Energy Use in Swedish Forestry and its Environmental Impact

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Abstract

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The commitments to sustainable development made by the member countries of the UN, together with the Kyoto Protocol, has raised the profile of issues related to the ecological evaluation of products, production processes and services.

In each of the studies underlying this thesis a LCA (Life Cycle Assessment) perspective was adopted. Firstly, site-specific data were collected from three forest management regions in northern, central and southern Sweden in the late 1990s. Secondly, silvicultural and technological forestry developments between the early 1970s and late 1990s were evaluated by comparing the energy use in the forestry system at each of these times.

Secondary transport of timber was found to be the most energy-demanding part of the forestry system usually, accounting for about 50 percent of the energy demands, and logging was generally the second most energy-demanding process (33-40 percent), except in systems involving mechanized logging operations in 1972, when logging required the most energy (60 percent). These findings show that increased mechanization since 1972 has not resulted in a rise in total energy use; in fact, it has led to more energy-efficient logging machines, from motor-manual and early mechanised systems, to current machines that are on the verge of automisation.

In contrast, energy use in silviculture has increased, possibly due to the use of more supposedly advanced technology and more intensive silvicultural treatments. The same is also true for secondary haulage because of the greater use of road vehicles and longer haulage distances.

An analysis of future possible secondary timber transport scenarios involving lorry or lorry-and-train combinations using a variety of potential fuels/energy carriers showed that in biobased-fuel cycles the greenhouse gas emissions are about 95 percent lower than in corresponding fossil fuel cycles. In addition, they involve little fossil energy. Given the expected future scarcity of fossil fuels, and potential consequences of global warming, it could be advantageous for the forest sector to both produce and use a renewable fuel, since it could increase the overall value of forest products and have a low environmental impact.

Keywords: biobased-fuel, energy carriers, environmental impact, ethanol, emission, environment, Fischer-Tropsch Diesel, forestry, LCA, methanol, secondary transport.

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Content

Appendix

Paper I-III

This thesis is based on the following papers, which are referred to in the text by the corresponding Roman numerals. Published papers are appended and reproduced with kind permission of the publishers.

I. Berg, S. & E-L, Lindholm. 2005. Energy use and environmental impacts of forest operations in Sweden. *Journal of Cleaner Production 13,* 33-42.

II. Lindholm & Berg. 2005. Energy use in Swedish forestry in 1972 and 1997. *International Journal of Forest Engineering*, 27-37.

III. Lindholm, E-L & Berg, S. 2005. Timber transport – efficiency and environmental impacts. *Scandinavian Journal of Forest Research 20,* 184-191.

Notes on the authorship of the papers

For Paper I, the planning and collection of the data were performed by Staffan Berg & Ulf Hallonborg. The data were analysed and interpreted by Lindholm and Berg. Berg and Lindholm jointly wrote the paper, and Berg was responsible for its final revision.

For Paper II, the modelling was planned by Lindholm and Berg, Lindholm constructed the model, analysed and interpreted the results and wrote the paper, but Berg was responsible for its final revision.

For Paper III, the modelling was planned by Lindholm and Berg, Lindholm constructed the model, analysed and interpreted the results and wrote the paper, but Berg revised it.

Introduction

The use of energy in industrial activities is having major adverse environmental consequences. The commitments to sustainable development made by the member countries of the UN, together with the Kyoto Protocol, has raised the profile of issues related to the ecological evaluation of products, production processes and services. In addition several types of environmental decision support tools have been developed to identify, characterise and communicate the environmental impact of specific goods and processes. Furthermore, the ISO 14 000 series of environmental management standards has made environmental issues integral concerns of the management of accredited organisations, and organisations seeking accreditation (Swedish Standards Institution, 1997).

A number of tools are currently used to identify and communicate the impact of specific goods and services on the environment, such as forest certification, eco-labelling and life cycle assessment (LCA). In an LCA, different options for reducing the environmental impact of a product, or different products that could be used for the same purpose, can be compared. In relation to forestry, this is especially useful for comparing energy from forest products with energy from other resources.

A key challenge for the future is to meet the conflicting demands imposed by increasing global energy requirements, the increasing scarcity of energy resources and the need to reduce the levels of greenhouse gases in the atmosphere. The European Community has provided a strategy for increasing the proportion of energy generated within the EU from renewable energy sources from 6 percent in 1997 to 12 percent in 2010 (European Parliament, 2001). In Sweden, transport accounted for approximately 69 percent of the overall use of oil products in 2002 (Swedish Energy Agency, 2005). Of all domestic transport by lorry in Sweden, approximately 21 percent is currently related to the forest industry (SIKA institute, 2005).

