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Life Cycle Assessment for Sustainable Forest Management

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Abstract

This research focuses on the evaluation of the potential for the adoption of life cycle assessment (LCA) methodologies for exploring the concept of sustainable forest management in the boreal forest. The work includes a review of LCA and suggests a possible framework for its implementation with the aim of making the complex task of sustainable forest management (SFM) easier to tackle. It is suggested that the LCA technique per se might not be powerful enough to handle such an enormous task. However, the underlying concept of life cycle thinking might be a good candidate for dealing with some of the encompassing issues characterising SFM. LCA is basically a methodology that evaluates the environmental burdens associated with the entire life cycle of a product or activity. This involves identification and quantification of materials and energy use and waste discharges to the environment followed by a characterisation of the respective environmental impacts. Current methodologies, based on life cycle thinking, are still evolving in an effort to improve the evaluation of environmental effects and to incorporate additional environmental issues, including socio-economic aspects.

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Life Cycle Assessment for Sustainable Forest Management

"Lacking... consensus, not solely by economists and government officials but by the local communities and by those concerned with ecosystem maintenance, there cannot be fully acceptable plans and policies. Without it there will continue to be deep and bitter dispute over the wisdom of specific dam projects, effluent control programs, schemes for maintenance of biodiversity, projects for reversal of desertification, and many other environmental programs."

(White, 1996, p. 60)

Introduction

Sustainable forest management (SFM) is a complex management process requiring the convergence of knowledge from several sources. Such knowledge may arise from diverse sets of stakeholders or interest groups that are likely to hold different perspectives (or agendas) and levels of influence. Naturally, the question arises of how one can fashion a consensus, based upon rational decision-making, in the presence of such influences. Clearly, it would be helpful to identify tools that one can use to facilitate the consensus-building and decision-making processes. With this main motivation, this working paper proposes the utilisation of life cycle assessment (LCA) as a potential tool to make the complex task of sustainable forest management easier to tackle. As it is suggested below, the LCA technique *per se* might not be powerful enough to handle such an enormous task. However, the underlying concept of life cycle thinking might be a good candidate for dealing with the encompassing issues characterising SFM.

Forest management is at a crossroads -- as it has been for some time (Prescott and Drapeau, 1995). Sustainable forest management seems to be attracting sufficient interest that it may become more than just a catchword. Hopefully, it will come to represent the key direction for the future. The Sustainable Forest Management Network (SFMN) is grappling with the underpinning twin questions of sustainable forestry: what is sustainable forest management; and how can it be achieved?

The term sustainability *"…calls for more than economic and technical adjustments… It is inadequate to ask how we can sustain current rates of production and consumption. Rather we must ask how we can promote the technology, together with social learning and social change, necessary to bring our patterns of production, … and consumption into concert with the capacity of the ecosystem to perform life-giving functions over the long run… and in such a way that the process fosters intragenerational as well [as] intergenerational equity"* (Pezzoli, 1997, p. 557). Thus, inherent to the concept of sustainability are the observations that human society has been using natural capital (natural resources and services) at a faster pace that it can be replenished and that society is capable of achieving a higher level of welfare with less (Schwab, 1997).

The concept of sustainability spreads over four dimensions: economic viability, ecological security, social equity, and technical feasibility (Moser, 1996). It is an interdisciplinary concept. As such, it is a concept that cannot be seen as merely a combination of modular terms. Thus, sustainability deals with a whole that is more than the sum of its parts (Lifset, 1998). Sustainability thus demands an approach that, from the beginning, emphasises this wholeness, instead of one that narrowly focuses on individual components and then attempts to create a bigger picture. Given the dynamics and uncertainty associated with natural and socio-economic systems, sustainability should be considered less of an achievable goal than a moving target. Progressing toward sustainability thus implies a continuous process of evaluation and adjustment (Proops *et al.*, 1996).

To approach sustainability means to rely on measures which focus on the heart and linkages of existing problems, i.e., that are intentionally designed to address more than one problem at a time, therefore, triggering a cascade of environmental, ecological, social, and economic effects (Schwab, 1997). This undoubtedly requires a balancing of many competing goals and values. However, consensus-seeking through creative problem-solving – that is, experimenting with novel concepts and ideas – can help minimize unnecessary friction among stakeholders. In the context of the boreal forest, this suggests experimenting with a variety of management approaches and thus a natural disturbance model should be viewed as solely one among several sustainability options to be explored.

The process of pursuing sustainable management of the boreal forest will have to address several aspects of the problem. First, the recognition of a current situation, which may be characterised by an unsustainable level of present and anticipated future demands for resources from the boreal forest. Second, the notion that overcoming this situation will begin with the determination of an adequate level of demand (including all potential industrial uses of the boreal forest, such as forestry, oil exploration, and mining) for those resources that is fully compatible with a sustainability paradigm. For example, this might involve an identification, through emulation of natural disturbance, of the precautionary (safe) levels for the utilisation of the boreal forest capital. Finally, to maximise the likelihood of staying within those safe bounds, it may be necessary to identify practical "dematerialisation" approaches for bringing societal activities to a level compatible with sustainability. These approaches might include: (1) a more efficient manufacture and use of forest industry products (e.g., improvement of forest products-related activities over the entire life cycle) as well as products from the oil and mining industries; (2) an integration through appropriate spatial and temporal linkages of the activities of forest products industries with other industrial and societal activities to foster an efficient utilisation of a wide range of natural resources (e.g., an array of fibre sources such as tree plantations, crops, agriculture residues, urban waste, etc.); (3) a shift of some societal needs into alternate and intrinsically more sustainable products and services of a higher information content (e.g., wood/fibre composites, electronic publishing, etc.); and (4) changes in social institutions to promote sustainability.

As a result of these dematerialisation strategies, which promote a reduction in the materials and energy throughput per unit of economic output, one might expect an important uncoupling of the production and consumption of goods and services (economic activity) from the environment (Robinson and Tinker, 1997). However, Robinson and Tinker (1997, p. 85) argue that in addition to dematerialisation, a resocialisation strategy is also needed that "…*uncouples human well-being from the consumption of goods and services, offering the possibility of reconciling economic and social goals.*"

This paper does not further attempt to characterise the concept of sustainability, but rather focuses on a decision-making framework to guide progress toward what appears to be sustainable forest management. However, it is essential to have at least a rough picture of where one is headed, and the notions of sustainability provided above can fulfil that purpose. It should be noted that before one makes any significant real progress toward the goal of SFM, it is possible and easy, to become lost in the details and nuances along the way. The SFMN should be prepared to make a sincere commitment to an holistic approach to the problem and be careful enough to avoid the common mistake of taking the means as the end.

