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Forest industry and the environment: a life cycle assessment study from Finland

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Abstract

Management of forest resources and related industries has a significant effect on the Finnish environment. Therefore there was an obvious need for a study to assess environmental impacts and to identify needs and options for environmental improvements in the forest sector. It was against this background that the Finnish Environment Institute carried out a life cycle assessment (LCA) of the Finnish forest industry. This application included methodological innovations compared with the traditional product-related LCA because it was a study of the whole production system of the mechanical and chemical forest industry. Areas for improvement of environmental protection in the forest sector for the year 2005 were identified on the basis of the inventory (emissions, wastes, etc.), environmental impact assessment and other available data. During the study a new impact assessment procedure was developed in order to assess more actual impacts of country-specific systems. Although the prioritized factors found were not strongly ranked against each other it can be concluded that maintaining biodiversity in the context of forestry practices and increasing the efficiency of energy use are the key issues in the environmental protection of the forest sector. Before detailed ranking of emissions and other stressors can be produced there is a need for more reliable stressor data, better understanding of stressor–effect relationships and more consensus on the importance of different environmental problems. Despite the limitations and needs for further development, the presented LCA approach can be regarded as a useful tool for providing a deeper understanding of the key issues in the environmental protection of a whole production system. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Forests are a vital renewable natural resource in Finland and the forest sector is most important to the Finnish national economy. Finland's forest resources have grown by 22% in the 40 years from the beginning of the 1950s [1], and the total standing stock is now more than two billion cubic metres [2]. Forests are harvested in a sustainable way with a total harvested volume of 55 million cubic metres in 1994 [1]. Various estimates give figures of 70–80 million cubic metres per annum for sustainable harvest from 2010 onwards.

Forestry, serving the needs of the forest industry practically throughout the country, has had adverse effects on forest ecosystems. Furthermore, the forest industry is a significant consumer of primary energy and is responsible for a substantial part of industrial emissions. Development in the forest industry is thus of crucial importance for the future state of the Finnish environment.

Environmental protection has long traditions in the Finnish forest industry, but new challenges are increasingly put to the industry by the markets and by the authorities. Reducing emissions is not enough any more; there are growing demands from markets to improve the ecological sustainability of forestry practices in particular.

It was against this background that the concept of an environmental programme for the forest industry was first discussed in the Ministry of the Environment, Finland. The preparatory work started in spring 1995 as a life cycle assessment (LCA) of the forest industry and was carried out by the Finnish Environment Institute.

The aim of this presentation is to describe the methodological aspects of LCA and the possibilities to use an LCA approach to the production of data and to the prioritization of areas of environmental protection in the forest industry including its main life cycle stages. The LCA results are also briefly described.

2. Goal definition and scoping

The LCA study [3] had three main objectives: (1) to assess environmental impacts of Finland's forest industry and its life cycle stages, (2) to identify needs for environmental improvements in the forest sector during the next 10 years, and (3) to assess environmental policy instruments aiming at enhancing sustainable development within the forest sector.

So far most LCAs have been studies of a single product or service system, or comparative studies of a limited number of alternatives. However, this application was a study of the whole production system of the Finnish forest industry. Both the mechanical and chemical forest industry were studied. There were 170 sawmills, 21 panel mills and 50 impregnation plants in Finland in 1995. The pulp and paper, i.e. chemical forest industry, comprises 47 mills.

The functional unit of the study was the whole annual production of Finland's forest industry. The main product groups were: (i) mechanical and chemical pulp, (ii) paper, paperboard and converted products, (iii) sawn wood, and (iv) panels (plywood, particle board, fibreboard).

Information on time and spatial detail in today's LCA framework concept is very limited. In the study there was a need for a new impact assessment procedure in order to assess actual impacts of localised systems. In addition, there was a need for a method to identify priority areas of environmental protection in the forest sector over the next 10 years.

Human health impacts, as well as employment issues, were excluded from the study because the main focus of the environmental programme for the forest industry is planned to be ecological sustainability.

The starting point of the study was the analysis of environmental issues under the present conditions and in the future. Geographically the LCA was mainly limited to Finland.

3. Inventory

In the life cycle inventory, the forest sector was divided into subsystems according to life cycle. Data on *stressors*, i.e. inputs (materials and energy) and outputs (products and emissions into the atmosphere and watercourses, wastes, forestry practices and other stressors) of each subsystem were collected.

The main systems of the forest sector, i.e. the life cycle stages are: (a) *forestry* (forestry practices, transports to forest roads); (b) *production* (manufacturing of forest products, energy production within the forest industry, treatment of emissions and wastes); (c) *energy* production outside the forest industry; (d) *chemicals* production (oil refinery, production of chemicals used in pulp and paper mills); (e) *waste* management outside the Finnish forest industry (fibre-based waste in municipal landfills); (f) *transports* inside Finland; and (g) *transports* outside Finland (Fig. 1, Table 1).

The inventory included both the existing data of 1993 and the predicted data for the years 2000 and 2005. The data used in the inventory came from a wide range of sources with varying quality and reliability. There is little uncertainty concerning the present consumption of natural resources and the emissions of production in the forest industry. The reliability of data is poorer for the other factors. Rough estimates have been made for the emissions of transports, nutrient releases of forestry and methane of landfills in particular. All these and system boundary issues are addressed in detail in the main reports of the LCA study [3–5]. A summary of key inventory data for 1993 is given in Tables 2–5.

The prediction was based on a 'business as usual scenario' in which the most important factors affecting the data in the future were the assumptions made on the production volumes of the pulp and paper industry and on the new technologies adopted. The following forecasts for the production volumes (in 1000 t/annum) were made in 1994:

	1993	2000	2005
Paper and board	9990	11 150	12 400
Mechanical and chemical pulp	9801	10 750	11 560

According to the latest predictions, the production of paper and board in 2005 may be 15–20% higher than the figure given above.

