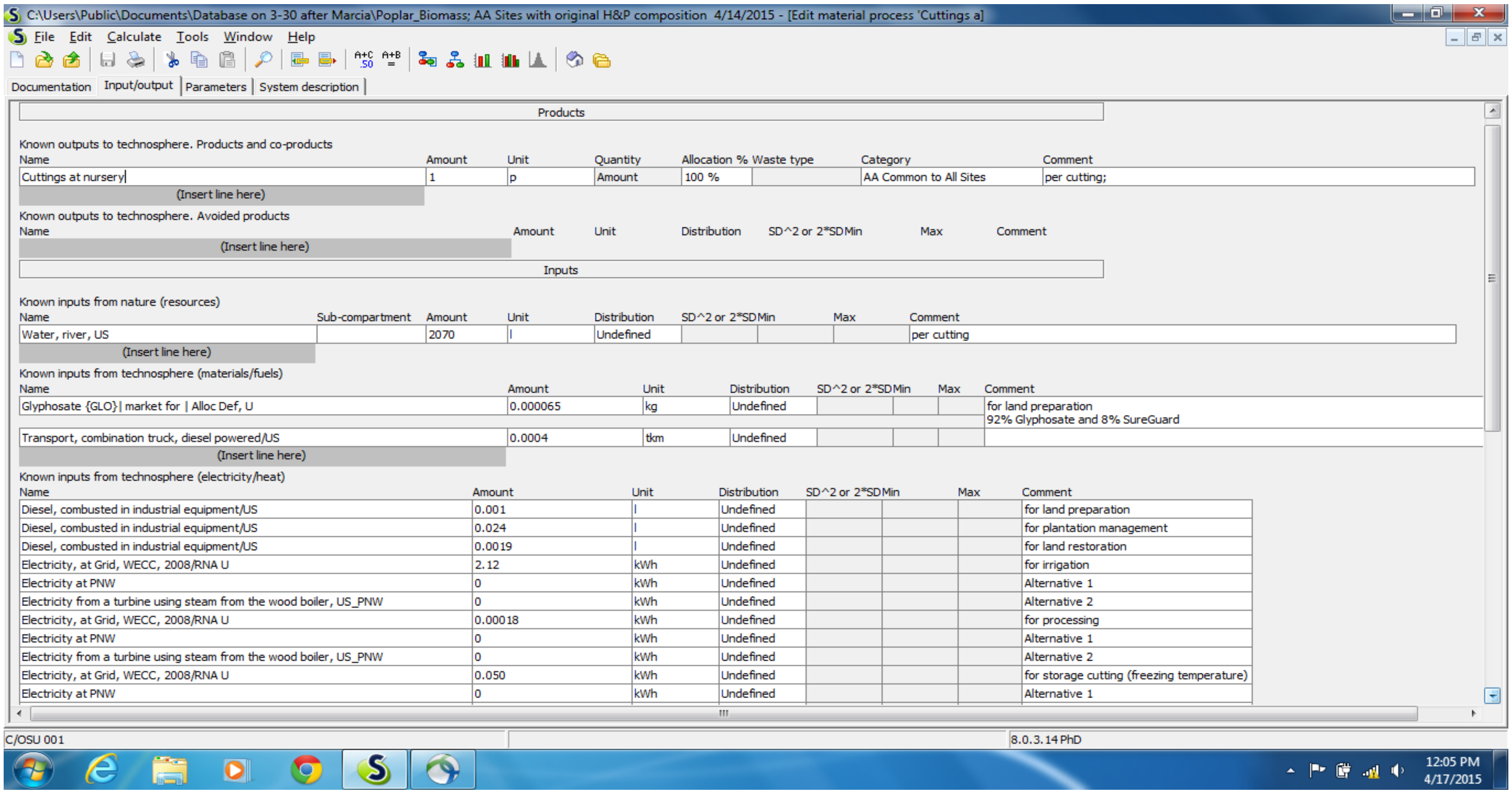


Figure D 1. Screen of SimaPro inputs of cuttings at nursery

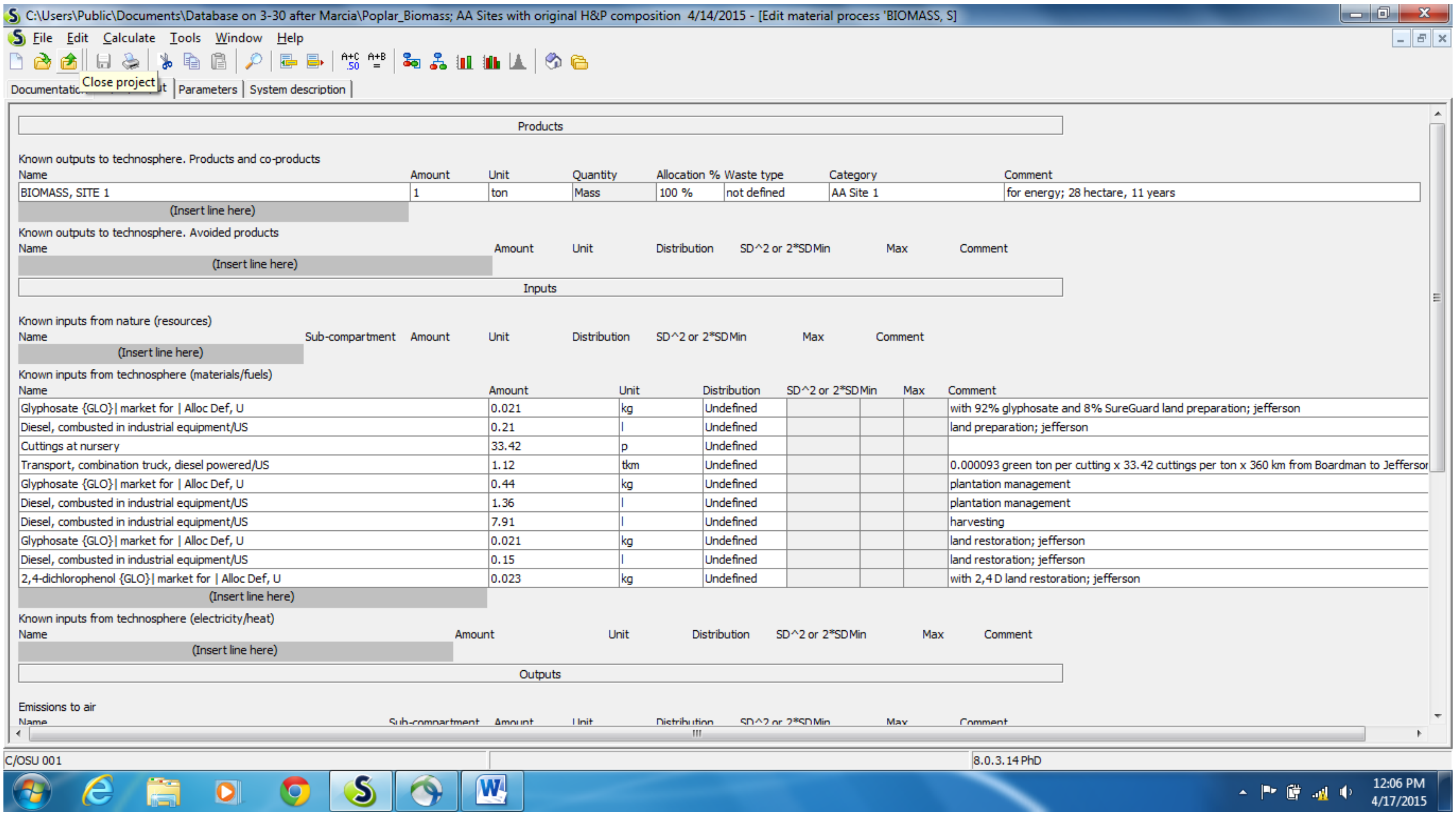


Figure D 2. Screen of SimaPro inputs for Site 1

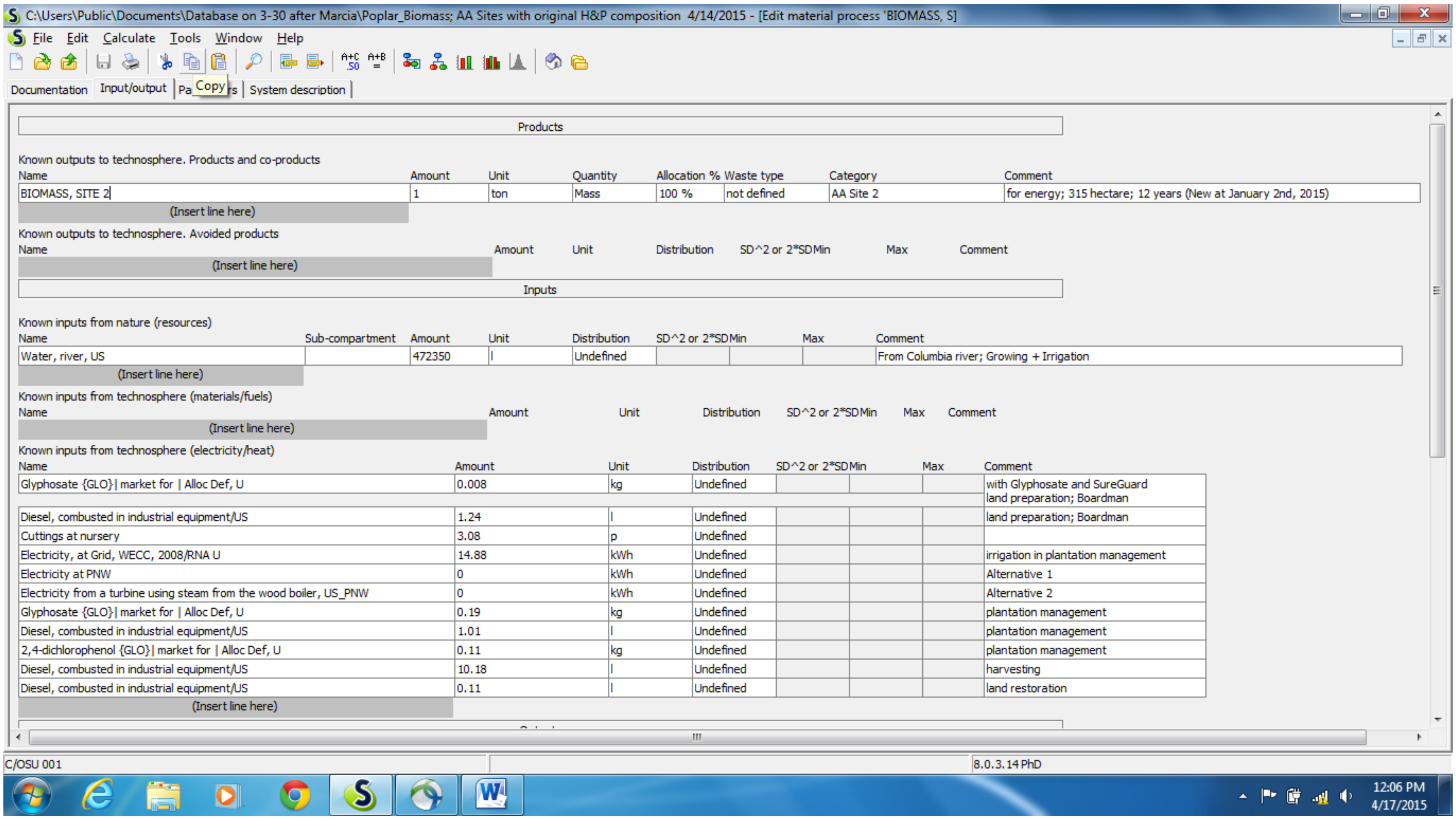
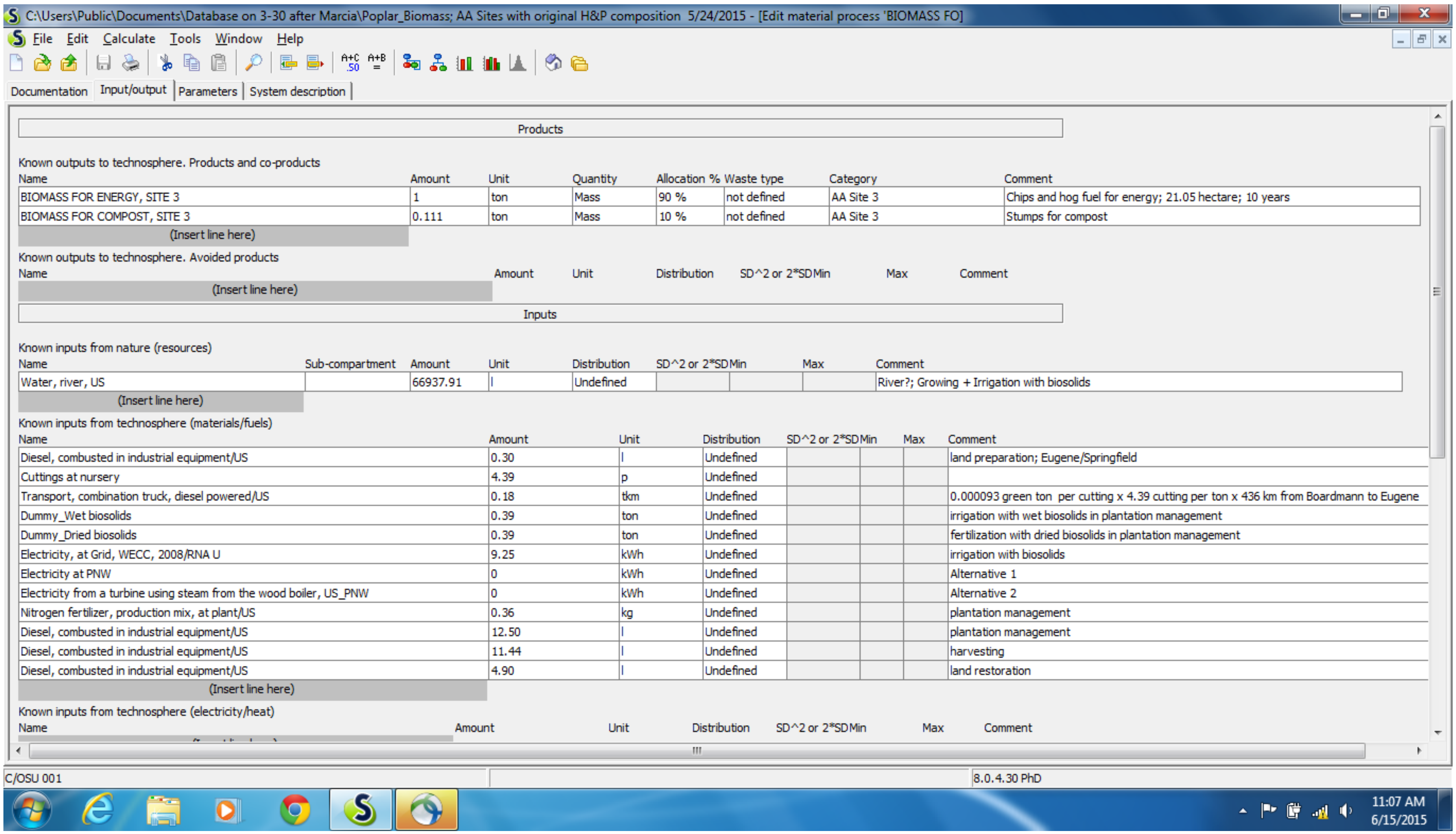


Figure D 3. Screen with SimaPro inputs for Site 2



Name	Amount	Unit	Quantity	Allocation %	Waste type	Category	Comment
BIOMASS FOR ENERGY, SITE 3	1	ton	Mass	90 %	not defined	AA Site 3	Chips and hog fuel for energy; 21.05 hectare; 10 years
BIOMASS FOR COMPOST, SITE 3	0.111	ton	Mass	10 %	not defined	AA Site 3	Stumps for compost
(Insert line here)							

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Water, river, US		66937.91	l	Undefined				River?; Growing + Irrigation with biosolids
(Insert line here)								

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Diesel, combusted in industrial equipment/US	0.30	l	Undefined				land preparation; Eugene/Springfield
Cuttings at nursery	4.39	p	Undefined				
Transport, combination truck, diesel powered/US	0.18	tkm	Undefined				0.000093 green ton per cutting x 4.39 cutting per ton x 436 km from Boardmann to Eugene
Dummy_Wet biosolids	0.39	ton	Undefined				irrigation with wet biosolids in plantation management
Dummy_Dried biosolids	0.39	ton	Undefined				fertilization with dried biosolids in plantation management
Electricity, at Grid, WECC, 2008/RNA U	9.25	kWh	Undefined				irrigation with biosolids
Electricity at PNW	0	kWh	Undefined				Alternative 1
Electricity from a turbine using steam from the wood boiler, US_PNW	0	kWh	Undefined				Alternative 2
Nitrogen fertilizer, production mix, at plant/US	0.36	kg	Undefined				plantation management
Diesel, combusted in industrial equipment/US	12.50	l	Undefined				plantation management
Diesel, combusted in industrial equipment/US	11.44	l	Undefined				harvesting
Diesel, combusted in industrial equipment/US	4.90	l	Undefined				land restoration
(Insert line here)							