LCA Methodology

The history of the fundamental concept underlying life cycle assessment, i.e., a system-wide analysis from cradle-to-grave, can be traced back to the early 1970s' energy analysis studies motivated by the oil crisis (Ayres, 1995; Curran, 1996). Since then, LCA has steadily evolved by including the consideration of environmental issues, to become a somewhat mature and mainstream environmental assessment tool. More recently, in the early 1990s, the Society of Environmental Toxicology and Chemistry (SETAC) -- an international scientific organisation -- was crucial in proposing a set of standardised procedures for LCA (Fava *et al.*, 1991; Consoli *et al.*, 1993; Fava *et al.*, 1993). Others, notably the U.S. Environmental Protection Agency (USEPA, 1993) and the Canadian Standards Association (CSA, 1994a), have also published conceptual guidelines for conducting LCAs. Some of these guidelines, particularly those related to the impact assessment component, are still the subject of discussion and controversy within the LCA community. Therefore, the standardisation process is still evolving, not only through the work of SETAC but also through the International Standards Organisation forthcoming ISO 14000 standards.

Definition

The Canadian Standards Association (CSA, 1994a, p. 6) defines LCA as *"a concept and a method to evaluate the environmental effects of a product or activity holistically, by analysing its entire life cycle. This includes identifying and quantifying energy and materials used and wastes released to the* *environment, assessing their environmental impact, and evaluating opportunities for improvement."* LCA has four complementary components or phases, namely (1) initiation, (2) inventory, (3) impact assessment, and (4) improvement assessment. Figure 1 presents an overview of the LCA methodology.

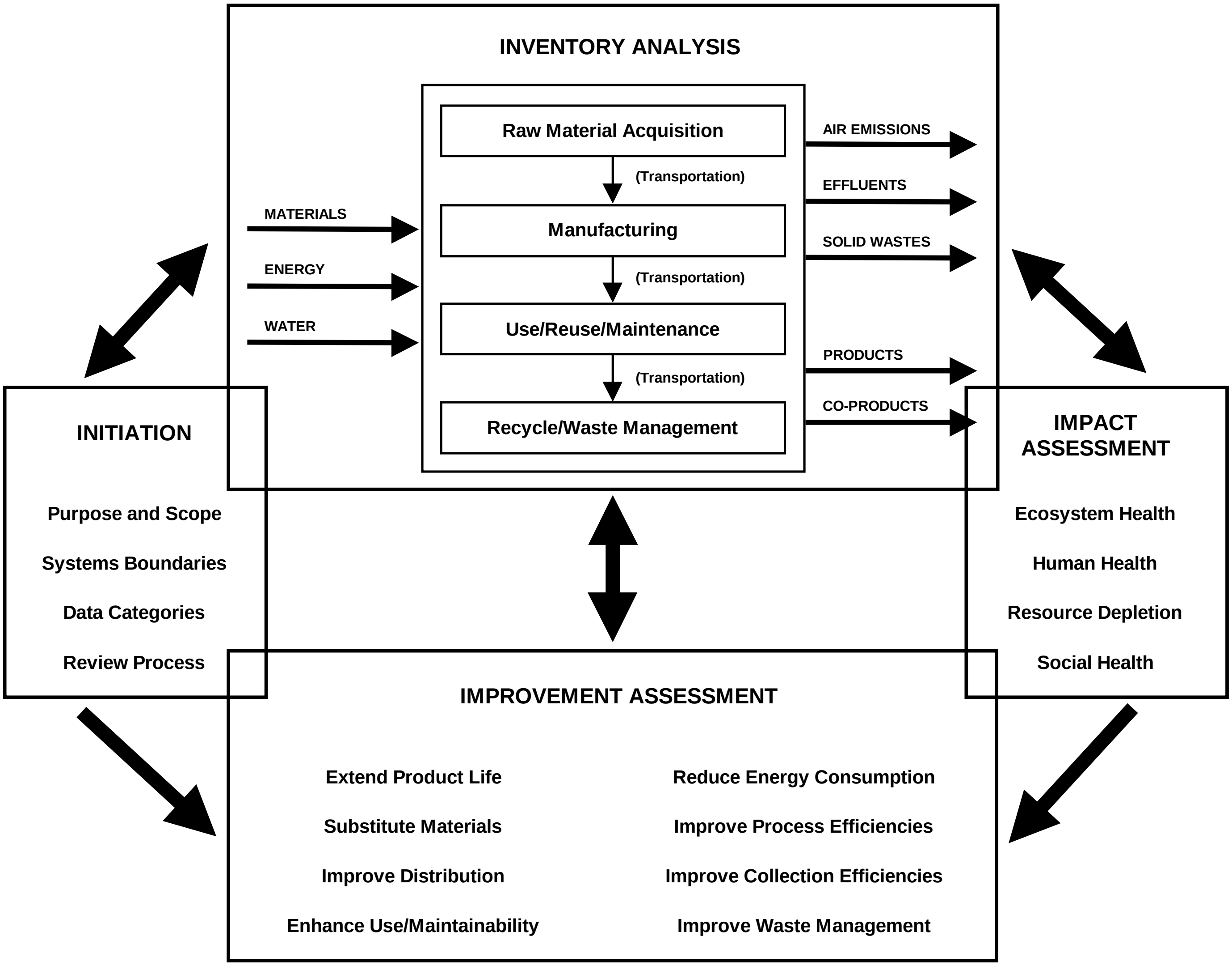

Figure 1 – LCA methodology. (Adapted from CSA, 1994b, p. 4).

In the initiation phase, the purpose and objectives of the study are stated and the boundaries of the product system are defined accordingly (Tillman *et al.*, 1994; Boguski *et al.*, 1996). In general, a cradle-to-grave system is considered, including all sequential stages associated with a product or activity, namely raw materials and energy acquisition, materials and product manufacture, transportation/distribution, product use/reuse/maintenance, and product recycling and disposal. System boundaries must also delineate the geographical area and time horizon of the LCA. For instance, the acquisition of raw materials, production, consumption, and waste management may be confined to specific geographic regions, while the lifetime environmental impact of a product may depend on the adopted time frame. Moreover, the initiation phase has to define the functional unit, i.e., the unit of product output, relative to which the inventory data will be presented.

The inventory phase, usually referred to as LCI (life cycle inventory), is the process of identifying and quantifying the energy and material inputs and the environmental releases or emissions associated with each life cycle stage. For example, the evaluation of the amount of water consumed and wastewater biochemical oxygen demand (BOD) generated during production of a tonne of wood pulp (the functional unit) would be considered in an LCI. The impact assessment phase attempts, through a classification and characterisation procedure, to translate the inventory data on energy and material resources use and environmental emissions into environmental impact categories. Furthermore, a subsequent valuation of impacts across all the impact categories might lead to an overall impact score. Examples of impact categories are (1) global warming, (2) ozone depletion, (3) resource depletion, (4) acidification, (5) eutrophication, (6) human toxicity, and perhaps (7) ambient odours. Finally, the improvement assessment phase deals with the evaluation of opportunities for reductions of the life cycle environmental burdens associated with a product or activity.

