Life Cycle Sustainability Analysis Sub-project of the Woody Biomass Innovative Project:
A Preliminary Assessment

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British Columbia

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ABSTRACT

This preliminary study addresses the life cycle sustainability analysis sub-project of the Woody Biomass Innovative Project, which proposed to assess the future bioenergy potential for British Columbia from a broad perspective that includes energy, greenhouse gas considerations and climate change, impacts on soil and biodiversity, and socio-economic sensitivities and to consider the need for guidance and policy development. This preliminary study reviews currently available assessment methodologies and proposes a framework for a life cycle sustainability assessment of current and emerging wood-based biofuel products used in three sectors (i.e., residential, institutional, and industrial) in British Columbia. In addition, this study defines data requirements and data availability for a detailed assessment, and outlines the possible policy implications that might be drawn from a detailed study.

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LIST OF ABBREVIATIONS

CALCAS	Co-ordination Action for Innovation in Life-Cycle Analysis for Sustainability
Eco-LCA	Ecologically-based Life Cycle Assessment
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MOF	Ministry of Forests, Lands and Natural Resource Operations
PM	Particulate Matter
ToSIA	Tool for Sustainability Impact Assessment
TRACI	Tool for the Reduction and Assessment of Chemical and other environmental Impacts
US-EI	Americanized-ecoinvent database
U.S. EPA	United States Environmental Protection Agency

1 INTRODUCTION

1.1 Study Background

The Woody Biomass Innovative Project, a research collaboration between the British Columbia Ministry of Environment and the British Columbia Ministry of Forests, Lands and Natural Resource Operations, is assessing existing and future woody biomass potential for the province. The assessment is based on a complete supply chain analysis that starts with resource extraction from forests categorized under the timber harvesting land base and short-rotation intensive culture, through biomass transportation to and from processing, to final utilization (i.e., combustion for energy). The work is expected to support (1) competitiveness and innovation (i.e., expansion of new markets and products [bioenergy], mitigation of climate change, integration of forest and range research with socio-economic and new product research), (2) forest and range resource stewardship, and (3) Ministry field operations. Three components are being considered: biophysical resources, life cycle assessment (LCA), and overarching guidance and policy development.

The life cycle sustainability assessment component aims to evaluate the woody biomass potential for British Columbia in terms of energy, greenhouse gas and climate change, impacts on soil and biodiversity, and other environmental concerns plus socio-economic sensitivities of this emerging sector. FPInnovations was commissioned to develop a framework document that examines methods of assessing the environmental and socio-economic impacts of current and emerging wood-based biofuel products in British Columbia from a sustainability viewpoint. In addition, this study addresses data requirements and data availability for harvest-to-combustion impact assessment of wood-based biofuels, and provides potential policy implications that could be identified based on a detailed study and additional data required for policy purposes.

1.2 Overview of the Wood-based Biofuel Sector in British Columbia

In British Columbia, wood-based biofuel has been used as a heat energy source for the residential, institutional, and industrial sectors (Beauchemin and Tampier 2008). There is an abundance of wood residue in the province: logging residues, sawmill residues, and timber killed by the mountain pine beetle. These wood residues may provide an opportunity for an emerging sector.[1]

1.2.1 Current and emerging wood-based biofuel products and technologies Hog fuel, pellets, and firewood are the three common types of wood biofuel manufactured and used in the province. The residential sector uses firewood and pellets for heating, and the institutional and industrial sectors burn wood pellets and hog fuel in boilers. Cellulosic ethanol is another biofuel that has growth potential due to the federal regulation that requires mixing 5% of ethanol with gasoline on a volume basis (Environment Canada 2010a). While hog fuel and cellulosic ethanol can be manufactured from both forest logging residues and sawmill residues, the main feedstocks for the production of pellets are sawdust and wood shavings generated in sawmills (Samson et al. 1999). Biomass from short-rotation intensive culture could also be used for pellet manufacturing (Samson et al. 1999) or cellulosic ethanol production.

1 www.energyplan.gov.bc.ca/PDF/BC_Energy_Plan_Alternative_Energy.pdf

There are three main types of wood-fired boilers operating in British Columbia: grate burners, fluidized bed burners, and gasifiers (Beauchemin and Tampier 2008). Gasification technology is becoming more popular than the other boiler types in industrial and institutional applications in British Columbia due to its greater efficiency and lower emissions.[2,3,4] Syngas produced from gasification is used to produce other fuel types, such as biomethane (natural gas), methanol, and ethanol ((S&T)² Consultants Inc. 2005). In the residential sector, conventional wood appliance users are generally changing to more efficient appliances that create lower emissions (Xue and Wakelin 2006).

1.2.2 Issues with woody biofuels Wood-based biofuels may contribute to achieving climate, environmental, and economic goals. There are, however, environmental and socio-economic implications associated with woody biofuels, starting from resource extraction from forests, through fuel production and combustion in boilers, to final wood ash disposal. An overview of the impacts of each of these life cycle stages is provided below.

Resource extraction from forests Forest policy and practices in British Columbia forests seek to minimize negative impacts on biodiversity, soil erosion, and downstream sedimentation.[5] Forests in British Columbia are rich in biodiversity; harvesting of forests can have significant effects on biodiversity at the landscape, stand, and species level (Gayton 2007). Forest harvesting also affects hydrological functions due to effects on stream water quantity and quality, which affects stream ecosystems and fish habitats (MacIsaac 2003). First Nations, whose livelihoods are dependent on traditional resources, such as berries, root vegetables, and salmon, have been affected by declines in biodiversity and forest harvesting effects on valuable ecosystem functions (Turner 2007). Intensive removal of forest biomass also affects biodiversity due to the loss of dead wood, which provides habitat for saprophytic organisms (Berch et al. 2011).

Wood biofuel production and combustion Significant environmental impacts occur during combustion. For instance, human health effects occur due to inhalation of particulate and carcinogenic (dioxin and furan) emissions from wood burning (Environment and Human Health Inc. 2010). Particulate matter poses significant respiratory health risks and is a serious social concern in British Columbia (Beauchemin and Tampier 2008). Dioxin, a carcinogenic emission from the combustion of wood that has been exposed to salt water during transport, is commonly associated with wood fuel produced from British Columbia's coastal forests (Beauchemin and Tampier 2008). The possible creation of photochemical smog is another concern in some regional districts (Metro Vancouver 2005). These emissions from wood burning, however, can be reduced with the control technologies. Carbon emissions that occur during biofuel production and transport are small and result mostly from energy consumption during these processes (Mahalle 2011).

2 www.pulpandpapercanada.com/news/kruger-s-biomass-gasifier-fuels-customers-need-for-green/1000402062/
3 www.unbc.ca/green/energy.html
4 www.sustain.ubc.ca/story-package/ubc-project-generate-clean-energy-and-new-knowledge
5 www.for.gov.bc.ca/code/

In addition, there are economic considerations associated with the production and combustion of woody biofuels, including both the potential benefits from reduced net carbon emissions and the problems associated with human health effects of criteria air pollutant emissions (Sáez et al. 1997).

Ash disposal Wood ash contains elements that, depending on their concentrations, might be toxic to living organisms (Patterson 2001). They include trace metals and heavy metals that cause human health impacts (i.e., carcinogenic and toxic effects).

2 METHODOLOGY FOR THE ASSESSMENT

The production and combustion of woody biofuels have effects not only on the environment but also on the province's social and economic sectors. So, from the project team's viewpoint, the framework for this assessment should integrate social, environmental, and economic considerations at every stage of the life cycle of wood-based biofuels. This section reviews available methodologies and their applicability to this type of assessment and proposes a framework for evaluating the emerging sector.

2.1 Available Assessment Methodologies

The following are currently available assessment methodologies:

- ISO-framework for life cycle assessment (ISO-LCA)
- Co-ordination action for innovation in life-cycle analysis for sustainability (CALCAS)
- Tool for sustainability impact assessment (ToSIA)
- Ecologically-based life cycle assessment (Eco-LCA)

A brief description of each of these methodologies, the types of impacts they address, and their application limitations is given below.

2.1.1 ISO-LCA The International Organization for Standardization (ISO) provides a framework for life cycle assessment (LCA) in its ISO-14040 series, Environmental management – Life cycle assessment. As per the ISO, LCA is an analytical tool designed for comprehensive quantification and interpretation of the flows to and from the environment, including emissions to air, water, and land, and the consumption of energy and other material resources, over the entire life cycle of a product or process or service. LCA provides a comprehensive view of the environmental aspects of a product and a more accurate picture of the true environmental trade-offs in product selection throughout the product life cycle. An overview of ISO-LCA is provided in Appendix 1. The methodology consists of four iterative phases: goal and scope definition, inventory analysis, impact assessment, and interpretation.

The four-phase LCA methodology defined in the ISO-14040 series can be used to assess the environmental considerations of different wood-based biofuel product systems. LCA starts with defining the goal and scope of the study (Phase I, including system boundaries, Figure 1), which is followed by an inventory analysis (Phase II). In the inventory analysis, a flow model of inputs