4. Impact assessment

The purpose of the life cycle impact assessment was to produce relevant information on the following questions: (1) Where do the environmental impacts of the Finnish forest sector occur and how are they caused? (2) How great are the impacts of different life cycle stages within the forest sector when compared to each other

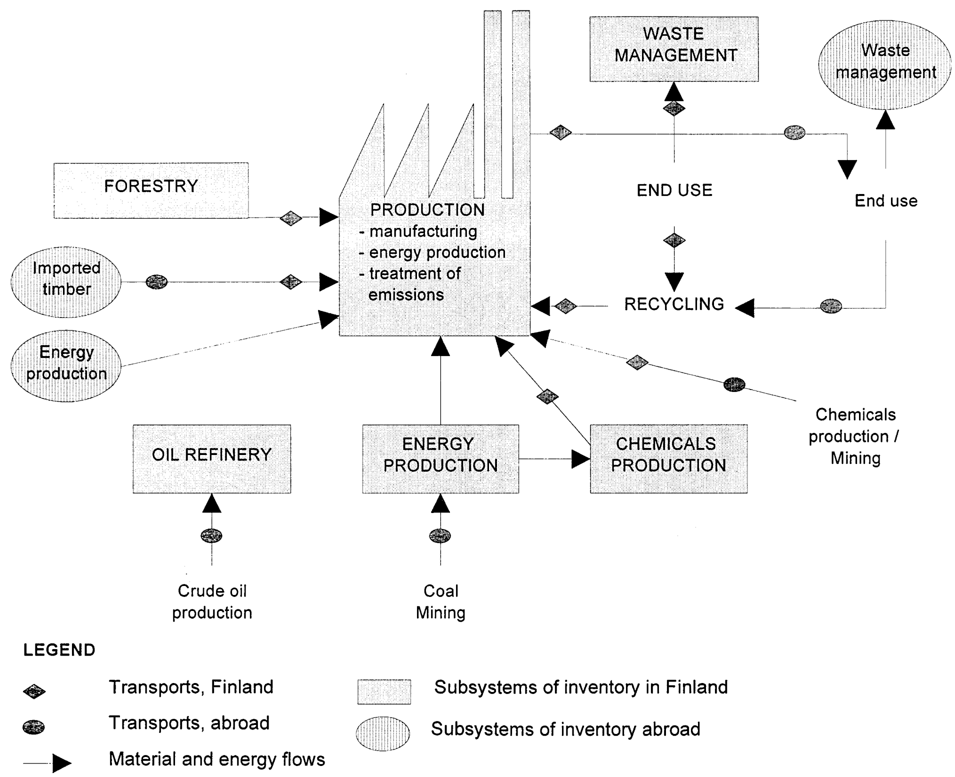

Fig. 1. A simplified flow chart of the LCA study of the Finnish forest industry [3]. Arrows from the subsystem oil refinery are not presented in order to maintain clarity.

Table 1
Life cycle stages included in the LCA study of the Finnish forest industry [3]

Forestry
Forestry practices:
harvesting (timber felling, pruning and topping)
ditching
site preparation operations
forest fertilization
Transports to forest roads
Production
Manufacturing of forest products
Energy production within forest industry
Treatment of emissions and solid wastes
Energy production outside forest industry
Chemicals production outside forest industry
Oil refinery
Production of chemicals used in pulp and paper mills
Waste management outside forest industry
Fibre-based waste in municipal landfills
Transports inside Finland
Transports of timber from forest roads to production mills
Transports of products from mills to harbours
Transports of chemicals used in pulp and paper mills
Transports related to recycling
Transports of imported timber
Transports outside Finland
Transports of products from harbours to abroad
Transports of chemicals used in pulp and paper mills
Transports of fuels (coal, oil) to Finnish harbours
Transports related to recycling

and to the impacts caused by human activities in Finland as a whole? (3) What is the relative significance of different stressors (e.g. NO_x, forestry practices) within the forest sector and its various life cycle stages?

The impact assessment was based on both qualitative information and quantitative model calculations. The quantitative approach applied was developed during the project [4]. The method is called decision analysis impact assessment (DAIA). It is based on the multiattribute value theory (MAVT) and a general procedural framework suggested by the Society of Environmental Toxicology and Chemistry (SETAC) [6]. MAVT is an axiomatically based decision theory in which decision makers' preferences determine the appropriate model for aggregating the results (e.g. Refs. [7,8]). Note that only domestic data (activities in Finland) of the year 1993 were used in the quantitative impact assessment.

Method comparison [4] has shown that the simple version of DAIA applied in the study corresponds to the Environmental Theme method (ET) (e.g. Refs. [9,10]) or the CML method [11]. In practice, the ET and the simple DAIA differ in the handling of stressor data and judgment input.

Table 2
Consumption (1000 t/annum) of natural resources in the Finnish forest sector in 1993 [3]

	Oil	Gas	Coal	Uranium	Peat	Kaolin	Talc
Forestry	60.3	0	0	0	0	0	0
Production	255	624	432	0	845	983	217
Energy production	38	123	1.057	0.121	879	0	0
Chemicals production	2.3	19	65	0.01	84	0	0
Waste management	0	0	0	0	0	0	0
Transports							
Finland	112	0	0	0	0	0	0
Abroad	270	0	0	0	0	0	0
Total							
Forest sector[a]	468	766	1554	0.131	1808	983	217
Finland	8546	2895	6063	0.451	5800	983	227
World	3 119 000	2 135 000	3 615 000	31	27 000	25 082	8251
World reserve[b]	137 000	93 160	710 899	2.084	25 087	19 690	377

Finnish mills abroad excluded. The world consumption and reserve of oil expressed as raw oil.
[a] Transports abroad excluded.
[b] World reserve in 1 000 000 t.

