Integrating forestry into the life cycle assessment (LCA) of forest products

Simo Kaila
Vesa Imponen
Sari Pitkänen

Metsäteho Report 116
1.8.2001

Metsäteho Oy
P.O. Box 194
FIN-00131 Helsinki
Finland

Phone
+358 9 132 521

Fax
+358 9 659 202

www.metsateho.fi

Integrating forestry into the life cycle assessment (LCA) of forest products

Simo Kaila
Vesa Imponen
Sari Pitkänen

Metsäteho Report 116
1.8.2001

(Abridgement in Finnish: Metsätehon raportti 117)

Funded by the following shareholders:

A. Ahlström Osakeyhtiö, Koskitukki Oy, Kuhmo Oy, Metsähallitus, Metsäliitto Osuuskunta, Metsäteollisuus ry, Pölkky Oy, Stora Enso Oyj, UPM-Kymmene Oyj, Vapo Timber Oy, Visuvesi Oy

Part of Wood Wisdom and FIBRE programmes

Contact information:

Simo Kaila
Vesa Imponen
Metsäteho Oy
P.O. Box 194
FIN-00131 Helsinki, Finland
first name.surname@metsateho.fi

Sari Pitkänen
University of Joensuu
Faculty of Forestry
P.O. Box 111
FIN-80101 Joensuu, Finland
sari.pitkanen@forest.joensuu.fi

Keywords: biodiversity, environmental management, forest management, LCA

Helsinki 2001

CONTENTS

FOREWORD

This report aims to establish, which issues should be considered essential in LCA of forest products, and how such LCA studies should be carried out. The findings can be used e.g. in discussing the raw material aspects of forest products with the customers, and the general development work of LCA in the field.

The report is a product of the research and development project *Analysis and use of research information in evaluation of environmental impacts concerning identification of environmental aspects in environmental management systems (EMS)*. It is included in the research consortium *Tools for environmental management in wood procurement* [1], which is part of Finnish Forest Cluster Research Programme *Wood Wisdom* (1998 - 2001) [2].

The larger part of the project focuses on developing a forestry organisation's better-established management tools, including the identification of environmental aspects of EMS, and the evaluation of the related environmental impacts[3].

The research consortium also includes two other projects, *Measurement and monitoring of biodiversity*, and *Processes of wood production, logging and transport in LCA of forestry and forest products*. The latter project is further closely linked with two parallel *Wood Wisdom* projects, *Stand development and energy, carbon and nutrient balances in a stand* and *Development and utilisation of life-cycle assessment (LCA) in private forestry use*. The part of this report that demonstrates modelling in LCA is largely based on these last three projects.

[1] Official name: *Suitability of methods related to quality and environmental management systems (QMS, EMS) and life-cycle assessment (LCA) for analyses of forestry operations*

[2] The research consortium has obtained funding for *Wood Wisdom* projects from *Tekes*, the National Technology Agency of Finland. It has also been funded under the Finnish Biodiversity Research Programme *FIBRE* (1997-1999).

[3] Other reports (in Finnish only): *Tutkimustiedon soveltaminen ympäristöjärjestelmissä,* no. 80*; Asiantuntijanäkemykset ympäristövaikutusten arvioinnista,* no. 101; *Sidosryhmänäkemykset puuntuottamisen ympäristövaikutuksista,* no. 111; and *Puuntuotannon ympäristönäkökohtien tunnistaminen ja merkittävyys ympäristöjärjestelmässä,* no. 104.

ABSTRACT

Drastic changes have been made in forestry practices during the last decade to ensure that natural values are given greater consideration. These changes have been based on a general picture obtained from environmental research, rather than on its contribution to solving practical management problems. Developments in forestry are now at a stage where the further integration of "ecosystem management" is hampered by the fragmented and unclear nature of the relevant information, especially on biodiversity.

The way forward for integrating environmental development issues into practical forestry lies in improving the knowledge basis through research. The recently implemented Life Cycle Assessment (LCA) schemes, together with the associated Environmental Management Systems (EMS), can be expected at the same time to develop into useful management tools.

Originally, LCA was intended to cover product systems "from raw material acquisition through production, use and disposal". But for products based on renewable natural resources that are actively managed for specified raw material uses, raw material acquisition is not a satisfactory starting point for the production chain.

This report suggests that wood raw material production, including natural processes, should be specifically included as part of the product system in the LCA of forest products. Such an expansion of the scope of LCA is made possible by modelling, based both on forestry planning systems and data, and on ecological research related to forests. Two basic modelling options are outlined, i.e. the logging site and the forest area approaches. In the logging site approach, the material and energy flows, set off by the cuttings, are modelled over time. In the forest area approach, a larger forested area is seen as a black box type raw material source, and its material and energy flows are calculated over a convenient time-span, such as a year. In both cases, allocation problems must be appropriately resolved.

Biodiversity is in many respects the ultimate touchstone for environmental management systems. But quantitative assessments of biodiversity are still impracticable, given current levels of knowledge. In environmental management in general, LCA seems to be the best available tool for handling information on material and energy flows, whereas information on biodiversity can best be processed in EMS. In LCA biodiversity can evidently only feasibly be dealt with through qualitative indicators.

1 INTRODUCTION

Forest management has undergone a paradigm change during the last decade. Natural values have been given prominence alongside the demands of economics and long-term productivity. This development is also reflected on the international level, in conventions dealing with sustainable management and biodiversity of forests, and their role in strategies for slowing climatic change (1993a).

The consequent changes have been incorporated in practical management guidelines as well as legislation (1999). New modifications of silvicultural methods and practices have been adopted, and forest certification schemes are in use. In the Nordic Countries, these changes involve preserving decayed and old trees, mixtures of tree species, retention tree groups or forest cover in regeneration areas, and habitats of special biodiversity value. Prescribed burning during regeneration has also increased. In special areas, full-grown tree stands may be burned, and drained wetlands restored to their natural state. However, there is a consensus among experts that detailed, research-based knowledge on the impact of this "new forestry" on forest ecosystems is still lacking (Niemelä 1999).