Limitations

It has been argued that the impact assessment component of LCA cannot evaluate actual, or even potential, environmental impacts, and that the end products of a life cycle impact assessment exercise are best seen as environmental indicators or indices (Galeano, 1997; Owens, 1997). There are several reasons why life cycle impact assessment cannot establish the meaningful cause-effect linkage necessary for prediction of impacts (Galeano, 1997; Owens, 1997).

- The inventory of material and energy flows is normalised against a functional unit (e.g., 10 tonnes of wood pulp, 1 tonne of paper). There is no consideration of the absolute amounts of those flows, which is crucial for the assessment of specific environmental impacts.

- The inventory procedure frequently involves allocation (or splitting), of the original material and energy streams, among the diverse products coming out of a processing operation. Consequently, and because LCA focuses on a specific product, often only a fraction of the original material and energy flows is considered when addressing environmental impacts.

- Typically, it is impractical due to temporal and financial constraints to compile all relevant inventory data for the overall cradle-to-grave system. In addition, data quality considerations involving ranges or distributions of data and uncertainty analysis are often not included.

- The inventory procedure aggregates material and energy streams across the entire product system. For instance, the amount of a pollutant released during the life cycle stages of a product (extraction of raw materials, product manufacturing, transportation, use, recycling, and disposal) are summed into a single emission value. Moreover, the inventory data are also temporally aggregated, such that the duration, frequency, and intensity of environmental releases may be lost. This means the impact assessment could be based on a highly conservative and unrealistic single, overall environmental exposure. Thus, by leaving out spatial and temporal considerations during the inventory phase, LCA is unable to estimate transient ambient concentrations. To obtain exposures, LCA is forced to assume a very simplified -- non-threshold and strictly linear -- dose-response model.

- The level of accuracy of life cycle impact assessment varies widely, ranging from highest for global, long-term environmental processes, such as global warming and ozone depletion, to lowest for local, transient processes, such as ecological and human toxicity. Also, non-linear processes with thresholds, or those affected by complex levels of information beyond what is included in life cycle inventories, as is the case for biodiversity, are at present, poorly addressed through LCA.

- Uncertainties underlying the way inventory data are assigned (classification) into an impact category and the way these data are then combined (characterisation) to produce an impact value.

Even though it has limitations, LCA is a very useful tool whose capabilities could be complemented through association with other methodologies. As it is now *"...LCA is not capable or sufficient by itself of generating a comprehensive environmental assessment of any system. This does not diminish the several demonstrated benefits of LCA: (1) evaluate the overall material and energy efficiency of a system; (2) identify pollution shifts between operations or media as well as other trade-offs in materials, energy, and releases; and (3) benchmark system efficiency improvements and reductions in releases. LCA offers a broad screening approach using mass loadings to indicate numerous hypothetical consequences possible from releases. When the necessary data are collected in the inventory data set, LCA thus provides some insight and identifies possible issues in the environmental, resource, and human health areas"* (Owens, 1997, p. 47). This author further suggests the need *"...to recognise that LCA results are only directional indicators for each [impact] category. Conceptually, indicators aggregate and distill important data to identify an issue or issues and, over time, establish trends.... LCA's broad, but rudimentary, screening capabilities need to be integrated with other environmental tools in an overall environmental management framework. The goal is to have each tool or technique performing the task and providing the information to which it is best suited, while other complementary tools address its weaknesses and limitations"* (Owens, 1997, p. 47). Recently, conceptual models involving LCA in such a management framework have been put forward (White *et al.*, 1995; De Smet *et al.*, 1996; Galeano, 1997).

Areas of Active Research

Substantial discussion is underway on issues pertaining to further standardisation of LCA practices, both from a general perspective, as well as in the context of specific industrial sectors, such as the forest products industry. Recently, great progress has been made to standardise LCI procedures (Curran, 1996). The effort is now gradually shifting to standardisation of the methodologies for impact assessment and improvement assessment. Software tools and databases have come a long way and the process of advancement continues. This has contributed to a significant decrease in the costs of performing LCAs, and this trend is expected to continue.

A product system typically does not exist in isolation. There are linkages with overlapping systems through the generation and/or incorporation of common co-products. In an LCI, this implies using allocation procedures to specify the division of material and energy flows among co-products. In current LCA practice there is little standardisation of these allocation procedures (Galeano *et al.*, 1996). This produces serious difficulties when comparing LCA studies using different allocation rules, and undermines the credibility of LCA results. Work is well underway to establish an accepted set of procedures to guide the allocation process, particularly in the area of the forest products industry (Galeano *et al.*, 1996; International Working Group, 1996).

Standardisation procedures are also being called for to assure that uniform and compatible measurement units are used throughout the inventory data and that the quality of these data is not taken for granted without a careful analysis of their respective consistencies and physical likelihoods, possibility through mass-balance accounting (Ayres, 1995).

Given the usual high cost and level of effort required to conduct an LCA using the current standardised methodologies, research is underway to test and document the effect of methodology simplifications on LCA results. These streamlining approaches are intended to ease the effort and cost of implementing an LCA without seriously compromising its conclusions (Todd, 1996). Streamlining methods being considered include, among others, limitation or elimination of life cycle stages, emphasis on specific environmental impacts or issues, elimination of specific inventory parameters, and use of both qualitative and quantitative data, as well as surrogate data (Todd, 1996).

LCA for SFM

From the above discussion, the main conclusion to be drawn from looking at the LCA methodology, is that it focuses on the evaluation of processes or activities over the entire life cycle, i.e., from cradle-to-grave. One may logically propose that this same holistic view of the entire system, characteristic of LCA, also should be an integral part of any truly sustainable approach to forest management. Thus, it is natural to carry this fundamental life cycle thinking into SFM.

Depending on the relationship between alternative forest management practices, the evaluation of their relative degree of sustainability can be approached differently. The simplest case arises when the relationship between those alternatives is of a "win/no lose" nature, meaning that one alternative is clearly superior to the others. In this case, an LCI (inventory) methodology is powerful enough to rank the different alternatives. This situation may occur when one set of forest management practices is characterised by a systematic lower level of detrimental outputs, everything else being equal, in comparison to the alternatives. The superior alternative then offers a gain, or “win”, in the category of characteristics for which it is superior, without any “loss”, since in the other characteristic categories, it is equal to the alternatives.

There are some advantages that favour searching for "win/no lose" alternatives in forest management. If one alternative is superior in some categories, while not inferior in others, it is likely to be supported by all interested parties and therefore, is most likely to be implemented. Moreover, stepwise progress towards sustainability is assured. This would result since no management alternative would be adopted unless it represented a clear improvement in a sustainable direction. However, there are also disadvantages inherent in this approach. Prominent among these is the potential for missed opportunities, as "win/no lose" management alternatives could be harder to develop than "win/lose" alternatives. In other words, progress toward sustainability could be hindered since "win/lose" alternatives would be discarded even when they may represent a true improvement in a sustainable direction.