Firstly, the impact assessment included the definition of impact categories and classification. This process produced three different main impact categories—depletion of resources, ecological impacts and impacts on amenities and multiple-use—which were handled separately. Furthermore, each main impact category was

Table 3
Emissions (1000 t/annum) of gases into the atmosphere from the Finnish forest sector in 1993 [3]

	SO2	NO_x	N_2O	CO_2	CH_4	CO	NMVOC
Forestry	0.3	3.1	0.00	192	0.00	4.10	0.00
Production	24.8	22.0	1.20	4700	18.3	0.00	5.10
Energy production	10.5	10.3	1.36	3753	0.22	1.25	0.36
Chemicals production	1.2	1.2	0.09	400	0.02	0.19	0.18
Waste management	0.0	0.0	0.00	0	38.5	0.00	0.00
Transports							
Finland	0.5	5.3	0.00	345	0.00	1.20	0.31
Abroad	13.5	24.4	0.00	816	0.00	0.30	0.60
Total							
Forest sector[a]	37.3	41.9	2.65	9390	57.04	6.74	5.96
Finland	122	250	20	65 000	245	467	195

Finnish mills abroad excluded.
[a] Transports abroad excluded.

Table 4
Emissions (tonnes/annum) of metals into the atmosphere from the Finnish forest sector in 1993 [3]

	As	Cd	Cr	Hg	Ni	Pb	Se	Zn	V
Production	0.189	0 247	0.223	0.196	1.908	3.662	0.000	0.150	5.513
Energy production	0.156	0.082	0.291	0.178	0.669	0.880	0.300	0.650	1.862
Chemicals production	0.012	0.005	0.019	0.077	0.048	0.058	0.020	0.050	0.120
Total									
Forest sector	0.36	0.33	0.53	0.45	2.63	4.60	0.32	0.85	7.50
Finland	12.39	2.18	3.75	1.21	19.52	44.45	0.90	31.00	36.19

Finnish mills abroad excluded.

Table 5
Discharge (1000 t/annum) of organic matter and nutrients into watercourses from the Finnish forest sector in 1993 [3]

	BOD_7	COD_{Cr}	P	N
Forestry	0.0	0.0	0.22	1.30
Production	41.9	278.4	0.385	2.920
Energy production	0.0	0.0	0.000	0.000
Chemicals production	0.3	1.1	0.001	0.080
Waste management	0.0	3.9	0.000	0.000
Transports				
Finland	0.4	1.3	0.003	0.012
Abroad	0.0	0.0	0.000	0.000
Total				
Forest sector	42.6	284.7	0.61	4.31
Finland[a]	54.6	291	5.3	59

Finnish mills abroad excluded.
[a] Fisheries excluded for BOD_7; municipalities excluded for COD_{Cr}.

divided into subcategories and the stressors of life cycle stages were assigned correct categories on the basis of stressor–effect relationships. These were designed in an interactive process between the model analyst and 10–15 experts within the Finnish Environment Institute.

Each main impact category had its own phases in DAIA. Assessment of ecological impacts (Fig. 2) consisted of characterisation and valuation phases. In the characterisation a new ‘only above threshold’ approach [4] was used. The method integrates fate and effect aspects. New country-specific calculation rules for characterisation of acidification, ozone formation, ecotoxicological impacts and eutrophication were developed. Only those emissions causing adverse effects related to the impact categories were taken into account in the assessment procedure. These ratings were determined for each substance individually on the basis of scientific model results, empirical data or expert judgements. In this way, the method produces more actual impact value scores (see Ref. [4]).

Fig. 2. The model framework of ecological impacts, arranged hierarchically [4]. Legend: CO_2(F), carbon dioxide (fossil); N_2O, nitrous oxide; CH_4, methane; Halo, halocarbons (CFCs, HCFCs and HFCs); SO_2, sulphur dioxide; NO_x, nitrogen oxides; NH_y, reduced nitrogen; NMVOC, non-methane volatile organic compounds; CO, carbon monoxide; H-metals(A), release of heavy metals (As, Cd, Cr, Cu, Hg, Ni, Pb, Se, Zn) into the atmosphere; POP(A), release of persistent organic pollutants (e.g. PAHs, dioxins, pentachlorophenol) into the atmosphere; TOX(W), release of toxic compounds (e.g. heavy metals, phenols, organochlorine compounds, pesticides) into waters; P(W), phosphorus into waters; N(W), nitrogen into waters; Forestry practices, harvesting (timber felling, pruning and topping), draining, soil preparation after final felling, wood fertilisation; BOD/COD, biological/chemical oxygen demand. (Ozone depletion was not included because compounds with an ozone depletion potential are not used within the forest sector.)