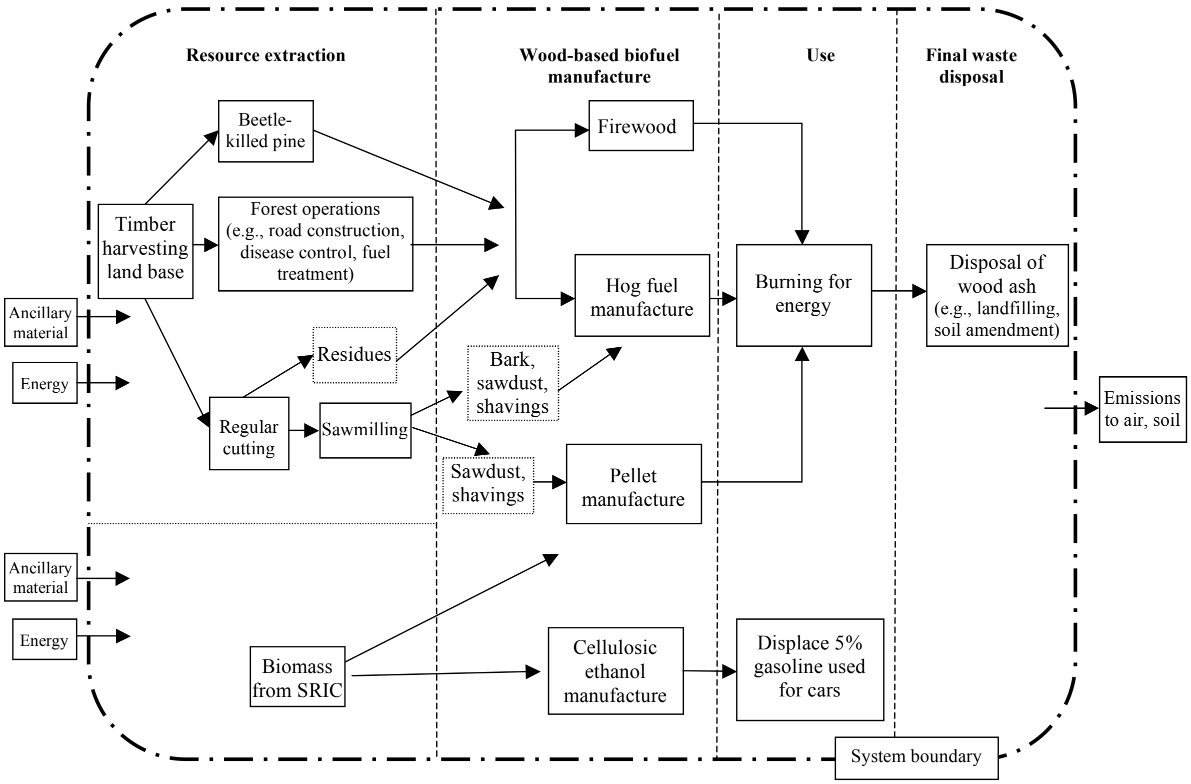

FIGURE 1 *System boundary for hog fuel product system (SRIC: short-rotation intensive culture).*

and environmental outputs is constructed to create a life cycle inventory. The inventory analysis is then followed by an impact assessment (Phase III), where characterization of the inventory data (i.e., sorting and assigning flow data to specific impact categories, such as acidification, eutrophication, global warming potential) is done in order to evaluate the significance of potential environmental impacts. Finally, the inventory analysis and impact assessment results are summarized in the interpretation phase (Phase IV) in order to provide conclusions and recommendations.

Applicability An overview the applicability of ISO-LCA to British Columbia is shown in Table 1. ISO-LCA has been designed for micro-level (i.e., product system) analysis only; the information generated from the product system analysis would need to be scaled up to be applicable at the provincial level. For example, LCA generates product-specific environmental impact information based on a functional unit—in this case, a unit amount of energy (one MJ or one GJ)—which has to be multiplied by the total amount of each biofuel type produced and used within British Columbia in order to determine the province-wide environmental burden from the sector.

ISO-LCA can be used for a comprehensive analysis of environmental impacts, but it does not account for social and economic implications of the product systems; this is the main limitation of using this methodology to evaluate British Columbia's wood-based biofuel sector. Additionally, although ISO-LCA explicitly mentions land use, it lacks a widely accepted impact assessment method to address land use impacts on biodiversity and life support

TABLE 1 *Required elements and status of ISO-LCA, CALCAS, ToSIA, and Eco-LCA*[a]

Assessment needs		ISO-LCA	CALCAS	ToSIA	Eco-LCA
Environment	Air, water, and soil impacts	Possible	Possible	Possible, but does not have representative data, and some indicators are missing	Focusses on ecosystem functions and lacks data for woody biofuels and comprehensive analysis of air quality and climate regulation
	Land use	No widely accepted method	Does not provide a method		
Economic element		Not possible	Suggests applying existing methods, such as cost-benefit analysis	Possible, but does not have representative data, and some indicators are missing	Possible, but does not have data for wood-based biofuels
Social element		Not possible	Suggests conducting social life cycle assessment	Possible, but does not have representative data, and some indicators are missing	Not possible
Software tool		Available	No available tool that incorporates all the listed methods	Available, but needs modifications	Available

[a] ISO-LCA: International Organization for Standardization-Life Cycle Assessment; CALCAS: Co-ordination Action for innovation in Life-Cycle Analysis for Sustainability; ToSIA: Tool for Sustainability Impact Assessment; Eco-LCA: Ecologically-based Life Cycle Assessment

functions. The three other methodologies—CALCAS, ToSIA, and Eco-LCA—have emerged to address the limitations of ISO-LCA.

2.1.2 CALCAS The framework proposed in CALCAS is a result of an ongoing effort to develop ISO-LCA into a broader scientific methodology by incorporating all components of sustainability. This methodology has strengthened the analysis by incorporating social, physical, economic, institutional, and political mechanisms into the assessment. It also has broadened the scope from product systems to sectors, markets, whole economies/countries, and the world (i.e., product-level, meso-level, and economy-wide techno-systems). In this framework, the inventory analysis and impact assessment phases defined in ISO-LCA have been combined to form one stage called "modelling." As a result, CALCAS consists of only three steps: goal and scope definition, modelling (inventory analysis and impact assessment), and interpretation.

The modelling stage is divided into three phases: semantic analysis (framing the question and decisions at stake), syntactic analysis (identifying available methods and models), and operational analysis (applying selected methods, and generating and verifying the numeric results).

CALCAS outlines methods that can be used in the syntactic analysis to evaluate technological, physical, and economic relations. A brief overview of these methods and their thematic coverage is provided below.

Technological relations:

- Life cycle costing—an analysis based on the costs of the whole life cycle of a product/service, including externalities
- Total cost accounting—a profitability analysis of business investment and operations
- Total cost ownership—an analysis of direct and indirect costs related to the purchase of a product
- Hybrid analysis—focusses on environmental impacts
- Life cycle activity analysis—an assessment of economic and environmental optimization of the supply chain
- Life cycle optimization—uses the LCA concept to identify specific, practical opportunities for reducing life cycle environmental burdens by taking into account environmental, technical, and economic aspects of a product
- Social life cycle assessment—accounts for social aspects throughout the product life cycle
- Carbon footprint—an analysis based on greenhouse gases
- Environmental risk assessment—an analysis of environmental and/or health and safety risks

Physical relations:

- Economy-wide material flow analysis—a mass balance that links flows of materials from natural resources to a national economy
- Substance flow analysis—an analytical method designed to quantify flow of materials or substances in a given product system
- Material input per unit of service—an analysis focussed on resource consumption of different solutions to produce the same service
- Energy/exergy analysis—a techno-economical assessment based on the first law of thermodynamics

Economic relations:

- Computable general equilibrium model—an economic model that uses actual economic data to estimate how an economy reacts to changes in policy, technology, or other external factors
- Input output analysis—an economic technique used to analyze interdependencies between different branches of national economy or among branches of different, even competing, economies
- Environmentally extended input-output analysis—an expansion of input-output analysis by incorporating the environmental dimension into analysis
- Partial equilibrium model—an economic model that can be used to analyze the effects of a policy action on a certain sector of an economy, ignoring its implications on the other sectors

Cost-benefit analysis has been added to the list (see page 39 of CALCAS 2006) for use at product-level, meso-level, and economy-wide analyses.

Applicability An overview the applicability of CALCAS to British Columbia is shown in Table 1. An assessment of British Columbia's woody biofuel sector would require a broad analysis of the environmental, economic, and social impacts at both the product and provincial level. The discussion provided in CALCAS on the inherent limitations of applying ISO-LCA to a broad sustainability assessment, incorporating the three components of sustainability at both product and provincial levels, would be quite useful in developing a suitable framework. However, merging the separate life cycle inventory (LCI) and life cycle impact assessment (LCIA) phases of the ISO-LCA approach into one modelling stage for CALCAS could confound the proposed British Columbia woody biomass assessment because both LCI and LCIA results would be required to make informed decisions. For instance, in ISO-LCA, a flow model of environmental inputs (materials and energy inputs) and outputs (pollutant emissions to air, water, and land) would be created and an inventory of these flows would be presented in the LCI phase. These LCI results are further calculated and then presented as impact indicator results of environmental impacts, such as climate change, human health effects, ozone depletion, and smog, in the LCIA phase. The proposed modelling phase in CALCAS does not separate LCI from LCIA, and its results may be less informative for decision-makers.

CALCAS does not provide a tool that can be used to easily incorporate the methods discussed under syntactic analysis; therefore, although the CALCAS methodology can be used, the work may be challenging because it would require complex calculations to be performed separately for each method and then those results to be combined for the purpose of discussion. In addition, the methods require a great deal of data, which are expensive and time consuming to gather. The methods other than carbon footprint, social LCA, and cost-benefit analysis may also not be relevant given the terms of reference for this project. Moreover, both ISO-LCA and CALCAS discuss land use impacts but neither provides a rigorous method to evaluate those impacts on biodiversity and life support functions. So for both methodologies, an alternative approach is needed to address this concern.

2.1.3 ToSIA ToSIA is a methodology developed by EFORWOOD, a project implemented by the European Union for sustainability analysis of the forest sector (EFORWOOD 2010). It has two databases: one for sustainability assessment, the other for policy analysis purposes. Both databases are of European origin; the policy database includes legislative and policy documents of the European Union. ToSIA can address the three components of sustainability (environmental, economic, and social) through an indicator framework. The criteria outlined for the application of indicators are relevance, technical feasibility, data availability, and cost of application. The tool uses multi-criteria analysis to compare indicators with different measuring units and has the possibility of weighting based on importance and ranking of the indicators. Cost-benefit analysis has been integrated into the tool and extended to monetize externalities in order to allow for comparisons of alternatives (EFORWOOD 2010). ToSIA uses a reference (i.e., benchmark or base case) for making comparisons and to address "what if" questions. Sensitivity analysis can be performed to evaluate uncertainties.

Applicability The tool has been successfully applied to four case studies, one of which is a woody biofuel study in which timber production, land expectation value, biodiversity, and other environmental services (such as water quality, water quantity, soil fertility, carbon sequestration, and carbon stock) have been quantified and tested to evaluate impacts of forest management alternatives (EFORWOOD 2010; Lindner et al. 2010). The indicators used, their relevance to British Columbia, and the missing indicators are shown in Table 2. ToSIA contains most of the indicators relevant to circumstances in British Columbia, but some key indicators, such as human carcinogenicity and respiratory potential, are missing from this tool. An overview of the applicability of ToSIA to B.C. is shown in Table 1.