Another change affecting forest management at the same time has been the introduction of tools for environmental management; firstly Environmental Management Systems (EMS) during the second half of the 1990s, and then Life Cycle Assessment (LCA) by the end of the decade. All Finland’s large forest industry corporations now use ISO 14 000-series environmental management systems and apply LCA studies for identifying environmental aspects and developing products. ISO 14 000 environmental management systems are also in use in all sectors of forestry – corporate and state forestry as well as private owners' forest management associations. Extending LCA studies to include the raw material aspects of forest products has also been started, but questions have arisen as to whether the really relevant problems concerning forestry can be dealt with by LCA.

Environmental issues in forestry differ from those affecting industrial production, where emissions and the use of resources are of the highest concern. LCA, like EMS, was originally developed to serve in industrial applications. As possible issues for special concern, ISO 14 001 lists emissions to air, releases to water, waste management, contamination, and the use of raw materials and natural resources (1996). The introduction to ISO 14 040 presents LCA as a technique for studying a product's life cycle “from raw material acquisition through production, use and disposal” (1997). This definition implicitly excludes the production of raw materials from the product system.

Confining analysis to a traditional LCA study, with the phase life cycle inventory (LCI) starting from raw material extraction, inevitably means an under-utilisation of the available information on relevant points related to wood as a raw material, and also results in a poor connection to the next phase. Though life cycle impact assessment (LCIA) contains impact categories like greenhouse gas balance, and depletion themes like damage to biodiversity and life support, it obviously lacks modular integrity, if based on incomplete LCI with regard to all the relevant associated energy and material flows. An expansion of the scope of LCA studies is needed: wood production must be modelled into a part of the product system as a specific phase within LCI, with both silvicultural operations and the natural processes included.

In order to improve the application of LCA, European Concerted Research Action, COST E9, which aimed to develop the LCA of forestry and forest products, was set up in 1997. According to its memorandum of understanding (1997b), the reasons for performing LCA studies are:

- to obtain quantified and reliable information for the emotive debate on the environmental impact and benefits of wood products, so that this information can be used by industry and policy makers
- to improve production and recycling techniques by minimizing steps with high environmental impact, choosing different processing routes to reduce environmental impact, or highlighting compatibility between processing
- to highlight areas where information on the environmental impact of products is still unknown or uncertain
- to enable comparison between different materials (provided that products are used for the same purposes - e.g. railway sleepers made of wood, concrete, or steel).

Special problems described as relating to LCA in forestry included the considerable areas of land used; the long production and use chains of forest products, starting with wood production, and ending with disposal or energy use; the greatly varying life cycles of different products; and the complex relationships between products, by-products and waste.

2 PROBLEMATIC ASPECTS OF FORESTRY LCA

2.1 Defining the scope of LCA

Completely different themes are emphasised in forestry as primary environmental aspects compared to those applied generally in industry. The focus is on the extent to which wood production is practised in compliance with the ideals of sustainable development. With production chains starting from raw material acquisition, this issue is left out of competent analysis altogether.

In forestry, the functioning of forests as renewable natural resources is primarily of interest, along with biodiversity.

As to development work in forestry, the forest industry looks to LCA for a potential source of tools for measuring sustainable development, for use in promoting the sustainability of its products, and in environmental reporting. Where forestry is concerned, this means that wood production and the development of silvicultural methods should be economically, ecologically, and socially sustainable.

LCA as a tool is basically adapted to assessing the ecological aspects of sustainable development. Economical and social aspects have not usually been included, since LCA has explicitly been established as a method for analysing impacts on nature, rather than on man's other activities. Lindeijer et al. (1998), for example, propose an impact score for land use, which would comprise the impacts on *life support function* and *local biodiversity*. In forestry, the equivalent to this division could be the impacts on forests as renewable natural resources, and on biodiversity, mentioned above.

2.2 Forests as renewable natural resources

Forests are tended so that they provide certain mixes of raw materials and other goods and services, instead of merely for the exploitation of natural resources. Carbon, energy and nutrients entering the system become important alongside emissions and energy consumption. Finally, material flows and solar energy absorption also largely depend on the intensity of silviculture, as the choice of forest management system significantly affects the total balances of these material and energy flows (Karjalainen 1996).

There are good grounds to include all the relevant material and energy flows related to wood production in the scope of the LCA of forest products, because it is an active element of the production chain. This expansion of LCA can be carried out with reasonable integrity if sophisticated modelling tools, data management and forest ecological research are applied.

2.3 Biodiversity

In an assessment of the Finnish forest sector´s environmental loads, it was estimated to be responsible for almost half of domestic biodiversity problems, with forestry as the main factor (Seppälä & Jouttijärvi 1997). Values of this order point out that biodiversity should be given plenty of consideration in environmental management in the forestry sector, along with forests as renewable natural resources.

However, there are serious problems when it comes to accounting for biodiversity in the quantitative analysis required for LCI (1998). To comply with this qualification, quantitative approaches to measuring biodiversity have been suggested. Especially the species-diversity of vascular plants has been advocated as a variable indicating local or regional biodiversity (Lindeijer et al. 1998, Köllner 2000).

The concept of biological diversity is, however, considerably wider than simplified definitions can cover. The definition in the Convention on Biological Diversity reads: "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" (1993b).

Biodiversity is thus not to be considered as an unambiguous feature of a specified biological community that can be measured at a certain time with a single yardstick. It is rather an attribute characterising nature as a whole. It cannot validly be defined as a momentary state in a stand of trees; rather it should be examined simultaneously on multiple temporal and spatial scales, and analyses on different scales may even show contradictory results. It should also be noted that processes occurring on larger spatial scales also tend to take a longer time (Niemelä 1999). This problem of scale makes biodiversity such a complex issue that it can only be approached analytically with great difficulty.