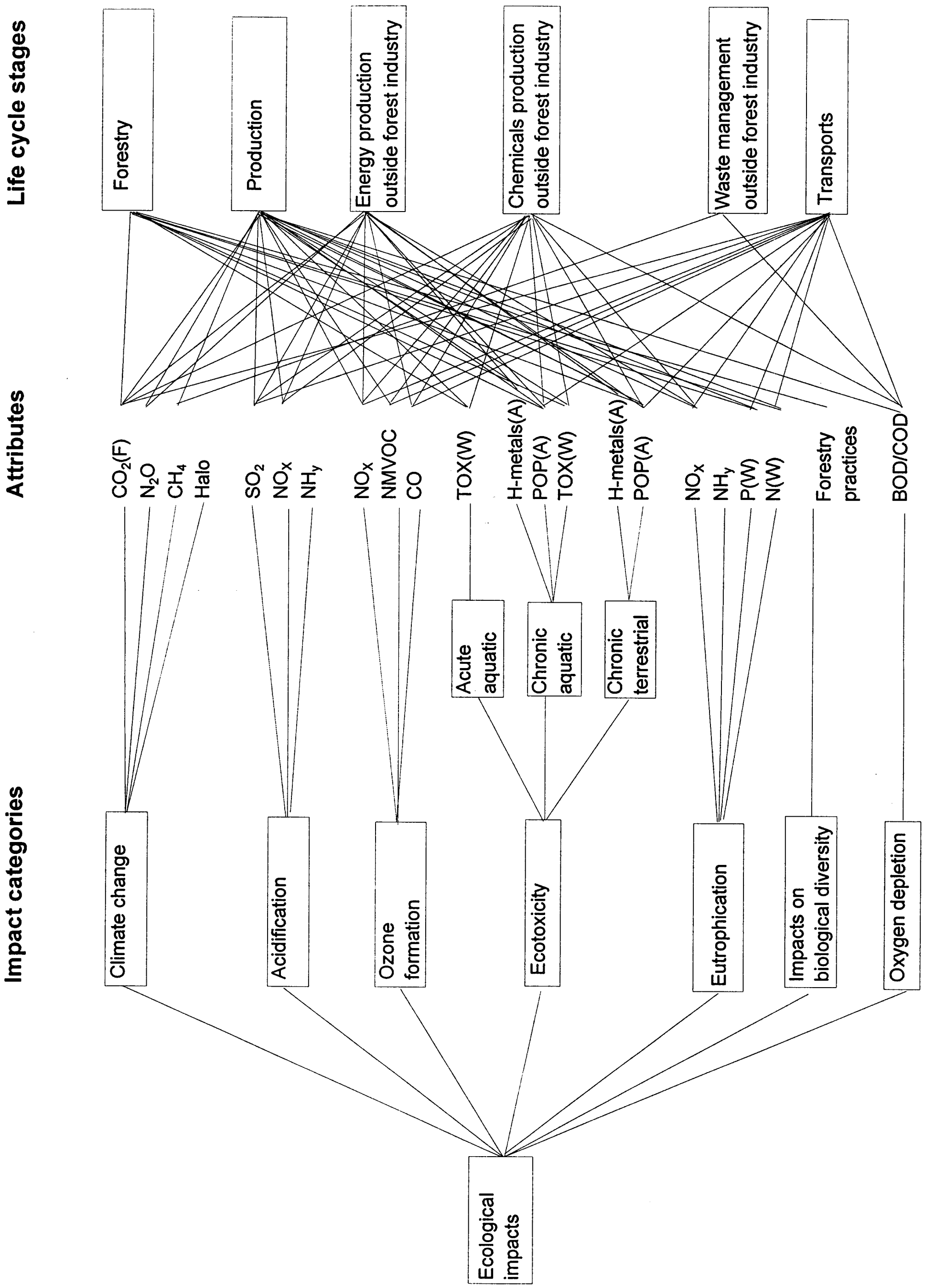
Life cycle stages
Forestry
Production
Energy production outside forest industry
Chemicals production outside forest industry
Waste management outside forest industry
Transports
Attributes
CO_2(F)
N_2O
CH_4
Halo
SO_2
NO_x
NH_y
NO_x
NMVOC
CO
TOX(W)
H-metals(A)
POP(A)
TOX(W)
H-metals(A)
POP(A)
NO_x
NH_y
P(W)
N(W)
Forestry practices
BOD/COD
Acute aquatic
Chronic aquatic
Chronic terrestrial
Impact categories
Climate change
Acidification
Ozone formation
Ecotoxicity
Eutrophication
Impacts on biological diversity
Oxygen depletion
Ecological impacts

Fig. 2.

Table 6
Impact category weights given by the different organisations [4]

Impact category	Impact category weight									
	FEI ($n=32$)		EC ($n=7$)		IND ($n=14$)		FMI ($n=5$)		All ($n=58$)	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Climate change	0.20	0.01–0.57	0.20	0.04– 0.42	0.19	0.03–0.49	0.25	0.03–0.63	0.21	0.01–0.63
Acidification	0.17	0.04–0.37	0.14	0.08– 0.25	0.22	0.09–0.49	0.13	0.04–0.33	0.18	0.04–0.49
Ozone formation	0.07	0.01–0.27	0.07	0.01– 0.22	0.11	0.01 0.39	0.13	0.01–0.34	0.08	0.01–0.39
Ecotoxicity	0.13	0.01–0.50	0.11	0.03– 0.32	0.11	0.01–0.29	0.20	0.04–0.39	0.13	0.01–0.50
Eutrophication	0.17	0.01–0.67	0.17	0.04– 0.54	0.19	0.02–0.48	0.15	0.04–0.30	0.17	0.01–0.67
Oxygen depletion	0.03	0.00–0.11	0.04	0.01– 0.09	0.07	0.01–0.26	0.05	0.00–0.21	0.04	0.00–0.26
Impacts on biodiversity	0.22	0.01–0.55	0.27	0.04–.0.45	0.11	0.02–0.34	0.09	0.02–0.28	0.19	0.01–0.55
	1.00		1.00		1.00		1.00		1.00	

Legend: FEI, Finnish Environment Institute; EC, Regional Environment Centres; IND, Confederation of Finnish Industry and Employers, Finnish Forest Industries Federation and Jaakko Pöyry Consulting Ltd.; FMI, Finnish Meteorological Institute.