ToSIA is an important milestone in terms of assessing the sustainability of forest products and the forest fibre supply chain; however, the following modifications would be needed in order for ToSIA to apply to the British Columbia Woody Biomass Innovative Project:

- Changes to indicators—the following indicators would need to be added:
  - Environmental—human health (respiratory and carcinogenesis), eutrophication, soil productivity
  - Social—social pressure to reduce emissions (e.g. particulates)
  - Economic—technological trends, utilization (combustion) efficiency
- Data collection protocols and databases:
  ToSIA data are of European origin, so it would be necessary to gather representative data from the industry operating in British Columbia.
  Pre-designed data collection protocols come with ToSIA, but they would need to be modified in order to add the new indicators. In addition, a separate policy database using British Columbia legislation would have to be developed.
- Changes to the ToSIA tool:
  The algorithms would need to be changed in order to accommodate new sustainability indicators.

TABLE 2 *Economic, social, and environmental indicators used for ToSIA,[a] and their relevance to British Columbia*

Economic		Social		Environmental	
EFORWOOD	**Relevance**	**EFORWOOD**	**Relevance**	**EFORWOOD**	**Relevance**
Investment		Education and training	Relevant	Forest biodiversity	Relevant
Gross value added		Innovation		Water and air pollution	Relevant
Total production	Relevant	Occupational safety and health		Generation of waste	Relevant
Trade balance		Consumer behaviour and attitude	Relevant	Forest damage	Relevant
Enterprise structure		Corporate social responsibility		Greenhouse gas emissions and carbon stock	Relevant
Labour productivity		Provision of public forest services		Forest resources	Relevant
Production costs	Relevant	Wages and salaries		Soil condition	Relevant
Missing	Externalities from emissions to air, water, and land	Missing	Social pressure to reduce emissions—e.g., particulates, dioxin/furan	Transport	
			Environmental concerns about logging		
				Water use	Relevant
				Missing	Human health—respiratory and carcinogenicity

a Tool for Sustainability Impact Assessment

Gathering industry data could be the most challenging of these tasks. Meaningful data collection might not be possible if manufacturers have not kept relevant records, and companies may be unwilling to provide their private information.

2.1.4 Eco-LCA Eco-LCA is another emerging alternative methodology that accounts for the role of ecosystem goods and services in economic activities.[6] Eco-LCA is not intended to replace conventional LCA but rather complement it by including methods for resource accounting and by considering the role of natural capital. It has an on-line tool and a database; however, the database is of U.S. origin. Data for Canada and British Columbia may be different. The database also does not have comprehensive data for certain ecosystem services, such as air quality regulation and climate regulation, and it does not have data for woody biofuels. An overview the applicability of this methodology to British Columbia is shown in Table 1.

Applicability This framework addresses only a part of sustainability, and its application to the proposed British Columbia assessment is constrained by its lack of local data and woody biofuels data. Much work would have to be done to fill these gaps.

2.2 Proposed Framework for Sustainability Analysis

In view of the application limitations of the alternative methodologies discussed above, the practical approach would likely be to use ISO-LCA to address the environmental component and to use other methodologies to assess the remaining components of sustainability as separate elements. So the framework is made up of LCA, land use impacts, and socio-economic elements with an overarching scope.

2.2.1 Scope In consideration of current and potential emerging uses, it is suggested that the scope include three wood-based biofuel systems (hog fuel, pellets, and cellulosic ethanol). According to the project proposal, the assessment would focus on the following woody biomass sources:

- biomass generated through rehabilitation of young pine stands severely affected by mountain pine beetle from the timber harvesting land base in the province
- biomass from short-rotation intensive culture
- biomass from forest operations (e.g., stumps removed for road construction and for treatment of Phellinus, Tomentosis, and Armillaria diseases, and fuel treatment for fire abatement)
- residues from logging in the timber harvesting land base
- sawmill residues (e.g., sawdust, planer shavings, bark)

2.2.2 Life cycle assessment elements

System boundary The flow diagram in Figure 2 shows cradle-to-grave life cycle stages of the three wood-based biofuel types in the proposed study scope. Feedstock biomass flows to each of the biofuel types were drawn

6 http://resilience.eng.ohio-state.edu/eco-lca/index.htm

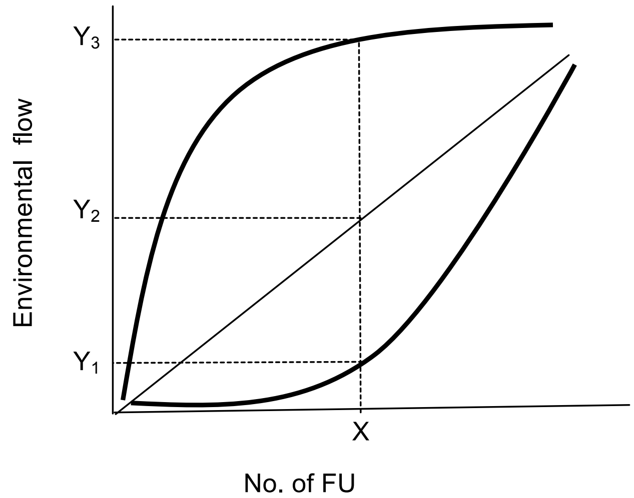

FIGURE 2 *Possible relationships between environmental flows and number of functional units (FU). Depending on the type of relationship between FU and land use impacts, different levels of environmental flows (Y_1, Y_2, and Y_3) can occur.*

according to current production and consumption and potentially emerging sources and trends described in Section 2.2.1. In order to get an accurate account of all of the environmental stresses associated with the three wood-based biofuels, other than energy and material inputs, it is suggested that ancillary materials, such as lubricating oil, hydraulic fluid, and grease, be included in the system boundary. Currently, pellets are manufactured for both local and export markets, but most of the pellets manufactured in British Columbia leave the province, which means that flows to the environment from pellet use occur outside of British Columbia and Canada. Depending on the intended use, the geographic boundary for the detailed study can either be set as the province of British Columbia or extended to other places where pellets are exported. For example, from a provincial policy perspective, the geographic boundary would be the province in order to capture all flows to and from the environment due to pellet production and consumption within the province, and to exclude the flow of pellets outside the province. However, from a global environmental perspective, the geographic boundary would be extended beyond the province in order to capture all the flows occurring inside and outside of British Columbia

Functional unit As defined in ISO 14040 series, a functional unit is the quantified performance of a product system for use as a reference unit. In LCA, all environmental inputs and outputs within the system boundary are normalized to a functional unit that best represents the function of the system to permit the comparison of product systems performing a similar function. In this case, with more than one biofuel product system involved, a functional unit can be defined as either one MJ or preferably GJ of energy content of the relevant biofuels that can be expressed in terms of their higher heating values. In normalizing flows to a functional unit, it is assumed that a linear relationship exists between the flows and the number of functional units, which is generally valid for flows to and from manufacturing processes. However, land use impacts on biodiversity and soil quality are generally non-linear and depend on the scale of land use, an issue that LCA practitioners face in incorporating impacts from land use in LCA (Canals et al. 2006).

A detailed study of woody biofuels in British Columbia would involve making projections for the future based on calculated "per functional unit" flows. Figure 2 depicts possible relationships between environmental flows and the number of functional units. If a linear relationship is assumed and projections into the future are made based on the functional unit for an environmental flow that is actually non-linear, either $Y_2–Y_3$ may be overestimated or $Y_2–Y_1$ may be underestimated. This is an issue that needs to be properly addressed when attributing land use impacts to a functional unit.

Human activity and capital infrastructure Human activity involved in resource extraction from forests and biofuel manufacture and combustion has effects on the environment. However, the data collection required to properly quantify human activity is particularly complicated, and allocating such flows to resource extraction and biofuel manufacture and use, as opposed to other societal activities, is not feasible for a study of this nature. For these reasons, it is suggested that human activity be excluded from the system boundary.

The environmental effects of manufacturing and installing capital equipment and buildings have generally been shown to be minor relative to the throughput of materials and components over the useful lives of the buildings and equipment, but province-wide estimates of these environmental effects could indicate that they are significant. The procedure described below should be applied when dealing with capital infrastructure.

Exclusion of insignificant flows The following cut-off criteria would be useful for excluding all insignificant input and environmental output flows within the two system boundaries:

- Mass—if a flow is less than 1% of the cumulative mass of the model flows, it may be excluded, providing its environmental relevance is minor.
- Energy—if a flow is less than 1% of the cumulative energy of the system model, it may be excluded, providing its environmental relevance is minor.
- Environmental relevance—if a flow meets the above two criteria but is determined (via secondary data analysis) to contribute 2% or more to a product life cycle impact category, it should be included within the system boundary.

Data quality requirements Data requirements can be met either by gathering first-hand data or using existing LCI and/or non-LCI data. If first-hand data are gathered, it is recommended that they be validated through mass and/or energy balances. Suggested data quality criteria for secondary (i.e., existing) data for a study of this nature are as follows:

- Age of data: less than 10 years old for technologies
- Geographic coverage: province of British Colombia
- Technology coverage: average technologies operating in British Columbia
- Data completeness: percentage of total data that is measured or estimated (see exclusion of insignificant LCIA flows for limits)

- Representativeness: secondary data used to fill data gaps should be representative of the situation in British Columbia and should meet the age and technology criteria

Secondary data should already be critically reviewed for precision, consistency, and reproducibility in order to limit uncertainty.

Treatment of missing data Missing data should be clearly identified, and the treatment of missing data should be clearly documented. For example, first-hand data for hog fuel manufacturing in the province is not available. Secondary data can be used to fill this data gap as long as they represent the technologies actually used in British Columbia. Technologies that use electricity as the energy source do not represent the situation in British Columbia if diesel is the energy source used in the manufacture of hog fuel. These estimates should meet the data quality criteria stated above.

Allocation procedure Two of the three wood-based biofuel types, namely hog fuel and pellets, considered for the proposed woody biofuel assessment use wood fibre from multiple wood products systems. For instance, lumber manufacturing is a multi-product system in that mill residues generated during manufacturing (e.g., bark, sawdust, and planer shavings) are considered to be co-products since the mills generate substantial revenue from these residues. Logging residue, although currently considered to be a waste due to the lack of a market, could become a co-product in the future due to its emerging use as a fibre source for bioenergy. In both cases, there is a need to show how the initial environmental burden of the wood fibre sources should be allocated to the co-products used for hog fuel and pellet manufacture in modelling the cradle-to-grave environmental impacts.

At the same time, wood fibre sources from multi-product systems undergo changes in their inherent properties (e.g., particle size, bulk density) during the hog fuel manufacturing process; hence, it is suggested that the environmental burden of wood wastes created during lumber manufacturing be allocated according to the principles stated in Section 4.3.4 of ISO 14040/44: 2006, taking into account the physical relationships of the products and co-products and their economic values.