3 FINDING A SUITABLE LCA APPROACH FOR MODELLING IN FORESTRY

3.1 Modelling in forestry

Forestry can be defined as a part of the forest industry's product system, which can be divided into the processes of wood production, logging, and transportation.

Logging and *transportation* form the extraction of wood raw material. These processes have typically a short time scale – in Finnish wood procurement systems typically a few weeks or months – and can therefore be dealt with in LCA studies of forest industry products quite straightforwardly. The processes can be described as transparent, with plenty of accurate information available for application in LCI and subsequent stages of LCA.

Wood production, however, is more problematic where LCA is concerned, not least because it operates on a time scale of several decades. Moreover, the production units are more or less natural ecosystems, whose processes are directed but not completely controlled man's silvicultural operations. Many aspects of these processes are complex, and information on them is scarce and often of uncertain accuracy. Because of the time scale problems, these processes cannot be covered by simplistic inventories. For instance, annual silvicultural operations have no direct causal links with simultaneous wood raw material logging. Obviously, forestry should not be subjected to LCIA based on averaged inventory values without considering the complex nature of the silvicultural system.

To include wood production into the LCA framework, LCI needs a special modelling phase. The modelling calculations lead to an additional factor of uncertainty. However, the forestry sector has for a long time inventoried the growth and yield of forests, and modelled the development of stands and single trees, as well as the consequences of logging and silvicultural operations. Process modelling based on eco-physiological and forest ecology research has also made it possible to simulate energy, carbon, and nutrient flows in stands, and their dependence on forestry operations. Through combining forest growth, forestry operations, and eco-physiological models, a new set of models has been devised to produce analysis results of the relevant order of magnitude which also have the necessary sensitivity to distinguish between optional management systems.

There are two basic options in modelling wood production:

- assessing the material and energy flows associated with the amount of raw material needed for the functional unit of the *product*
- assessing the material and energy flows associated with raw material production in a *forestry area*.

The first option fits into forest product analysis, and the second into an eco-balance type assessment. The first option can further be realised by modelling together with the actual process of logging either all the events leading up to logging from the beginning of the rotation period, or all subsequent events until the end of the next rotation period. The choice is a pragmatic one: the retrospective system involves uncertainty concerning previous developments, and a review decades back into history may not be appropriate considering the purposes of an LCA study. The forecasting system contrastingly assumes that silviculture is predictable, and that the models are workable enough.

In order to meet both the needs of forestry development and forest product LCA, two kinds of end products are required. They were outlined as:
1) the logging site approach, and 2) the forest area approach. The same basic models are intended for use in applications using either approach.

The *logging site approach* is designed especially for LCA applications for forest products, where the functional unit is a certain amount of the product, and the raw material is extracted from certain stands. In logging and transportation, the approach meets with some allocation problems, because the trees felled in a stand are cut to different timber assortments for different uses, such as saw logs and pulpwood. Wood production can be practically considered as a result of logging, but forecasting problems arise, which must be resolved through proper modelling. The assumed silvicultural system will have a strong effect on the modelling results, and must be specified accurately. However, the strength of this approach is in its relevant causality chain.

The forest *area approach* is more applicable for eco-balance type analysis of forestry. In this approach, a larger forest area is seen as a production unit, which has a continuous output of raw material mix, and an input of resources. Operations, growth, and hence carbon sequestration and solar energy absorption can be basically monitored and inventoried during a suitable time period, such as a year. Over a larger area, forestry operations and timber flows can also be analysed on a scale relevant for practical wood procurement.

These approaches are ideal type options, and they are not incompatible. In practical LCA studies and eco-balance calculations, depending on the task, applications that include features of both these options may be the most practicable solutions.

Neither of these approaches covers biodiversity. Research and development work done in the consortium (see p. 4) has shown biodiversity to be beyond quantitative assessing in the context of practical forestry, because of conceptual, scale, and measurement problems. Even if some kind of a shortcut could be worked out, there would still be problems with interpreting the results and relating them to forestry. The use of the results would be hindered by the following anomalies:

- the variety of habitats and the number of species are generally dependent on soil fertility and climate
- forestry operates annually on some 1 - 2 per cent of the total forest area on average; the observable habitat situation and biodiversity are products of successive developments triggered by earlier management practices and natural disturbances
- many species exist in networks of several interconnected local populations (Hanski 1994), and may only exhibit a delayed reaction to habitat changes, when certain source areas are lost.

For the time being, this second possible point of interest in LCA, which cannot be assessed through energy and material flows, is thus generally considered to be impossible to evaluate through quantitative analysis. An approach based on qualitative indicators seems to be the only practicable option for taking it into account.

3.2 Modelling tools

3.2.1 Process-based modelling

The model described here provides a tool for simulating the effects of the main factors determining stand growth and nutrient cycles in forest ecosystems (Fig.1). It can be used in LCI to connect wood production to the LCA framework. Here a tree stand is considered as a set of separate trees with spatially-explicit positions within the stand, and the local interactions of trees with their neighbours, including competition for light, soil water, and nutrients, are all described as processes. In the model tree growth is restricted by three factors: climate, light conditions within the stand, and nitrogen turnover.