This suggests a more complex comparison scenario, corresponding to a "win/lose" situation, in which there is no clear evidence of superiority of any the alternatives, based on an inventory methodology alone. In this case, alternative sets of forest management practices may be superior in some aspects of the comparison, while being inferior in others. This means that trade-offs would need to be addressed when comparing and ranking the available alternatives. However, when subjective decisions on "win/lose" trade-offs have to be made, the possibility always exists that some criteria, intentionally or not, will be favoured at the cost of others. The question of whether one “win/lose” alternative really is in fact, more sustainable than the others, requires more than an LCI for consideration.

When one is dealing with a set of "win/lose" management options, an impact assessment phase within an LCA is often essential to achieve an aggregated level of analysis which facilitates comparative evaluation of trade-offs associated with alternative management strategies, and the ranking of those alternatives. A number of methodologies have been put forward for the assessment of the environmental impact associated with the inventory of materials and energy use and emissions (Fava *et al.*, 1993; Guinee *et al.*, 1993; Baumann and Rydberg, 1994; Guinee and Heijungs, 1995; Krotscheck and Narodoslawsky, 1996; Moser, 1996; Postlethwaite and de Oude, 1996). Some of these methods were reviewed recently by Hertwich *et al.* (1997). Although important issues characterising SETAC's framework for life cycle impact assessment remain to be resolved, the reviewers considered it to be the most rigorous attempt made to address all environmental impacts. The methodology also benefits from its underlying scientific basis and transparency. Future improvements in the impact assessment phase of LCA should involve consideration of uncertainty issues and how to use simple methods to incorporate the diverse knowledge of the many environmental sciences (Hertwich *et al.*, 1997).

Within the accepted framework for the SETAC life cycle impact assessment, Antonsson and Carlsson (1995) proposed an approach to assess impacts on the work environment. The authors suggested using readily available statistical data on health effects on workers as inventory data . Given this approach for incorporating impacts on the work environment, one can further generalise that statistical, monitoring, experimental, and theoretical data could be used as inventory values side-by-side with the inventory flows of materials and energy for a typical LCI. Perhaps this could lead to a description of an array of ecological, human health, social, and economic impacts. Table 1 illustrates this concept for a few impacts.

Nevertheless, the inherent limitations of LCA, as described above, have resulted in a methodology with a comprehensive, system-wide approach, but at a cost to the level of detail achievable in the analysis of each system component. This becomes apparent when LCA is seen in the context of the research focus of the SFMN. The extensive level of detail that the network is placing on the analysis of the full set of ecological, social, and economic factors affecting the management of the boreal forest using a natural-disturbance-based model, makes the analytical capabilities of LCA pale by comparison. In other words, within the framework of emulating natural disturbance in the boreal forest, the SFM network is already fully engaged in a search for understanding the possible impacts of forest management and harvesting at the ecological, social, and economic levels. This work is being carried out through research Legacies 1 and 2. These are "understanding disturbance", and "strategies and institutions for sustainable forest management", respectively. Furthermore, these legacies' activities encompass both direct and indirect impacts, as well as their appropriate temporal and spatial scales. As seen before, LCA is a tool that bases its analysis on inventories of flows of materials and energy, and is able to evaluate impact endpoints only in reference to "abstract" temporal and spatial scales. Of course, its advantage is the ability to characterise, over an entire life cycle, those impact endpoints that can be easily related to the flows of materials and energy. This suggests that the primary role of LCI/LCA, within the SFM research framework, should be one of complementing the analyses carried out using other methodologies.

The role of LCI/LCA should then be to identify the trade-offs in material and energy flows and other (e.g. socio-economic) inventory data, or in the associated impact endpoints, for the array of possible technology alternatives for processing wood resources into manufactured products. The LCI/LCA approach could also be applied to all other life cycle stages upstream and downstream (i.e., transportation, use, recycling, and disposal of products) of the manufacturing stage. These other stages could include activities related to harvesting and managing the forest, such as fertiliser/pesticide application, fuel and other resource use during road construction, during harvesting and during transport of wood logs to a processing facility, etc. Some of the inventory data might also, in some way, be involved during evaluation of impacts through the work of research Legacies 1 and 2. However, at the LCI/LCA level, the data are used solely within a more limited life cycle framework.

The relationship between LCI/LCA, which is part of the research Legacy 3, and the other research components of the SFM network is illustrated in Figure 2. This figure shows that the LCI/LCA tool could play a role in guiding the selection of the most beneficial/least detrimental technological paths for the forest products industry over its entire life cycle. Moreover, at the forest management/harvesting level, the knowledge and recommendations derived from the extensive work under all research legacies, in fact has the benefit of reducing the degrees of freedom by constraining the available options that might be worthwhile to incorporate in an LCI/LCA analysis. In this way, the purpose of LCI/LCA is to eventually refine the conclusions derived from the network research. For example, it is likely that best forest management practices derived from the emulation of natural-disturbance might allow for multiple layouts in the transportation infrastructure. LCI/LCA could then identify the trade-offs for each layout in the amount of energy used during the construction of the infrastructure and during the transportation activities associated with wood harvesting. Furthermore, the natural disturbance-based model should lead to recommendations for sustainable management regarding wood harvest quantity and quality (e.g., softwood of certain diameter). This should affect the manufacturing options to be considered through an LCI/LCA and even the conclusions regarding the most beneficial/least detrimental pathways. Thus, the LCI/LCA is closely coupled to, and builds upon, the integrative knowledge base developed by the research network as a whole.

Some practical considerations that arise during the implementation of an LCI/LCA deal with the choice of the functional unit, i.e., the specified unit of reference for the flows of materials and energy and the related impact endpoints. While comparing differing technology options for the production of a similar forest product (e.g., pulp), a given amount of the product (e.g., 1000 kg of pulp) constitutes a suitable functional unit. When comparing completely different products (e.g., paper versus lumber) other choices of functional unit, other than the product, might be more appropriate, such as a reference amount of wood resource input, economic output, or level of employment. The final decision regarding the choice of functional unit depends to a large extent upon the objective of the analysis, as well as any intended emphasis.