Impact categories and indicators ISO 14044 does not specify a methodology or support the underlying value choices used to group the impact categories and indicators. Because the LCA study is intended for use in public policy formulation, the impact categories for the study should be selected based on the common concerns regarding the use of wood-based biofuel and the breadth of life cycle resource and materials inputs and releases to air, water, and land. ISO 14044 states that the indicators for an impact category can be chosen anywhere along the impact pathway. There are two types of indicators for impact assessment: midpoint and endpoint (Figure 3). Midpoint indicators lie between the pollution source and receptor in the cause-and-effect chain of an impact category (prior to the endpoints) and can be used to show the relative importance of emissions or resource extraction. Commonly used midpoint indicators include global warming potential, ozone depletion potential, and photochemical ozone (smog) formation potential. Endpoint indicators include human health impacts, such as disability adjusted life years

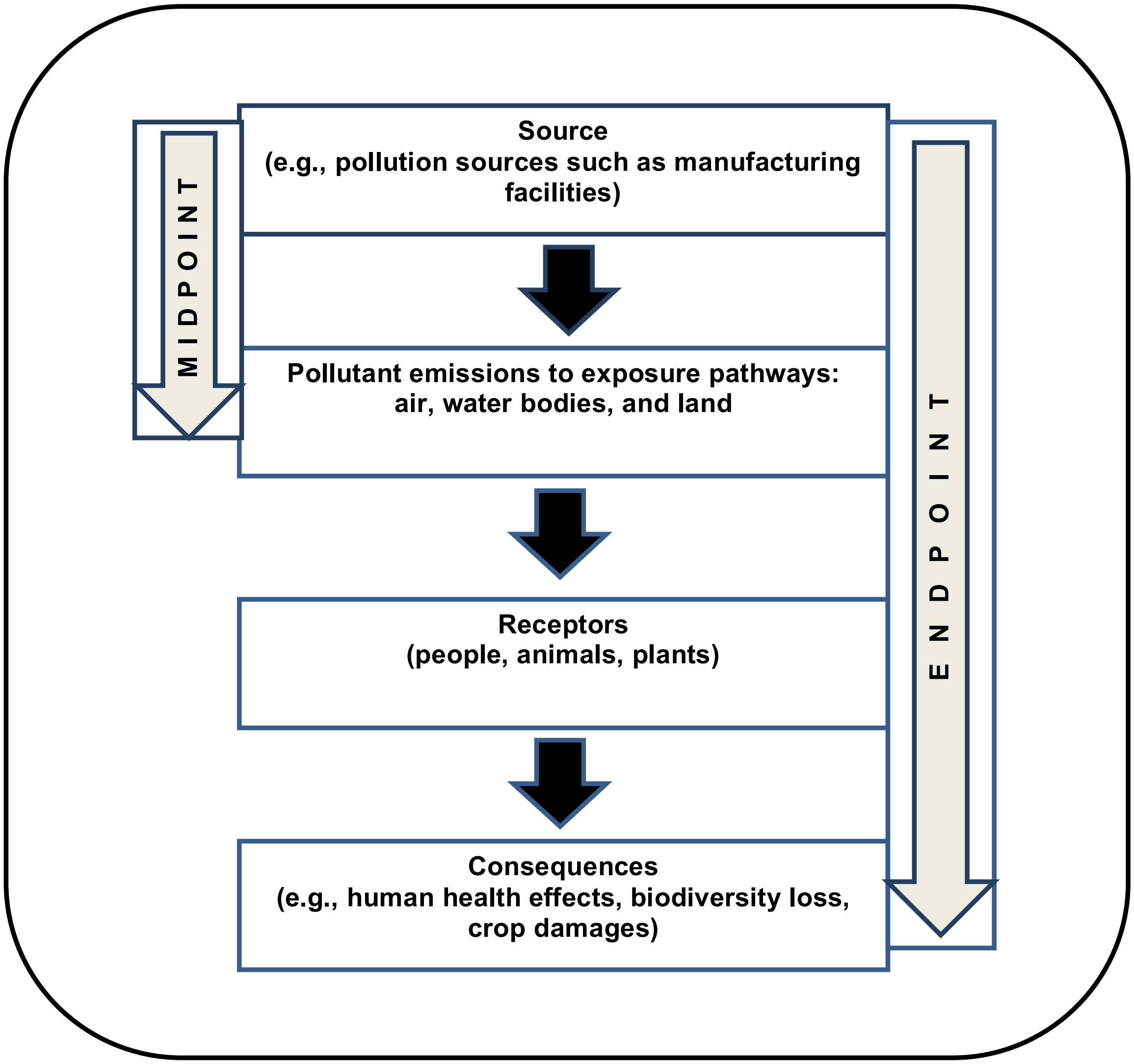

FIGURE 3 *Source-pathway-receptor-consequence conceptual model and indicators.*

for carcinogenicity, respiratory effects, climate change, ozone depletion, photochemical ozone creation, or impacts from changes in biodiversity. From a policy perspective, endpoint indicator results would be more informative to decision-makers than would midpoint indicator results, but they could be misleading because very low accuracy results from the significantly higher uncertainty associated with endpoint indicators (Bare et al. 2000, p.320).

Impact assessment methods Because of its applicability to North American circumstances, the U.S. Environmental Protection Agency's (EPA's) Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) LCIA method (Bare 2003) is the recommend tool for characterizing the LCI flows of the three biofuel types in British Columbia. Table 3 summarizes the impact categories supported by TRACI. The method addresses fossil fuel depletion (on a global scale), but it does not report primary energy consumption as an impact category. In order to avoid this weakness,

TABLE 3 *TRACI[a] impact categories*

Impact category	Natural environment	Human health
Global warming	♦	
Acidification	♦	♦
Ozone depletion	♦	♦
Eutrophication	♦	♦
Smog formation	♦	♦
Ecotoxicity	♦	
Human particulate		♦
Human carcinogens		♦
Fossil fuel depletion		

a Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts.
Note: See Appendix 2 for definitions of the indicator categories.

TRACI can be combined with cumulative energy demand (Frischknecht and Jungbluth, 2003), a European LCIA method that reports primary energy consumption by sources, including fossil fuel, bioenergy, nuclear, hydro, wind, and solar.

The use of the environmental impact assessment categories for the sustainability assessment (Table 3) and the major emissions assigned to each of the indicators (Table 4) is recommended for this project in British Columbia. The method can be modified by adding carbon dioxide from air as a negative emission, which would enable an accurate accounting of actual (net) carbon emissions from combustion while taking into consideration carbon dioxide sequestered in biomass during tree growth.

TRACI addresses all environmental emissions, but land use–associated concerns, such as impacts on biodiversity, and soil erosion, are not resolved with this methodology. TRACI addresses land use impacts on biodiversity in terms of threatened and endangered species living in a specific area (Bare 2003), but it does not provide characterization factors for a rigorous assessment of biodiversity impacts from land use.

Three other optional steps may be undertaken as a part of the LCIA:

- Normalization—calculation of the magnitude of the category indicator results relative to some reference value (e.g., global warming potential of biofuel relative to the total per capita global warming potential of British Columbia in a single year)
- Grouping (by spatial effect)—assignment of impact categories according to geographic effect (e.g., global, regional, or local)
- Weighting—conversion and aggregation of individual indicator results across entire impact indicator categories to arrive at a single score (e.g., combining global warming and eutrophication impacts)

Weighting is not recommended because it is based on value choices that are not scientifically based, as reported in ISO 14044: 2006. For instance, dif-

TABLE 4 *Summary of the life cycle impact assessment indicator categories recommended for the life cycle assessment element of a British Columbia woody biofuels sustainability assessment*

Indicator category[a]	Major environmental emissions/energy sources[a]	Unit equivalent basis[b]
Global warming potential	Carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4)	kg CO_2 equivalent
Acidification potential	Sulphur oxides (SO_x), nitrogen oxides (NO_x), ammonia (NH_3), hydrogen chloride (HCl), hydrogen sulphide (H_2S)	mol H^+ equivalent
Ozone depletion potential	Ozone-depleting substances (e.g., chlorofluorocarbons [CFCs])	kg CFC-11 equivalent
Eutrophication potential	Phosphate (PO_4), nitrogen oxides (NO_x), nitrogen dioxide (NO_2), nitrates, ammonia (NH_3)	kg N equivalent
Smog formation potential	Non-methane volatile organic compounds	kg NO_x equivalent
Ecotoxicity potential	Chemicals that cause ecological toxicity (e.g., agrochemicals, such as 2,4-D)	kg 2,4-D equivalent
Human particulate potential (respiratory effects)	Particulate matter (PM_{10} and $PM_{2.5}$), nitrogen oxides (NO_x), sulphur dioxide (SO_2), total suspended particulates (TSP)	kg $PM_{2.5}$ equivalent
Human carcinogenic potential	Carcinogenic chemicals and metals (e.g., benzene, butadiene, dioxin, formaldehyde, and carcinogenic poly aromatic hydrocarbons [PAHs], arsenic, chromium)	kg benzene equivalent
Human non-cancer effects	Non-carcinogenic chemicals and metals (e.g., toluene, fluoranthene, copper, cobalt, lead)	kg toluene equivalent
Non-renewable fossil fuel use	All fossil energy sources (e.g., natural gas, coal, diesel, gasoline)	MJ equivalent

Sources:
a Bare 2003
b Goedkoop et al. 2008

ferent individuals, organizations, and societies have different preferences, and different parties can reach different weighting results based on the same indicator results or normalized indicator results. Some European LCIA methods (such as Ecoindicator, CML 2001, Ecological Scarcity, EPID 2003, ReCiPe Endpoint) incorporate factors for weighting and normalization, but these methods use different factors; consequently, they produce different normalization and weighting results.

Uncertainties It is highly recommended that quality assurance and quality control be performed wherever applicable during data gathering and model development in order to limit uncertainties. Validity of the assumptions made should be checked through sensitivity analysis, and wherever first-hand data are gathered, those data should be validated through mass/carbon balances.

2.2.3 Land use impacts element Land use impacts are either location or region specific (Oyewole 2010). Currently, there is no widely accepted methodology at the international level for land use assessment (Canals et al. 2007a). While some European LCIA methods have already included characterization factors for biodiversity evaluation, efforts to develop a widely accepted methodology are ongoing.