Figure D 4. Screen of SimaPro inputs for Site 3

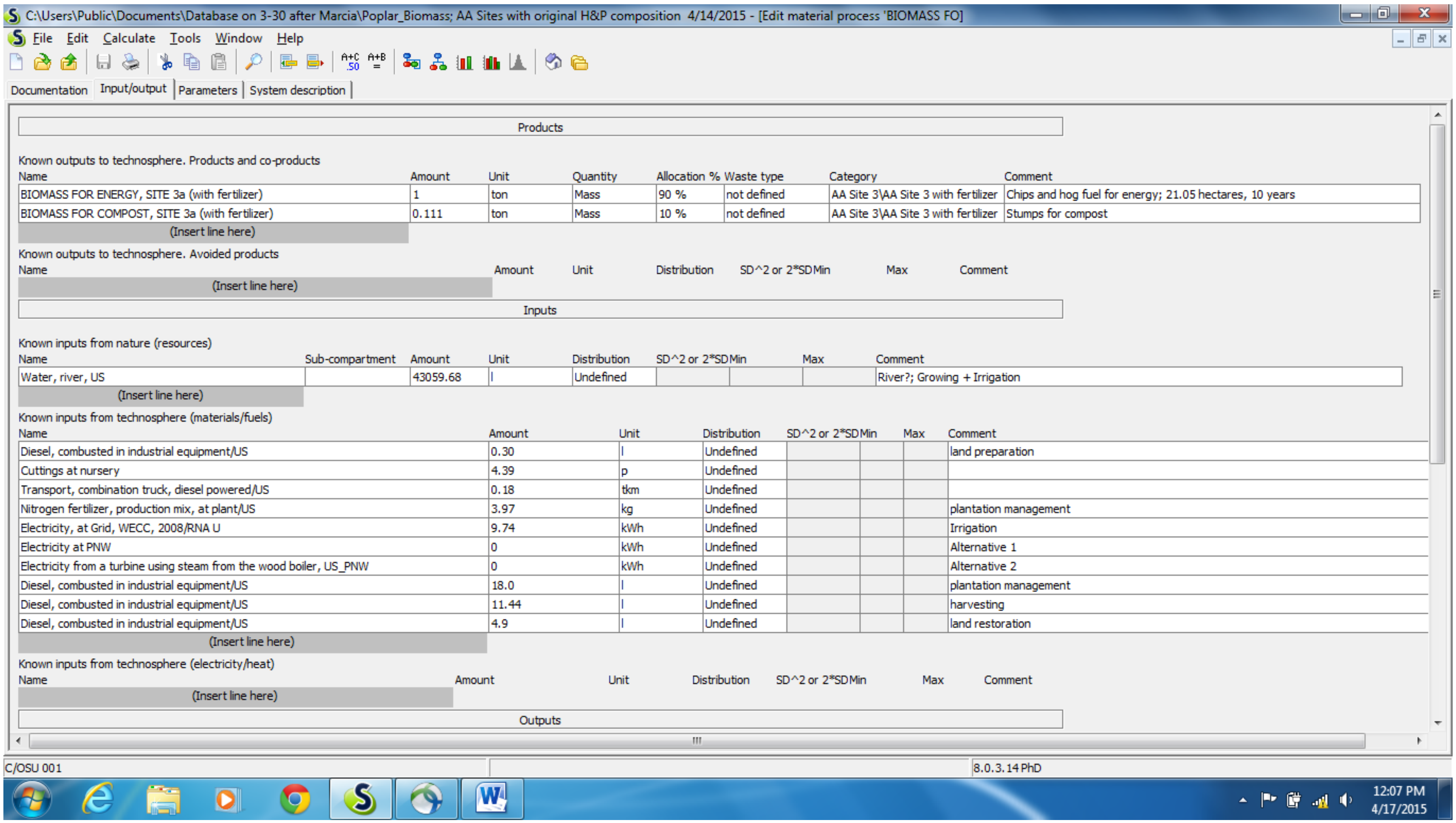


Figure D 5. Screen of SimaPro inputs for Site 3a

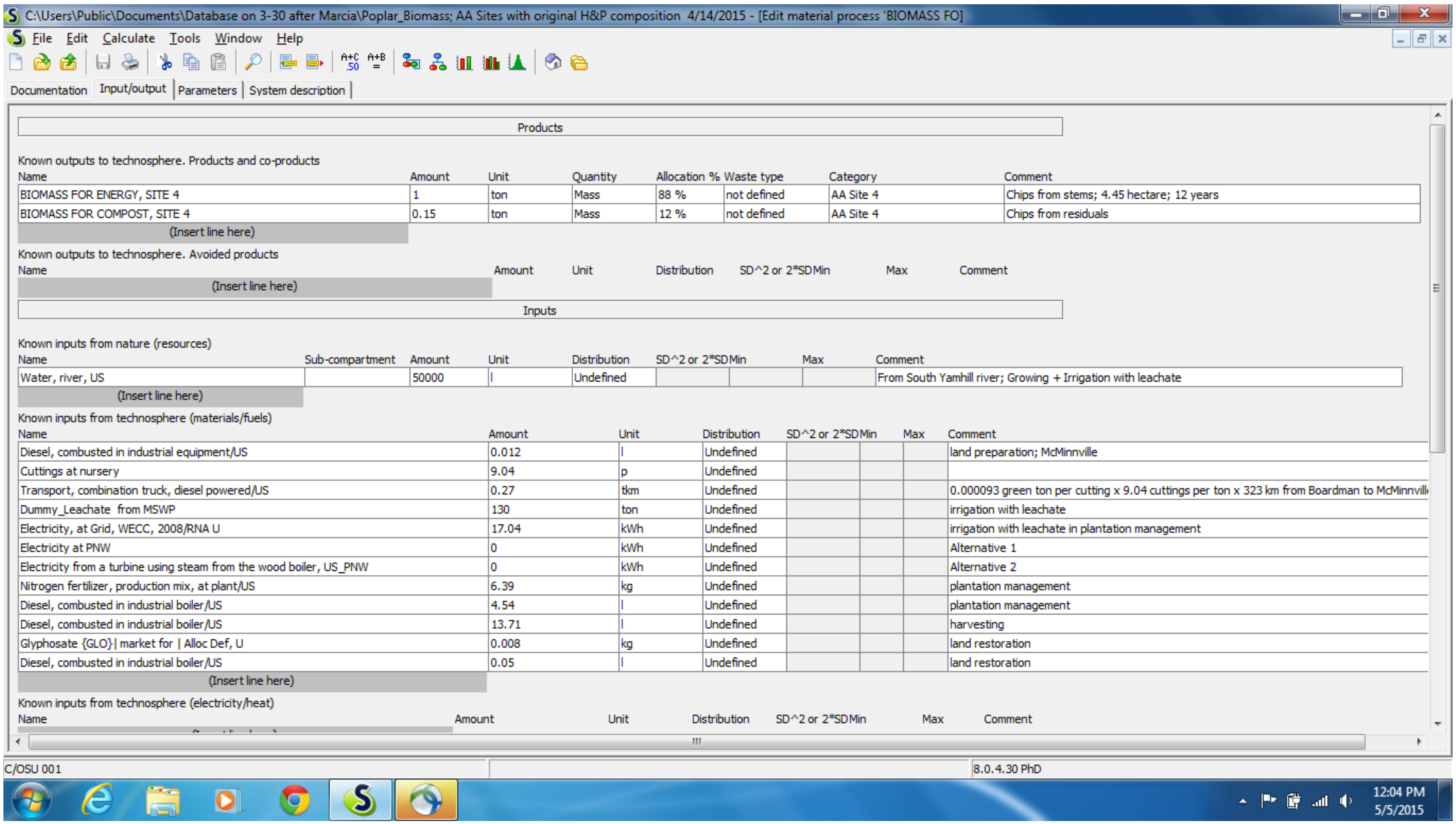


Figure D 6. Screen of SimaPro inputs for Site 4

Appendix E. LCIA networks

Cuttings at nursery

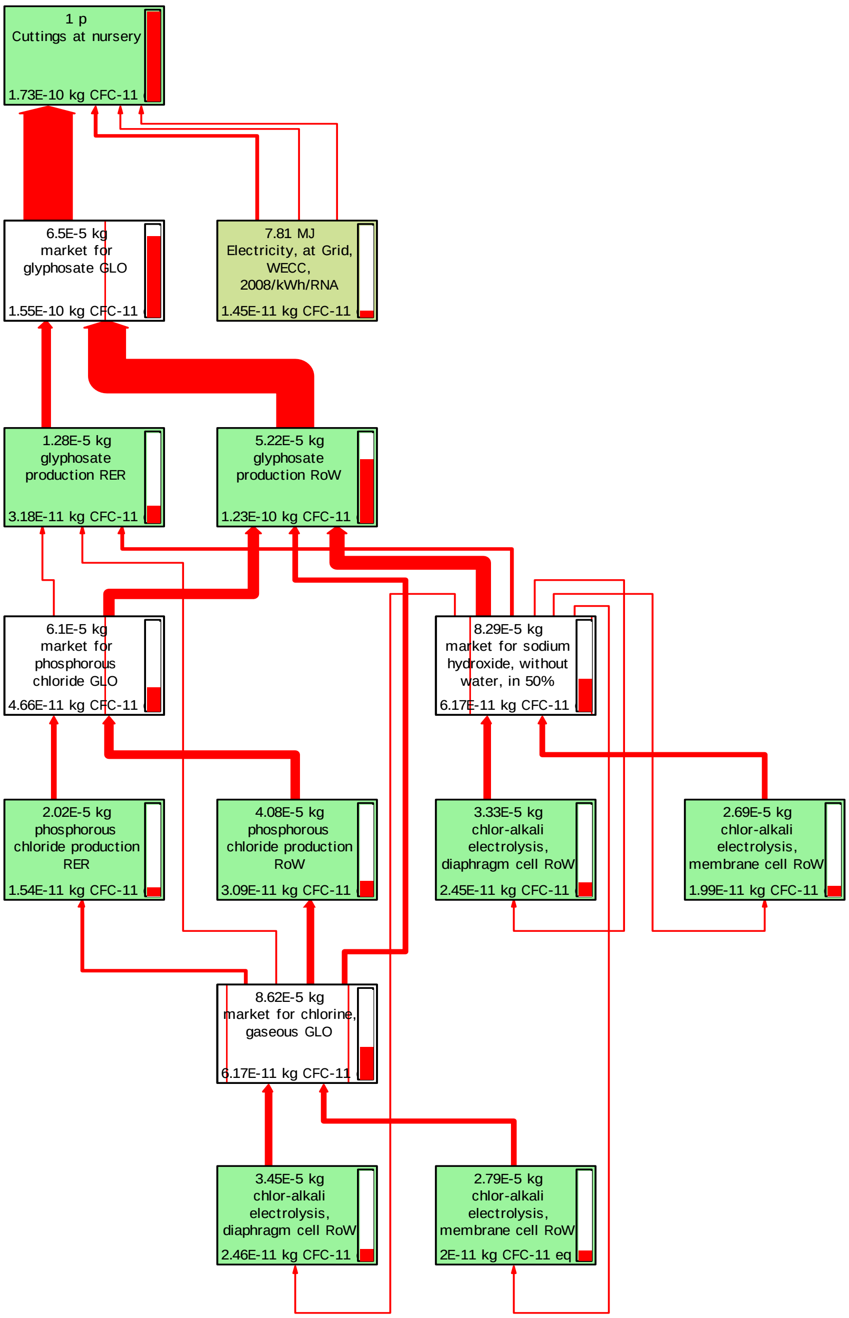


Figure E 1.1 Network of Ozone depletion (Decrement node cut-off: 8%)

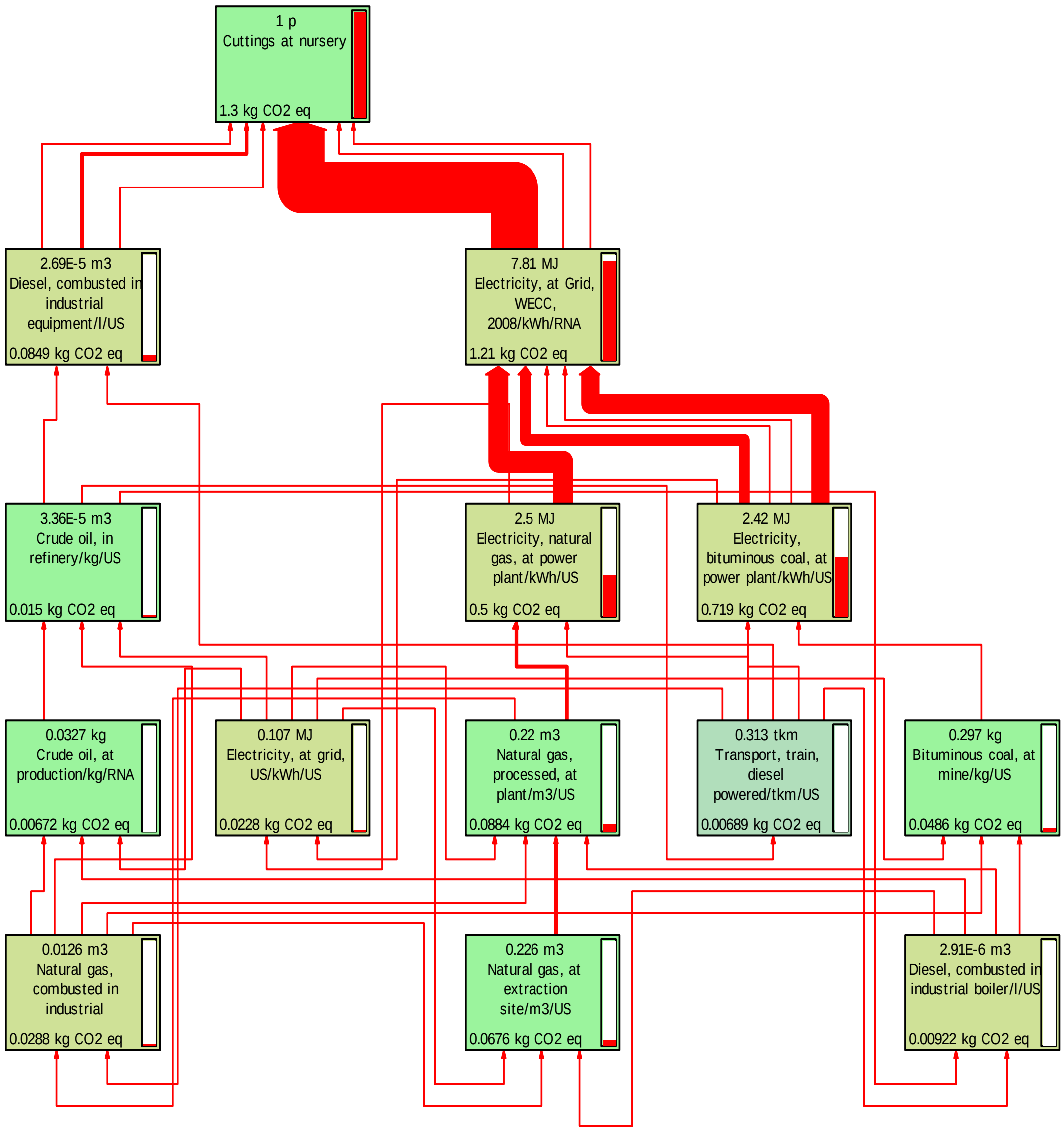


Figure E 1.2 Network of Global warming (Decrement node cut-off: 0.5%)

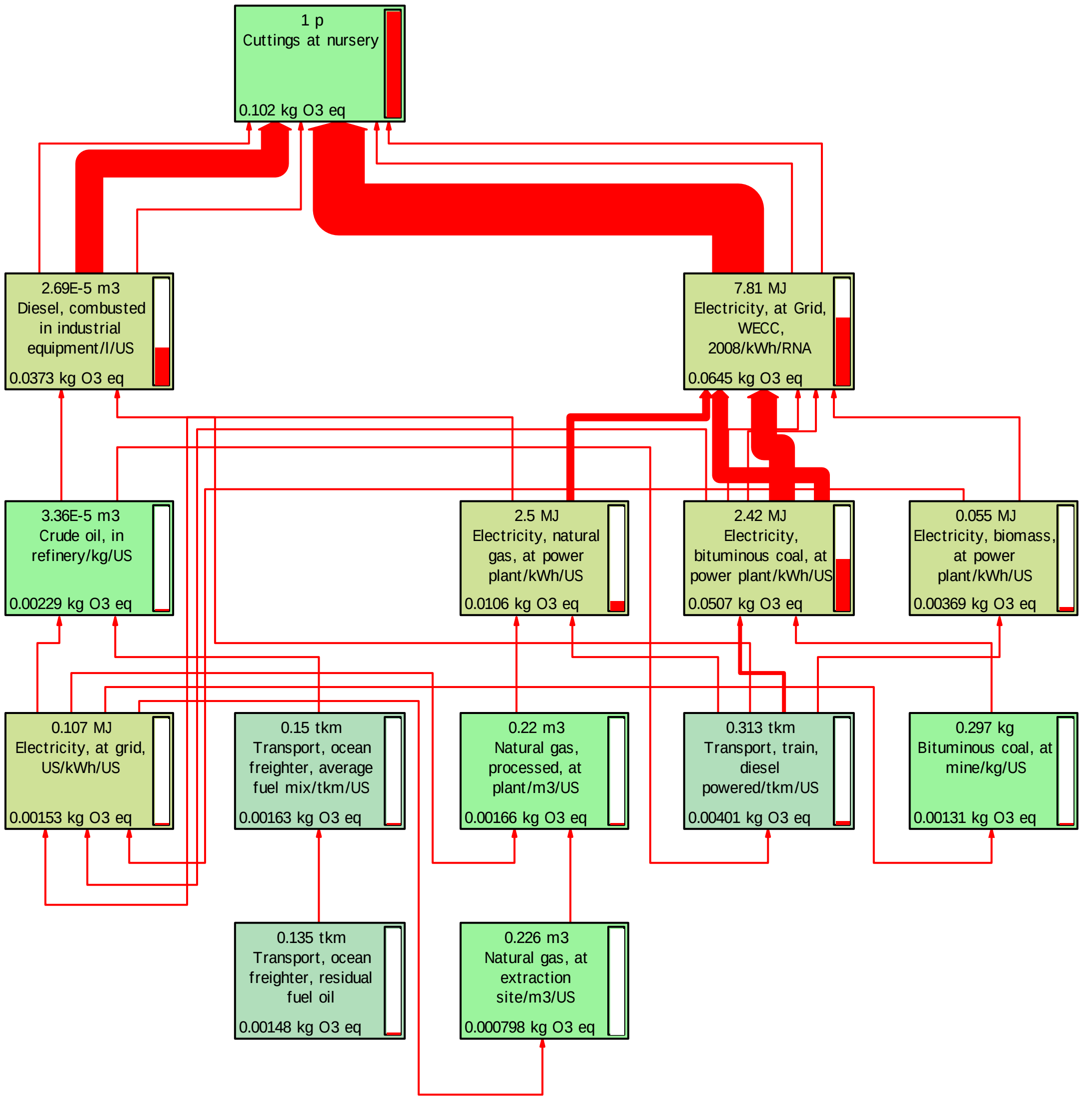


Figure E 1.3 Network of Smog (Decrement node cut-off: 0.7%)

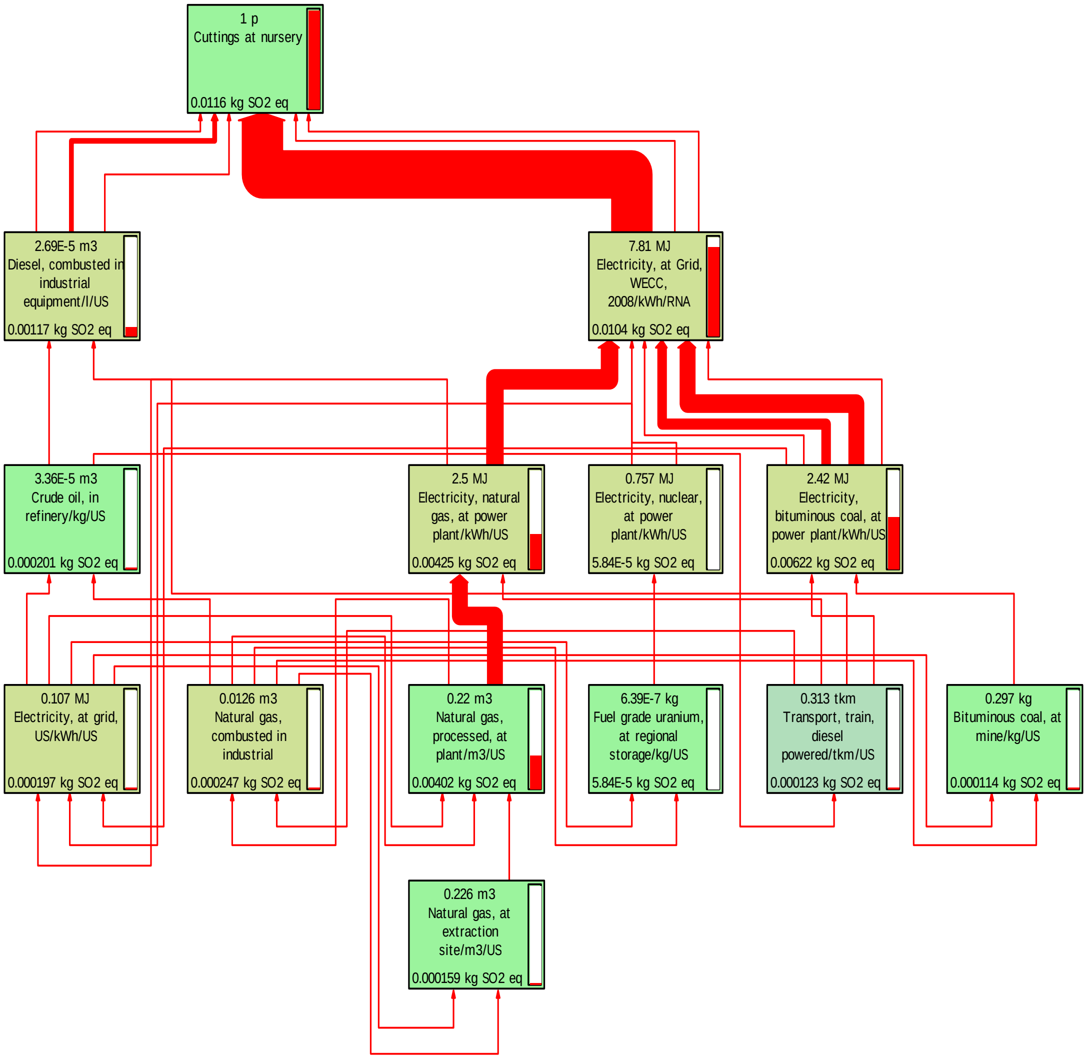


Figure E 1.4 Network of Acidification (Decrement node cut-off: 0.5%)