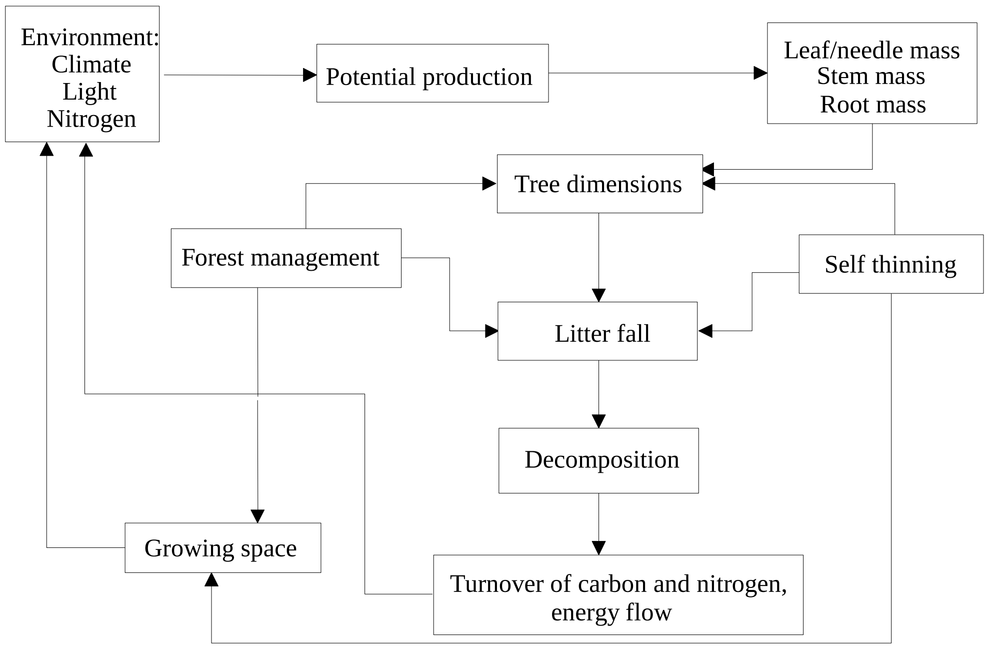

Figure 1. An outline of the framework for calculations.

Tree growth is calculated as the biomass production of a tree. Biomass production is based on a calculation of the potential biomass increment, known as tree net primary production (NPP), which refers to the maximum possible biological productivity of leaves or needles. This depends on the supply of soil nutrients and the ability of a tree to utilise this supply (specific nutrient consumption rate). Each tree needs a certain amount of nutrients for the synthesis of a unit of tree biomass (Chertov, 1983).

This model allows us to estimate the effects of the nutrient supply on stand growth and nitrogen turnover in the forest ecosystem with regard to a tree's position in the stand and the relevant site characteristics (Fig. 2). Different cutting regimes, the possibility to define the user's own cutting specifications, and a consideration of the ensuing consequences of cuttings are all included in the model. The tree-soil system model has been developed from an existing model (Chertov et al., 1999). A related model of soil organic matter dynamics is described in Chertov & Komarov (1997) and in Chertov et al. (2000). This simulation model can be used for Scots pine (*Pinus sylvestris* L.), Norway spruce. (*Picea abies* L. Karst.), and Pendula birch (*Betula pendula* L.) stands as well as in mixed stands of these species in Finland.

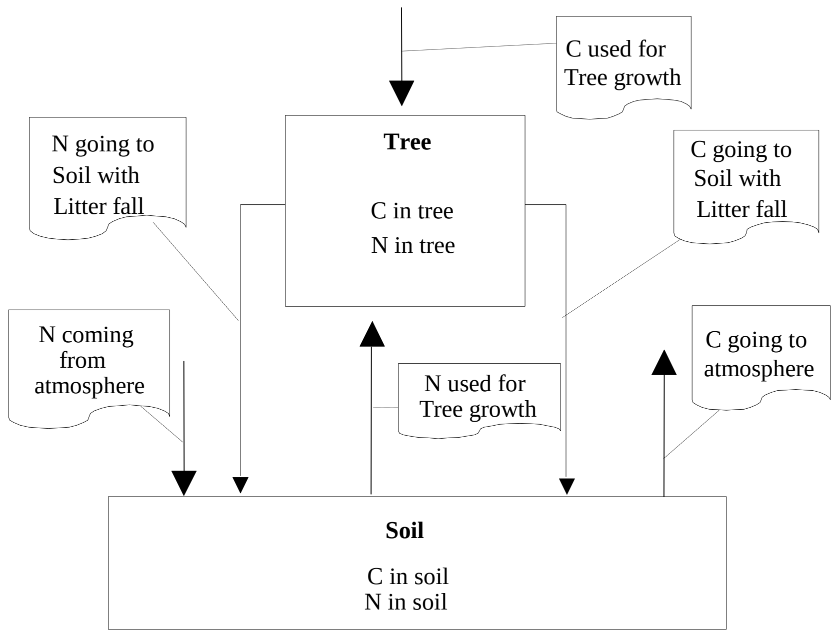

Figure 2. Nitrogen and carbon flows in the model.

The actual growth of tree biomass is dependent on the local light intensity, available nutrients, and water supply, and is determined as a potential growth that is reduced according to certain growth coefficients (Botkin et al., 1972; Kellomäki et al., 1992, 1993). A detailed consideration of the water regime of the stand is omitted, assuming that the stands are growing in optimum conditions of air humidity and soil moisture. The response to weather changes is simulated in a soil sub model.

Tree biomass increment is calculated with species-specific equations by Marklund (1988) that are of the general form:

$W_d=\exp(b_0+b_1*D/(D+g)+b_2H+b_3\ln(H))$,

where W_d is dry weight (kg), D is diameter at breast height (cm), H is height (m) and $b_0,\ldots,b_3$ and g are parameters. The biomass is calculated for different tree compartments (stem, branches, leaves, fine roots, coarse roots). This biomass increment is then converted back to diameter and height increments, which are used again in biomass calculations. The biomass increment of a tree is dependent on the available light and the proportion of available nitrogen in the soil.

The different constituents of tree litter fall (leaf, root, and branch) are calculated for every tree with the total mass and nitrogen of every constituent. The litter constituents are decomposed at rates depending on climatic conditions and the quality (e.g. nitrogen and ash contents) of the litter that contributes to the pool of organic matter in the soil. When a tree dies, the additional elements of dead wood and thick roots are included in the soil model. Tree mortality is defined in two different ways. Firstly, there is a deterministic procedure of self-thinning based on a lethal ratio of leaf mass to total biomass, under which conditions the tree dies. Secondly, the model incorporates a probabilistic mortality procedure.