There are two categories of LCIA methods for land use assessment: direct assessment and indirect assessment.

Key elements in land use assessment Canals et al. (2007a) discussed key elements that should be included in land use assessment. They stated that land use impact assessment should cover the ecological functions of land, referred to as land quality. The three important ecological functions identified were intrinsic value of biodiversity, biotic production (i.e., soil fertility and use value of species), and regulatory functions, such as water and climate regulation, and carbon and nutrients cycling. The authors provided additional insight into the processes that can be included in the assessment. The two processes related to land use are land occupation and land transformation. Land occupation refers to use of a land area for a human-controlled purpose (measured in surface-time units [e.g., ha/yr]), whereas land transformation involves changing to a new type of occupation (measured in surface units [e.g., acres, hectares]). Moreover, the authors suggested that it is important to address all three dimensions affected by land use, namely area of land, time (i.e., duration of land occupation and transformation processes), and quality (i.e., quantitative description of the occupation and transformation processes), and to provide a suitable reference situation (i.e., a default land use defined as "no use" of the same piece of land or alternative land uses, depending on the goal and scope of the study).

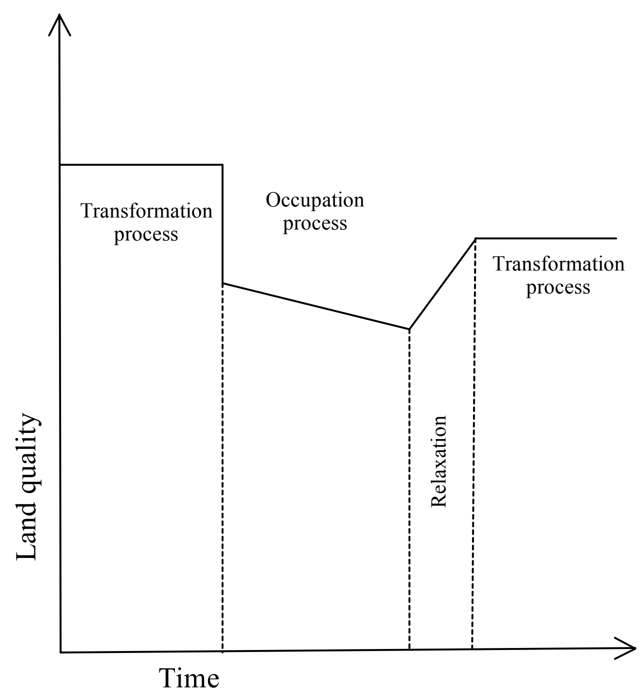

FIGURE 4 *Change in land quality before, during, and after a human activity (adapted from Weidema and Lindeijer 2001).*

The biomass pathways shown in Figure 1 include natural forests, forest plantations, and short-rotation intensive culture. Figure 4 depicts a possible evolution of land quality over time resulting from the logging of natural forests, including regular cutting and biomass extraction from mountain pine beetle–infected forests. Once logging has been completed, natural forces may restore the logged areas to their original state during the relaxation period, but the original land quality may not be achieved. The case for natural forests is different from that for biomass derived from short-rotation intensive culture because changes in land quality would depend on the original state of the land. For instance, agricultural crops have a very short lifespan and they are managed more intensively than short-rotation intensive culture because they require frequent land preparation and fertilizer and agrochemical (pesticide and herbicide) application (Lengal 2001). As a result, improvement in land quality can be expected when agricultural lands are converted to short-rotation intensive culture. Conversely, land in existing forests may follow the same evolution pattern presented in Figure 4 because some quality deterioration could occur with the conversion to short-rotation intensive culture.

Direct land use assessment methods Direct assessment methods are based on organismic dimensions of ecosystems, such as species, populations, communities, and ecosystems. The most commonly used indicator is species richness of vascular plants. Eco-indicator, a widely used European LCIA method, uses characterization factors to evaluate land use impacts on species diversity, notably the species-pool effect potentials method developed by Kollner (2000), which is based on vascular plant diversity. Kollner (2000) developed a scale using field observations to assess land use impacts on species diversity, which takes into account both regional and local effects. The damage that results from either land conversion or occupation is expressed as the potentially disappeared fraction of species·m^2·yr/m^2 (Goedkoop et al. 2008).

An issue with the existing LCIA methods is the absence of characterization factors for life support functions. Also, there is criticism over using only vascular plant as an indicator. Michelsen (2008) and Lawton et al. (1998) found that the change in species richness of one group can predict only 10–11% of the variation in species richness of another group.

Species abundance (Chapin et al. 2000) and evenness (Hengeveld and Duffield 1995) are also important in assessing land use. As Michelsen (2008) noted, it is very difficult to address biodiversity as defined by the United Nations Environmental Programme.[7] Many authors now use indirect indicators and conditions (i.e., environmental factors that affect species survival) that are important for maintaining biodiversity.

Indirect land use assessment methods Indirect assessment methods focus on ecosystem structures, functions, and processes to assess land use impacts (Oyewole 2010). Two recent indirect assessment methods have been developed: one by Michelsen (2008) for biodiversity assessment, which is

7 The 1992 United Nations Earth Summit in Rio de Janeiro defined biodiversity as "the variability among living organisms from all sources, including, 'inter alia', terrestrial, marine, and other aquatic ecosystems, and the ecological complexes of which they are part: this includes diversity within species, between species and of ecosystems."

illustrated by forest operations in Norway; the other by Canals et al. (2007a), which focuses on life support functions.

Michelsen's (2008) indirect land use impact assessment method for biodiversity follows the key elements suggested by Canals et al. (2007a and 2007b); the three dimensions taken into account are a measure of quality, area affected, and duration of the impact. The indicators are based on the 17 key structural factors introduced by Larsson (2001) for assessing biodiversity in European forests (Table 5).

This framework uses three indicators to assess quality: ecosystem scarcity, ecosystem vulnerability, and conditions that would maintain biodiversity (e.g., structural indicators, including dead wood). The land quality measure is a product of the three indicators. The method suggests assessing spatial and temporal impact duration of the intervention together with quality difference. The indicator results are normalized and attributed to a functional unit.

The indirect land use impact assessment method for life support functions uses soil organic matter as a single indirect indicator. Canals et al. (2007b) provided a summary of the roles of soil organic matter in life support functions, which was compiled from various sources (Table 6). As an indicator, soil organic matter is capable of addressing a wide range of life support functions; however, it does not represent some impacts on life support functions

TABLE 5 *Key factors for assessing biodiversity in European forests according to Larsson (2001)*

Scale	Structural key factors	Compositional key factors	Functional key factors
National/regional	Total area of forest with respect to: legal status/utilization/protection forest ownership tree species and ageold growth/forest left for free development afforestation/deforestation	Native species	For all scales
		Non-native or not "site original" species	
		Species with specific landscape-scale requirements	Natural disturbance: – Fire – Wind and snow – Biological disturbance
Landscape	Number and type of habitats (including water courses)	Non-native or not "site original" tree species	
	Continuity and connectivity of important habitats		Human disturbance
	Fragmentation		Forestry
	History of landscape use		Agriculture and grazing
Stand	Tree species	Species with specific stand type and scale requirements	Other land use
	Stand size	Biological soil conditions	Pollution
	Stand edge/shape		
	Forest history		
	Habitat type(s)		
	Tree stand structural complexity		
	Dead wood		
	Litter		

TABLE 6 *Role of soil organic matter in life support functions*

Land function	Role of soil organic matter
Biotic production (soil fertility)	Physical fertility: soil structure that allows for root penetration, and contributes to erosion resistance and land stability; reduction of susceptibility to compaction; soil aeration
	Chemical fertility: nutrient pool; nutrient protection (cation exchange capacity to hold nutrients and prevent leaching; pH control; plant growth regulation
	Biological fertility: enhancing soil biota (food source); nutrient cycling (degradation capacity and nutrient availability); microbial activity
Chemical regulation	Global climate: carbon cycle
	Local climate: link to vegetation cover; reduction of the albedo of exposed soil
Maintenance of substance cycles	Freshwater circuit: water-holding capacity; cation exchange capacity for its filter function; water conductivity; water infiltration
	Carbon and nutrient cycling: carbon pool
	Immission[a] protection: cation exchange capacity and degradation capacity

a Environmental concentration of a pollutant

such as erosion, compaction, toxic substance build up, acidification, and salinization. The method involves estimating total impacts (i.e., impacts during occupation and relaxation) based on a reference point and calculating the significance with respect to the potential soil organic matter of the soil studied.

Applicability Combining the land use impact categories available in the eco-indicator method with TRACI could be an option for addressing the land use issue. However, those characterization factors may not represent conditions in British Columbia's forests, so a careful review of their applicability to British Columbia is recommended. Given the issues with the direct assessment method and the amount of work needed to evaluate European-based characterization factors, it might be fruitful to adopt Michelsen's (2008) framework for addressing land use impacts of the emerging woody biofuel sector. To do so, it would be necessary to identify the key structural factors relevant to the province's forests and locate or collect data to address them. From a policy perspective, however, Michelsen's (2008) framework produces little important information on land use effects on threatened and endangered species, species richness, and species abundance. One way to address this issue could be to supplement that framework with relevant data from British Columbia.

2.2.4 Socio-economic element The production and consumption of wood-based biofuels also have social and economic considerations. Economic considerations include externalities and contributions to economic goals, such as employment gains. An extended cost-benefit analysis can be performed to determine if there is any social gain from the emerging sector.

Monetization can be used to quantify and integrate externalities into planning. There are two ways to quantify externalities: control costs and damage costs. Damage costs are estimates of the actual damage caused by emissions, but they are difficult to estimate. Control costs—that is, additional costs of equipment to control emissions to some specified level—are often used as a proxy for the actual damage caused by emissions (Swezey et al. 1994). In addition, emission fees can be used as a proxy to monetize externalities. Similarly, it is possible to monetize carbon benefits using a market price of carbon (National Academy of Sciences 2005).

The guidelines stated in the United Nations Environmental Program/Society of Environmental Toxicology and Chemistry (UNEP/SETAC) document for social LCAs (UNEP 2009) can be used to address social issues. These guidelines have been developed in line with the ISO guidelines for LCA, so both environmental and social indicators can be analyzed based on the same principles. The UNEP/SETAC guideline document provides a list of stakeholder categories and indicators for each category that need to be addressed in a social LCA (Table 7).