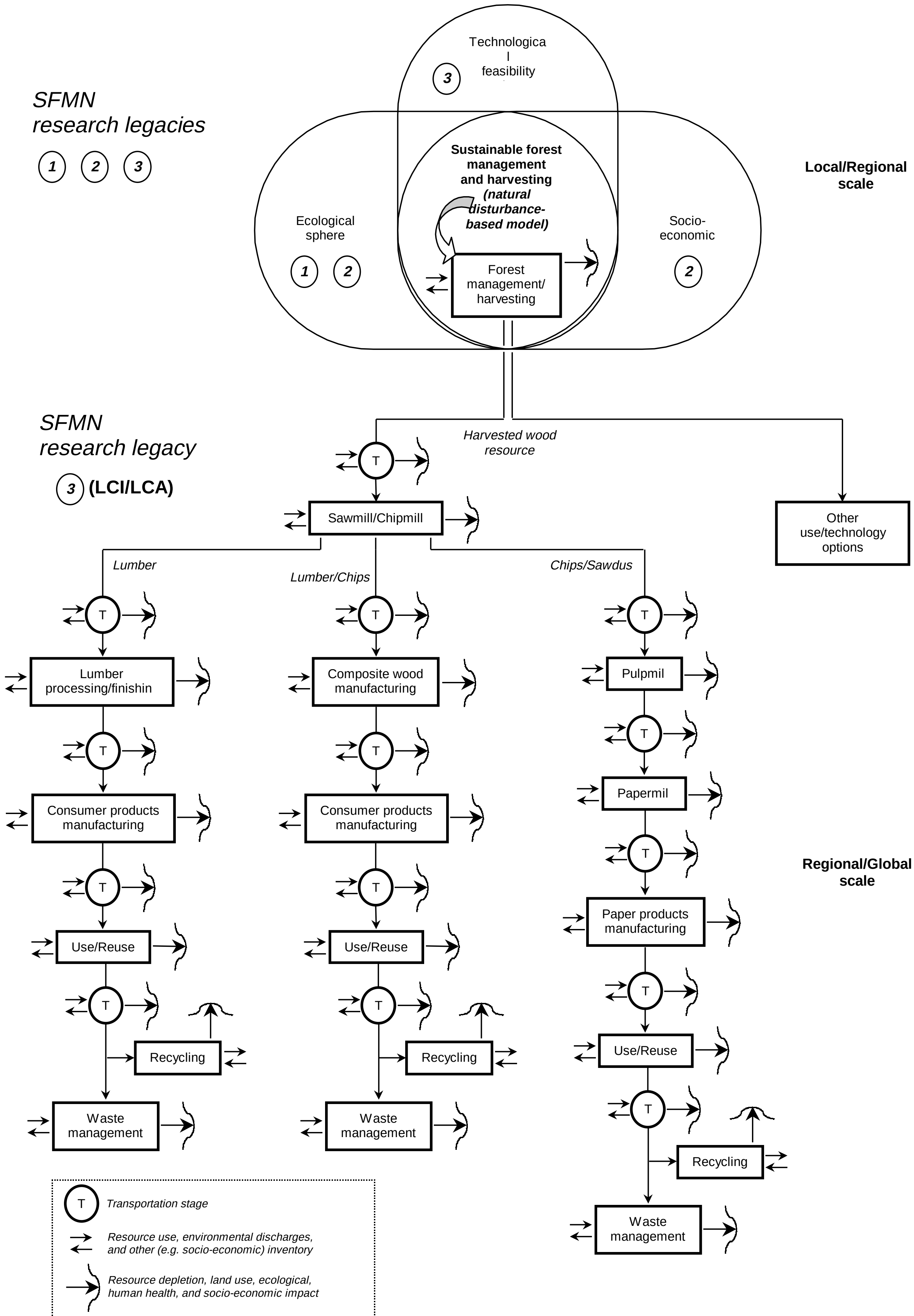

Figure 2 – Role of LCI/LCA within the context of the SFMN research legacies.

While the current LCA framework addresses many impact categories, the inclusion of impacts on such things as land use and biodiversity remains elusive. However, substantial efforts are underway to incorporate these environmental effects into an LCA-compatible framework. Chief among these is probably the novel approach developed through a sponsored effort by a few forest products and publishing companies from Europe and Canada (Axel Springer Verlag, Stora and Canfor, 1998). The developers have proposed a methodology for the assessment of the impact of forestry land use within an LCA context. The method leads to forestry land use as a new life cycle impact category, concentrating on ecological effects of forestry land use, but not considering any socio-economic aspects. Other types of land use impacts that could have been addressed, such as impacts due to transport infrastructure, buildings, mining, etc., should be compatible with the proposed methodology, but have not yet been developed.

This proposed forestry land use methodology builds upon a set of quantitative and qualitative criteria and indicators of SFM, selected from the list put forward through The Santiago Agreement (Journal of Forestry, 1995). This list is the result of the Working Group on criteria and indicators for the conservation and sustainable management of temperate and boreal forests, in which Canada is an active participant (Journal of Forestry, 1995; Riley, 1995). Not surprisingly, a substantial degree of explicit and implicit subjectivity is involved in the step of moving from indicators of SFM to a numerical, semi-quantitative, representation of forestry land use impacts compatible with current LCA practice. Some important characteristics of the approach are that it is based on the evaluation of management practices instead of life cycle inventory data and it underscores the significance of considering qualitative information within an LCA context. This seems to contrast with SETAC's LCA framework, which has been driven by an emphasis on a quantitative approach, building on a life cycle inventory.

More specifically, the method bases its analysis on a set of 13 indicators of SFM, derived from the following three criteria (Journal of Forestry, 1995; Axel Springer Verlag, Stora and Canfor, 1998): (1) conservation of biological diversity (species, ecosystem and genetic), (2) maintenance of forest ecosystem condition and soil productivity, and (3) conservation of water resources. Forestry practices affecting each indicator are evaluated on a qualitative scale of *A* to *E* defined as follows (Axel Springer Verlag, Stora and Canfor, 1998, p. 9).

(A) "Practices are in place which have virtually no measurable effect on the concern under consideration, or where the specific safeguard is fully and securely in place. Studies and measurements exist that confirm that the action is applied and effective…";

(B) "Measurements have been made and action plans developed when necessary. Practices or safeguards do exist and they have been implemented in ways that largely address the particular concern…";

(C) *"…Some practices or safeguards have been developed but their implementation is poor or fragmented; or appropriate measurements have not been made, and so the scale of the problem is largely unknown…";*

(D) *"A total absence of practices or safeguards which address the particular problem…";*

(E) *"Unsustainable practices leading to further ecosystem degradation… Land which was previously forested has been converted to another use (deforestation)".*

On this scale, a level *A* results from a full implementation of forest certification, such as the FSC (Forest Stewardship Council) or CSA (Canadian Standards Association) certification standards, and is therefore fully sustainable. The level *C* is considered representative of current forest industry average management practices. The previous evaluation is converted into a semi-quantitative scale through an expert-panel-based numerical rating of the *A*-*E* scale. This rating establishes a relative score, which defines how many times more damaging unsustainable practices are, relative to sustainable conditions (level *A*).

Although the methodology for forestry land use being discussed has a role to play in an LCA, it seems that the analysis carried out is implicitly subjective and potentially overlooks many variables that might be involved in land use impacts. Moreover, research Legacies 1 and 2 are setting up to deal with ecological and socio-economic land use impacts from forestry, as well as from other competing societal activities, at a much finer level of detail. As such, the forestry land use methodology does not appear to bring any beneficial perspective to the SFM research network. However, land use impacts, other than from forestry, related to activities not included in the research under those legacies (such as possibly from transportation infrastructure and buildings) as well as all land use impacts in the downstream life cycle stages should benefit from an LCA land use impact methodology.