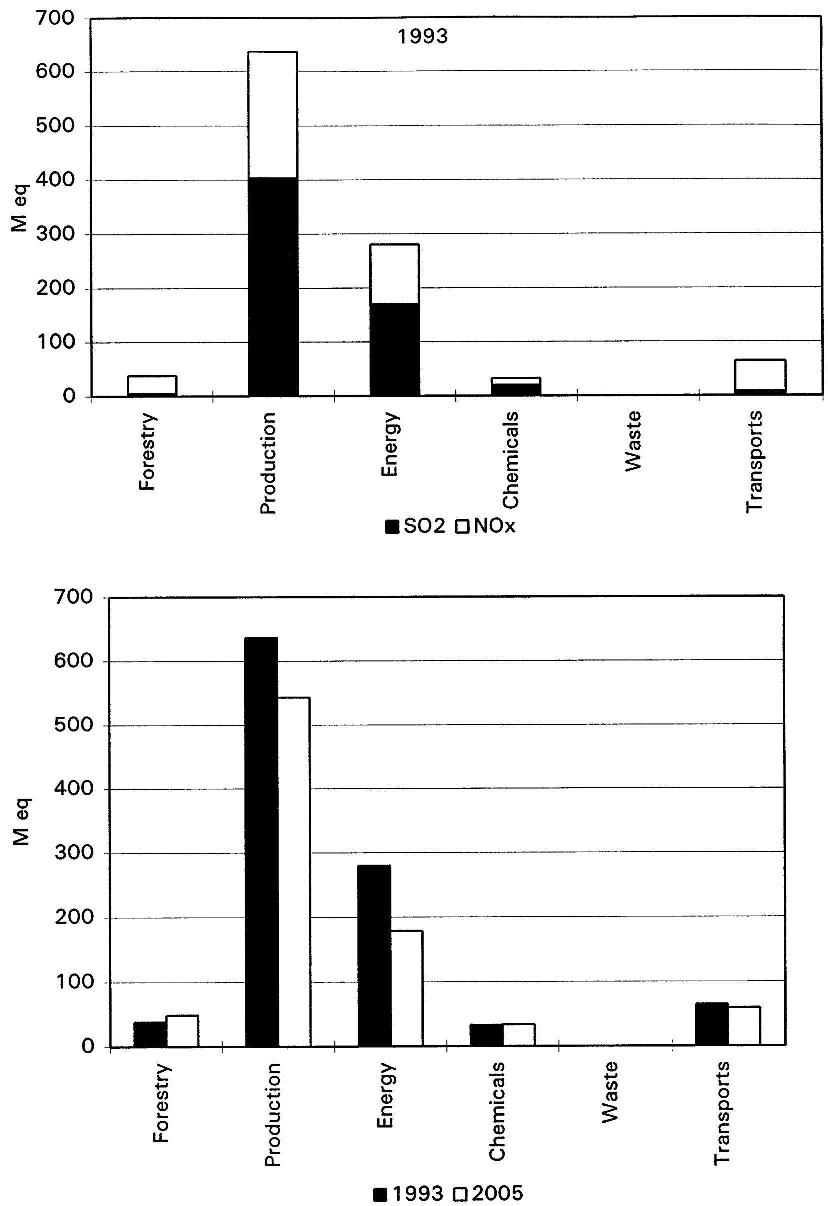

Fig. 3. Calculated potential acidifying depositions (M eq) from the forest sector in 1993 and 2005 [3]. Note that only domestic transports are taken into account.

assessment the forest sector is responsible for 10–50% of the ecological impacts caused by domestic stressors (Fig. 7).

Forestry and production are the most adverse life cycle stages of the Finnish forest sector (see Fig. 5). They together account for approximately 80% of the ecological impacts (climate change, acidification, tropospheric ozone formation, eutrophication, oxygen depletion, ecotoxicity, impacts on biodiversity) caused by the whole domestic forest sector.

The following stressors, related to ecological impacts, were found to be the most significant from the point of view of more effective environmental protection: forestry practices, CO_2, NO_x and sulphur emissions into the atmosphere, and discharges of toxic compounds and phosphorus into watercourses. The stressors were not strongly ranked against each other. The criteria were a high value score calculated by the preference model and/or the fact that the stressor has no discernible descending trend in the prediction used. The significance increases if, according to the prediction, the regulations or international conventions will not be fulfilled. In addition, qualitative information was used in the prioritization. The final prioritization and options for environmental improvements in the forest sector were identified and evaluated by group discussion.

The model value scores of the waterborne emissions of organic matter (BOD_7/COD_{Cr}) caused by the forest industry were high. However, these discharges were not prioritized to the group of the most important emissions since they are predicted to decrease in all branches of forest industry. In practice all the plants

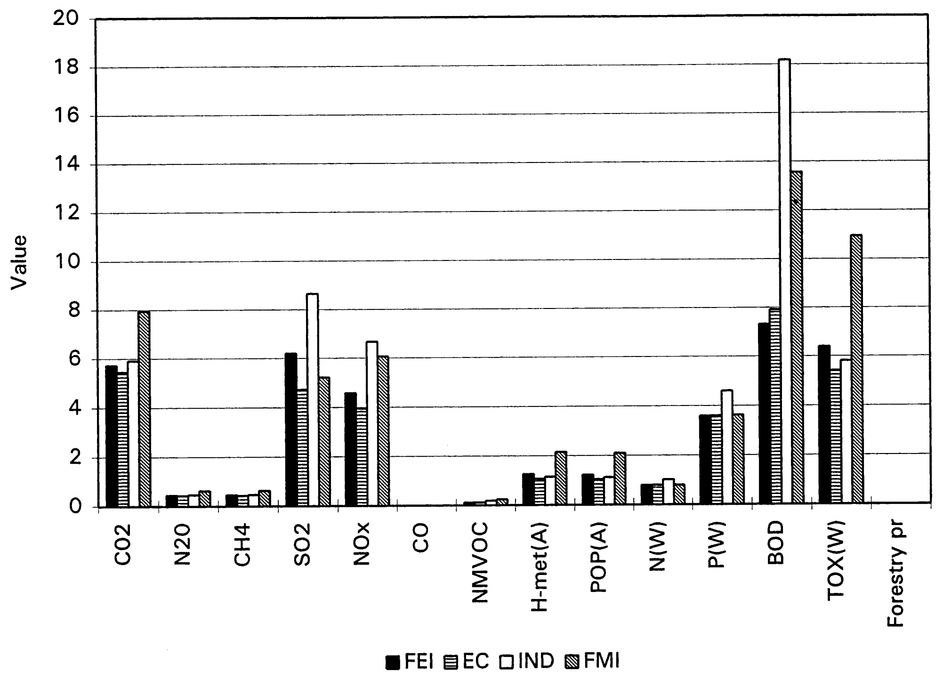

Fig. 4. Calculated group average scores of ecological impacts for the stressors of the production stage [4]. Legend: FEI, Finnish Environment Institute; EC, Regional Environment Centres; IND, Confederation of Finnish Industry and Employers, Finnish Forest Industries Federation and Jaakko Pöyry Consulting Ltd; FMI, Finnish Meteorological Institute.