Blom and Solmar (2009) conducted an exploratory study on how to apply UNEP/SETAC guidelines to biofuels. The three biofuels assessed were ethanol, biogas, and biodiesel. The authors conducted a detailed analysis using the stakeholders and indicators listed in Table 7, and suggested that avoiding practitioner subjectivity by developing a universal set of indicators and well-functioning characterization models is necessary for its future implementation of the guidelines. This study provides valuable information on quantifying and attributing social impacts to a functional unit, and would be particularly useful in conducting a social assessment.

Applicability From an environmental policy perspective, it would be possible to limit the economic analysis to externalities in order to identify policy implications for government intervention that could be used to correct potential market failures caused by pollutant emissions.

Some regional districts in British Columbia, such as Metro Vancouver, charge emission fees for criteria air pollutant emissions. These fees can be

TABLE 7 *Stakeholders and category indicators for social life cycle assessments*

Stakeholder categories	Category indicators
Workers/employees	Freedom of association and collective bargaining, child labour, fair salary, working hours, forced labour, equal opportunities/discrimination, health and safety, social benefits/social security
Consumers	Health and safety, feedback mechanism, consumer privacy, transparency, end-of-life responsibility
Local community	Access to material resources, access to immaterial resources, delocalization and migration, cultural heritage, safe and healthy living conditions, respect of indigenous rights, community engagement, local employment, secure living conditions
Society	Public commitments to sustainability issues, contribution to economic development, prevention and mitigation of armed conflicts, technology development, corruption
Value chain actors	Fair competition, promotion of social responsibility, supplier relationships, respect of intellectual property rights

Source: UNEP (2009)

used to monetize the externalities of wood fuel combustion in boilers for the purpose of energy production. Although the current carbon market in British Columbia is not perfectly competitive, the price offered by the Pacific Carbon Trust to buy carbon credits can be considered as a proxy in monetizing carbon offset benefits.

The human health impact associated with particulate emissions from wood combustion is a sensitive health and safety issue, especially in large urban areas; particular attention should be paid to this issue when performing a social LCA.

2.2.5 Carbon neutrality of wood-based biofuels Carbon neutrality of wood-based biofuels is a controversial issue. Forests are considered to be carbon stores, and scientists argue that harvesting forests removes carbon from the carbon pool, which could contribute to climate change. Johnson (2008) stated that in order to rectify this issue, a carbon stock change line could be added in carbon emissions calculations for biofuels rather than applying carbon sequestration credits and combustion debits. Lippke et al. (2010) noted that both carbon emissions and carbon stores are important, and that the issue needs to be viewed from a broad perspective because any omissions of wood product carbon pools (displaced carbon emissions that results from substituting wood energy for fossil fuels and forest carbon changes in sustainably managed forests) could produce incorrect conclusions. Further, they argued that as far as sustainably managed forests are concerned, all carbon releases from decaying forest harvesting residues and carbon stored in logs taken to mills for processing can be offset by forest carbon uptake during regrowth.

Applicability In light of all these controversies, the use of a detailed carbon analysis is recommended for all woody biomass pathways, which will provide answers to questions that may be raised by interested parties. The analysis should include a scenario on displaced carbon emissions from substituting wood energy for fossil fuels, forest carbon response (including soil carbon) to standing tree harvest, and carbon stored in wood products over time (International Panel on Climate Change [IPCC] uses 100 years). Emissions from processing and transporting wood-based biofuels may be significant, as described by the IPCC[8]; hence, it is recommended that these factors also be included in the analysis. In addition, the uncertainties associated with forest carbon pools, such as forest fires, should also be included in the analysis because they could influence the final carbon results.

3 DATA AVAILABILITY AND GAPS

This section identifies required data and available data sources for inputs and environmental outputs of the three cradle-to-grave biofuel product systems. This section also identifies existing data gaps and ways to fill them. In addition, an overview of the background LCI data sources required to model material and energy inputs and ancillary materials consumed during the life cycle of the biofuel products is provided.

8 www.ipcc-nggip.iges.or.jp/faq/FAQ.pdf

3.1 Data Requirements for the Life Cycle Assessment Element

3.1.1 Process inputs and emissions data by life cycle stages Data requirements by life cycle stage for the three woody-based biofuel types are shown in Table 8. In addition to these data requirements, it is necessary to determine the average transportation distances between life cycle stages to complete the cradle-to-grave LCIAs for the three biofuel types. Both resource harvesting and biofuel manufacture consume energy and ancillary materials, and the proposed study requires both energy and ancillary material consumption data per unit of output produced at each of the stages; that is, per cubic metre of harvested roundwood and tonnes (litres, in the case of ethanol) of manufactured biofuel. Material inputs such as fertilizer and agrochemicals (pesticides and herbicides) may be applied in both forestry and short-rotation intensive culture; a detailed analysis requires this information in order to model ecotoxicity and other environmental impacts of agrochemical use.

3.1.2 Combustion emissions data Wood combustion emissions vary with the types of appliances and technologies used to burn wood (Beauchemin and Tampier 2008). Conventional stoves, advanced stoves, fireplaces, and furnaces are used in the residential sector to generate energy (Xue and Wakelin 2006), whereas boilers are used in the industrial and institutional sectors. The proposed sustainability assessment requires information on all energy

TABLE 8 *Data requirements by life cycle stage*

Life cycle stage			
Resource extraction from forests	**Processing—firewood, hogfuel, pellet, ethanol**	**Combustion**	**Disposal of wood ash**
Energy (e.g., diesel, gasoline)	Energy (e.g., electricity, diesel, gasoline)	Process inputs (e.g., wood biofuel quantities, energy by source [e.g., electricity, diesel/natural gas])	Ash composition (e.g., carbon trace metals, content, other inorganics for the three boiler types)
Material inputs (e.g., fertilizer, agrochemicals)	Ancillary materials(e.g., lubricating oil, grease, hydraulic fluid)	Environmental emissions (e.g., emissions to air and soil through wood ash)	Means of disposal (i.e., landfilling/soil amendment)
Ancillary materials (e.g., lubricating oil, grease, hydraulic fluid)	Waste		Distance to disposal site
Forest carbon responses to standing tree harvest			
Carbon composition of source wood species			
Density and higher heating values of source wood species			

inputs to, and environmental emissions from, combustion for all residential appliances and the three boiler types operating in British Columbia. A summary of the data requirements for different types of emissions to air is provided below. The list of pollutants of concern prepared by Beauchemin and Tampier (2008) based on the risk assessment conducted by Washington State in 2005 for more than 90 chemicals, and the emissions data required for the TRACI method were considered in preparing the following two lists.

Data requirements for combustion emissions:

Emissions to air

- Greenhouse gases
  - Carbon dioxide
    - Biogenic
    - Fossil
  - Methane
    - Biogenic
    - Fossil
  - Nitrous oxide
    - Biogenic
    - Fossil
- Carbon monoxide
  - Biogenic
  - Fossil
- Nitrogen oxides (NO_2 equivalent)
- Sulphur dioxide (SO_2)
- Total particulate matter (PM)
  - Particulate matter (PM < 2.5)
  - Particulate matter (PM < 10)
  - Particulate matter (PM > 10)
- Volatile organic compounds
- Carcinogenic air emissions
- Dioxin/furan
- Benzene
- Formaldehyde
- Poly aromatic hydrocarbons (PAHs)
  - Benzo(a)anthracene
  - Benzo(a)pyrene
  - Benzo(b)fluoranthene
  - Benzo(k)fluoranthene
  - Dibenzo(a,h)anthracene
  - Indeno(1,2,3-c,d)pyrene
- Metals (carcinogenic)
  - Arsenic
  - Cadmium
  - Chromium
  - Chromium VI
  - Lead
  - Nickel
- Solid waste
- Ash

Required data for combustion particulate matter analysis:

Beryllium	Manganese
Cadmium and compounds	Molybdenum
Chromium	Nickel
Chromium, hexavalent metal and compounds	Phosphorus
Cobalt	Selenium
Copper	Silver
Iron	Thallium
Lead	Zinc
Magnesium	Arsenic
	Mercury

Source: Beauchemin and Tampier (2008)

3.1.3 Ash elemental analysis data Combustion produces ash that requires disposal. Ash analysis data for trace and heavy metals, inorganics, and organics, including dioxin/furan, are needed to calculate the environmental impacts from wood combustion ash disposal. The associated data requirements are shown.

Required ash analysis data:

Poly aromatic hydrocarbons (PAHS)
Dioxin/furan
Trace metals
Antimony
Arsenic
Barium
Beryllium
Boron
Cadmium
Chromium
Chromium VI
Cobalt
Copper
Iron
Lead
Mercury
Nickel
Selenium
Silver
Thalium
Uranium
Vanadium
Zinc
Zirconium
Other—inorganics and carbon
Sulfate
Carbonate
Sulphur
Chloride
Carbon

3.2 Additional Data Requirements for Policy Purposes

The proposed sustainability assessment is expected to generate adequate data to support province-wide estimates of changes in greenhouse gas emissions, increases in other pollutants and waste (ash), and economic benefits/disbenefits from the emerging wood-based biofuel sector. LCA results are based on a functional unit (e.g., 1 MJ or 1 GJ) of products (i.e., the three biofuel types) only; hence, the following information is required in order to develop these province-wide estimates:

- province-wide estimates of CO_2 and other environmental emissions
  - current amounts of woody biomass production and consumption data by species, sources, fuel, and boiler types
  - projected future woody biomass production and consumption data by species, sources, fuel, and boiler types
- estimates of economic benefits/disbenefits
  - carbon credit prices in British Columbia (e.g., Pacific Carbon Trust's prices)
  - externalities of other criteria pollutants; charges levied by regional districts such as Metro Vancouver for criteria pollutant emissions

3.3 Available Data and Data Gaps for the Life Cycle Assessment Element

Gathering first-hand data for this type of a study is very expensive and time consuming; hence, it is important to examine existing LCI and non-LCI data sources for the three wood-based biofuel systems to fulfill the data requirements. The usual practice in LCA is to use representative data that are applicable to the geographic region under consideration. If there are no representative data, the next option is to adapt data from other regions. The basic assumption is that the processes are generally similar but the data need to be adapted for the geographic region by modifying electricity grids, fuels, transportation modes, and distances so that that they reflect the situation under consideration. Given the data quality criteria set for the proposed study, the most relevant data sources were used to fill existing data gaps. The British Columbia Ministry of Environment's Industrial Air Emissions Section was contacted to determine whether the Ministry had wood combustion emissions data for the three main boiler types operating in British Columbia. The Ministry has data on particulates, nitrogen oxides, and carbon monoxide emissions, but the other data mentioned in lists found on pages 24 and 25 are missing (T. Wakelin, B.C. Ministry of Environment, pers. comm., Aug. 8, 2011). The existing data sources for each life cycle stage are presented below.