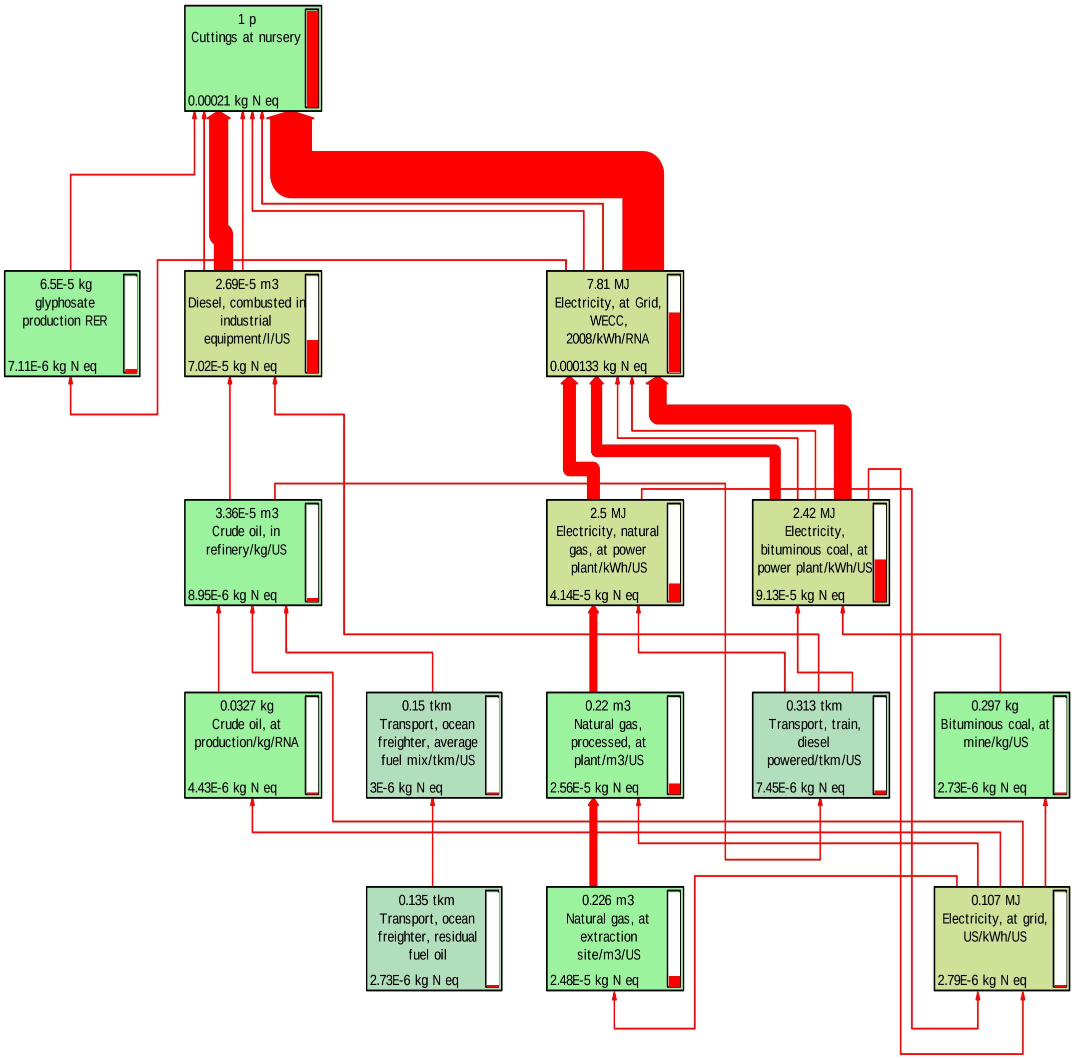


Figure E 1.5 Network of Eutrophication (Decrement node cut-off: 1.2%)

Site 1

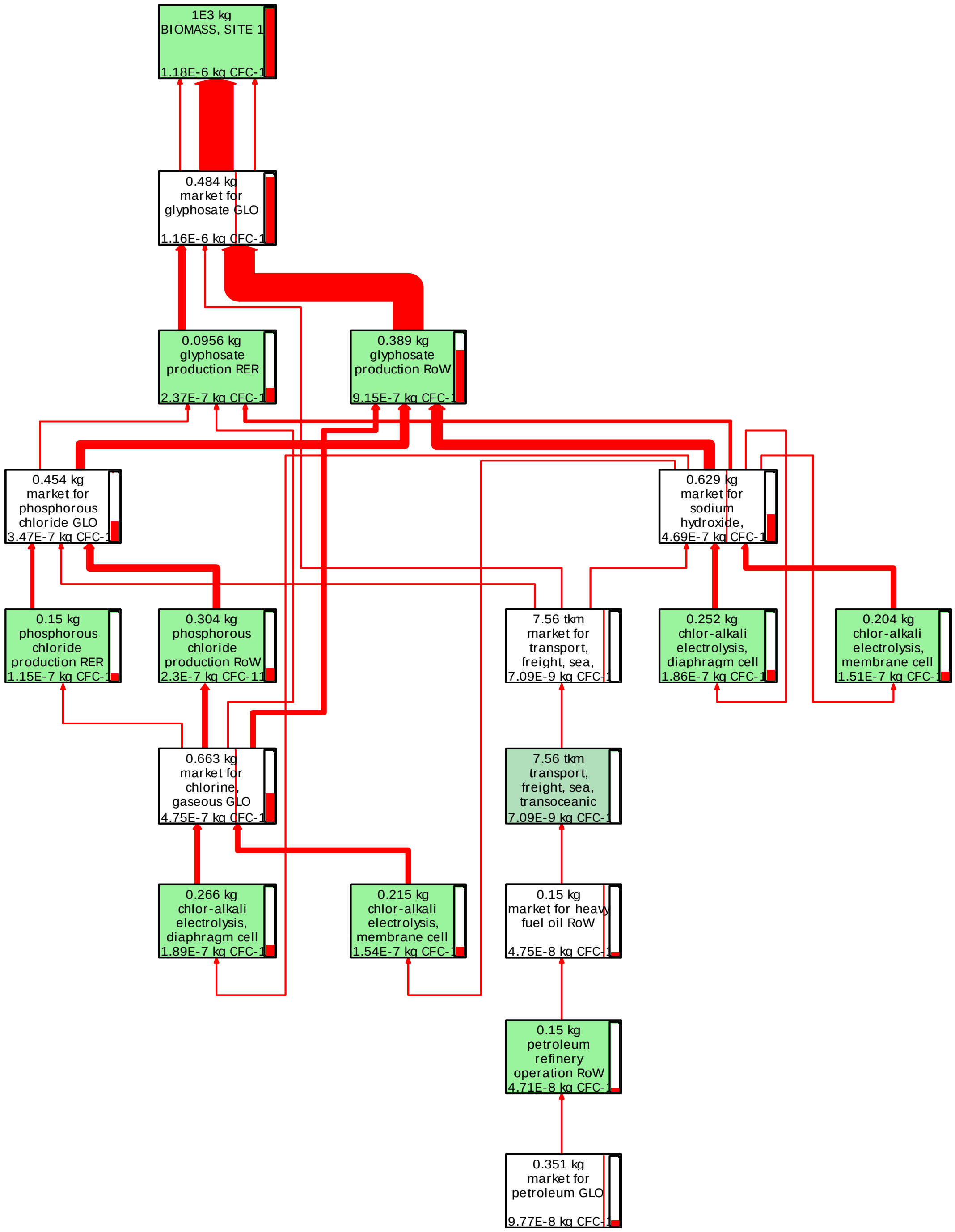


Figure E 2.1 Network of Ozone depletion (Decrement node cut-off: 8.2%)

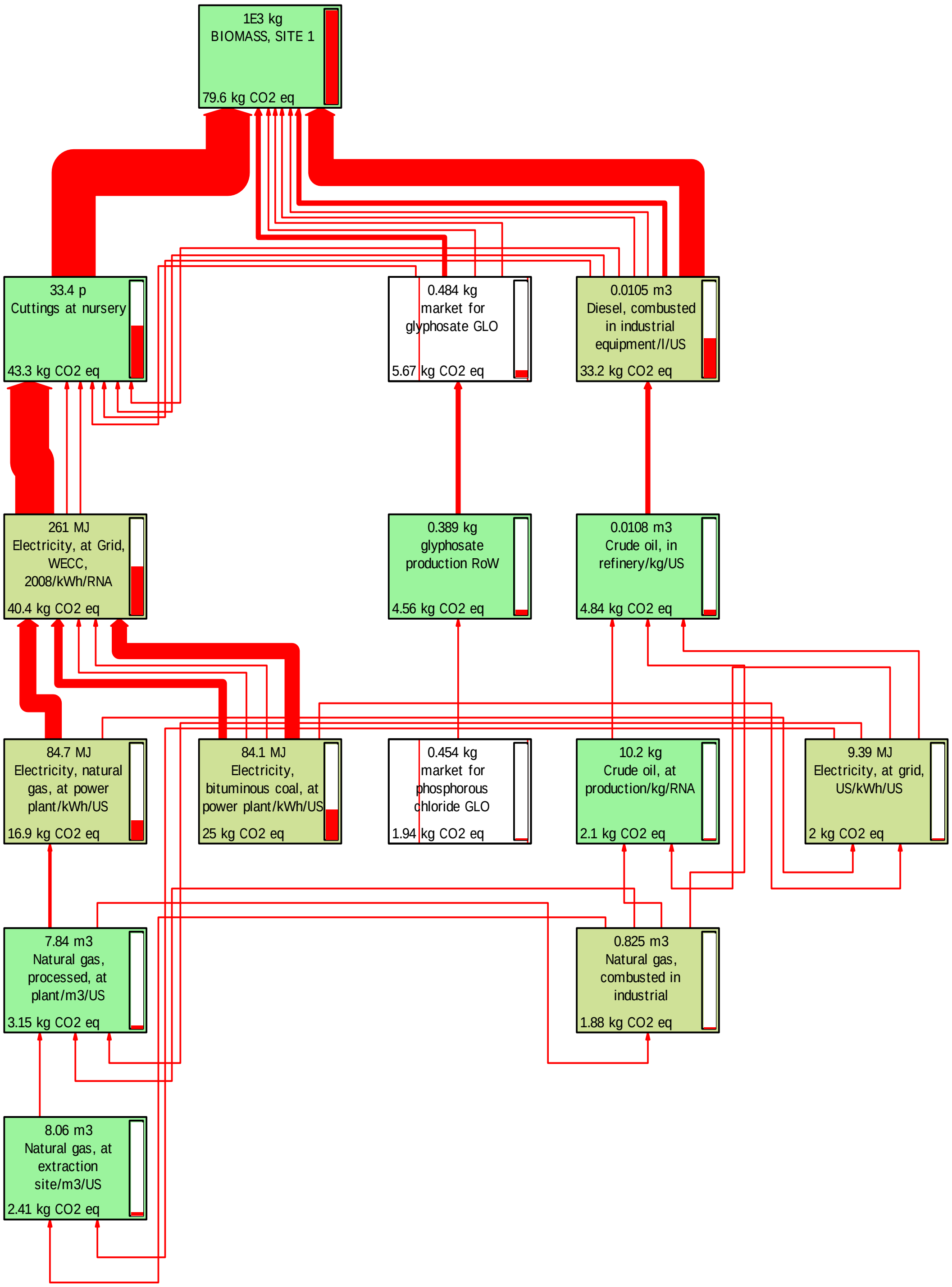


Figure E 2.2 Network of Global warming (Decrement node cut-off: 2.2%)

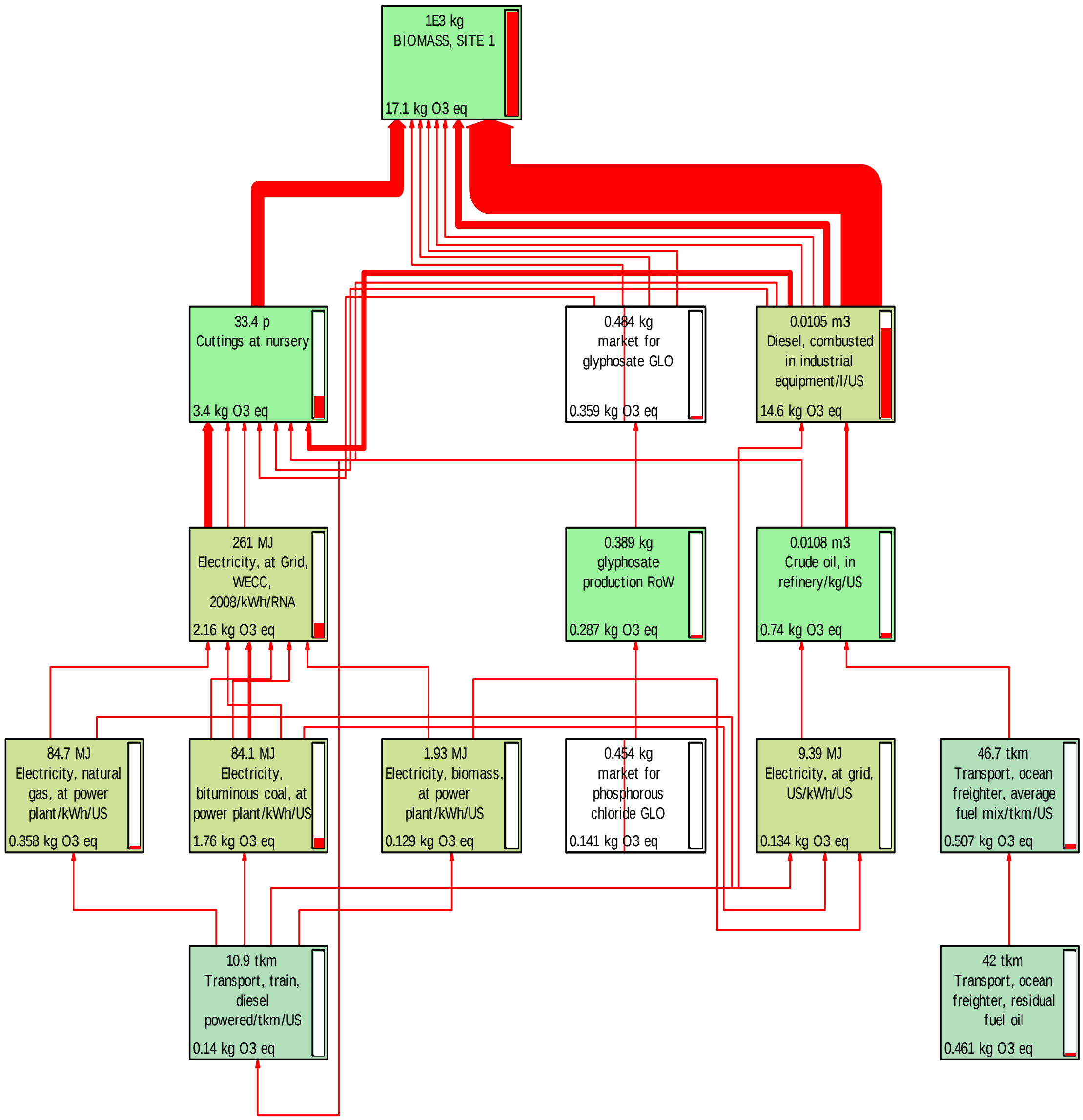


Figure E 2.3 Network of Smog (Decrement node cut-off: 0.6%)

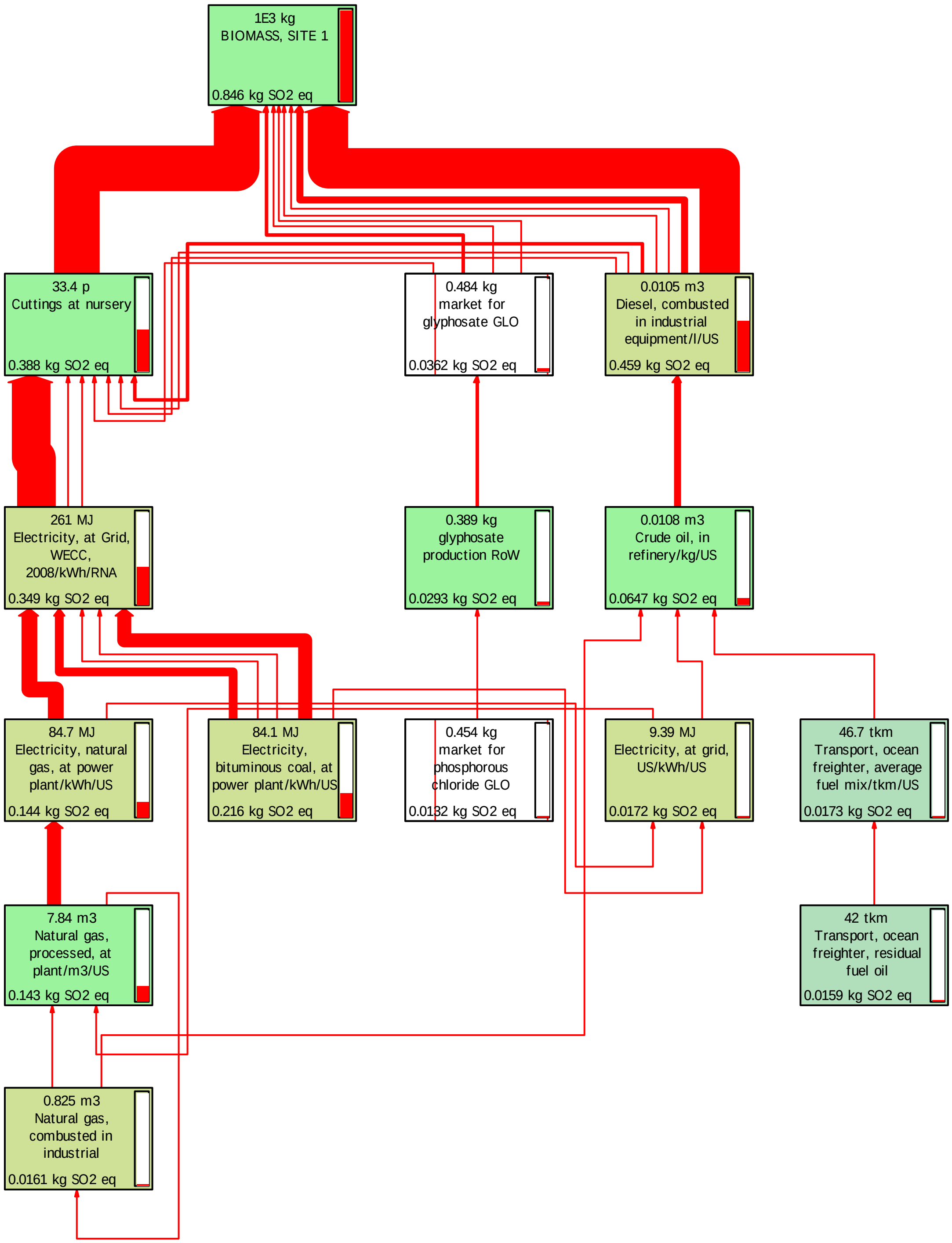


Figure E 2.4 Network of Acidification (Decrement node cut-off: 1.2%)

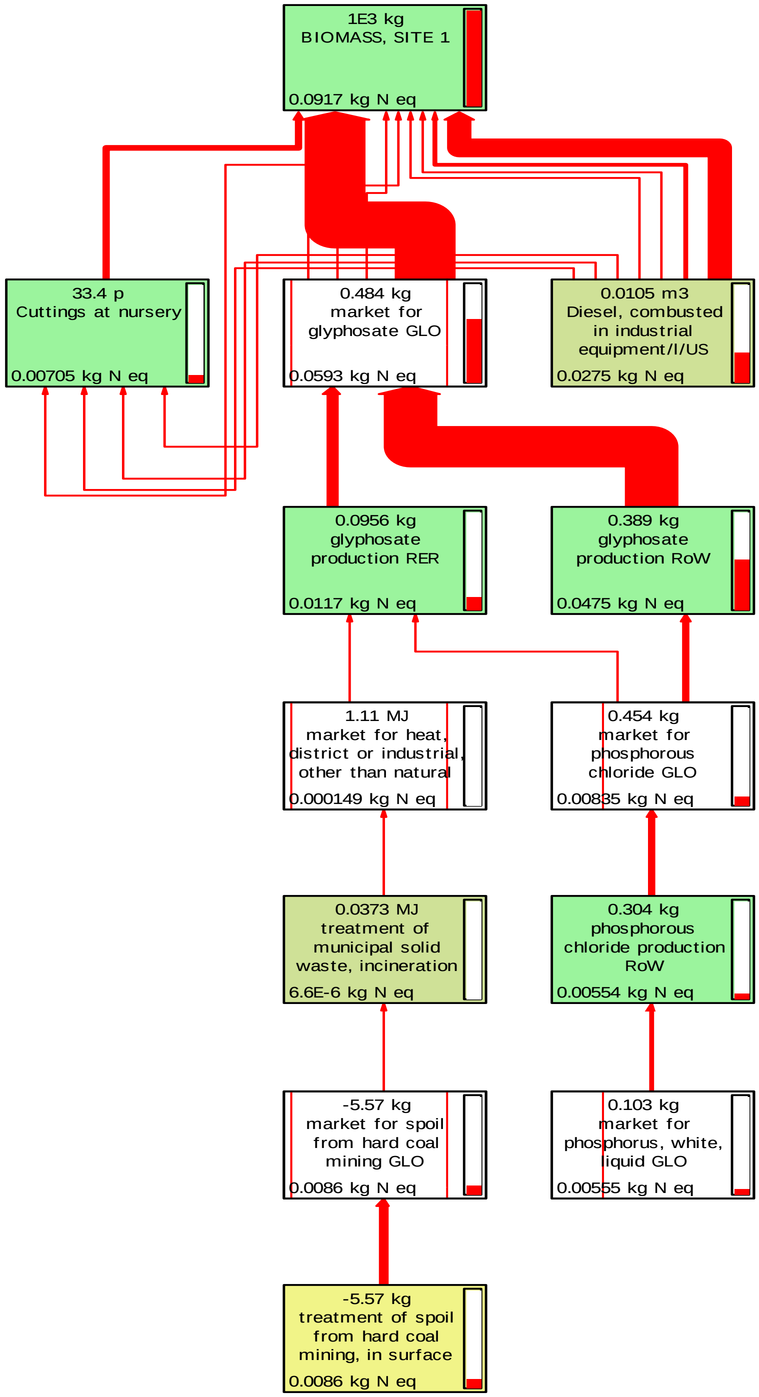


Figure E 2.5 Network of Eutrophication (Decrement node cut-off: 5.8%)