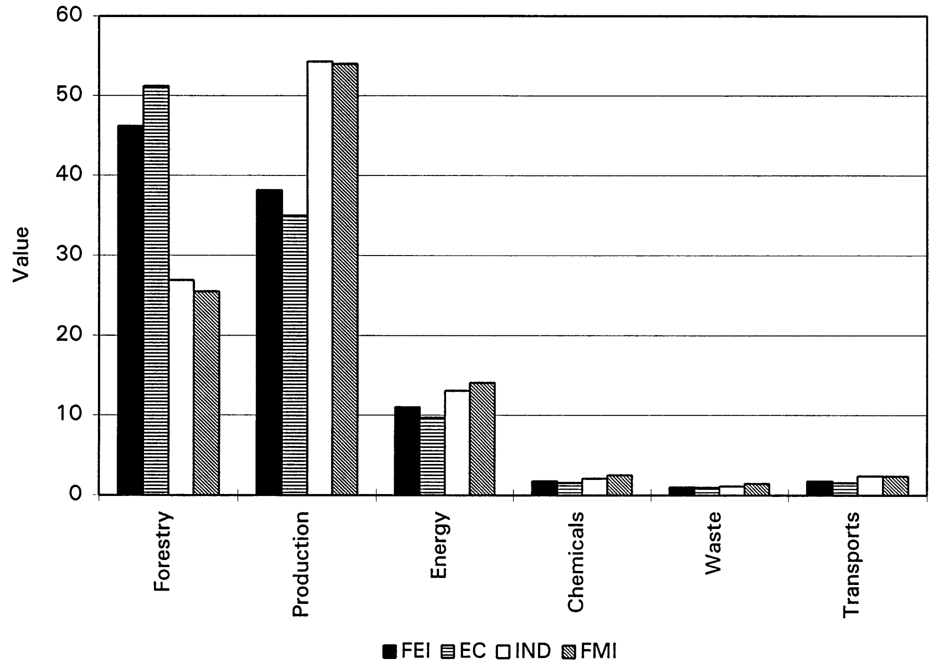

Fig. 5. Group average scores of ecological impacts for the life cycle stages of the Finnish forest sector [4]. Legend as in Fig. 4.

discharging large amounts of organic matter into watercourses will be equipped with efficient biological treatment plants by the year 2005. In addition, a probable error in the preference model concerning oxygen depletion (see Ref. [4]) was also taken into account in the ranking.

The model value scores of phosphorus in different life cycle stages were rather low. Furthermore, nutrient emissions caused by the growing and harvesting of trees have been estimated to decrease by over 25% and the emissions caused by production processes by over 35% by 2005. However, the forest sector may locally still be a significant factor in the eutrophication of inland waters in Finland, where phosphorus is limiting algal production.

Although the maintenance of biodiversity is increasingly taken into account in forestry practices, loss of biological diversity must be regarded as the major single problem caused by the forest sector. Most impacts on amenities and multiple-use of forest resources are also caused by forestry. Maintaining the biological diversity of forests will also require further development of the nature conservation network, especially in southern Finland. In addition, characteristics typical of natural forests should be increased in the economically managed forests as well.

Timber is the most important renewable raw material used by the forest industry. The use of timber does not contribute to resource depletion because forest growth exceeds the harvest in Finland. However, shortage of wood is possible in some regions and wood categories if biodiversity of forests is effectively secured. The use of birch in the Finnish forest industry already exceeds the amount that could be sustainably harvested in Finland alone.

The importance of mills and landfills for the depletion of land was considered to be negligible because these areas are rather small (approximately 90 km^2) and they will not increase in the future. Forest roads nowadays occupy a rather large area (1300 km^2) and is still growing. However, forest roads are not considered as an irreversible type of land use.

The forest industry's use of fossil fuels, talc and kaolin causes depletion of nonrenewable natural resources. The forest sector consumes about 25% of the fossil fuels used in Finland. The consumption is still growing due to increasing production and the energy production structure in Finland.

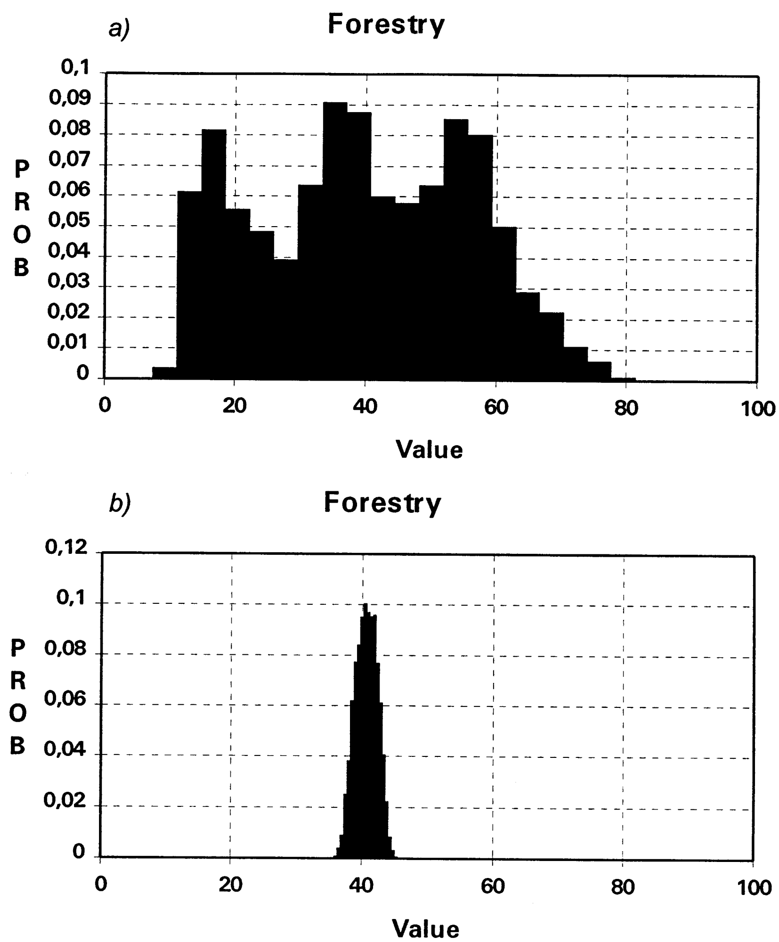

Fig. 6. Results from Monte Carlo simulations [4]. (a) Uncertainty in the value scores for the life cycle stage of forestry due to uncertainty in all model input variables. (b) Uncertainty in the value scores for the life cycle stage of forestry due to uncertainty in model input variables other than the impact category weights.