A switch in the fuels used in forest operations to renewable energy sources is an attractive option in several respects, especially since forest companies produce timber, which is a renewable resource, provided the forests are managed sustainably. The high amounts of inherent energy in timber compared to the energy used in forest management makes timber a very attractive energy carrier. Since timber is renewable, producing alternative fuels from it (Ahlvik & Brandberg, 2001) is an attractive option to consider in situations where use of nuclear power or fossil energy is to be reduced or phased out.

Renewable fuels like forest fuel are considered to be carbon dioxide neutral, although fossil fuels are often required for their production and distribution. However, previous studies have shown that the fossil CO_2 emissions generated from bio-based fuel cycles are 85-90 percent lower than those of fossil fuel cycles (Arnäs *et al.* 1997).

Objectives

The overall goal of the work underlying this thesis was to improve our knowledge of the forestry system in order to identify opportunities to reduce the environmental impact of the system.

In the study described in Paper I the aim was to describe the forestry system up to the late 1990s and to identify the most significant forestry processes in terms of energy inputs and outputs of timber and emissions.

In order to evaluate the effects of silvicultural and technological forestry developments between the early 1970s and late 1990s, the study described in paper II compares the forestry systems in Sweden in these periods, focusing on energy use and emissions of greenhouse gases.

The results presented in Papers I and II showed that secondary transport was the most energy demanding part of the forestry system. Paper III presents a change-oriented study in which the main aim was to analyse future possible secondary timber transport scenarios in order to identify approaches that could reduce the use of energy and environmental impacts of the system.

Background

Environmental assessment tools

Several tools have been developed for assessing environmental impacts, which can be classified according to the type of impact(s) they evaluate (Finnveden & Moberg 2005). Material Flow Accounting, Ecological Footprint and Energy Analyses all evaluate the use of natural resources while Risk Assessments evaluate environmental impacts. Other tools consider both use of resources and environmental impacts, like Strategic Environmental Assessment, Environmental Assessment, Environmental Management Systems and Life Cycle Assessment. A final group of tools, including Cost-benefit, Input-Output and Life Cycle Cost Analyses, can be used to assess economic aspects of systems as well as their environmental impact and use of resources.

In each of the studies underlying this thesis a Life Cycle Assessment (LCA) perspective was adopted. LCA was initially developed as a learning and decision support tool for companies and industrial sectors. It is one of the most widely applicable tools for evaluating environmental impacts since it can be used both for expressing the impact of a product or process, and for facilitating their design and development (UNEP, 1996). Furthermore, LCA is well-known, widely accepted and international standards have been developed for LCA by the International Standardisation Organisation (Swedish Standards Institution, 1997).

Life Cycle Assessment

LCA is a tool that focuses on the effects of a product, including its production and disposal, or process over the whole course of its life or duration (*i.e.* from cradle-to-grave). The results from a life cycle study can be applied in various ways, for example to identify opportunities to improve the environmental aspects of a product. An LCA includes four phases (Swedish Standards Institution, 1997):

1. Definition of the goals and scope of the LCA.
2. Inventory analysis, consisting of gathering data concerning the resources used, energy use, emissions and products resulting from each activity in the production chain.
3. Life cycle impact assessment, in which the results are evaluated to elucidate the magnitude of the potential environmental impacts of a product system. In this phase of the LCA all emissions that may cause problems such as global warming, acidification, eutrophication and photochemical ozone creation are characterised, weighted and summed to provide an indication of the overall impact of the product and process.
4. Interpretation of results and identification of components that have the most significant environmental impacts.

Limitations of LCA

The ISO 14 040 standards promote LCA as a technique for assessing the effects of a product throughout its entire life cycle – *i.e.* for compiling and evaluating all the relevant material and energy flows and their potential environmental impacts from "raw material acquisition through production, use and disposal". In practice, however, some relevant impacts are ignored. For example, the effects of land-use on the flora and fauna, which are difficult to assess in an LCA, the effects on soil productivity and aesthetic, cultural and recreational values of the landscape or ecosystem.