The product of the model consists of information on a simulated tree stand. The situation of the tree stand; i.e. height, diameter, basal area, biomass, volume, etc., at the end of the simulation are expressed as a table and time series. The quantities of nitrogen and carbon in trees and in soil, as well the nitrogen and carbon balances, are also available as time series. The output also includes volumes, the amounts of logging residue, pulpwood, saw timber, and energy wood, as well as the other cutting information. Figures for nitrogen, carbon, and energy in the tree stand are presented as tables for the different tree compartments, and for harvested trees, natural removal, and standing trees.

An example case simulation by the model, concerning a Vaccinium site type pine stand on till soil, regenerated by disc trenching and direct sowing, with a rotation period of 80 years, and three thinning operations, is presented below. The input data, characterising the growing stock in the stand at the age of 15 years, were set as in Fig. 3.

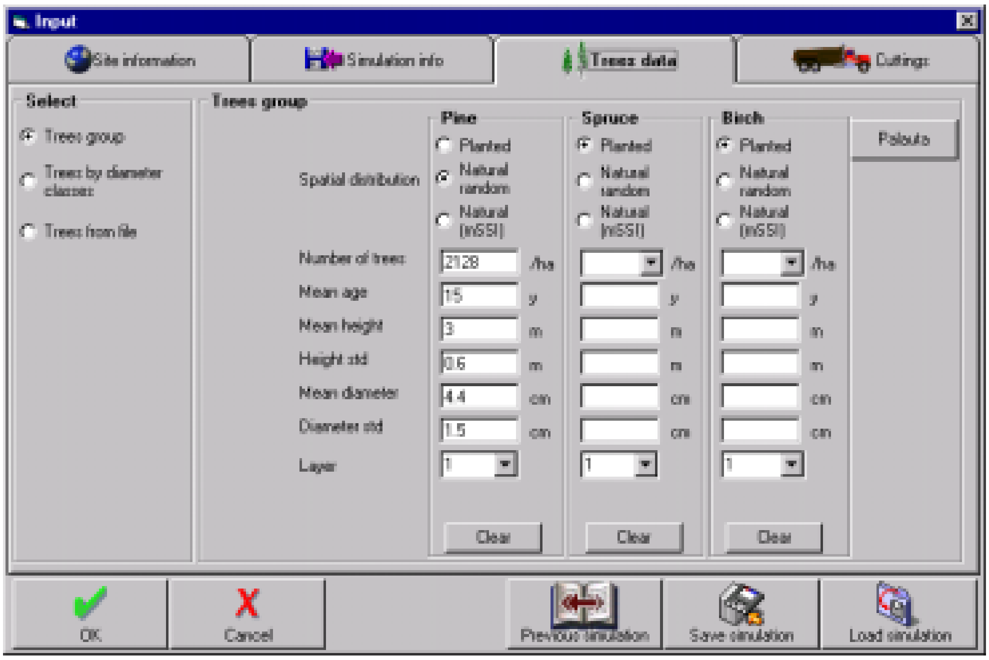

Figure 3. Growing stock input data.

The simulation menu shows also the carbon and nitrogen stress in the trees and in the soil. The initial state at the age of 15 years is shown in Fig. 4.

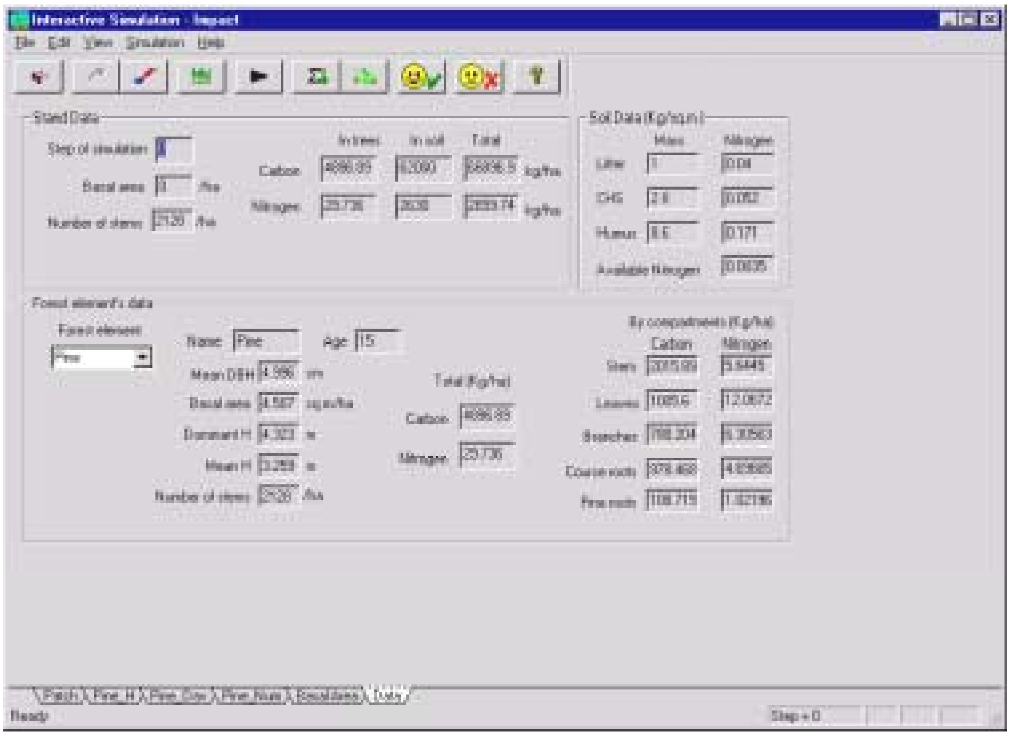

Figure 4. Simulation menu.

An example of cutting information is seen in Fig. 4.