As pointed out earlier, the SETAC framework for LCA builds upon an inventory of materials and energy. This inventory, known as and LCI, is an extremely useful tool to evaluate the material and energy efficiencies of industrial systems on a system-wide basis. Through the development of an LCI, industrial activities can be improved from the standpoint of the materials and energy used. Any such gains might lead to subsequent benefits to the environment, for instance the benefits associated with an increased energy efficiency. Nevertheless, there is no clear link between an LCI and specific environmental effects. This is because the assessment of environmental impacts requires information that is not usually embedded in an LCI, i.e., the assessment of environmental impacts goes beyond a simple collection and later interpretation of materials and energy data. To develop a relationship between measurable materials and energy flows and actual environmental effects, a comprehensive impact assessment approach is required. This means that one should "*… adapt inventory to the needs of impact assessment rather than allow impact assessment to be subordinated to the role of merely interpreting inventory data*" (Rhodes and Brown, 1996, p. 288). This is the philosophy behind the enhanced LCA approach, referred to as life cycle stressor-effects assessment (LCSEA), being proposed within the international LCA community (Rhodes and Brown, 1996; Brown *et al.*, 1996). The LCSEA framework has been developed to meet the resolution and accuracy requirements of the ISO 14000 environmental management standards (Rhodes and Brown, 1996).

At the centre of this new approach lies the concept of causal-chains or stressor-effects networks, which "*…are the interlocking physical, biological, and chemical events that connect a specific cause or 'stressor' to an identified environmental effect or effects*" (Rhodes and Brown, 1996, p. 288). Figure 3 provides an example of a stressor-effects network. These networks are useful for the identification of direct and indirect impacts, and therefore, lead to an analysis that crosses disciplinary lines, since for instance, the consideration of impacts on soil can subsequently lead to the effects on water, fisheries, and economics (Erickson, 1994). Furthermore, the establishment of these stressor-effects networks is based on an identification of the site-specific conditions, and therefore on an assessment process relevant to some specific societal activity. This assessment involves: (1) spatial and temporal analysis characterising the geographic scope (e.g., local, regional, continental, global) and the time period for the environmental effects; (2) threshold and dose-response analysis characterising the existence of discontinuities and the linearity/nonlinearity of the relationship between stressor and environmental effects; and (3) environmental background analysis characterising the baseline level of the the stressor baseline and the

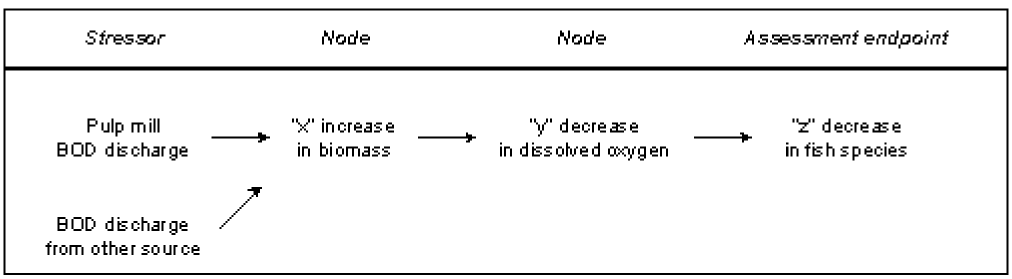

Figure 3 - Example of a simplified stressor-effects network. (Adapted from Rhodes, 1997, p. 63).

presence of similar stressors from other systems (Brown *et al.*, 1996). Establishing the stressor-effects networks, however, requires knowledge about the components and dynamics of the system, while often it is difficult to evaluate the relative merit of different causal-chains (Erickson, 1994).

"*The LCSEA approach thus represents a merging of the cradle-to-grave* breadth *of LCA and the contextual* depth *of the environmental impact assessment sciences*" (Brown *et al.*, 1996, p. 7). In other words, LCSEA is primarily an environmental impact/risk assessment carried out over the entire life cycle of a product system. One anticipates that the basic tools currently used and under development for environmental impact/risk assessment equally could play a role in an LCSEA. Moreover, the strengths and weaknesses of these tools will carry over into the LCSEA methodology. In spite of the larger capabilities and complexities of the LCSEA approach, its proponents claim that the goal of LCSEA is nevertheless to present the end results in an LCA-like fashion, i.e., in reference to a functional unit, a comprehensive list of impact categories, and cumulatively over the life cycle of a product or activity (Scientific Certification Systems, 1997). However, the LCSEA approach calls for the impacts to be evaluated prior to, rather than after, any allocation, aggregation, and normalisation to a functional unit.

Contrary to the level of resolution of standard LCA, LCSEA appears detailed enough to address the research requirements of the SFM network at all stages of the forest products life cycle. For example, LCSEA could be used to characterise and compare the actual impacts of natural disturbance to those of natural disturbance-based models for management and harvesting of the boreal forest. This would entail the identification of the appropriate stressor-effects networks describing the multitude of impacts, including those at the ecological, human health, and socio-economic levels, of the forest products life cycle associated with the boreal forest of Canada.

In Conclusion

LCA has the capabilities to be used for comparative screening of management practices to select for increased eco-efficiency, based on broad holistic criteria. This represents a clear departure from other, more traditional, narrowly-focused environmental management approaches. Although the LCA technique -- primarily the impact assessment phase -- is still evolving, it is clear that it can be used to characterise specific impact endpoints. However, the inherent inability of LCA to characterise actual or potential environmental impacts suggests that the role of LCA within the SFMN should be complementary to the research integration activities of the network. This view of the role of LCA was illustrated in Figure 2.

Another possible role of LCA within the network has been described through the enhanced LCA approach known as LCSEA. LCSEA provides an analytical framework with a level of resolution and accuracy that is compatible with the requirements of the natural disturbance-based model and the remaining stages of the life cycle of wood products.

Finally, a combined approach involving both LCA and LCSEA can be envisioned, in which LCSEA would be implemented where most needed to characterise the natural disturbance-based model for SFM, while the remaining stages of the life cycle of wood products would be analysed through standard LCA. This would minimise the research requirements, since LCA is inherently simpler to implement than LCSEA. A decision regarding which of the above paths to follow is likely to be embedded within the objectives, priorities, and constraints of the SFM research network.

Future Work

Further research should include the development, application, and evaluation of the life cycle concepts in the context of SFM as outlined above. However, in the near future, the work should focus on the development of an LCI. If warranted, based on experience gathered through the development of a preliminary LCI-based tool, the research effort could later evolve to include an evaluation of impacts typical of a full life cycle assessment.

LCI could be particularly useful to investigate the life cycle-level consequences associated with fibre supply through intensive forest management. These effects are anticipated to occur at the forest level and at the mill level as well, given the typical dependency of mill processes upon the characteristics of the fibre supply. More specifically, the overall goal for this initial work should be to develop a dynamic LCI for a system linking fibre supply and wood products manufacturing. It is proposed that boreal forest lands of Alberta-Pacific Forest Industries Inc. (Al-Pac) of Boyle, Alberta be selected to serve as the case study site. Al-Pac has generated an extensive database that would aid in the proposed work and shown interest i a modeling effort of this kind. In addition, research work, involving Al-Pac, on fast-growing trees in Alberta is already underway and represents a substantial commitment by the company toward future commercial tree plantations (Arnold, 1995; Thomas *et al.*, 1998).