3.3.1 Resource extraction Table 9 presents an overview of data sources for resource extraction related to the three biofuel product systems. The softwood lumber report *A Cradle-to-Gate Life Cycle Assessment of Canadian Softwood Lumber* (Athena 2009) provides the most recent representative and comprehensive data for British Columbia and other provinces. The report is based on first-hand data gathered from the companies involved in softwood harvesting and lumber manufacturing, and it provides the necessary LCI data for harvesting and sawmill residues used to manufacture hog fuel, and sawdust and planer shavings used to manufacture pellets. Athena (2009) performed mass balances to check the validity of the data. These data meet the data quality requirements stated earlier.

Data would need to be gathered for the other two softwood biomass sources (i.e., beetle-killed pine biomass and biomass from other forest opera-

TABLE 9 *Suggested data sources for resource extraction, and missing data*

Biomass type	Data source	Description of data	Missing data and comments
Residues from pine forest logging	Athena Sustainable Materials Institute (2009)	Cradle-to-gate softwood lumber harvesting life cycle inventory data	No missing data
Beetle-killed pine rehab biomass	–	–	Need to gather data, or Athena softwood lumber harvesting data may be used as proxy data
Biomass from forest operations	–	–	Need to gather data, or Athena softwood lumber harvesting data may be used as proxy data
Sawmill residues	Athena Sustainable Materials Institute (2009)	Cradle-to-gate softwood lumber harvesting life cycle inventory data	Report contains necessary representative data
Biomass from short-rotation intensive culture	Huang (2007)	Information on energy and other inputs (fertilizer and herbicides) consumption for poplar	Data requirements may be fulfilled either by using these data or gathering first-hand data from the Kalamalka Forestry Centre
Forest carbon responses to harvesting	Forest carbon studied conducted by MFNLRO	Carbon emissions from decaying forest residues, carbon re-sequestration, and soil carbon changes	

tions, such as road construction and disease response), or the Athena (2009) softwood data could be used as a proxy to fill the data gaps.

For short-rotation intensive culture, the LCI data in Huang (2007) could be used; however, first-hand data would be more representative.

3.3.2 Biofuel manufacture Currently, a few companies are involved in manufacturing seasoned firewood in British Columbia, but there is no available data source for firewood manufacturing in the province. Data sources for the manufacture of the other three biofuels are provided in Table 10.

FPInnovations has LCI data for a hog fuel manufacturer in the Lower Mainland who uses diesel as the energy source. These data, however, may not represent the entire manufacturing situation in British Columbia because of the scale of production, differences in energy sources consumed, and technological differences with other manufacturers in the province. Data could be gathered from a few other manufacturers to create a representative environmental profile of the province's hog fuel manufacturing industry, based on a weighted average.

Pa (2010) provides recent representative LCI data for wood pellet manufacturing in northern British Columbia but does not provide information on binder consumption during pellet manufacture.

Cellulosic ethanol manufacture is still at the pilot stage in British Columbia; hence, there currently are no data on the commercial production of cellulosic ethanol in the province. A Canadian firm, Lignol Innovations,

TABLE 10 *Suggested data sources for biofuel manufacture, and missing data*

Fuel type	Data source	Description of data	Missing data and comments
Hog fuel	Mahalle (2011)	Life cycle inventory data for a single manufacturer	Need to gather data from a few more manufacturers to create representative industry data
Pellets	Pa (2010)	Information on energy consumption by sources for pellet production	Recent representative data; information on pellet binder is missing
Ethanol from short-rotation intensive culture	Huang (2007)	Information on the substitution of ethanol for gasoline but no material input data on the ethanol manufacturing process	Data may not represent the province's ethanol manufacturing technology, which currently is at the pilot scale. Therefore, a life cycle inventory should be created for the pilot plant, which could be used for the proposed sustainability assessment study of British Columbia's wood-based biofuel sector.
	Gonzalez-Garcia et al. (2009)	Details on material inputs to poplar biomass production and the ethanol manufacturing process	

based in Vancouver, B.C., is working on promoting commercial-scale cellulosic ethanol manufacture using a technology that it acquired from General Electric and Repap Enterprises.[9] Pilot data could be gathered from the company and used to create an environmental profile for cellulosic ethanol production in British Columbia. As an alternative, Huang's (2007) LCI data on cellulosic ethanol production could be used, but they may not represent the technology promoted by Lignol Innovations, which will most likely become the commercial cellulosic ethanol technology used in the province.

3.3.3 Wood fuel combustion and ash disposal Data sources for wood-based biofuel combustion and ash disposal are shown in Table 11. Beauchemin and Tampier (2008) provide only particulate emissions data; all other data described in Table 8 and in lists found on pages 24 and 25 need to be gathered. As far as the other sectors are concerned, the British Columbia Ministry of Environment has wood-fired boiler combustion emissions data only for a few criteria air pollutants, such as particulates, nitrogen oxides, carbon monoxide, for facilities operating in the province, but most of the required data mentioned in lists found on pages 24 and 25 are missing (T. Wakelin, B.C. Ministry of Environment, pers. comm., Aug. 8, 2011).

The U.S. EPA (2008) and the Washington State Department of Ecology (2005) provide required data for assessing the environmental impacts of all emissions from wood-fired boilers. These two studies provide emission factors for more than 90 chemicals, and the U.S. EPA study contains data on 26 trace metals emitted from wood-fired boilers to the air. The lack of wood combustion ash composition analysis data for the metals and other substances listed on page 25 is an issue with the existing data. Also, these data are

9 www.lignol.ca/about.html

TABLE 11 *Suggested secondary life cycle inventory and non–life cycle inventory data sources for wood-based fuel combustion and ash disposal*

Data	Data source	Description of data	Missing data and comments
Residential sector	Xue and Wakelin (2006)	Particulate emissions data	All other emissions data, including wood ash, are missing
Grate burners Fluidized bed burners	Beauchemin and Tampier (2008)	Emission factors for CO, NO_x, particulates, and volatile organic compounds	Information on all other emissions to air and combustion ash composition is missing
Gasifiers	Mahalle (2011)	Hog fuel combustion data that represent the technology invented by Nexterra	Recent complete data, but the hog fuel source tree species was not known
Other studies	U.S. EPA (2008)	Emission factors for wood combustion emissions to air	Information on ash composition and wood species is missing
	Eastern Research Group (2001)	Revised emission factors for criteria air pollutants	Other information, including ash composition data, is missing
	Washington State Department of Ecology (2005)	Emission factors for wood combustion emissions to air	Information on ash composition and wood species is missing
	Dones et al. (2007)	Emissions factors for emissions to air for softwood boilers in Europe	Data are not representative, and ash composition data are missing
	Environmental Risk Limited (1996)	Emissions factors for all emissions to air from wood-chip fired furnaces except SO_2, N_2O, and CH_4	Ash data and information on source wood species are missing
	Huang (2007)	Data on pulp mill boiler wood ash	Information on carbon content and dioxin/furan is missing
Ash disposal	Mahalle (2011)	Hog fuel combustion data for gasification —represent the technology invented by Nexterra	Recent complete data, but the hog fuel source tree species was not known. Wood ash combustion data for grate burners and fluidized bed burners are missing

quite generic, and the actual emissions from wood-fired boilers vary depending on wood species, moisture content and composition of the wood fuel, boiler type, and emission control equipment used (Washington State Department of Ecology 2005).

Facilities operating in British Columbia annually report their emissions to the National Pollution Release Inventory[10] and other programs. Usually, landfills in British Columbia ask for ash content analysis data before dumping wood combustion ash in their sites.

10 The National Pollutant Release Inventory is Canada's legislated, publicly accessible inventory of pollutant releases (to air, water, and land), disposals, and transfers for recycling. www.ec.gc.ca/inrp-npri/default.asp?lang=En&n=4A577BB9-1

An inventory of information on wood fuel combustion in wood-fired boilers should be created based on a representative sample of facilities that use pine as wood fuel and have various types of emission control equipment. This would provide a more representative data set on wood-fired boiler emissions than using generic data in other studies. This type of inventory would improve the validity and transparency of the results of the proposed study.

3.4 Background Life Cycle Inventory Data Sources

Biomass extraction, wood-based biofuel manufacture, and burning biofuel for energy require energy (e.g., diesel, gasoline, electricity) and ancillary materials, such as lubricating oil and hydraulic fluid. The energy and ancillary materials may be consumed in small quantities, but to obtain an accurate account of the environmental burden created, the environmental impacts associated with their use within the province should be included in the analysis.

Two secondary LCI data sources are applicable to North America: the U.S. Life Cycle Inventory Database (www.nrel.gov/lci) and US-EI Database (www.earthshift.com/software/simapro/USEI-database). The U.S. LCI Database is limited because some processes are missing for some products, which could create issues related to data completeness. The US-EI Database was created to address the completeness issue. For example, 144 of the 178 dummy processes in the U.S. LCI Database have been replaced with "ecoinvent" data (version 2.01), a European database that contains 3952 unit processes (www.ecoinvent.ch/). The processes were modified by replacing European electricity with U.S. electricity in order to make those data more representative of electricity grids for energy sources in North America. However, the completeness issue has not been completely resolved because there are still 34 dummy processes in the US-EI Database. This data incompleteness issue should be examined along with its possible implications on the final results when using secondary LCI data from the US-EI Database.

Canadian electricity grid data are missing from both the US-EI and U.S. LCI Databases. However, this gap can be filled by creating a British Columbia electricity profile based on the data available in both databases for various energy sources. Information on British Columbia's electricity grid, which is comprised of various energy sources, can be found in the document *National Inventory Report: Greenhouse Gas Sources and Sinks in Canada* (Environment Canada 2010b).