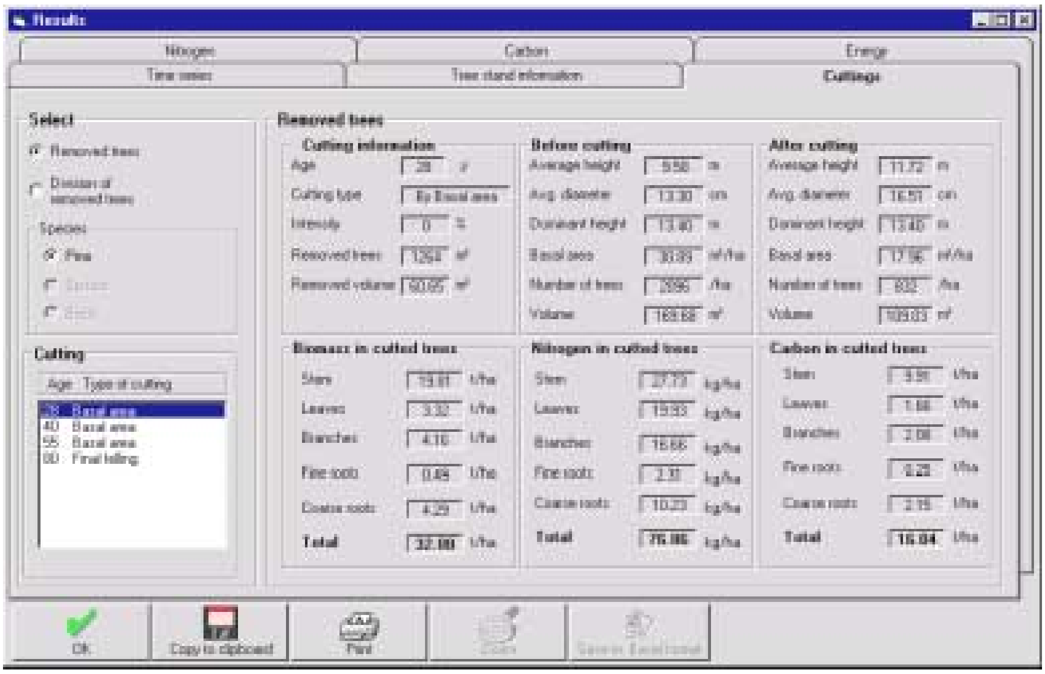

Figure 4. Cutting information: first thinning.

Results of calculations concerning the amounts of carbon stored in the growing stock, and in the soil, are shown in Fig. 5.

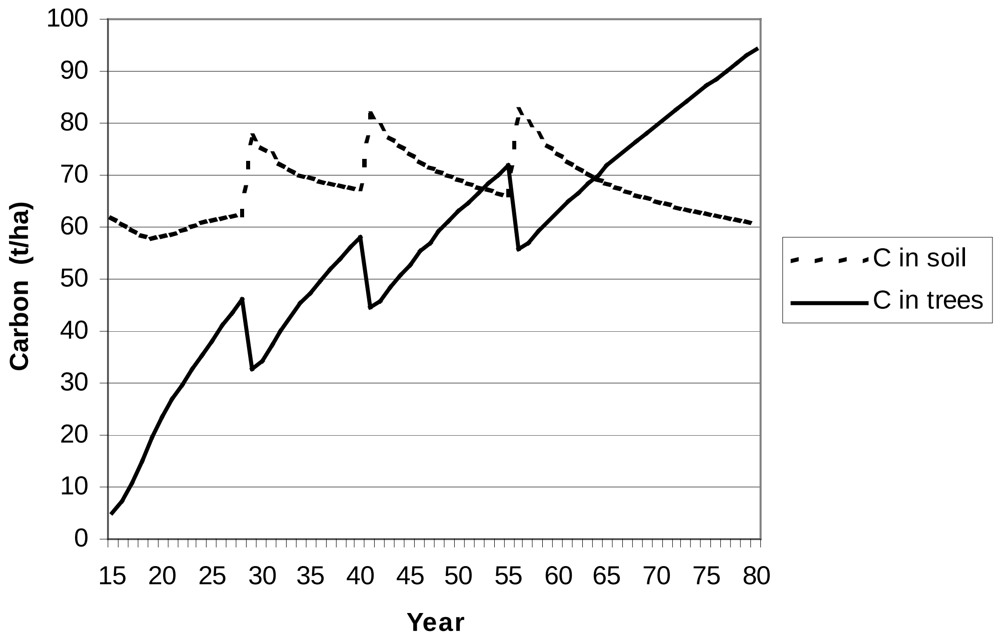

Figure 5. Carbon stored during the simulation period.

The ability of the model to handle mixed-species stands with different canopy structures, which are difficult to assess in standard growth models, was also tested. A case study was set up, simulating a situation where all silvicultural operations and thinning had been totally neglected after regeneration. The stand consisted of birch, pine, and spruce seedlings with respective mean heights of 5 m, 3 m, and 1 m. The results proved that this model could also be applied for such comparisons (Fig. 6).