Site 2

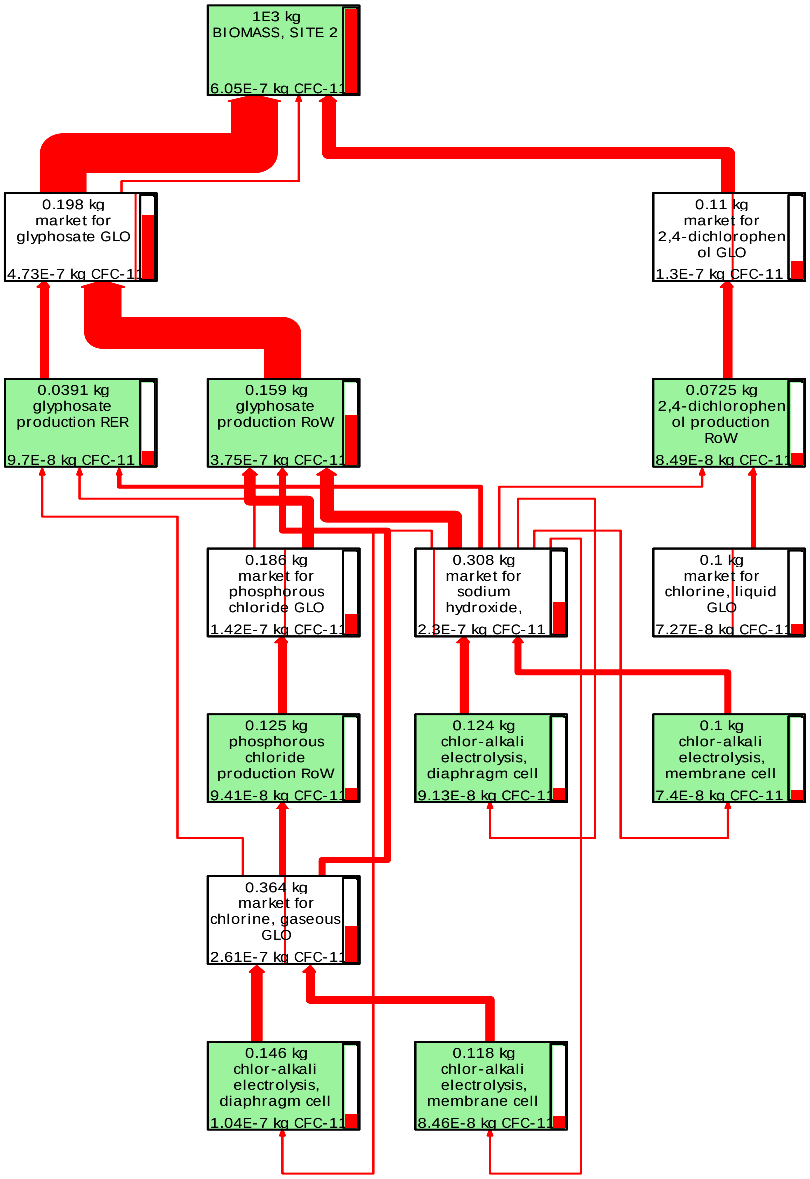


Figure E 3.1 Network of Ozone depletion (Decrement node cut-off: 12%)

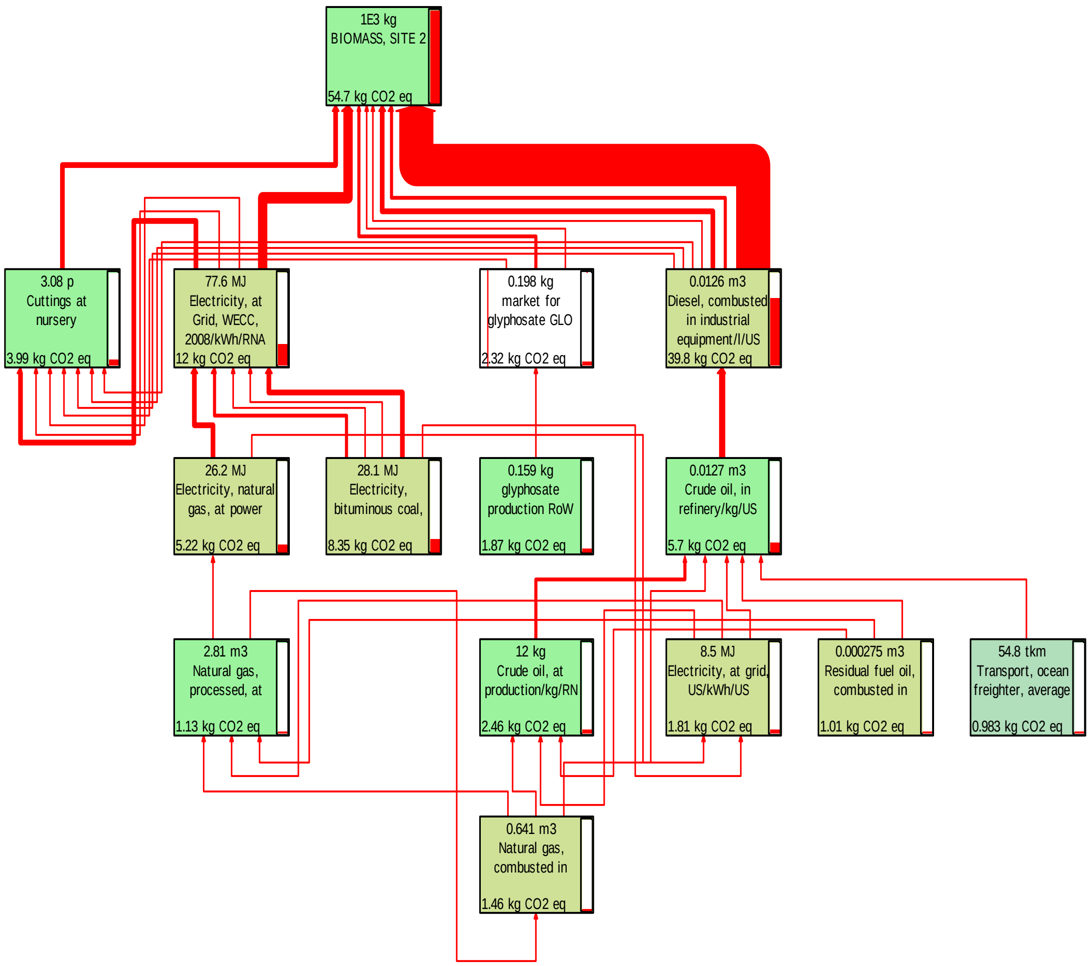


Figure E 3.2 Network of Global warming (Decrement node cut-off: 1.7%)

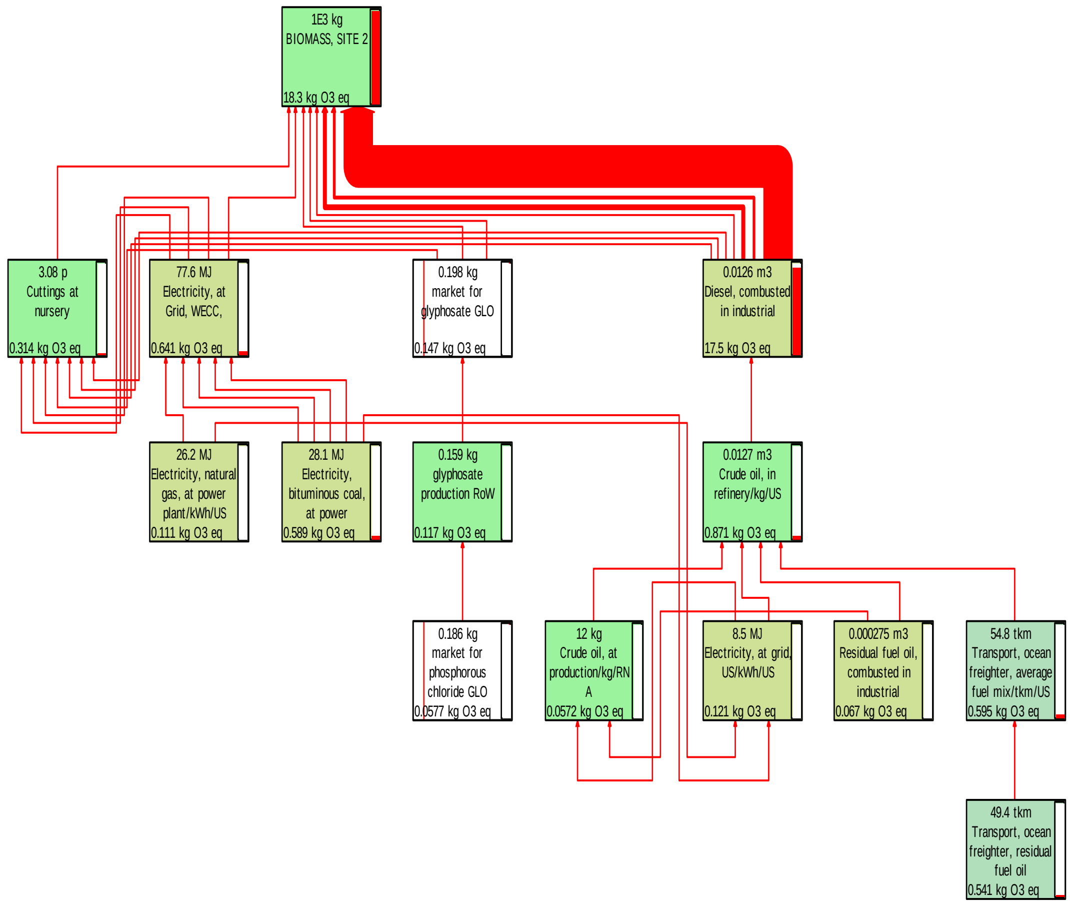


Figure E 3.3 Network of Smog (Decrement node cut-off: 0.31%)

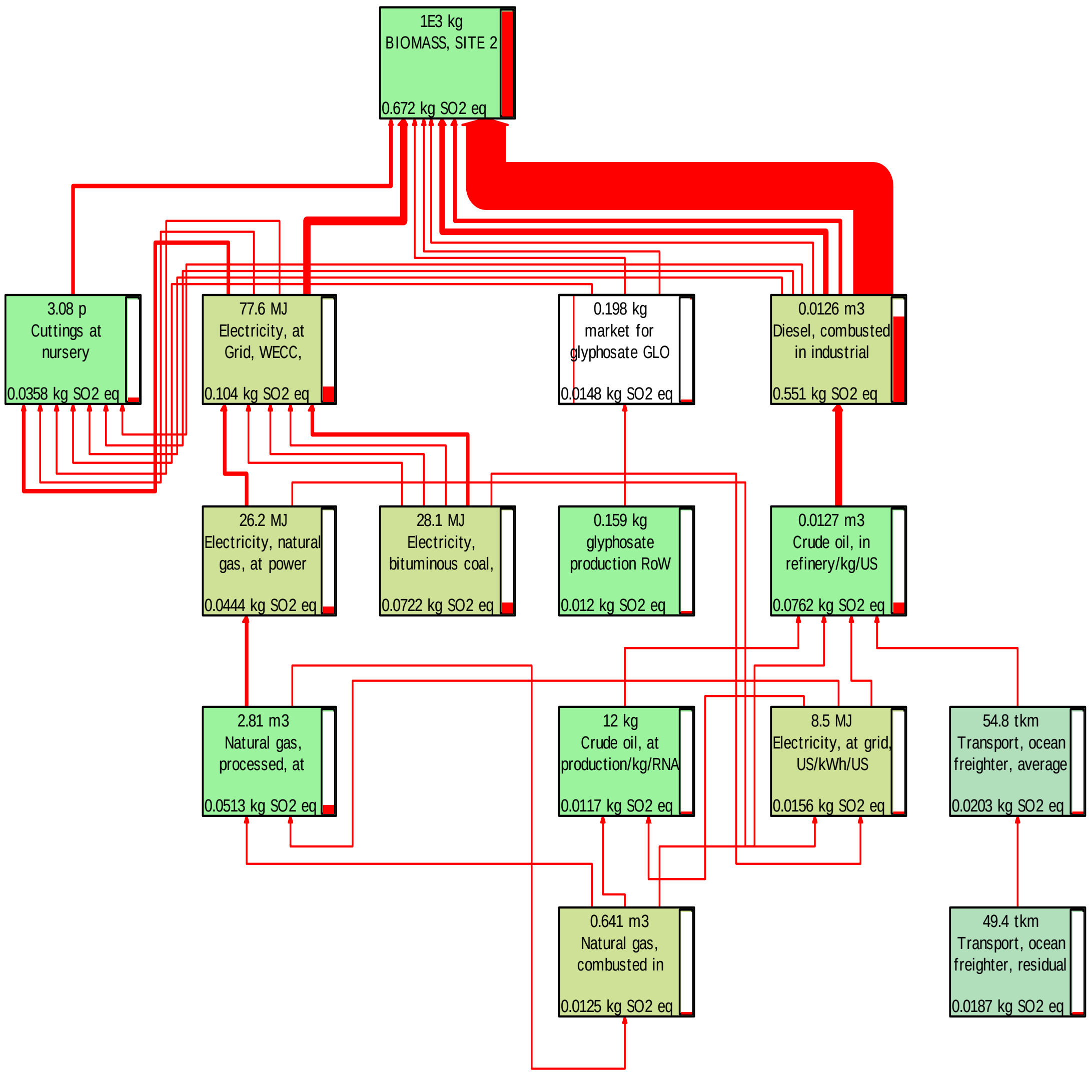


Figure E 3.4 Network of Acidification (Decrement nodecut-off: 0.81%)

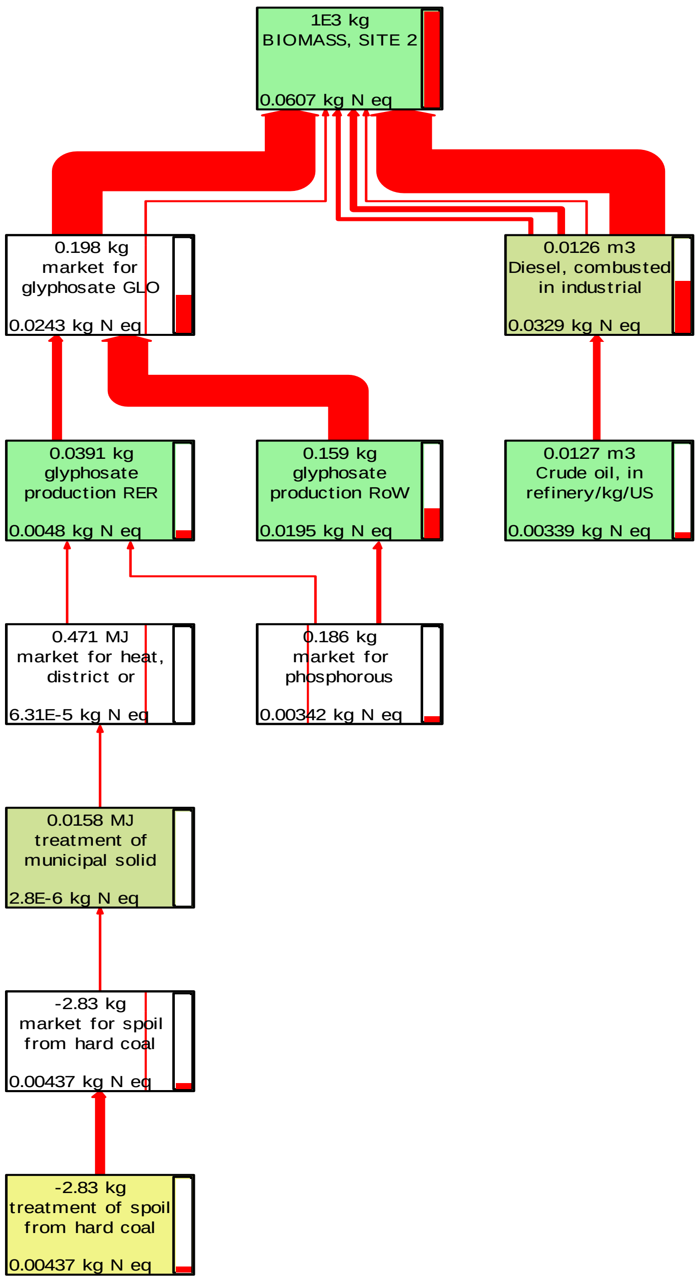


Figure E 3.5 Network of Eutrophication (Decrement node cut-off: 4.2%)

Site 3

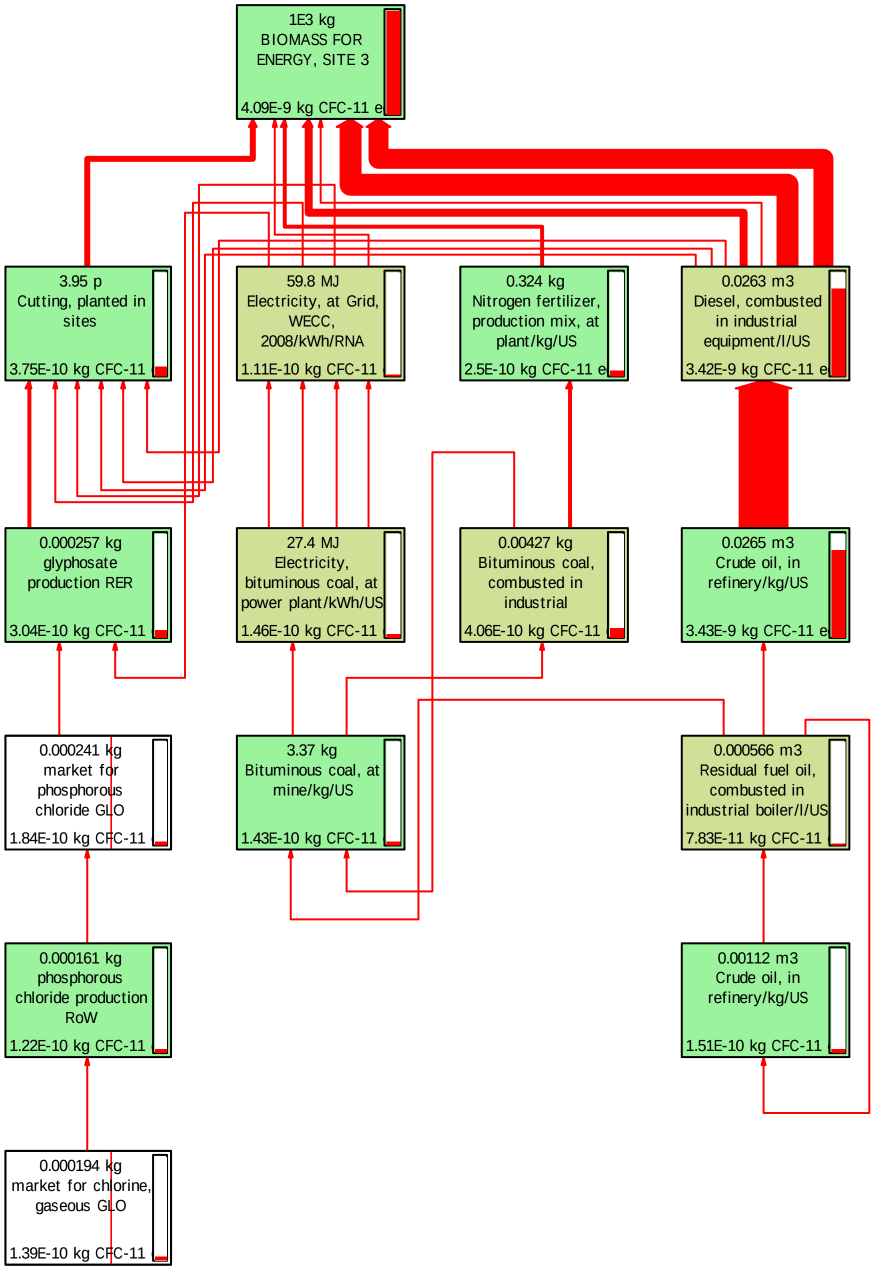


Figure E 4.1 Network of Ozone depletion (Decrement node cut-off: 1.9%)