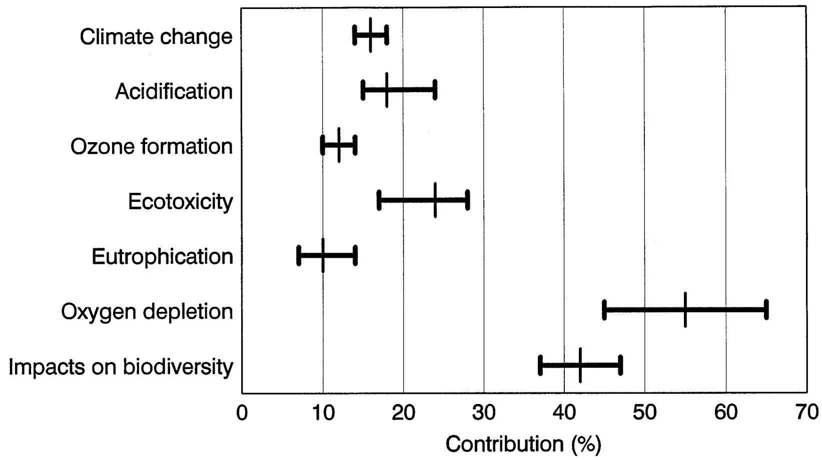

Fig. 7. Ranges and means of the contribution of the forest sector to ecological impacts in Finland [3]. Note that only domestic stressors are taken into account.

According to predictions the amount of sludge from wastewater treatment and the process waste in the production stage will increase faster than production, which contradicts the waste reduction objectives of the Finnish National Waste Plan.

At present, the net effect of the Finnish forest sector on the greenhouse gas balance is positive, i.e. the carbon sinks are bigger than emissions. However, increasing harvesting of wood resources will reverse this net effect by the beginning of the next century if the activities abroad (transports, waste management) related to the Finnish forest products are taken into consideration in the calculations. According to forecasts used in the study, the greenhouse gas emissions from the domestic forest sector will increase by 40% from the 1993 level by 2005. This is due to increasing harvesting of wood resources and energy use in the forest industry.

Increasing the energy efficiency is thus one of the key issues in the environmental protection of the forest sector (Fig. 8). This would affect the use of fossil fuels and also the emissions of CO_2, SO_2 and NO_x. Emissions of NO_x, in particular, are estimated to grow in all life cycle stages if no additional measures are taken. Approximately 45% of the NO_x emissions of the forest sector originate in transports abroad which deserves due attention. On the other hand the emissions of SO_2 are decreasing, with correspondingly reduced acidification.

The wide range of environmental impacts of the forest sector emphasizes the need to use several policy instruments simultaneously. Voluntary environmental management and auditing systems are promising, but they can never totally replace legislative and economic instruments.

According to the results of this study, further research and development in the forest sector should focus on the maintenance of biodiversity and on the development of resource- and energy-saving technologies. Deeper knowledge of the emissions and impacts of toxic compounds is also called for.

6. Discussion and conclusions

This study demonstrated that the developed LCA approach is applicable to the production of data and prioritization areas of environmental protection, not only for single products but also for whole production systems.

LCA applications which will be used to identify priorities of environmental protection for the whole industrial sector may have different data needs and system boundaries compared to the typical product-related LCA. For example, the decision where to cut off the boundary is not as critical in the case study of the Finnish forest sector as in the product-related comparative studies. The comparative elements in the case study were life cycle stages in which activities were different. The aim of the study was not to examine the differences between alternatives with the same service or function.

In this case study of the Finnish forest sector, it was demonstrated how spatial aspects of stressors and impacts are important in the interpretation of the results. The impact assessment approach developed during the study has the advantage of taking into account spatial variations. However, the impacts assessed by the method are still to be considered as potential impacts because of the limited information on time (and space) and due to the use of linear modelling of environmental processes.

On the basis of the guidelines on LCA (e.g. Refs. [6,11,13]), it can be stated that inventory and characterisation should mainly be based on objective data, i.e. measurements, observations, statistical analysis or scientific analysis of the relevant processes. However, subjective data must always be used in order to make

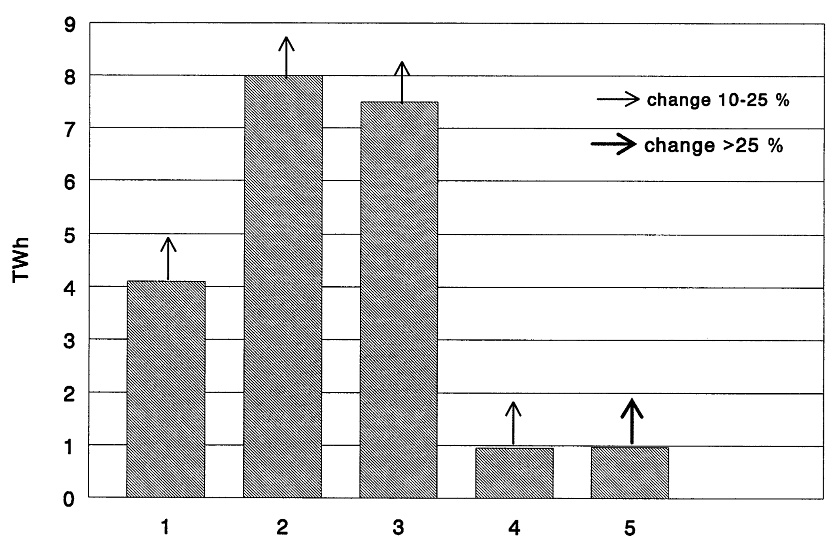

Fig. 8. The consumption of electricity in the Finnish forest sector in 1993 and its predicted growth until 2005 [3]. Legend: 1, chemical pulps; 2, mechanical pulps; 3, paper and board; 4, mechanical forest industry; 5, chemicals production.

quantitative impact calculations. The decision analysis framework provides a formal way of handling subjectiveness in life cycle impact assessment because one of the most important methodological issues in decision analysis is the encoding of subjective judgements. In addition, the decision analysis framework provides a theoretical basis for calculation rules in the model.

Because an empirical test is not applicable to the verification of the results, the use of sensitivity and uncertainty analyses are essential in the interpretation of the modelling results. The experiences of sensitivity analysis in multiobjective decision making can be used in LCA. However, it appears that an uncertainty analysis based on Monte Carlo simulations is also a useful tool for analysing value scores obtained from the impact model.