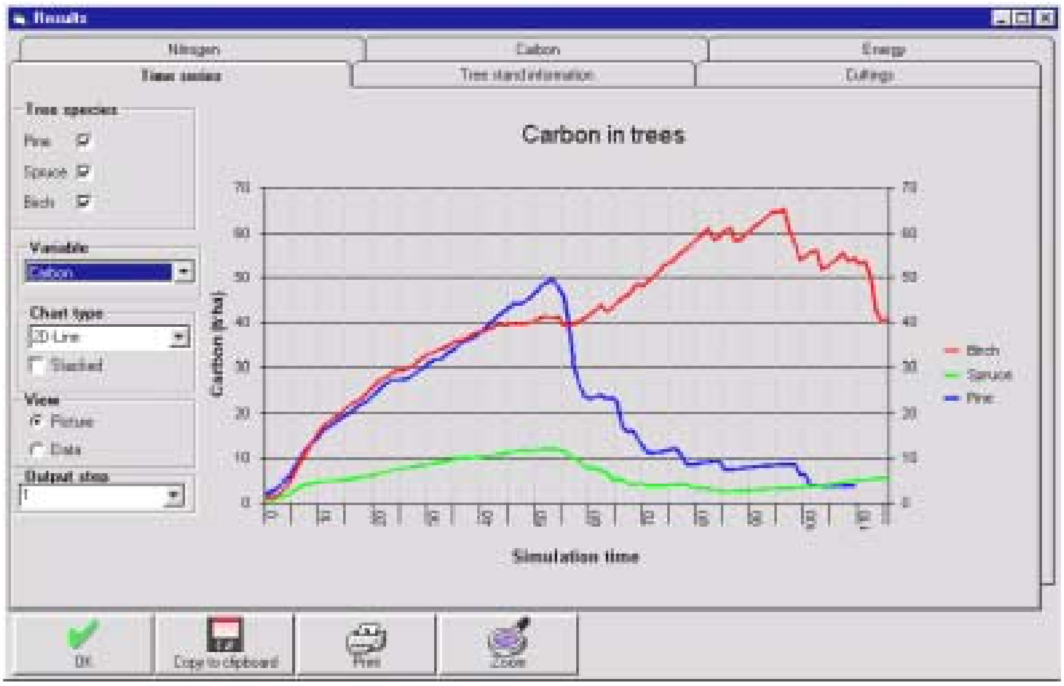

Figure 6. Development of a mixed stand left unmanaged after the age of 10 years: a case study.

3.2.2 Modelling based on regional forestry data

Another type of modelling was tried, based on the forestry data collected by the Finnish Forest Research Institute and regional Forestry Centres, as processed for the regional forestry planning carried out by the Centres. This was attempted in order to find out, how existing information, statistics, and planning systems can be used in calculating material flows for the LCA of wood raw material production. A special project was launched for this purpose by the Forestry Development Centre Tapio. The aim was to determine whether the relevant information can be acquired from various existing sources, and to demonstrate the usefulness of such information for LCA.

Nutrient balances for nitrogen and phosphorus were calculated on the basis of information covering some 1.4 Million ha of forested land, obtained from the Forestry Centre of Central Finland, one of the country's 13 regional forestry centres (Fig. 7).

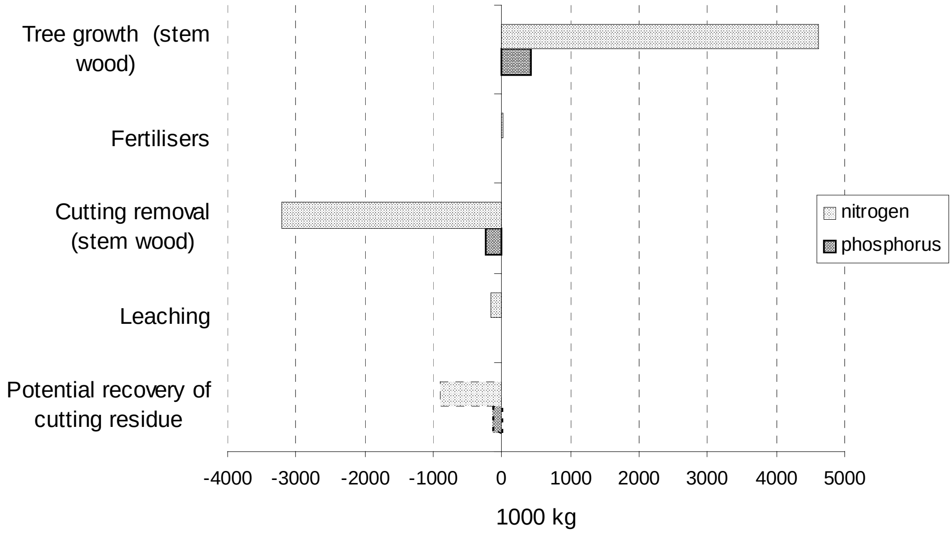

Figure 7. Major nitrogen and phosphorus flows in forests covered by the regional forest centre for Central Finland in 1999.

In the same region, forecasts made under the regional forestry planning system expressing the largest sustainable cutting removals from 2000 to 2030 gave results for the average annual changes in the carbon store as shown in Fig. 8.

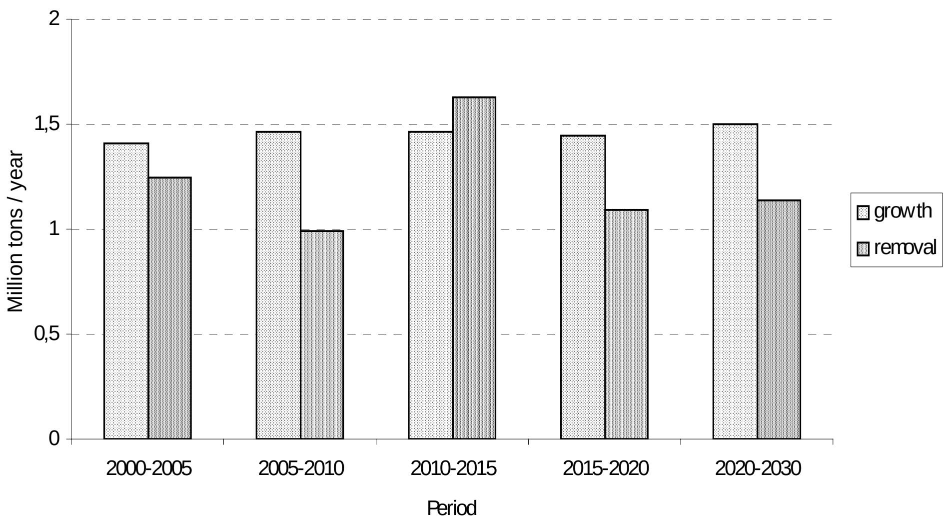

Figure 8. Annual changes in the carbon store in growing stock in forests covered by the regional forest centre for Central Finland by calculation period.