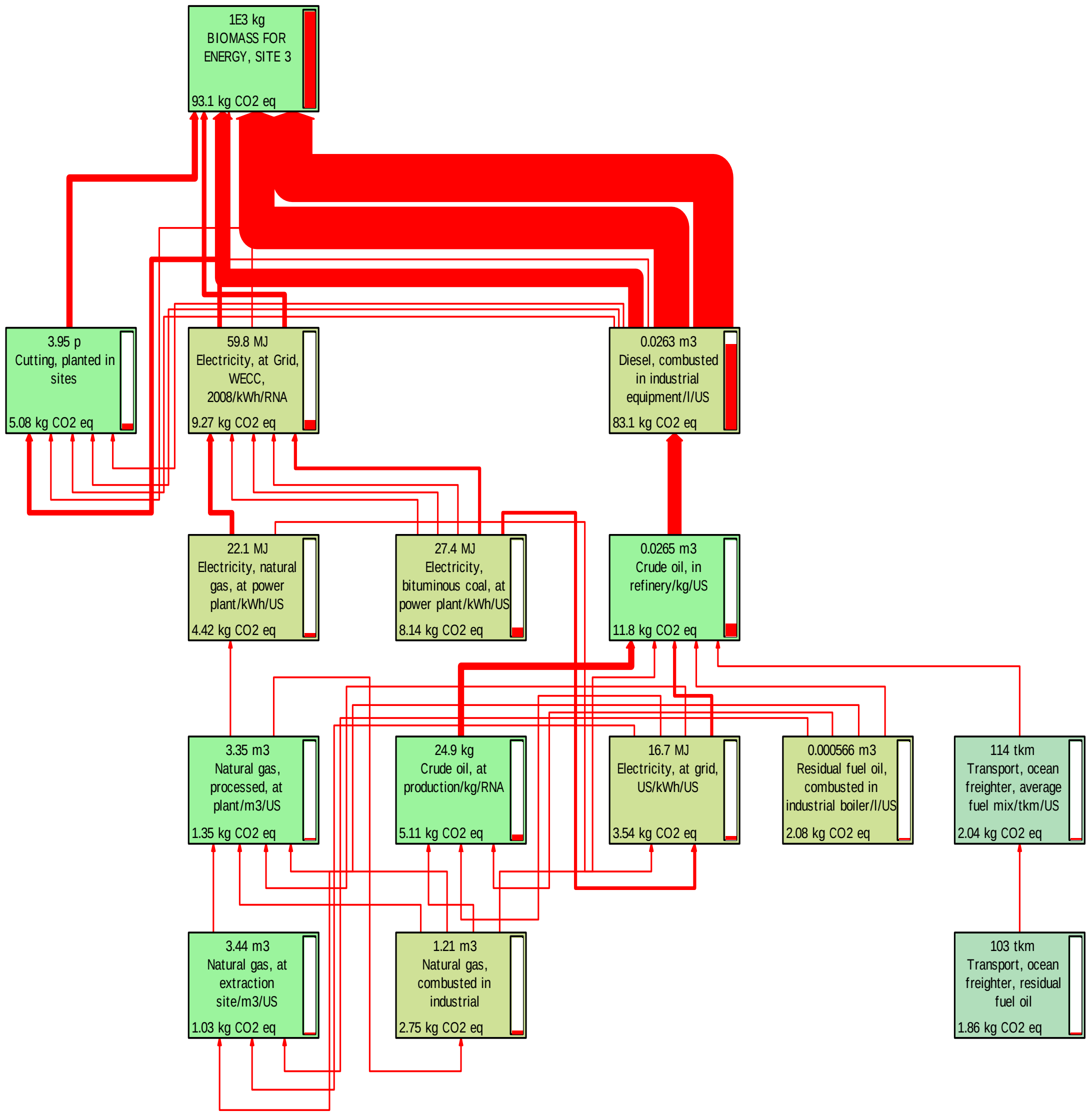


Figure E 4.2 Network of Global warming (Decrement node cut-off: 0.69%)

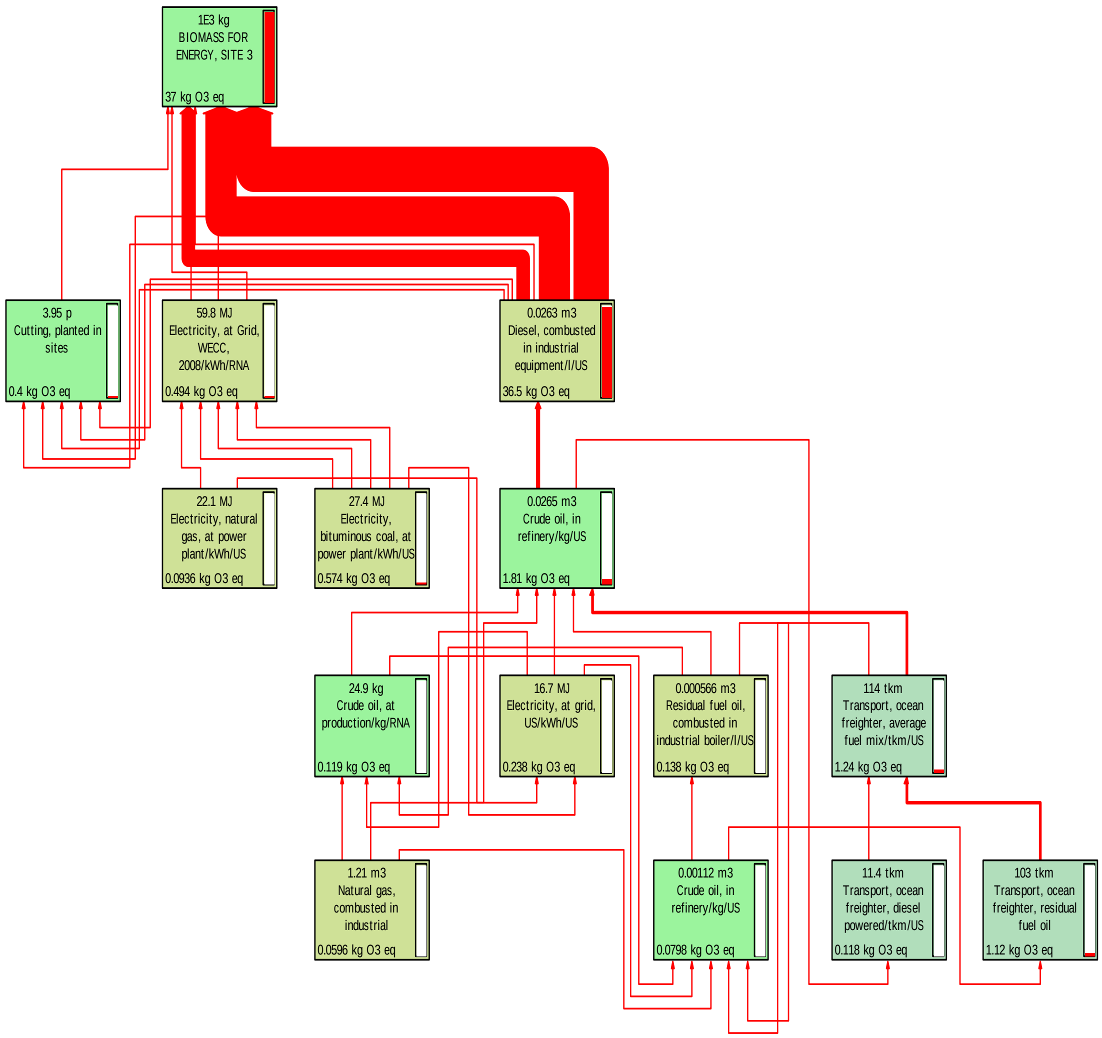


Figure E 4.3 Network of Smog (Decrement node cut-off: 0.14%)

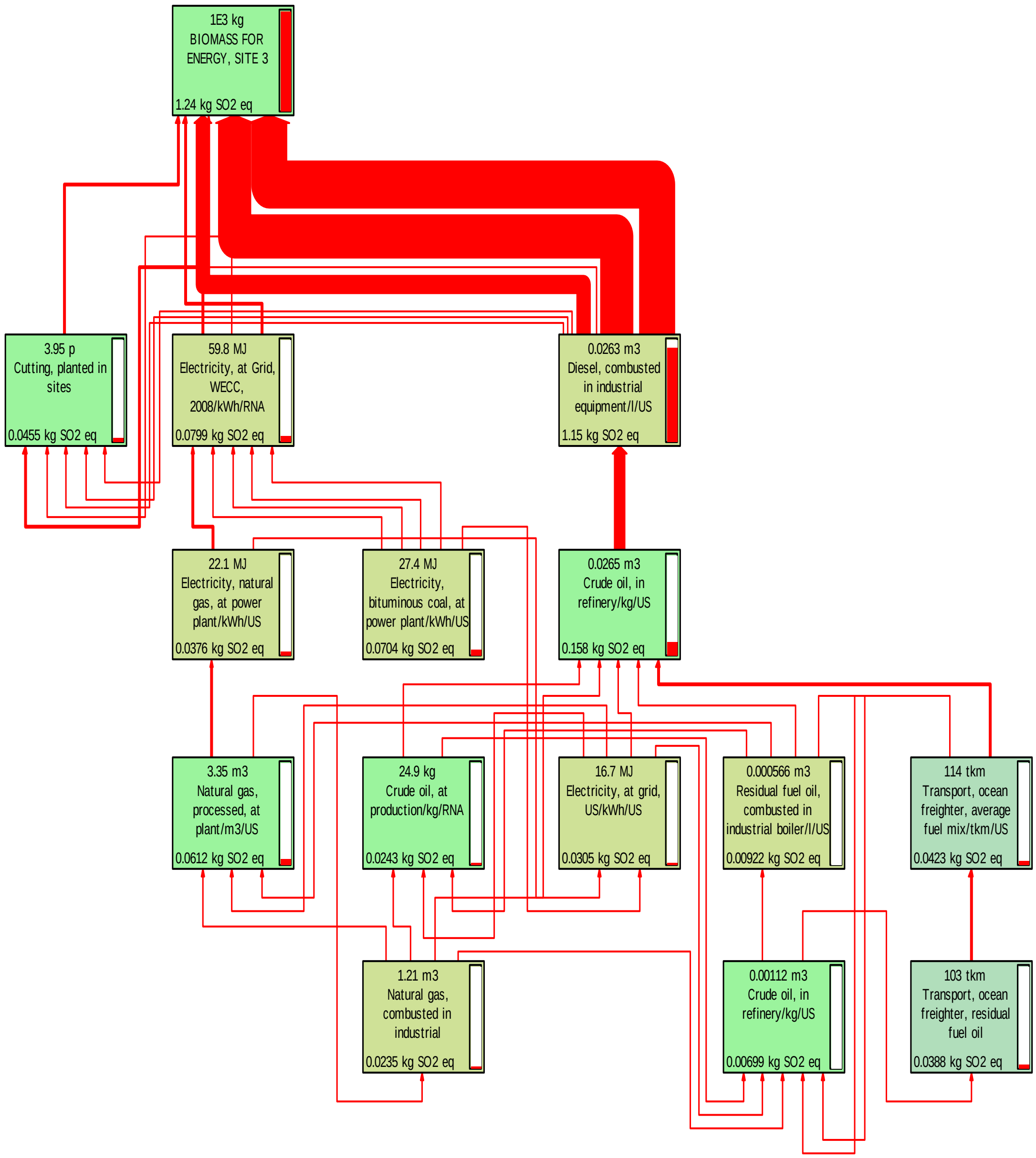


Figure E 4.4 Network of Acidification (Decrement node cut-off: 0.53%)

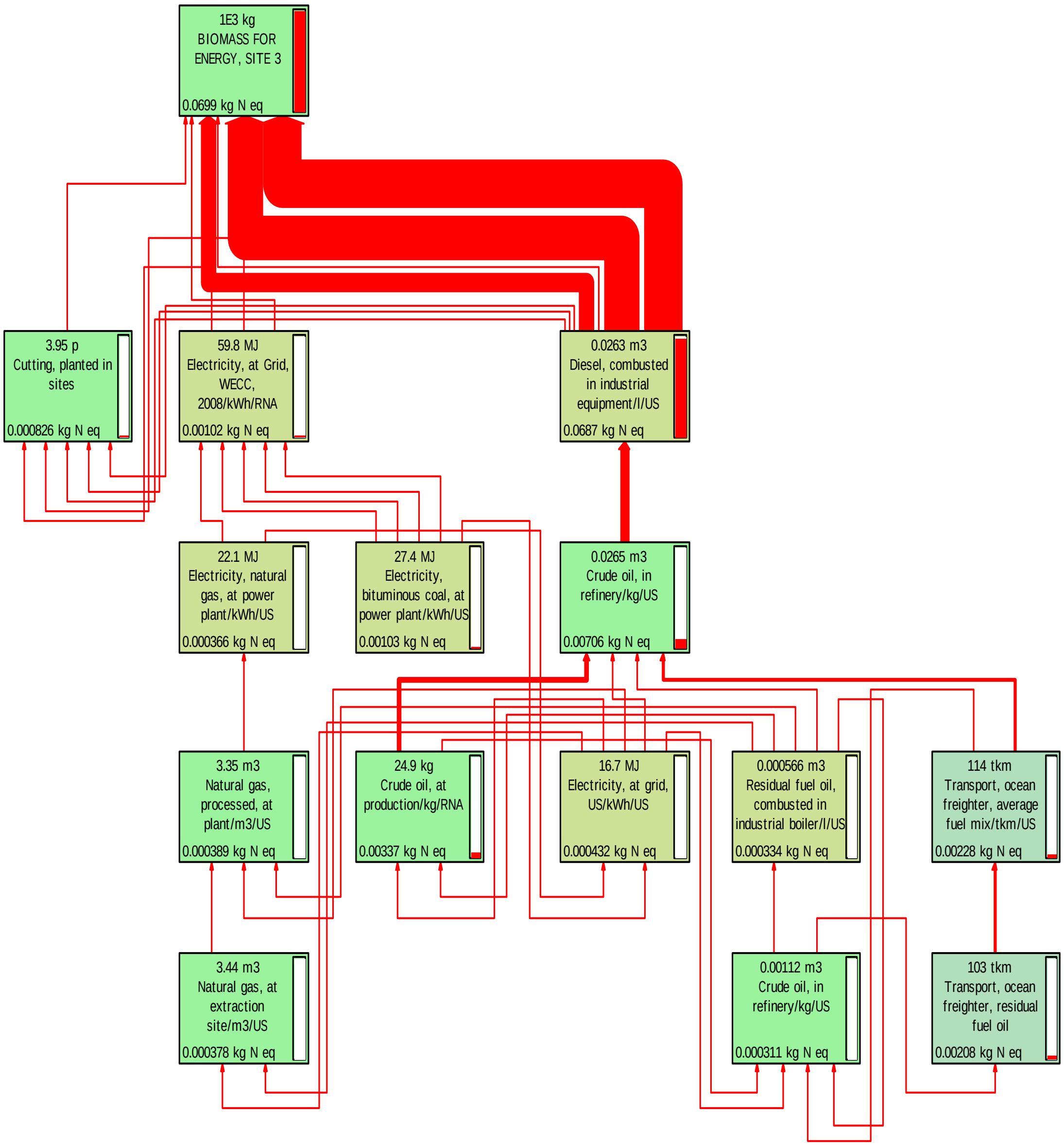


Figure E 4.5 Network of Eutrophication (Decrement node cut-off: 0.34%)

Site 3a

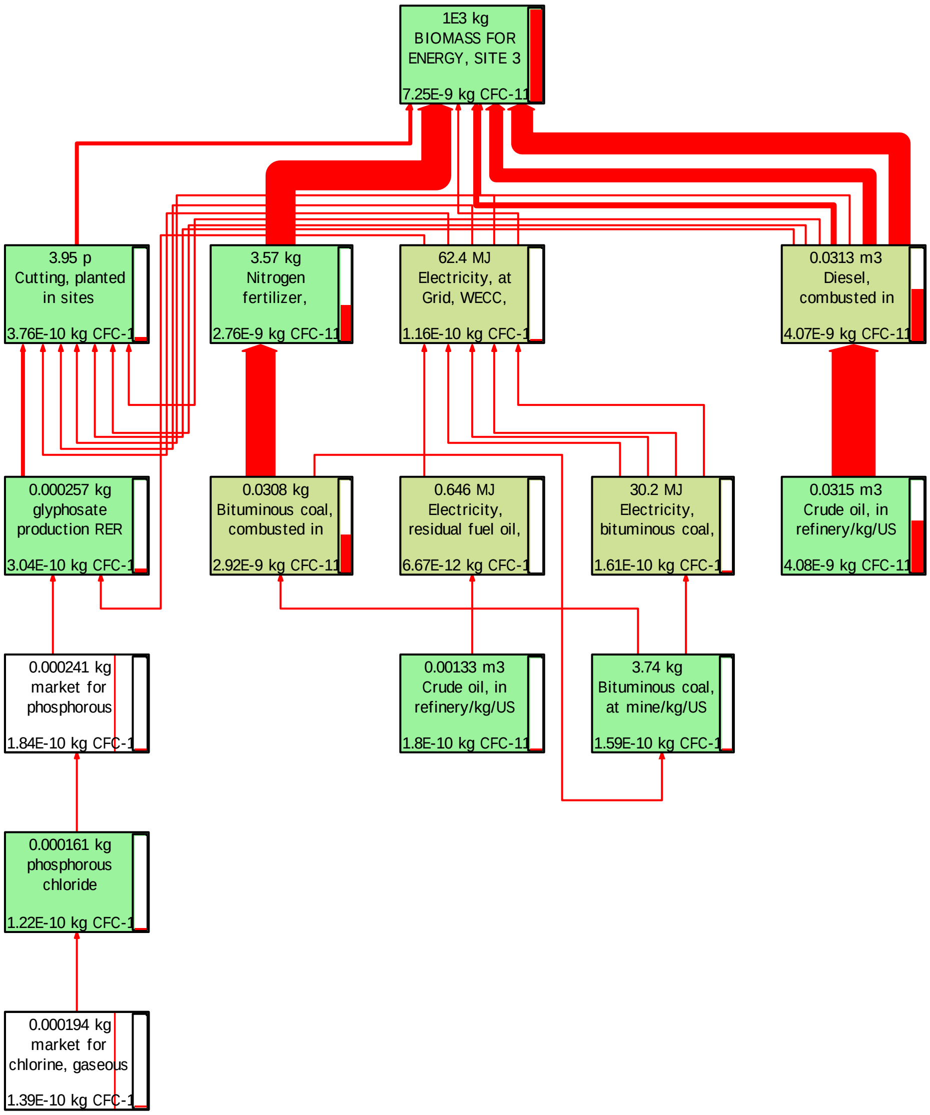


Figure E 5.1 Network of Ozone depletion (Decrement node cut-off: 1.31%)

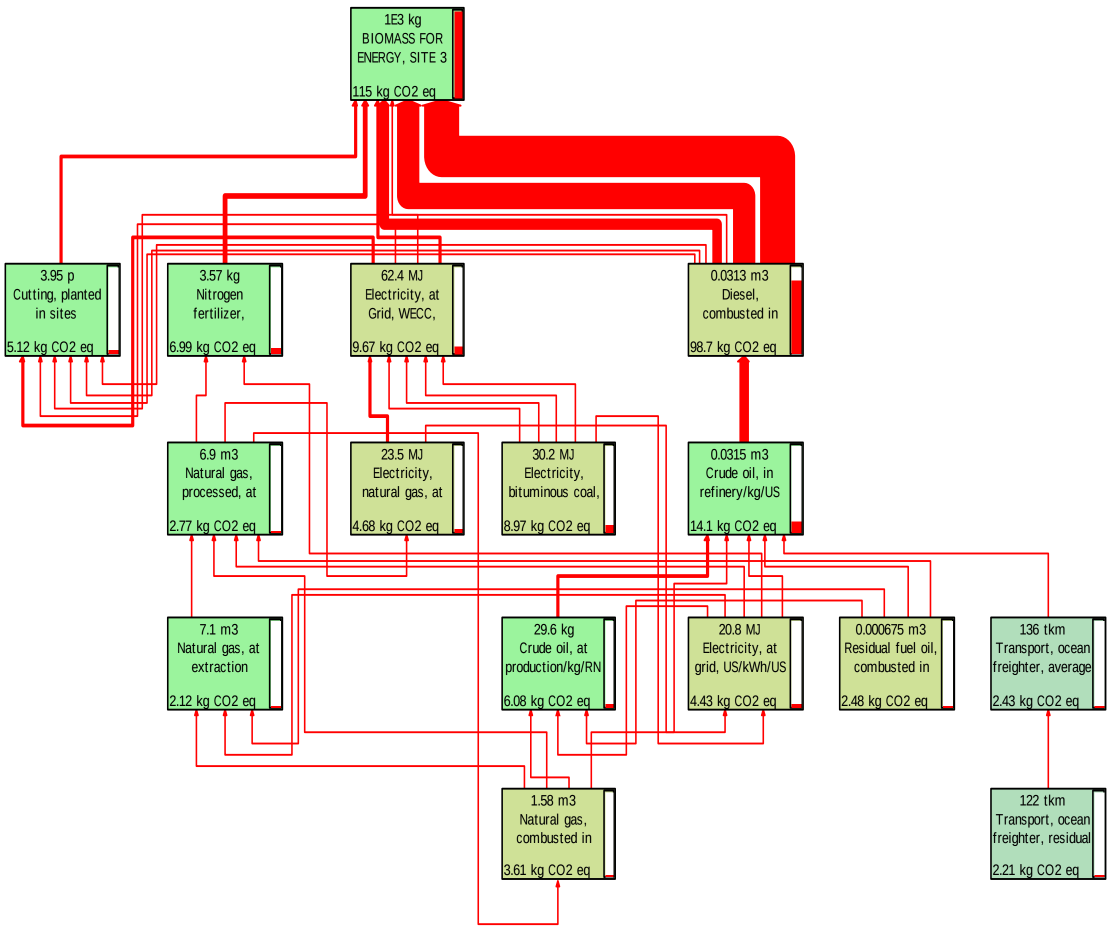


Figure E 5.2 Network of Global warming (Decrement node cut-off: 1.31%)