4 POTENTIAL POLICY IMPLICATIONS

Results of the proposed LCA element of the sustainability analysis could be used to indentify policy implications in the following areas:

4.1 Greenhouse Gas Emission Reductions from the Province and the Carbon Market

British Columbia's Climate Action Plan legislated a reduction in greenhouse gas emissions of 33% by 2020 and 80% by 2050 compared to 2007 levels; the use of wood-based biofuel was identified as one of the potential areas in which to achieve these emission reduction targets.[11] The proposed LCA study can generate estimates of the greenhouse gas mitigation potential of project-

11 www.env.gov.bc.ca/cas/pdfs/climate_action_21st_century.pdf

ed woody biomass use for energy and associated fossil fuel displacement benefits[12]. This information could be used to identify important policy implications related to achieving the emission reduction targets for the province through substitution for fossil fuels. In addition, proposed estimates of potential net social gains from carbon mitigation (i.e., the net externality results from reduced carbon emission benefits minus external costs associated with the criteria air pollutant emissions) could be useful in formulating policies regarding the carbon market.

4.2 Wood Ash Disposal

Increased burning of wood biofuel for energy could generate enormous amounts of wood ash. In British Columbia, wood ash from wood-fired boilers is currently disposed of in landfill sites, but this practice might not be feasible in the future because about 60% of the landfill sites in the province are predicted to close within the next 10 years.[13] Wood combustion produces two types of ash: bottom ash (ash remaining in the boiler) and fly ash (particles suspended in, and collected from, the exhaust gas). Fly ash is an excellent alternative liming material, and it can be used as a fertilizer on agricultural lands, reclamation sites, and forest lands (Sylvis 2008). The British Columbia Ministry of Environment Soil Amendment Code of Practice[14] currently regulates the beneficial use of fly ash, whereas a permit or approval from the Ministry is required to apply bottom ash to soil. Fly ash from wood that has been immersed in salt water, during marine transport for instance, is banned from use as a soil amendment or fertilizer because exposure to salt water increases the chlorine content in wood. Chlorine is a precursor to dioxin formation during combustion.

Wood ash could be viewed as a resource rather than a waste. The proposed LCA addresses the regulatory concerns with wood ash and its human health and ecological risks; therefore, important policy implications could be identified with respect to regulations to manage the beneficial use of wood ash.

4.3 Human Health Aspects from Particulate, Dioxin/Furan, and Toxic Metal Emissions

With increased sector activity, there would be an increase in particulates, dioxin/furan, and toxic metal loading levels in the province's airshed, which in turn could pose greater risks to human health. The proposed study is expected to generate estimates of the current potential human health impacts on British Columbians, probable future elevated criteria pollutant loading levels, and potential human health impacts from the increased pollutant loading levels. This information could be used to evaluate the adequacy of current regulatory standards and identify possible policy revisions required to manage pollutant emissions.

12 Biomass generation is one potential clean resource of many for BC Hydro to acquire power under its legislated target; a side effect of this target is that clean displaces clean. Therefore, it may be best to determine absolute estimated life cycle emissions according to approved methodologies. In heat production applications, biomass generation may more directly displace natural gas and deliver fossil fuel displacement benefits (J. Buchanan, B.C. Ministry of Energy, Mines, and Natural Gas, pers. comm.).

13 www.tpsgc-pwgsc.gc.ca/biens-property/gd-env-cnstrctn/page-9-eng.html

14 The Ministry has established a code of practice for the beneficial use of specified industrial by-products on land. This code of practice provides consistent requirements across the province and protects the quality of soil as well as the surface and groundwater on sites where the by-products are applied. www.env.gov.bc.ca/epd/industrial/regs/codes/soil_amend/index.htm

4.4 Land Use Impacts on Biodiversity and Life Support Functions

The land use and biodiversity indicators from the sustainability assessment may inform development of forest stewardship policies and regulations.

5 CONCLUSIONS

The following conclusions were drawn from this preliminary assessment:

- None of the existing methodologies, namely ISO-LCA, CALCAS, ToSIA, and Eco-LCA, fully met the Woody Biomass Innovative Project team's needs for a sustainability assessment.
- Based on the application limitations of the existing methods, it will likely be most practical to use ISO-LCA to address the environmental component, and to assess land use, economic, and social aspects of sustainability as separate elements.
- The proposed sustainability assessment requires input and output data for cradle-to-grave life cycle stages—that is, resource extraction (harvesting), biofuel manufacture and combustion, and ash disposal. Part of these data requirements could be addressed by using information from available data sources, and a combination of published information and newly gathered information could be used to fill existing data gaps.

5.1 Potential Policy Implications

Results of the proposed study would be useful in identifying important policy implications in the following areas:

- provincial legislated carbon emission reduction targets and the future carbon market
- regulatory revisions to promote the beneficial use of wood combustion ash for soil amendment on agricultural lands and forest lands
- review and revision of existing regulations to manage the anticipated criteria pollutant emission loading in the province's airshed and its implications on human health
- use of land use and biodiversity indicator results from the sustainability assessment to inform development of forest stewardship policies and regulations

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The international standards in the ISO 14040-series[15] set out a four-phase methodology framework for completing a life cycle assessment (LCA).

Goal and scope definition
An LCA starts with an explicit statement of the goal and scope of the study, the functional unit, the system boundaries, the assumptions and limitations and allocation methods used, and the impact categories chosen. The goal and scope includes a definition of the context of the study, which explains to whom and how the results are to be communicated. The goal and scope of an LCA are clearly defined and consistent with the intended application. The functional unit is a reference unit defined for quantified performance of a product system to which all flows in the LCA are related. Allocation is the method used to partition the environmental load of a process when several products or functions share the same process (ISO 2006b).

Life cycle inventory analysis
In the inventory analysis, a flow model of the technical system is constructed using data on inputs and outputs, and is called a life cycle inventory (LCI). The flow model is often illustrated with a flow chart, which includes the activities that are going to be assessed, and it gives a clear picture of the technical system boundary. The input and output data needed for the construction of the model (such as resources, energy requirements, emissions to air and water, and waste generation for all activities within the system boundaries) are collected. Then, the environmental loads of the system are calculated and related to the functional unit (FU).

Life cycle impact assessment
Inventory analysis is followed by an impact assessment, where LCI data are characterized in terms of their potential environmental impact (e.g., acidification, eutrophication, global warming potential effects). The impact assessment phase of the LCA is aimed at evaluating the significance of potential environmental impacts based on the LCI results. In the classification stage, the inventory parameters are sorted and assigned to specific impact categories.

The calculation of indicator results (characterization) involves the conversion of LCI results to common units and the aggregation of the converted results within the same impact category. This conversion uses characterization factors. The outcome of the calculation is a numerical indicator result typically stated on an equivalence basis. In many LCAs, characterization concludes the analysis; this is also the last compulsory stage according to ISO (2006b). However, some studies involve the further step of normalization, in which the results of the impact categories from the study are compared with the total impact in the region. During weighting, the different environmental impacts are weighted against each other to arrive at a single score for the total environmental impact.

15 ISO 14040:2006, *Environmental Management - Life Cycle Assessment - Principles and Framework* and ISO 14044:2006, *Environmental Management - Life Cycle Assessment – Requirements and Guidelines.*

Interpretation
The results from the inventory analysis and impact assessment are summarized during the interpretation phase. Conclusions and recommendations are the outcome of the interpretation phase of the study. According to ISO (2006a), the interpretation should also include:

- identification of significant issues for the environmental impact, and
- evaluation of the study, considering completeness, sensitivity, and consistency.

The working procedure of LCA is iterative in that information gathered in a later stage can affect an earlier stage. When this occurs, the stages have to be reworked, taking into account the new information. Therefore, it is common for an LCA practitioner to work at several stages at the same time.

The following is a brief description of each of the impact indicators used in the Tool for Reduction and Assessment of Chemicals and other environmental Impacts (TRACI) (Bare 2003):

a. ***Global warming potential***—The methodology and science behind the global warming potential calculation can be considered to be one of the most accepted life cycle impact assessment (LCIA) categories. Global warming potential is expressed on an equivalency basis relative to CO_2—in kg or tonnes CO_2 equivalent.
b. ***Acidification potential***—Acidification is a more regional rather than global impact that affects fresh water and human health when high concentrations of SO_2 are attained. Acidification is a result of processes that contribute to increased acidity of water. Acid rain generally reduces the alkalinity of lakes. The acidification potential of an air or water emission is calculated on the basis of its moles H^+ ion equivalence.
c. ***Photochemical ozone formation potential*** (smog)—Under certain climatic conditions, air emissions from industry and transportation can be trapped at ground level where, in the presence of sunlight, they produce photochemical smog, a symptom of photochemical ozone creation potential. While ozone is not emitted directly, it is a product of interactions of volatile organic compounds and nitrogen oxides (NO_X). The smog indicator is expressed on a mass of equivalent NO_X basis.
d. ***Eutrophication potential***—Eutrophication is the fertilization of surface waters by nutrients that were previously scarce. When a previously scarce or limiting nutrient is added to a water body, it leads to the proliferation of aquatic photosynthetic life. This may lead to a chain of further consequences ranging from foul odours to the death of fish. The calculated result is expressed on an equivalent mass of nitrogen (N) basis.
e. ***Human health potential*** (respiratory effects)—Particulate matter of various sizes (PM_{10} and $PM_{2.5}$) has a considerable impact on human health. The U.S. Environmental Protection Agency has identified "particulates" (from diesel fuel combustion) as the number one cause of human health deterioration due to their impact on the human respiratory system (e.g., asthma, bronchitis, acute pulmonary disease). Particulates are an important environmental output of wood product production and need to be traced and addressed. The U.S. Environmental Protection Agency used TRACI's "Human Health Particulates from Mobile Sources" characterization factor, on an equivalent $PM_{2.5}$ basis, in the final set of impact indicators.
f. ***Ozone depletion potential***—This is the reduction of protective ozone within the atmosphere caused by emissions of ozone-depleting substances, such as chlorofluorocarbons (CFCs). Reduction in ozone in the stratosphere leads to increased ultraviolet-B radiation reaching Earth, which can affect human health and damage crops, materials, and marine life. Ozone depletion potential is reported in units of equivalent CFC-11.
g. ***Carcinogenicity potential***—This is the potential of chemicals released into an evaluative environment to cause human cancer effects. The calculated result is expressed on an equivalent mass of benzene basis.

h. ***Human health potential*** (non-cancer)—This is the potential of a chemical released into an evaluative environment to cause human non-cancer effects. The calculated result is expressed on an equivalent mass of toluene basis.
i. ***Ecotoxicity potential***—This is the potential of a chemical released into an evaluative environment to cause ecological harm. It expresses the impact of the release of chemicals to a compartment (e.g., soil, water, or air) in terms of equivalent quantities of 2,4-D released to that same compartment.