The project would focus on compiling an inventory database of the input and output flows of materials and energy (pollutant emissions, and energy and raw materials consumption), and economic costs, as well as pertinent ecological and socio-economic issues (such as natural habitat depletion, jobs, etc.) associated with Al-Pac's industrial activities. This work intends to provide an inventory characterisation over time, i.e., a dynamic evaluation of an LCI, and therefore it must directly incorporate the long-term dynamics and time-lags for the processes involved. As such, and contrary to most life cycle assessment undertakings that provide only a static analysis or snapshot of the system activities, this work would attempt to investigate how the overall system unfolds through time as a result of anticipated trends or possible future changes due to technological improvements, regulatory requirements, policy shifts, or any strategic decisions motivated by a search for sustainable practices.

The potential implications of this analysis are substantial. For example, consider the subject of net emissions of greenhouse gases. An evaluation of the future roles that sources and sinks of these gases will play under alternative management scenarios is crucial to shed light on the best approaches to be pursue. Nevertheless, the applicability of the research does not limit itself to the subject of climate change. Its broader context encompasses sustainability issues for the management of the boreal forest. Within this context, one fundamental question that this work should address relates to the potential implications of shifting the emphasis on fibre supply from extensive management of the boreal forest towards intensive forest management (industrial tree plantations). More specific issues to address include the environmental, ecological, and socio-economic consequences and trade-offs, and how these effects change as a function of the rate at which plantations are adopted. These are questions that can be elucidated through a comprehensive dynamic analysis effort comprising life cycle linkages of the various activities involved. Some early work already exists (notably Vasara and Jallinoja, 1997) that indicates a growing emphasis on life cycle assessment of the forest products sector using dynamic approaches. Others have conducted dynamic analysis, including modeling of energy and resource use through time, that resembles the concept of LCI over time (Ruth, 1998).

The concept of using intensive forest management to cultivate fibre has been and remains somewhat controversial (Sedjo and Botkin, 1997; Journal of Industrial Ecology, 1998). Nevertheless, given the current, almost total dependence on wood as the source of virgin fibre worldwide, there are growing compelling arguments for considering timber plantations. These plantations offer an enormous opportunity to reduce the required land base to sustain a specified level of wood supply (Sedjo and Botkin, 1997; Wernick *et al.*, 1998). It is argued that when tree plantations are pursued on already cleared or marginal agricultural lands and following appropriate management practices (such as protecting riparian zones, controlling erosion, using ecologically compatible pest management methods, minimising fertiliser use, and planting native tree species when possible) they can lead to overall environmental benefits (Sedjo and Botkin, 1997; Nilsson, 1998).

Within the boundaries of the LCI system to be investigated, there will be several activities. Regarding the subsystem of fibre supply through extensive management of the boreal forest, the life cycle stages to consider include road construction, woodlands management, tree cutting (logging) and transport (hauling), and wood storage, chipping, and pulping, as well as other required stages for ancillary raw material and energy extraction, transport, and processing. For the subsystem of fibre supply through industrial tree plantations, those stages include breeding of genetic pools of fast-growing trees, site infrastructure set up (such as roads, and irrigation lines), site preparation (such as tilling and soil conditioning), tree planting, growth (including watering, fertilising, weeding, and pest management), harvest (logging), and transport (hauling), and wood storage, chipping, and pulping, as well as ancillary raw material and energy extraction, transport, and processing. Figure 4 illustrates some of the stages to be included in this LCI analysis. Also shown are some of the inventory variables to be considered.

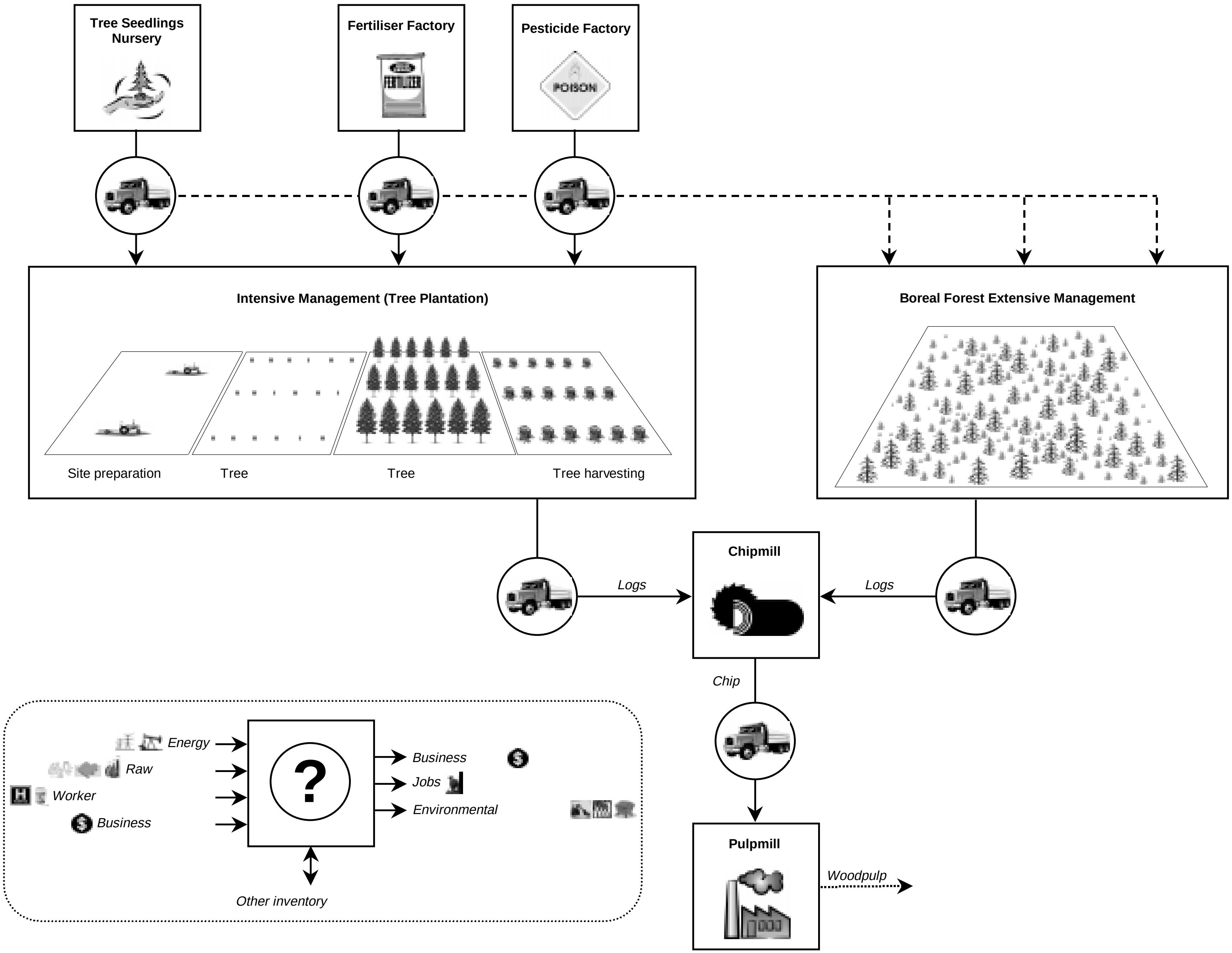

Figure 4 - Life cycle stages and inventory variables for the proposed LCI dynamic model.