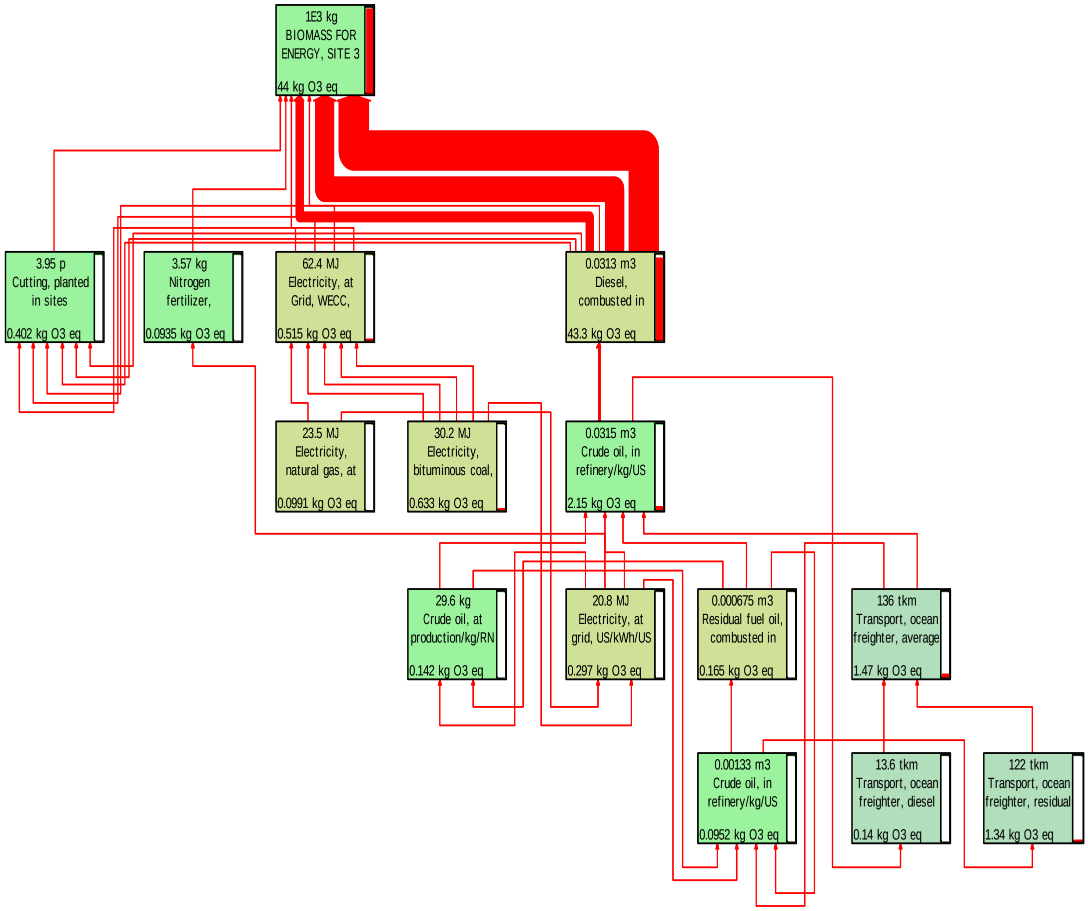


Figure E 5.3 Network of Smog (Decrement node cut-off: 0.2%)

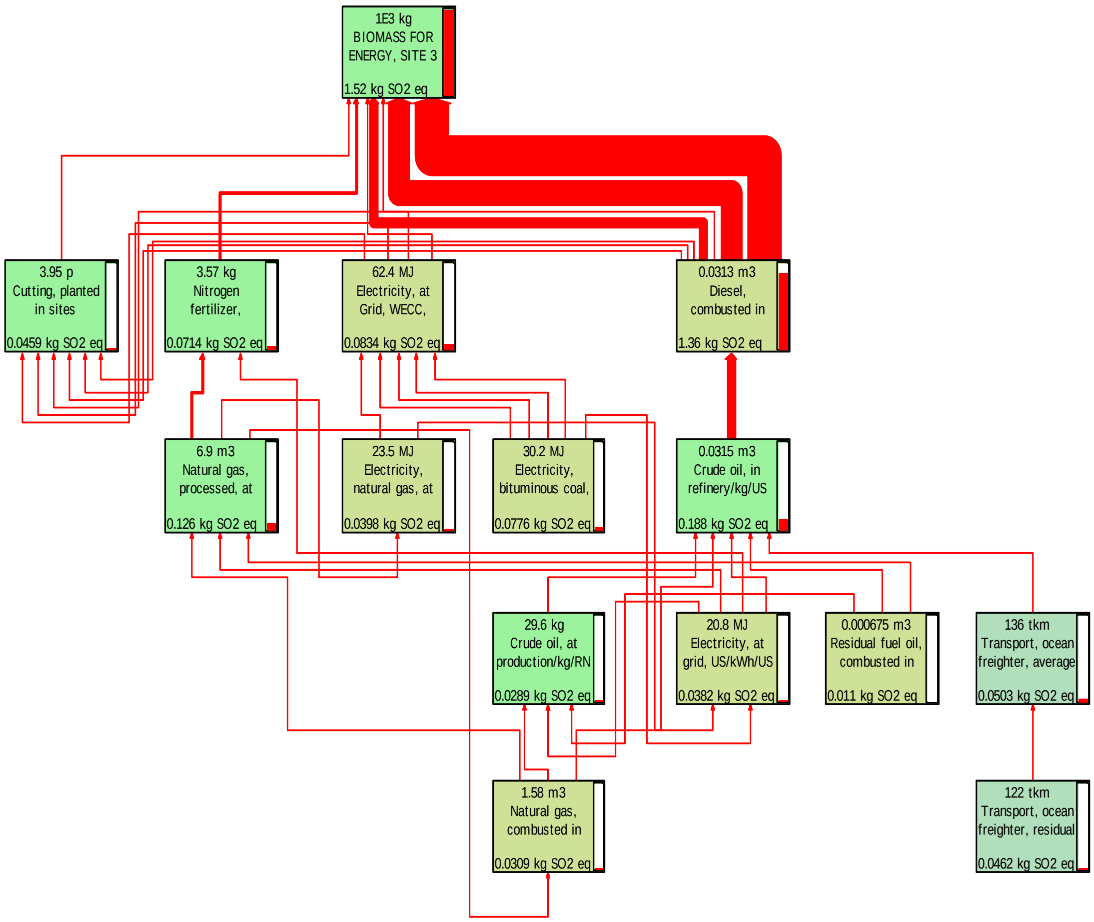


Figure E 5.4 Network of Acidification (Decrement node cut-off: 0.6%)

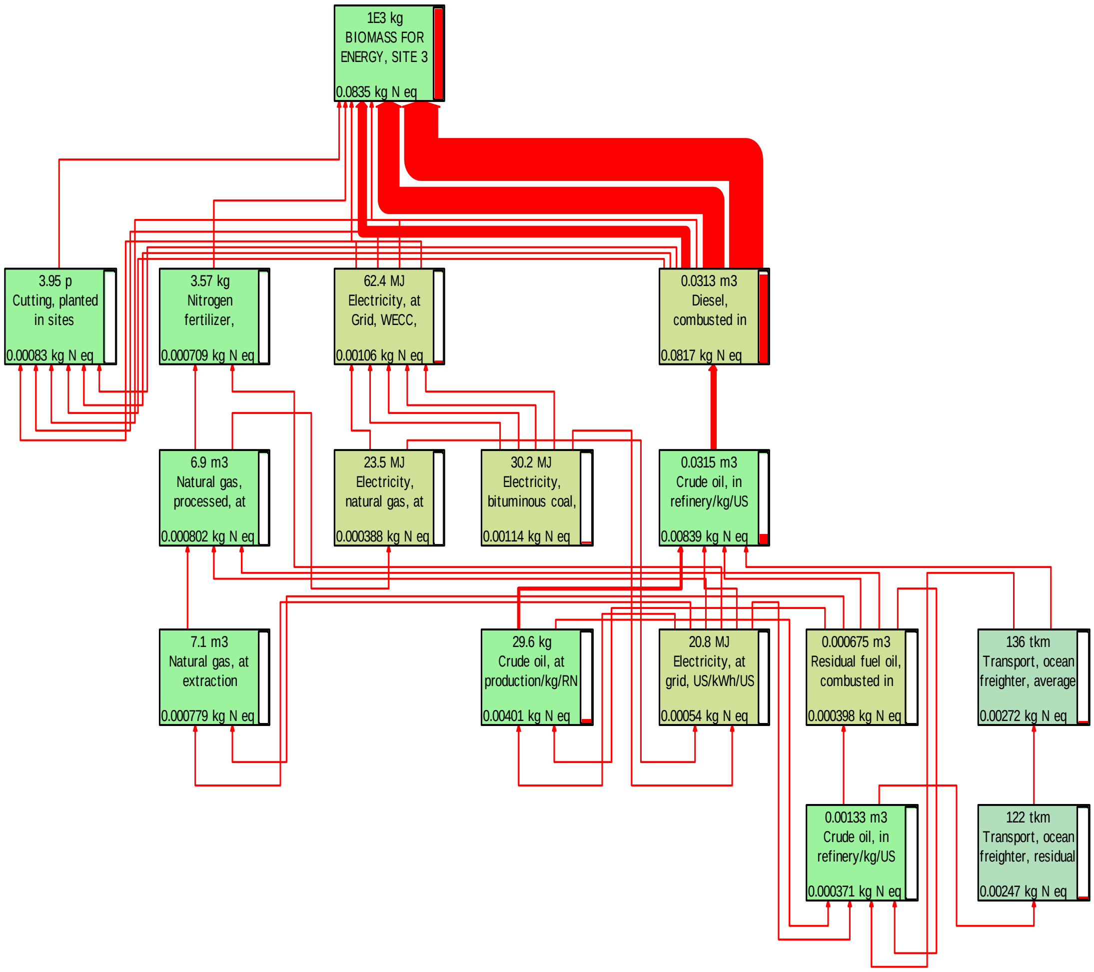


Figure E 5.5 Network of Eutrophication (Decrement node cut-off: 0.4%)

Site 4

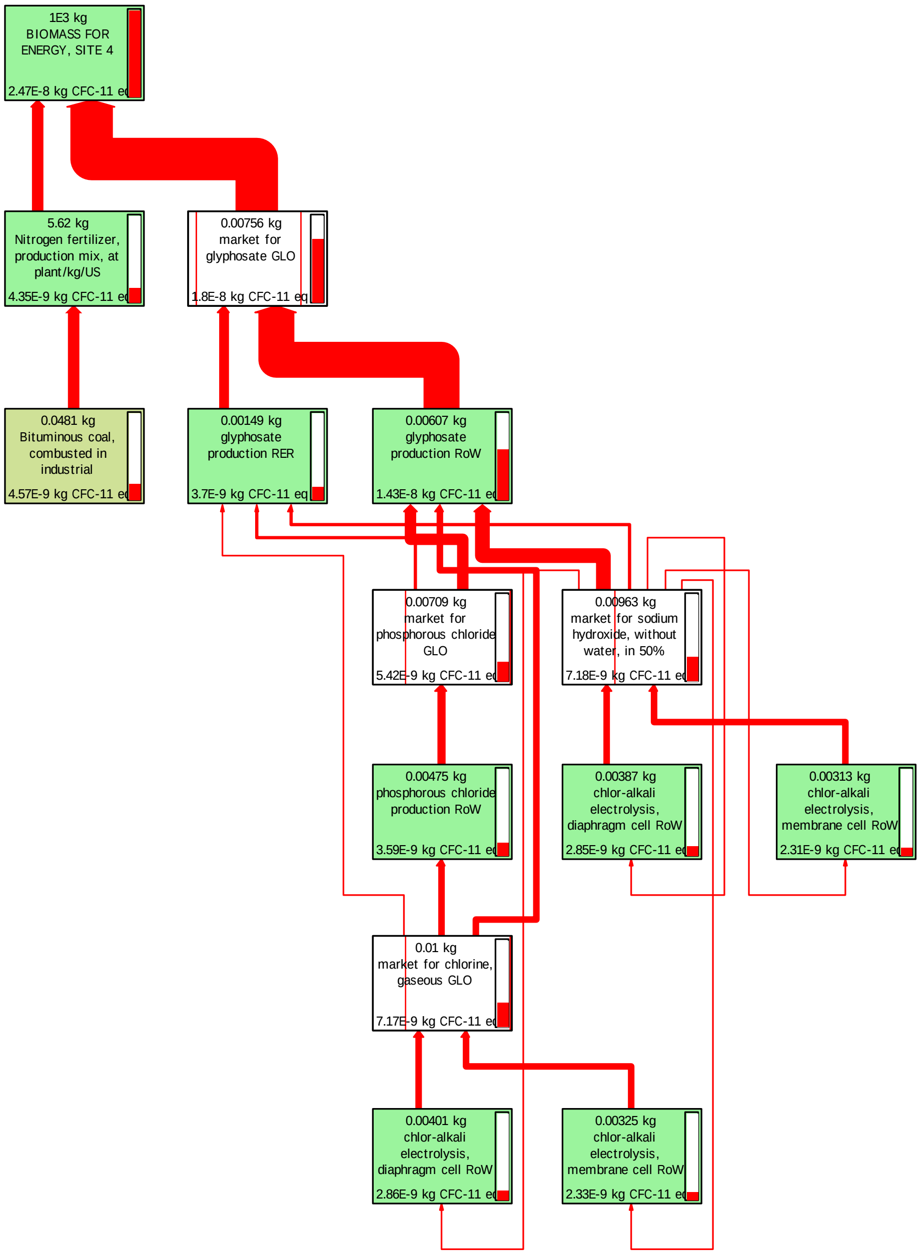


Figure E 6.1 Network of Ozone depletion (Decrement node cut-off: 9.3%)

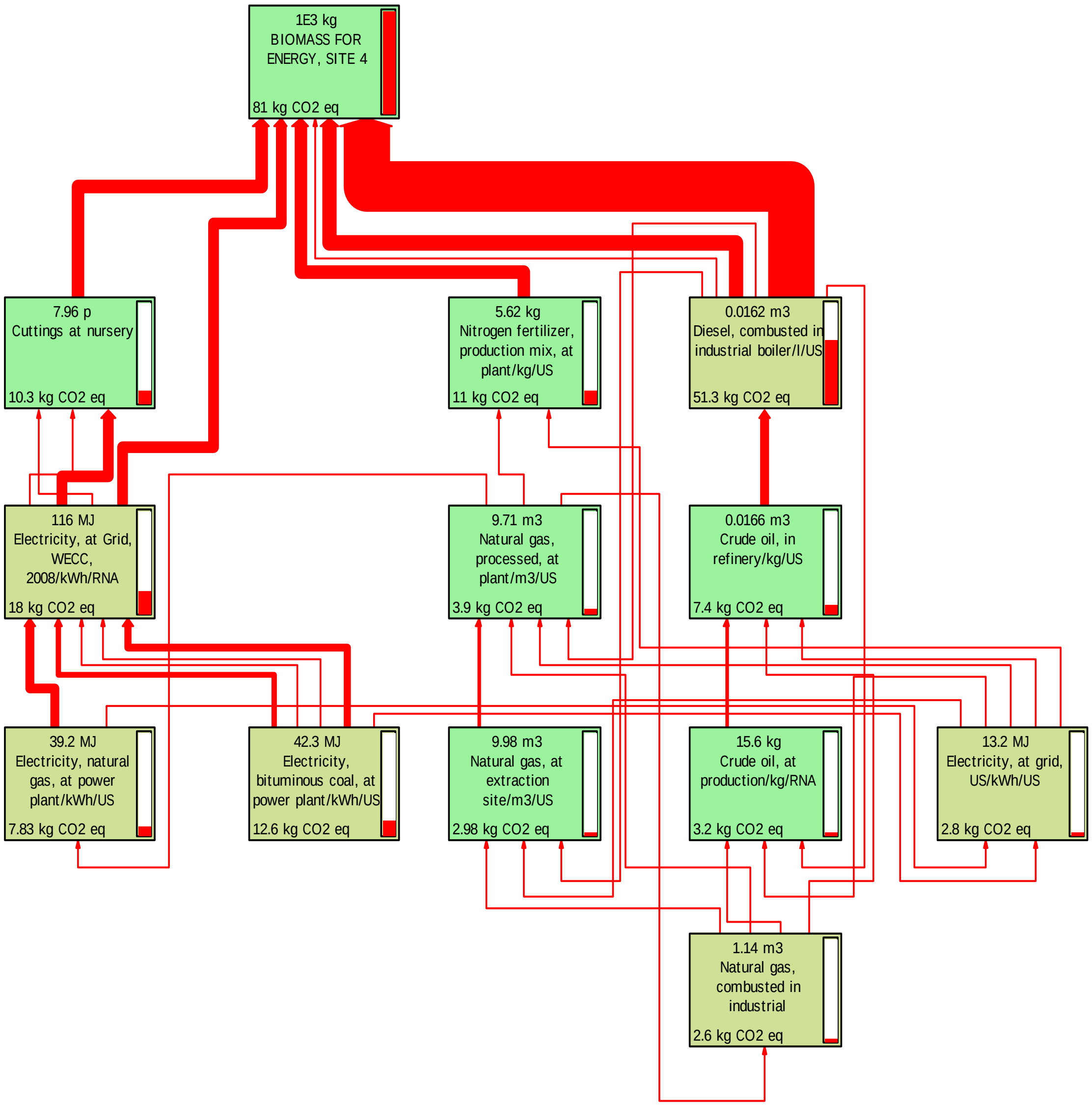


Figure E 6.2 Network of Global warming (Decrement node cut-off: 2%)