The case study revealed that even experts working with environmental issues have considerable differences in their opinions about the importance of environmental problems. This leads to a problem in interpreting the modelling results, because the rankings produced by the preference model depend mainly on the impact category weights. Therefore, a special procedure is required to determine generic weighting sets which some group can in principle legitimate.

The use of the quantitative impact model helped to clarify the issue for individual project members and provided a deeper understanding of priorities. However, in the final prioritization there was a need for more data, such as predicted trends of stressors, costs of abatements and compliancies with international conventions, as well as for understanding of cause–effect relationships in environmental issues.

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References

[1] Metsäntutkimuslaitos. Metsätilastollinen vuosikirja 1995 (Statistics on Finnish forest resources in 1995). Metsäntutkimuslaitos, Espoo (in Finnish), 1995.

[2] Metsäkeskus Tapio. Tapion taskukirja (Data and guidelines on forest resources and management). Metsäkeskus Tapio, Helsinki (in Finnish), 1994.

[3] Seppälä J, Jouttijärvi T, editors. Metsäteollisuus ja ympäristö (Forest industry and the environment). Suomen ympäristö 89. Helsinki: Edita Ltd (in Finnish), 1997.

[4] Seppälä J. Decision analysis as a tool for life cycle impact assessment. The Finnish Environment 123. Helsinki: Edita Ltd, 1997.

[5] Jouttijärvi T, editor. 1997. Suomen metsäteollisuuden luonnonvarojen käyttö ja päästöt (The use of natural resources and the emissions of the Finnish forest industry). Mimeograph Series of the Finnish Environment Institute 77, Helsinki (in Finnish).

[6] Consoli F, Allen D, Boustead I, Fava J, Franklin W, Jensen AA, de Oude N, Parrish R, Perriman R, Postlethwaite D, Quay B, Seguin J, Vigon B, editors. Guidelines for Life Cycle Assessment: A 'Code of Practice'. Brussels: Society of Environmental Toxicology and Chemistry, 1993.
[7] French S. Decision Theory: An Introduction to the Mathematics of Rationality. Chichester: Ellis Horwood, 1988.
[8] von Winterfeldt D, Edwards W. Decision Analysis and Behavioral Research. New York: Cambridge University Press, 1986.
[9] McKinsey & Company. Integrated Substance Chain Management. A Publication of the Association of the Dutch Chemical Industry—VNCI, 1991.
[10] Baumann H. Decision making and life cycle assessment. Chalmers University of Technology, Technical Environmental Planning, Gothenburg. Report 1995:4.
[11] Heijungs R, Guinee JB, Huppes G, Lankreijer RM, Udo de Haes HA, Sleeswijk AW. Environmental life cycle assessment of products. Leiden: MultiCopy, CML (Centre of Environmental Science) Report 9267, 1992.
[12] Guinee JB, Heijungs R. A proposal for the definition of resource equivalency factors for use in product life-cycle assessment. Environ Toxicol Chem 1995;14(5):917–25.
[13] Lindfors L-G, Christiansen K, Hoffman L, Virtanen Y, Juntilla V, Hanssen O-J, Ronning A, Ekvall T, Finnveden G. Nordic Guidelines on Life-cycle Assessment. Århus: AKA-PRINT A/S. Nord 1995:20.

Valuation of the ecological impacts included the weighting and aggregation of different environmental impact categories in order to obtain value scores, i.e. to compress multi-dimensional information into decision making. The purpose of the weighting was to assess the relative significance of the different ecological impact categories according to their environmental effects. Weighting was carried out using a questionnaire with the aid of decision analysis technique. The population of respondents consisted of 58 experts working with environmental issues (see Ref. [4]). The group weights of the ecological impact categories were calculated for four different expert groups (Table 6).

Two different types of ecological value scores were calculated. Firstly, the value scores of different life cycle stages obtained from the characterisation were calculated for eutrophication, acidification (Fig. 3), ozone formation and climate change. These calculations did not include any subjective weighting data. Secondly, the value scores obtained from the preference model were calculated. The model uses the weighting results according to the MAVT's calculation rules. In this model the group average scores of ecological impacts for the stressors of the different life cycle stages (Fig. 4) and for the life cycle stages (Fig. 5) were calculated from average input values of the model. The higher the value score, the more undesirable is the life cycle stage or the stressor. Forestry was ranked as the most harmful life cycle stage by the environmental administration (EC and FEI in Fig. 5), whereas production was emphasized by the 'industry group' (IND in Fig. 5). In practice, there was a large uncertainty in the results. Sensitivity and uncertainty analyses showed that the ranking of defined life cycle stages and stressors is highly sensitive to changes in the impact category weights (Fig. 6) (see Ref. [4]).

In this study, depletion of resources was divided into three categories with stressor variables as follows: (a) depletion of non-renewable resources (kaolin, $CaCO_3$, talc, crude oil, gas, coal, uranium, peat, other minerals); (b) depletion of renewable resources (timber); and (c) depletion of land (permanently occupied land areas). Only semi-quantitative characterisation was conducted in the case of resources. The quantification was based on a 'reserve-to-use' approach [12].

Impacts on amenities and multiple-use were divided into nine subcategories: (1) smell, (2) noise, (3) decrease of air quality (dust, ash, particles), (4) decrease of water quality (colour, aesthetic aspects), (5) adverse effects on landscape, (6) adverse effects on outdoor activities, (7) adverse effects on fishing and hunting, (8) adverse effects on picking berries and mushrooms, (9) adverse effects on reindeer husbandry. The basic version of the quantitative model requires that the impacts can be assessed with the aid of quantitative stressor variables, i.e. attributes. However, in the case of amenities and multiple-use, it was difficult to find suitable attributes. The problem of quantifiable attributes was solved by weighting the impacts directly and thus no attributes were used in this category (see Ref. [4]).

5. Interpretation and results

The forest sector, in its various life cycle stages, has a significant impact on the Finnish environment. According to the characterisation results of the impact