The project will begin with the following phases and specific activities:

(1) Initiation. This will include a definition and justification coherent with the scope of the study for the criteria used to establish the exact system boundaries. It will deal with the definition of the functional unit and other methodological procedures such as input/output allocation and data quality evaluation. Furthermore, it will describe the set of initial modeling scenarios to be considered. For the scenario analysis to fulfil a practical purpose, these scenarios will have to satisfy several criteria: (1) consider both typical and novel practices for intensive forest management as well as incorporate extensive forest management approaches relevant to research activities within the Network; (2) allow for a variable degree of combined intensive and extensive forest management approaches; (3) be technologically feasible to implement; (4) have a time horizon that reflects the level of confidence with which the future conditions represented can be predicted based on the available information; and (5) explore alternatives pertaining to both core system activities (such as pulping and logging) and peripheral activities dealing with extraction and production of ancillary materials and energy (such as pesticide and fertiliser, fuel, and electricity).

(2) Data gathering and verification. This will involve gathering of inventory data from multiple sources (literature, LCI databases, proprietary data, etc.) and will include a characterisation of data quality. The information on data quality will be used as a measurement of some of the uncertainty to consider during model simulations. Data verification will include mass and energy balances to check for data inconsistencies. These activities will be aided by the framework provided by PEMS, which is a software package and database developed by Pira International of the UK specifically to assist in the deployment of a life cycle inventory.

(3) Dynamic LCI implementation. This will involve the implementation of a dynamic model as an LCI over time. The general purpose and object-oriented dynamic programming environment provided by STELLA software (developed by High Performance Systems in the U.S.) will be used as the structure upon which to build the relationships describing the dependencies of the inventory values. STELLA will not be used to simulate the smaller time scale interactions for the processes involved (such as the mechanistic details underlying the operation of a pulp mill). Rather, it will focus on describing the comparatively simpler relationships that model the continuous or discontinuous changes in processes that occur over a larger time scale. For instance, to represent a decreased trend on job intensity associated with logging operations, or an anticipated improvement in the technological performance of kraft pulping.

(4) Model testing and exploring. This will involve testing of model sensitivity and exploring the initial scenarios and the effects of uncertainty. It will make use of STELLA's built-in analysis capabilities for assessing different scenarios and the effects on model results of data uncertainty. Then, through a "what if…" iterative process, the initial scenarios may be further refined to lead to improved outcomes.

(5) Progress and final reports. These reports will, respectively, summarise the progress of research activities during the project and provide a detailed presentation and interpretation of results, and

conclusions associated with the complete project duration as well as any eventual recommendations for future work.

It is anticipated that this LCI tool can lead to a cost-effective exploration of the short- and long-term consequences of an array of "what if…" scenarios and associated uncertainties. Figure 5 shows a qualitative representation of the kind of results to be expected for a scenario investigation using the proposed LCI dynamic model. The insights and conclusions gathered through this process should directly assist the evaluation of the potential and desirable time frame for intensive forest management as an integral constituent of a strategy for sustainable management of the boreal forest.

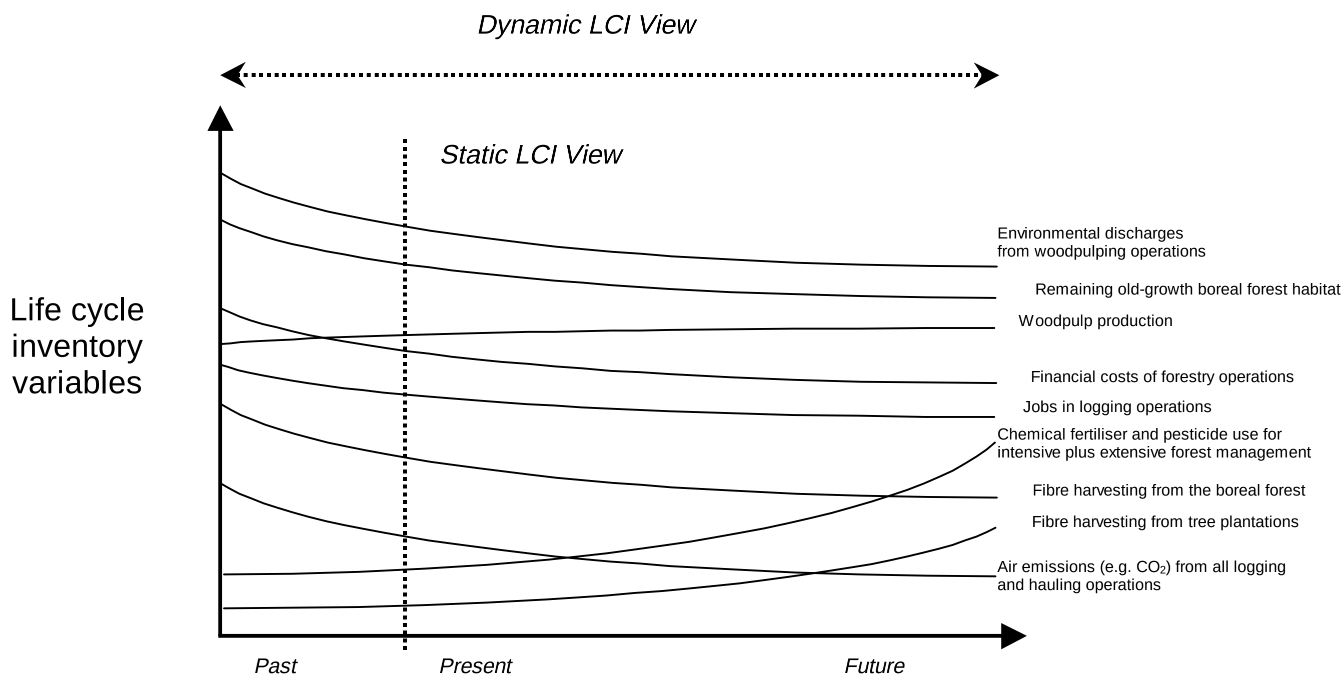

Figure 5 - Qualitative representation of the kind of results expected for a scenario investigation using the proposed LCI dynamic model.

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