4 CONCLUSIONS

Wood raw material production should and can be included in the LCA of forest products by expanding the scope of LCA studies, with support from advanced modelling techniques. In logging site approaches, process-modelling tools can be used to simulate development and operations in stands. In regional approaches, larger-scale forestry statistics and forestry planning systems are the main resources for use in modelling.

It is clear that a single comprehensive LCA application for the whole forestry and forest industry sector will not fulfil the different requirements relating to LCAs. For forestry development purposes, process and site-specific data and modelling are needed. For forest products and cross-sector LCA, simplified applications, using indicators rather than detailed quantitative analyses of aspects of raw materials, are necessary. However, different applications should not be developed separately, but ought to be based on the same research findings, and on a similar understanding of technological and natural systems.

Assessing biodiversity in quantitative terms for LCA purposes seems to be extremely difficult. There are serious conceptual and practical problems, and even if biodiversity could be assessed in a suitable way, it would still be difficult to determine how much the results would reflect current forestry practices.

REFERENCES

1993a. Ministerial Conference on the Protection of Forests in Europe, 16-17 June 1993 in Helsinki. Documents. Ministry of Agriculture and Forestry of Finland. Conference Secretariat.

1993b. Ministerial Conference on the Protection of Forests in Europe, 16-17 June 1993 in Helsinki. Resolution H2 'General Guidelines for the Conservation of the Biodiversity of European Forests'. Documents. Ministry of Agriculture and Forestry of Finland. Conference Secretariat.

1996. SFS-EN ISO 14001 (1996-09-23). Ympäristöjärjestelmät. Spesifikaatio ja ohjeita sen käyttämiseksi. Environmental management systems. Specification with guidance for use. Suomen Standardisoimisliitto SFS.

1997. SFS-EN ISO 14040 (1997-09-22) Ympäristöasioiden hallinta. Elinkaariarviointi. Periaatteet ja pääpiirteet. Environmental management. Life cycle assessment. Principles and framework. 22 pp. Suomen Standardisoimisliitto SFS.

1997b. Memorandum of Understanding for the implementation of a European Concerted Research Action designated as COST action E9, “Life cycle assessment of forestry and forest products”. Technical annex. Brussels, 11 April 1997. COST 233/97.

1998. SFS-EN ISO 14041. Ympäristöasioiden hallinta. Elinkaariarviointi. Tavoitteiden ja soveltamisalan määrittely ja inventaarioanalyysi. Environmental management. Life cycle assessment. Goal and scope definition and inventory analysis. 40 pp. Suomen Standardisoimisliitto SFS.

1999. Ministry of Agriculture and Forestry. Finland’s national forest programme 2010. Publications 2/1999.

Botkin, D.B., Janak, J.F. and Wallis, J.R. 1972. Some ecological consequences of a computer model of forest growth. Journal of Ecology 60: 849-872.

Chertov, O.G. 1983. Quantitative approach to species ecological parameters with special reference to Scots pine (*Pinus sylvestris* L., Pinaceae). Botanichesky. J. (Leningrad) 68:1318-1324 (in Russian with English abstract).

Chertov, O.G. and Komarov, A.S. 1997. SOMM: a model of soil organic matter dynamics. *Ecological Modelling* 94: 177-189.

Chertov, O.G. Komarov, A.S., Tsiplianovsky, A.M. 1999. A combined simulation model of Scots pine, Norway spruce and Silver birch ecosystems in the European boreal zone. *Forest Ecology and Management* 116: 189-206.

Chertov, O.G., Komarov, A.S., Nadporozhskaya, M.A., Bykhovets, S.S., Zudin, S.L. In press. ROMUL - model of forest soil organic matter dynamics as a substantial tool for forest ecosystem modelling. *Ecological Modelling*.

Kellomäki, S., Väisänen, H., Hänninen, H., Kolström, T., Lauhanen, R., Mattila, U. and Pajari, B. 1992. SIMA: a model for forest succession based on the carbon and nitrogen cycles with application to silvicultural management of the forest ecosystem. *Silva Carelica* 22. 85 pp.

Kellomäki, S., Väisänen, H. and Strandman, H. 1993. FinnFor: a model for calculating the response of the boreal forest ecosystem to climate changes. Research Note No 6, Faculty of Forestry, University of Joensuu, Finland. 120 pp.

Hanski, I. 1994. Patch-occupancy dynamics in fragmented landscapes. Trends in Ecology and evolution 9: 131-135.

Karjalainen, T. 1996. Model computations on sequestration of carbon in managed forests and wood products under changing climatic conditions in Finland. Journal of Environmental Management 47:311-328.

Köllner, T. (2000). Species-pool Effect Potentials (SPEP) as a yardstick to evaluate land-use impacts on biodiversity. Journal of Cleaner Production 8: 293-311

Lindeijer, E., Kampen, M., Fraanje, P., van Dobben, H., Nabuurs, G.-J., Schouwenberg, E., Prins, D., Dankers, M. & Leopold, M. 1998. Biodiversity and life support indicators for land use impacts in LCA. Ministry of Transport, Public Works and Water Management; Directorate-General of Public Works and Water Management. Publication series raw materials Nr 1998/07. W-DWW-98-059. Delft.

Marklund, L.G. 1988. Biomassafunktioner för tall, gran och björk i Sverige. Summary: Biomass functions for pine, spruce and birch in Sweden. Swedish University of Agricultural Sciences, Department of Forest Survey, Report 45, p.73 (in Swedish, with English summary).

Niemelä, J. 1999. Management in relation to forest disturbances and dynamics. Forest Ecology and Management 115:127-134.

Seppälä, J. & Jouttijärvi, T. (eds.) 1997. Metsäteollisuus ja ympäristö. Forest Industry and the Environment. The Finnish Environment 89. Finnish Environment Institute, Ministry of the Environment. In Finnish with English documentation page.