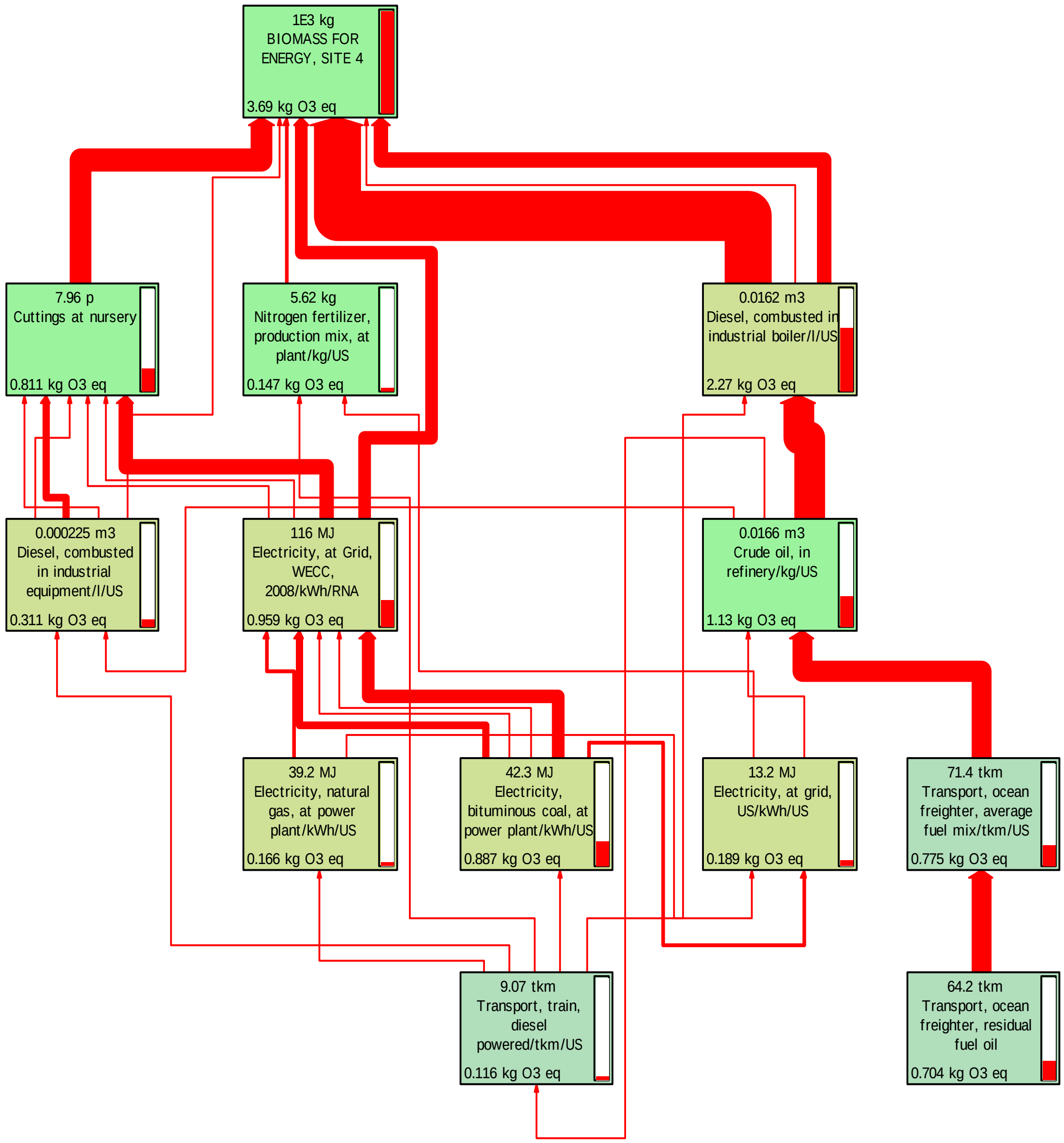


Figure E 6.3 Network of Smog (Decrement node cut-off: 2.6%)

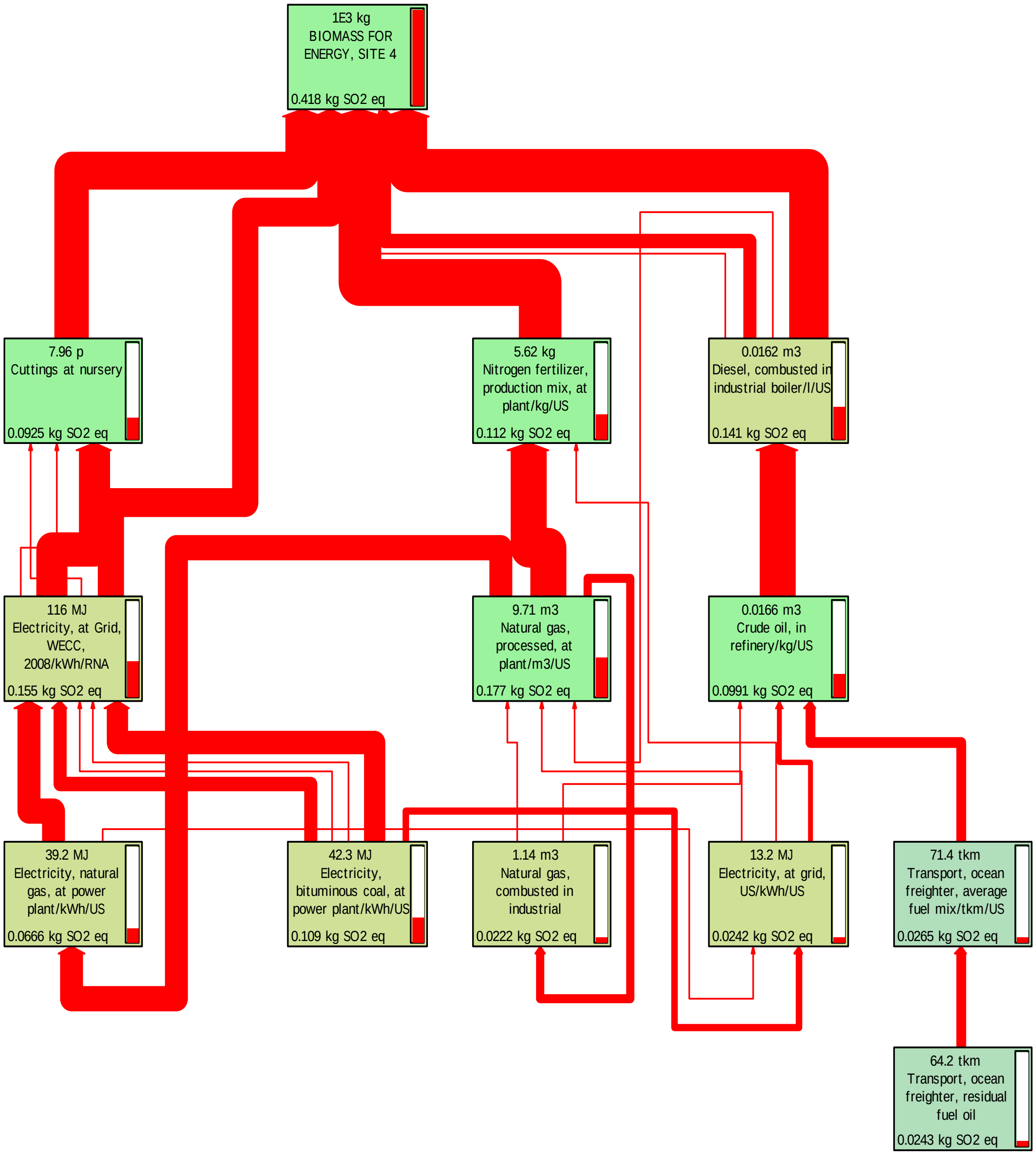


Figure E 6.4 Network of Acidification (Decrement node cut-off: 5%)

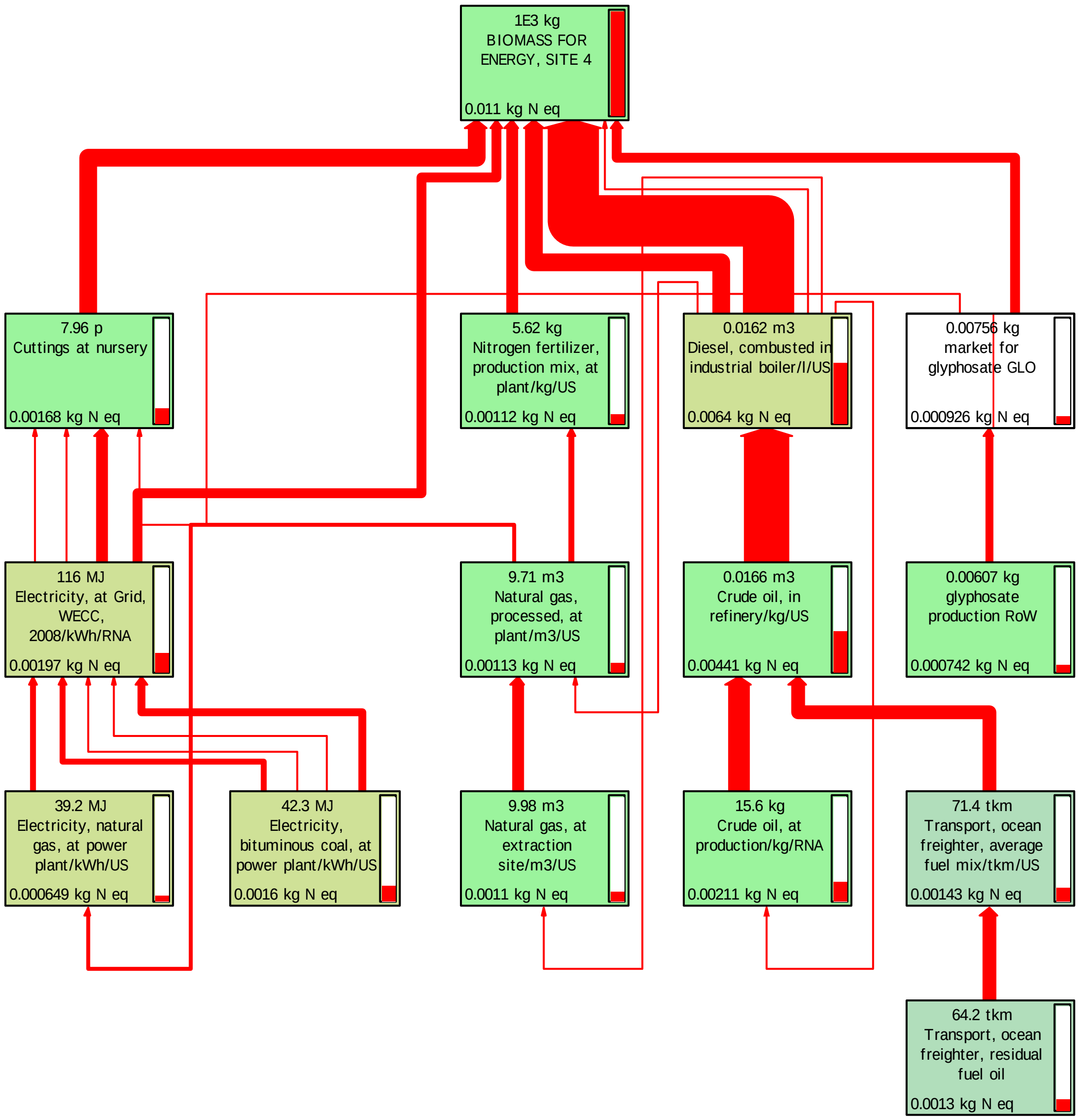


Figure E 6.5 Network of Eutrophication (Decrement node cut-off: 5.5%)

Appendix F. LCIA data with its respective percentage contribution. Table F.1Cutting at nursery

		Processes	Land preparation		Transport	Plantation management				Land restoration
Impact category	Unit (kg)	Total	Herbi-cide	Diesel	Transport	Diesel	Electri-city	Electri-city	Electri-city	Diesel
Ozone depletion	CFC-11 eq	1.73E-10	1.55E-10	1.30E-13	1.41E-15	3.12E-12	1.42E-11	1.20E-15	3.35E-13	2.47E-13
	% contribution		89.59	0.08	0.00	1.80	8.19	0.00	0.19	0.14
Global warming	CO_2 eq	1.30	0.00076	0.0031	3.71E-05	0.076	1.18	0.00010	0.028	0.0060
	% contribution		0.06	0.24	0.00	5.84	91.23	0.01	2.15	0.46
Smog	O_3 eq	0.10	4.82E-05	0.0014	6.06E-06	0.033	0.063	5.35E-06	0.0015	0.0026
	% contribution		0.05	1.36	0.01	32.66	61.88	0.01	1.46	2.59
Acidification	SO_2 eq	0.012	4.86E-06	4.36E-05	2.21E-07	0.001047	0.010192	8.65E-07	0.00024	8.29E-05
	% contribution		0.04	0.38	0.00	9.02	87.77	0.01	2.07	0.71
Eutrophication	N eq	0.00021	7.96E-06	2.61E-06	1.23E-08	6.26E-05	0.00013	1.10E-08	3.06E-06	4.96E-06
	% contribution		3.78	1.24	0.01	29.70	61.47	0.01	1.45	2.35

Table F 2. Site 1

	Processes		Land preparation		Cutting	Transport	Plantation manag.		Harves-ting	Land restoration		
Impact category	Unit (kg)	Total	Herbi-cide	Diesel	Cutting	Transport	Herbi-cide	Diesel	Diesel	Herbi-cide	Diesel	Pesti-cide
Ozone depletion	CFC-11 eq	1.18E-06	5.01E-08	2.73E-11	5.79E-09	3.96E-12	1.05E-06	1.77E-10	1.03E-09	5.01E-08	1.95E-11	2.71E-08
	% contribution		4.23	0.00	0.49	0.00	88.65	0.01	0.09	4.23	0.00	2.29
Global warming	CO_2 eq	79.5	0.25	0.66	43.3	0.10	5.16	4.29	24.9	0.25	0.47	0.12
	% contribution		0.31	0.83	54.43	0.13	6.48	5.39	31.37	0.31	0.59	0.15
Smog	O_3 eq	17.1	0.015	0.29	3.40	0.017	0.33	1.88	11.0	0.015	0.21	0.0077
	% contribution		0.09	1.70	19.87	0.10	1.90	11.00	63.99	0.09	1.21	0.04
Acidification	SO_2 eq	0.85	0.0016	0.0092	0.39	0.00062	0.033	0.059	0.34	0.0016	0.0065	0.00065
	% contribution		0.19	1.08	45.90	0.07	3.89	7.02	40.82	0.19	0.77	0.08
Eutrophication	N eq	0.092	0.0026	0.00055	0.0070	3.46E-05	0.054	0.0035	0.021	0.0026	0.00039	0.00044
	% contribution		2.81	0.60	7.69	0.04	58.78	3.87	22.51	2.81	0.43	0.48

Table F 3. Site 2

	Processes		Land preparation		Cutting	Plantation management				Harves-ting	Land restoration
Impact category	Unit (kg)	Total	Herbi-cide	Diesel	Cuttings	Electricity	Herbi-cide	Diesel	Pesti-cide	Diesel	Diesel
Ozone depletion	CFC-11 eq	6.05E-07	1.91E-08	1.61E-10	5.33E-10	9.96E-11	4.53E-07	1.31E-10	1.30E-07	1.32E-09	1.43E-11
	% contribution		3.16	0.03	0.09	0.02	75.00	0.02	21.47	0.22	0.00
Global warming	CO_2 eq	54.7	0.094	3.91	3.99	8.30	2.23	3.19	0.58	32.1	0.35
	% contribution		0.17	7.15	7.29	15.16	4.07	5.82	1.05	58.66	0.63
Smog	O_3 eq	18.3	0.0059	1.72	0.31	0.44	0.14	1.40	0.037	14.1	0.15
	% contribution		0.03	9.38	1.71	2.41	0.77	7.64	0.20	77.02	0.83
Acidification	SO_2 eq	0.67	0.00059	0.054	0.036	0.071	0.014	0.044	0.0031	0.44	0.0048
	% contribution		0.09	8.05	5.32	10.64	2.11	6.55	0.46	66.06	0.71
Eutrophication	N eq	0.061	0.00098	0.0032	0.00065	0.00091	0.023	0.0026	0.0021	0.026	0.00029
	% contribution		1.62	5.34	1.07	1.50	38.37	4.35	3.49	43.80	0.47

Table F 4. Site 3

	Processes	Land preparation	Cutting	Transport	Plantation management			Harvesting	Land restoration
Impact category	Unit (kg)	Total	Diesel	Cuttings	Transport	Electri-city	Fertili-zer	Diesel	Diesel	Diesel
Ozone depletion	CFC-11 eq	4.40E-09	3.51E-11	6.84E-10	5.73E-13	5.57E-11	2.50E-10	1.46E-09	1.34E-09	5.73E-10
	% contribution		0.80	15.55	0.01	1.27	5.69	33.23	30.42	13.03
Global warming	CO_2 eq	93.1	0.85	5.12	0.015	4.64	0.63	35.5	32.5	13.9
	% contribution		0.91	5.50	0.02	4.98	0.68	38.10	34.87	14.94
Smog	O_3 eq	37.0	0.37	0.40	0.0024	0.25	0.0085	15.6	14.3	6.11
	% contribution		1.01	1.09	0.01	0.67	0.02	42.13	38.56	16.52
Acidification	SO_2 eq	1.24	0.012	0.046	8.97E-05	0.040	0.0065	0.49	0.45	0.19
	% contribution		0.95	3.71	0.01	3.24	0.52	39.69	36.32	15.56
Eutrophication	N eq	0.070	0.00070	0.00083	5.00E-06	0.00051	6.43E-05	0.029	0.027	0.011
	% contribution		1.01	1.19	0.01	0.73	0.09	42.03	38.47	16.48

Table F 5. Site 4

		Processes	Land preparation	Cuttings	Transport	Plantation management			Harves-ting	Land restoration	
Impact category	Unit (kg)	Total	Diesel	Cuttings	Transport	Electri-city	Fertili-zer	Diesel	Diesel	Herbi-cide	Diesel
Ozone depletion	CFC-11 eq	2.47E-08	1.37E-12	1.38E-09	8.40E-13	1.00E-10	4.35E-09	5.19E-10	1.57E-09	1.68E-08	5.72E-12
	% contribution		0.01	5.57	0.00	0.41	17.58	2.10	6.34	67.97	0.02
Global warming	CO_2 eq	81	0.03	10.3	0.02	8.36	11.0	12.7	38.3	0.08	0.14
	% contribution		0.04	12.73	0.03	10.32	13.59	15.68	47.34	0.10	0.17
Smog	O_3 eq	3.69	0.01	0.81	0.00	0.45	0.15	0.56	1.70	0.01	0.01
	% contribution		0.40	21.95	0.10	12.07	3.99	15.22	45.97	0.14	0.17
Acidification	SO_2 eq	0.42	0.00	0.09	0.00	0.07	0.11	0.03	0.11	0.00	0.00
	% contribution		0.11	22.09	0.03	17.24	26.87	8.32	25.13	0.13	0.09
Eutrophication	N eq	0.011	0.000	0.002	0.000	0.001	0.001	0.002	0.005	0.001	0.000
	% contribution		0.25	15.27	0.07	8.35	10.16	14.40	43.49	7.85	0.16

Appendix G. Sensitivity analysis

Table G 1.1 Chemical sensitivity for overall process in Site 1

Impact category	Unit	Original	Ch+10%	Ch-10%
Ozone depletion	kg CFC-11 eq	1.18E-06	1.29E-06	1.08E-06
Global warming	kg CO_2 eq	79.5	80.1	79.0
Smog	kg O_3 eq	17.1	17.2	17.1
Acidification	kg SO_2 eq	0.84	0.85	0.84
Eutrophication	kg N eq	0.092	0.097	0.086
Percentage of change in category impact				
Ozone depletion	%		9.06E+00	-9.06E+00
Global warming			0.661	-0.66
Smog			0.194	-0.19
Acidification			0.40	-0.40
Eutrophication			5.92	-5.92

Table G 1.2 Diesel sensitivity for overall process in Site 1

Impact category	Unit	Original	D+10%	D-10%
Ozone depletion	kg CFC-11 eq	1.18E-06	1.19E-06	1.19E-06
Global warming	kg CO_2 eq	79.5	82.6	76.5
Smog	kg O_3 eq	17.1	18.5	15.8
Acidification	kg SO_2 eq	0.84	0.89	0.80
Eutrophication	kg N eq	0.092	0.094	0.089
Percentage of change in category impact				
Ozone depletion	%		0.61	0.59
Global warming			3.85	-3.80
Smog			7.78	-7.83
Acidification			4.98	-4.98
Eutrophication			3.04	-2.45

Table G 2.1 Chemical sensitivity in overall process in Site 2

Impact category	Unit	Original	CH+10%	CH-10%
Ozone depletion	kg CFC-11 eq	6.05E-07	6.66E-07	5.42E-07
Global warming	kg CO_2 eq	54.7	55.0	54.4
Smog	kg O_3 eq	18.3	18.3	18.3
Acidification	kg SO_2 eq	0.67	0.67	0.67
Eutrophication	kg N eq	0.06	0.06	0.06
Percentage of change in category impact				
Ozone depletion	%		10.16	-10.36
Global warming			0.54	-0.55
Smog			0.10	-0.10
Acidification			0.27	-0.28
Eutrophication			4.52	-4.55

Table G 2.2 Herbicide sensitivity at plantation management in Site 2

Impact category	Unit	Original	H at PM+10%	H at PM-10%
Ozone depletion	kg CFC-11 eq	6.05E-07	6.52E-07	5.57E-07
Global warming	kg CO_2 eq	54.7	55.0	54.5
Smog	kg O_3 eq	18.3	18.3	18.3
Acidification	kg SO_2 eq	0.67	0.67	0.67
Eutrophication	kg N eq	0.06	0.06	0.06
Percentage of change in category impact				
Ozone depletion	%		7.89	-7.89
Global warming			0.43	-0.43
Smog			0.08	-0.08
Acidification			0.22	-0.22
Eutrophication			4.04	-4.04

Table G 2.3 Diesel sensitivity for overall process in Site 2

Impact category	Unit	Original	D+10%	D-10%
Ozone depletion	kg CFC-11 eq	6.05E-07	6.05E-07	6.05E-07
Global warming	kg CO_2 eq	54.7	58.67	50.8
Smog	kg O_3 eq	18.3	20.0	16.6
Acidification	kg SO_2 eq	0.67	0.73	0.62
Eutrophication	kg N eq	0.06	0.06	0.06
Percentage of change in category impact				
Ozone depletion	%		0.03	-0.05
Global warming			7.20	-13.45
Smog			9.46	-17.29
Acidification			8.11	-15.02
Eutrophication			5.38	-10.22

Table G 2.4 Diesel sensitivity for harvesting in Site 2

Impact category	Unit	Original	D at H+10%	D at H-10%
Ozone depletion	kg CFC-11 eq	6.05E-07	6.05E-07	6.05E-07
Global warming	kg CO_2 eq	54.7	58.0	51.5
Smog	kg O_3 eq	18.3	19.7	16.9
Acidification	kg SO_2 eq	0.67	0.72	0.63
Eutrophication	kg N eq	0.06	0.063	0.058
Percentage of change in category impact				
Ozone depletion	%		0.02	-0.04
Global warming			5.88	-11.10
Smog			7.72	-14.33
Acidification			6.62	-12.42
Eutrophication			4.39	-8.41

Table G 3.1 Diesel sensitivity for overall process in Site 3

Impact category	Unit	Original	D +10%	D -10%
Ozone depletion	kg CFC-11 eq	4.09E-09	4.43E-09	3.75E-09
Global warming	kg CO_2 eq	93.1	101.4	84.9
Smog	kg O_3 eq	37.0	40.6	33.
Acidification	kg SO_2 eq	1.24	1.35	1.12
Eutrophication	kg N eq	0.070	0.08	0.06
Percentage of change in category impact				
Ozone depletion	%		8.33	-8.31
Global warming			8.92	-8.83
Smog			9.81	-9.80
Acidification			9.27	-9.21
Eutrophication			9.79	-9.78

Table G 3.2 Diesel sensitivity at plantation management in Site 3

Impact category	Unit	Original	D at PM+10%	D at PM_10%
Ozone depletion	kg CFC-11 eq	4.09E-09	4.24E-09	3.94E-09
Global warming	kg CO_2 eq	93.1	96.7	89.6
Smog	kg O_3 eq	37.0	38.6	35.4
Acidification	kg SO_2 eq	1.24	1.29	1.19
Eutrophication	kg N eq	0.070	0.07	0.07
Percentage of change in category impact				
Ozone depletion	%		3.59	-3.56
Global warming			3.85	-3.77
Smog			4.22	-4.21
Acidification			4.00	-3.94
Eutrophication			4.21	-4.20

Table G 3.3 Diesel sensitivity at harvesting in Site 3

Impact category	Unit	Original	D at H+10%	D at H-10%
Ozone depletion	kg CFC-11 eq	4.09E-09	4.22E-09	3.96E-09
Global warming	kg CO_2 eq	93.1	96.4	89.9
Smog	kg O_3 eq	37.0	38.4	35.6
Acidification	kg SO_2 eq	1.24	1.28	1.19
Eutrophication	kg N eq	0.07	0.07	0.07
Percentage of change in category impact				
Ozone depletion	%		3.27	-3.25
Global warming			3.52	-3.43
Smog			3.85	-3.84
Acidification			3.65	-3.59
Eutrophication			3.84	-3.83

Table G 4.1 Chemical sensitivity for overall process in Site 4

Impact category	Unit	Original	CH+10%	CH-10%
Ozone depletion	kg CFC-11 eq	2.47E-08	2.68E-08	2.26E-08
Global warming	kg CO_2 eq	81.0	82.1	79.9
Smog	kg O_3 eq	3.69	3.71	3.68
Acidification	kg SO_2 eq	0.42	0.43	0.41
Eutrophication	kg N eq	0.011	0.011	0.011
Percentage of change in category impact				
Ozone depletion	%		8.56	-8.56
Global warming			1.37	-1.37
Smog			0.41	-0.41
Acidification			2.70	-2.70
Eutrophication			1.80	-1.80

Table G 4.2 Fertility sensitivity at plantation management in Site 4

Impact category	Unit	Total	F at PM+10%	F at PM-10%
Ozone depletion	kg CFC-11 eq	2.47E-08	2.52E-08	2.43E-08
Global warming	kg CO_2 eq	81.0	82.1	79.9
Smog	kg O_3 eq	3.69	3.71	3.68
Acidification	kg SO_2 eq	0.42	0.43	0.41
Eutrophication	kg N eq	0.011	0.011	0.011
Percentage of change in category impact				
Ozone depletion	%		1.76	-1.76
Global warming			1.36	-1.36
Smog			0.40	-0.40
Acidification			2.69	-2.69
Eutrophication			1.02	-1.02

Table G 4.3 Herbicide sensibility at land restoration in Site 4

Impact category	Unit	Total	H at LR+10%	H at LR-10%
Ozone depletion	kg CFC-11 eq	2.47E-08	2.64E-08	2.30E-08
Global warming	kg CO_2 eq	81.0	81.0	81.0
Smog	kg O_3 eq	3.69	3.69	3.69
Acidification	kg SO_2 eq	0.42	0.42	0.42
Eutrophication	kg N eq	0.011	0.011	0.011
Percentage of change in category impact				
Ozone depletion	%		6.80	-6.80
Global warming			0.01	-0.01
Smog			0.01	-0.01
Acidification			0.01	-0.01
Eutrophication			0.79	-0.79

Table G 4.4 Diesel sensitivity for overall processes in Site 4

Impact category	Unit	Total	D+10%	D-10%
Ozone depletion	kg CFC-11 eq	2.47E-08	2.49E-08	2.45E-08
Global warming	kg CO_2 eq	81.0	86.1	75.9
Smog	kg O_3 eq	3.69	3.92	3.46
Acidification	kg SO_2 eq	0.42	0.43	0.40
Eutrophication	kg N eq	0.011	0.012	0.010
Percentage of change in category impact				
Ozone depletion	%		0.84	-0.84
Global warming			6.30	-6.30
Smog			6.15	-6.15
Acidification			3.35	-3.35
Eutrophication			5.81	-5.81

Table G 4.5 Diesel sensitivity for harvesting in Site 4

Impact category	Unit	Original	D at H+10%	D at H-10%
Ozone depletion	kg CFC-11 eq	2.47E-08	2.32E-08	2.83E-08
Global warming	kg CO_2 eq	81.0	73.7	90.0
Smog	kg O_3 eq	3.69	3.36	4.11
Acidification	kg SO_2 eq	0.42	0.38	0.47
Eutrophication	kg N eq	0.011	0.010	0.012
Percentage of change in category impact				
Ozone depletion	%		-6.29	14.62
Global warming			-9.01	11.18
Smog			-8.99	11.22
Acidification			-9.01	11.20
Eutrophication			-8.69	11.59
Average			-8.40	11.96

Appendix H. Contribution of processes and inputs to impact categories

Table H 1. Percentage of ozone depletion contribution for production of 1 BDmT

Processes	Input	Site 1	Site 2	Site 3	Site 4
Land Preparation	Herbicide	4.23	3.16		
	Diesel	0.00	0.03	0.80	0.01
Stock for initial planting	Cuttings	0.49	0.09	15.55	5.57
	Transportation	0.00		0.01	0.00
Plantation Management	Herbicide	**88.6**	**75.0**		
	Pesticide		21.47		
	Diesel	0.01	0.02	32.23	2.10
	Water				
	Electricity		0.02	1.27	0.41
	Biosolids				
	Leachate				
	Fertilizer			5.69	17.58
Harvest	Diesel	0.09	0.22	**30.4**	6.34
Land Restoration	Herbicide	4.23			**68.0**
	Diesel	0.00	0.00	13.03	0.02
	Pesticide	2.29			
	Ozone depletion (kg CFC-11eq x 10^{-6})$\cdot t^{-1}$	1.18	0.60	0.0044	0.025

Blanks indicate the material was not used.

Table H 2. Percentage of global warming contribution for production of 1 BDmT

Processes	Input	Site 1	Site 2	Site 3	Site 4
Land Preparation	Herbicide	0.31	0.17		
	Diesel	0.83	7.15	0.91	0.04
Stock for initial planting	Cuttings	**54.4**	7.29	5.50	12.7
	Transportation	0.13		0.02	0.03
Plantation Management	Herbicide	6.48	4.07		
	Pesticide		1.05		
	Diesel	5.39	5.82	**38.1**	15.7
	Water		0	0	0
	Electricity		15.2	4.98	10.3
	Biosolids			0	
	Leachate				0
	Fertilizer			0.68	13.6
Harvest	Diesel	31.4	**58.7**	34.9	**47.3**
Land Restoration	Herbicide	0.31			0.10
	Diesel	0.59	0.63	14.94	0.17
	Pesticide	0.15			
	GWP Kg CO2 eq·t^{-1}	79.5	54.7	93.1	81.0

Blanks indicate the material was not used.

Table H 3. Percentage of smog contribution for production of 1 BDmT

Processes	Input	Site 1	Site 2	Site 3	Site 4
Land Preparation	Herbicide	0.09	0.03		
	Diesel	1.70	9.38	1.01	0.40
Stock for initial planting	Cuttings	19.9	1.71	1.09	21.9
	Transportation	0.10		0.01	0.10
Plantation Management	Herbicide	1.90	0.77		
	Pesticide		0.20		
	Diesel	11.0	7.64	**42.1**	15.2
	Water				
	Electricity		2.41	0.67	12.1
	Biosolids				
	Leachate				
	Fertilizer			0.02	3.99
Harvest	Diesel	**64.0**	**77.0**	38.6	**46.0**
Land Restoration	Herbicide	0.09			0.14
	Diesel	1.21	0.83	16.52	0.17
	Pesticide	0.04			
	Smog kg O_3 eq· t^{-1}	17.1	18.3	37.0	3.69

Blanks indicate the material was not used.

Table H 4. Percentage of acidification contribution for production of 1 BDmT

Processes	Input	Site 1	Site 2	Site 3	Site 4
Land Preparation	Herbicide	0.19	0.09		
	Diesel	1.08	8.05	0.95	0.11
Stock for initial planting	Cuttings	**45.9**	5.32	3.71	22.1
	Transportation	0.07		0.01	0.03
Plantation Management	Herbicide	3.89	2.11		
	Pesticide		0.46		
	Diesel	7.02	6.55	**39.7**	8.32
	Water				
	Electricity		10.6	3.24	17.2
	Biosolids				
	Leachate				
	Fertilizer			0.52	26.9
Harvest	Diesel	40.8	**66.1**	36.3	**25.1**
Land Restoration	Herbicide	0.19			0.13
	Diesel	0.77	0.71	15.6	0.09
	Pesticide	0.08			
	Acidification kg SO_2 eq· t^{-1}	0.85	0.67	1.24	0.42

Blanks indicate the material was not used.

Table H 5. Percentage of eutrophication contribution for production of 1 BDmT

Processes	Input	Site 1	Site 2	Site 3	Site 4
Land Preparation	Herbicide	2.81	1.62		
	Diesel	0.60	5.34	1.01	0.25
Stock for initial planting	Cuttings	7.69	1.07	1.19	15.3
	Transportation	0.04		0.01	0.07
Plantation Management	Herbicide	**58.8**	38.4		
	Pesticide		3.49		
	Diesel	3.87	4.35	**42.0**	14.4
	Water				
	Electricity		1.50	0.73	8.35
	Biosolids				
	Leachate				
	Fertilizer			0.09	10.2
Harvest	Diesel	22.5	**43.8**	38.5	**43.5**
Land Restoration	Herbicide	2.81			7.85
	Diesel	0.43	0.47	16.5	0.16
	Pesticide	0.48			
	Eutrofication kg $_N$ eq· t^{-1}	0.092	0.061	0.070	0.011

Blanks indicate the material was not used.

Table H 6. Percentage of energy contribution for production of 1 BDmT

Processes	Input	Site 1	Site 2	Site 3	Site 4
	Coal	28.1	15.9	7.9	12.8
	Natural gas	24.7	14.5	9.39	28.5
	Oil	**34.7**	**63.0**	**80.1**	**52.5**
	Energy MJ $\cdot t^{-1}$	1381.8	877.4	1406.9	1343.5

Appendix I. Energy consumption with alternatives sources of electricity

Table I 1.1 Site 1 with PNW

	Unit	Total	Energy conversion	MJ	%
Fossil fuel					
Coal	kg	5.94	27.8	165.5	16.7
Natural gas	m3	3.47	38.4	133.3	13.4
Oil	kg	10.4	45.3	471.1	47.5
Fossil fuel - from Dummy process					
Petroleum				0	0.00
Tire derived fuel				0	0.00
Unspecified				0.048	0.00
Non-fossil fuel					
Uranium	kg	3.44E-05	3.81E+05	13.1	1.32
Non-fossil fuel - from Dummy process					
Biomass				0	0.0000
Wind				19.072	1.92
Geothermal				0.029	0.00
Hydropower				178.89	18.03
Solar					0.00
Photovoltaic				0.0013	0.00
Other fuels				11.0	
Total				**992.1**	98.9

Table I 1.2 Site 1 with Biomass

	Unit	Total	Energy conversion	MJ	%
Fossil fuel					
Coal	kg	3.13	27.8	87.3	11.2
Natural gas	m3	2.58	38.4	99.1	12.7
Oil	kg	12.6	45.3	571.4	73.4
Fossil fuel - from Dummy process					
Petroleum				0.03	0.003
Tire derived fuel				0.0003	0.0000
Unspecified				0.055	0.0071
Non-fossil fuel					
Uranium	kg	4.64E-05	3.81E+05	17.66	2.27
Non-fossil fuel - from Dummy process					
Biomass				0.04	0.01
Wind				0.23	0.03
Geothermal				0.21	0.03
Hydropower				2.65	0.34
Solar				0.01	0.001
Photovoltaic				0.0015	0.0002
MSW				0.0034	0.0004
Total				**778.6**	100.00

Table I 2.1 Site 2 with PNW

	Unit	Total	Energy conversion	MJ	%
Fossil fuel					
Coal	kg	2.63	27.8	73.3	9.63
Natural gas	m3	1.70	38.4	65.2	8.56
Oil	kg	12.1	45.3	550.6	72.31
Fossil fuel - from Dummy process					
Petroleum					0.00
Tire derived fuel				0	0.00
Unspecified				0.052	0.01
Non-fossil fuel					
Uranium	kg	2.54E-05	3.81E+05	9.69	1.27
Non-fossil fuel - from Dummy process					
Biomass				0	0.0000
Wind				5.68	0.75
Geothermal				0.031	0.00
Hydropower				53.63	7.04
Solar					0.00
Photovoltaic				0.0014	0.00
Other fuels				3.26	
Total				**761.5**	99.6

Table I 2.2 Site 2 with Biomass

	Unit	Total	Energy conversion	MJ	%
Fossil fuel					
Coal	kg	1.68	27.8	46.9	6.78
Natural gas	m3	1.37	38.4	52.5	7.59
Oil	kg	12.8	45.3	581	84.1
Fossil fuel - from Dummy process					
Petroleum				0.00	0.000
Tire derived fuel				0.0000	0.0000
Unspecified				0.054	0.0079
Non-fossil fuel					
Uranium	kg	2.67E-05	3.81E+05	10.17	1.47
Non-fossil fuel - from Dummy process					
Biomass				0.00	0.00
Wind				0.01	0.00
Geothermal				0.03	0.00
Hydropower				0.64	0.09
Solar				0.00	0.000
Photovoltaic				0.0015	0.0002
MSW				5.20E-05	0.0000
Total				**691.7**	100.00

Table I 3.1 Site 3 with PNW

	Unit	Total	Energy conversion	MJ	%
Fossil fuel					
Coal	kg	2.16	27.8	60.1	4.51
Natural gas	m3	2.18	38.4	83.8	6.29
Oil	kg	24.8	45.3	1125	84.5
Fossil fuel - from Dummy process					
Petroleum				0	0.00
Tire derived fuel				0	0.00
Unspecified				0.11	0.01
Non-fossil fuel					
Uranium	kg	3.21E-05	3.81E+05	12.22	0.92
Non-fossil fuel - from Dummy process					
Biomass				0	0.0000
Wind				4.47	0.34
Geothermal				0.065	0.00
Hydropower				42.81	3.22
Solar					0.00
Photovoltaic				0.0029	0.00
Other fuels				2.55	
Total				**1,331.5**	99.8

Table I 3.2 Site 3 with Biomass

	Unit	Total	Energy conversion	MJ	%
Fossil fuel					
Coal	kg	1.41	27.8	39.4	3.09
Natural gas	m3	1.92	38.4	73.8	5.78
Oil	kg	25.4	45.3	1149	90.0
Fossil fuel - from Dummy process					
Petroleum				0.00	0.000
Tire derived fuel				0.0000	0.0000
Unspecified				0.109	0.0086
Non-fossil fuel					
Uranium	kg	3.31E-05	3.81E+05	12.59	0.99
Non-fossil fuel - from Dummy process					
Biomass				0.00	0.00
Wind				0.03	0.00
Geothermal				0.07	0.01
Hydropower				1.28	0.10
Solar				0.00	0.000
Photovoltaic				0.0030	0.0002
MSW				4.07E-05	0.0000
Total				**1,276.8**	100.00

Table I 4.1 Site 4 with PNW

	Unit	Total	Energy conversion	MJ	%
Fossil fuel					
Coal	kg	2.64	27.8	73.5	6.28
Natural gas	m3	7.57	38.4	291	24.8
Oil	kg	15.5	45.3	702	60.0
Fossil fuel - from Dummy process					
Petroleum				0.00	0.000
Tire derived fuel				0.0000	0.0000
Unspecified				0.081	0.0069
Non-fossil fuel					
Uranium	kg	2.45E-05	3.81E+05	9.35	0.80
Non-fossil fuel - from Dummy process					
Biomass					0.00
Wind				8.50	0.73
Geothermal				0.05	0.00
Hydropower				80.27	6.86
Solar					0.000
Photovoltaic					0.0000
Other fuels, unspecified				4.88	0.4170
Total				**1,169.7**	100.00

Table I 4.2 Site 4 with Biomass

	Unit	Total	Energy conversion	MJ	%
Fossil fuel					
Coal	kg	1.22	27.8	34.0	3.19
Natural gas	m3	7.08	38.4	272	25.5
Oil	kg	16.5	45.3	748	70.3
Fossil fuel - from Dummy process					
Petroleum				0.00	0.000
Tire derived fuel				0.0000	0.0000
Unspecified				0.000	0.0000
Non-fossil fuel					
Uranium	kg	2.64E-05	3.81E+05	10.1	0.94
Non-fossil fuel - from Dummy process					
Biomass				0.00	0.00
Wind				0.02	0.00
Geothermal				0.05	0.00
Hydropower				0.99	0.09
Solar				0.00	0.000
Photovoltaic				0.0023	0.0002
MSW				7.78E-05	
Total				**1,065.2**	100.00

Appendix J. Environmental impacts with alternative sources of electricity

Table J 1: LCIA of energy with original source of energy (WECC) per BDmT

Impact category	Unit	Site 1	Site 2	Site 3	Site 4
Ozone depletion	kg CFC-11 eq	1.18E-06	6.05E-07	4.40E-09	2.47E-08
Global warming	kg CO_2 eq	79.5	54.7	93.1	81.0
Smog	kg O_3 eq	17.1	18.3	37.0	3.69
Acidification	kg SO_2 eq	0.85	0.67	1.24	0.42
Eutrophication	kg N eq	0.092	0.061	0.070	0.011

Table J 2: LCIA of energy with alternative source of energy (PNW) per BDmT

Impact category	Unit	Site 1	Site 2	Site 3	Site 4
Ozone depletion	kg CFC-11 eq	1.18E-06	6.05E-07	4.32E-09	2.46E-08
Global warming	kg CO_2 eq	51.0	46.3	86.5	68.3
Smog	kg O_3 eq	15.8	17.9	36.7	3.09
Acidification	kg SO_2 eq	0.60	0.60	1.18	0.31
Eutrophication	kg N eq	0.089	0.060	0.069	0.009

Table J 3: LCIA of energy with alternative source of energy (Biomass) per BDmT

Impact category	Unit	Site 1	Site 2	Site 3	Site 4
Ozone depletion	kg CFC-11 eq	1.29E-06	6.36E-07	2.87E-08	7.11E-08
Global warming	kg CO_2 eq	48.9	45.6	86.0	67.4
Smog	kg O_3 eq	23.6	20.2	38.5	6.57
Acidification	kg SO_2 eq	0.77	0.65	1.22	0.38
Eutrophication	kg N eq	0.11	0.065	0.073	0.018