LCAs are intended to analyse processes solely in terms of the quantity needed for a unit of the product, without explicitly focusing on events at specific sites and times. Forestry is problematic in this respect because of the widely differing time-scales of the wood production processes compared to logging and transportation processes. Furthermore, many of the environmental effects of raw material extraction only appear gradually, and this process must be investigated across time-scales extending for decades into the future or retrospectively, without explicitly focusing on events at specific sites and times.

There have been a few attempts to assess the impacts of land use on ecological systems (Baitz *et al.* 1998, Köllner, 2000, Lindeijer *et al.* 1998 and Muys *et al.* 2001 and Wessman et al. 2003). However, no methods have been developed to date that have overcome the main problems of assessing biodiversity (Wessman *et al.* 2003):

1. The effects of forestry on flora and fauna are very complex, and changes in the ecosystem are caused both by the dynamics of the forest ecosystem itself and external factors.
2. Data on biodiversity are generally not quantitative, i.e. numerical, which the ISO 14 040-43 standards stipulate is a requirement for LCAs.
3. Finding a comprehensive, reproducible way to describe changes in biodiversity associated with forest practices, and which have occurred in a forest landscape during a given period of time.

Other LCA-studies related to forestry

The new focus on ecological evaluation of products, production processes and services had profound implications for the forestry sector, prompting numerous LCAs and studies on energy use relating to forestry and forest products, notably in Germany (Schweinle 1996; and Schweinle and Thoroe 2001), and Switzerland (Winkler 1997; and Knechtle 1997, 1999). Karjalainen and Asiakainen (1996), Berg and Karjalainen (2003) present data on energy use and related emissions from forest operations in Sweden and Finland.

According to several European forestry studies over the past decade (Table 1), the energy use in silviculture and logging ranges from less than 100 MJ/m^3 timber up to 135 MJ/m^3. These findings have been corroborated by the studies of Schweinle and Thoroe (2001), which also considered road building, and provide estimates of 170–270 MJ/tonne of dry wood (70–120 MJ/m^3). Secondary haulage accounts for 90–125 MJ, raising total energy use to a level of 180–230 MJ/m^3. However, energy use has been shown to be higher in exceptionally difficult terrain conditions (Wegner, 1994), and in long-distance haulage of pulpwood (Schweinle and Thoroe, 2001).

Table 1. Studies on energy use in forest operations in the 1990s.

Energy use, MJ/m^3	Silviculture and logging	Secondary haulage	Total
Germany, saw logs, spruce (transport distance 50 km) (Schweinle, 1996).	135	92	227
Switzerland, Mechanized logging (Knechtle, 1997, 1999).	91	-	-
Switzerland, Motor-manual logging (Knechtle, 1997, 1999).	111	-	-
Germany, (Transport distance 50 km) (Wegner, 1994).	62	125	187

Material and methods

Methodology

The studies underlying this thesis are not intended to be complete LCAs according to the ISO 14 040 standards, but applied an LCA-perspective (Swedish Standards Institution, 1997). All of the studies focused on energy use in the systems and a few related environmental impacts, from the extraction of energy and production through to combustion.

System description

Papers I and II

Papers I and II considered the Swedish forestry system for the production of round wood from forest seedling production through to the secondary transportation of timber to the factory gate. This system includes operations such as seed production, the cultivation of forest seedlings, cut-over clearing[1], soil scarification[2], natural[3] or artificial regeneration[4], cleaning[5], logging operations[6] and secondary haulage[7]. Other transport elements included were the transport of labour, machinery and supplies to forest work sites. These operations were broken down into unit processes (Seedling Production, Silviculture, Logging and Secondary Haulage) that comprise the system shown in Fig. 1.

The studies in paper I and II relied on data from forest operations carried out over one full year. Paper I included data from both 1996 and 1997 and in paper II those data were compared with data from 1972. Data presented in Paper I related to typical forest management regions in northern, central and southern Sweden, Fig. 2.

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[1] Cut-over clearing: Eliminating unwanted vegetation in order to facilitate subsequent harvesting or regeneration treatment.

[2] Soil scarification: Loosening the top soil or breaking up the forest floor, in preparation for natural or artificial regeneration.

[3] Natural regeneration: The creation of a new stand by natural growth.

[4] Artificial regeneration: The creation of a new stand by sowing or planting.

[5] Cleaning: The elimination or removal of undesirable vegetation in a young stand.

[6] Logging: Here, the felling and extraction of timber, through to landing for changeover to road vehicles.

[7] Secondary hauling: The transport of timber from landing to the endpoint by road vehicles or railways.

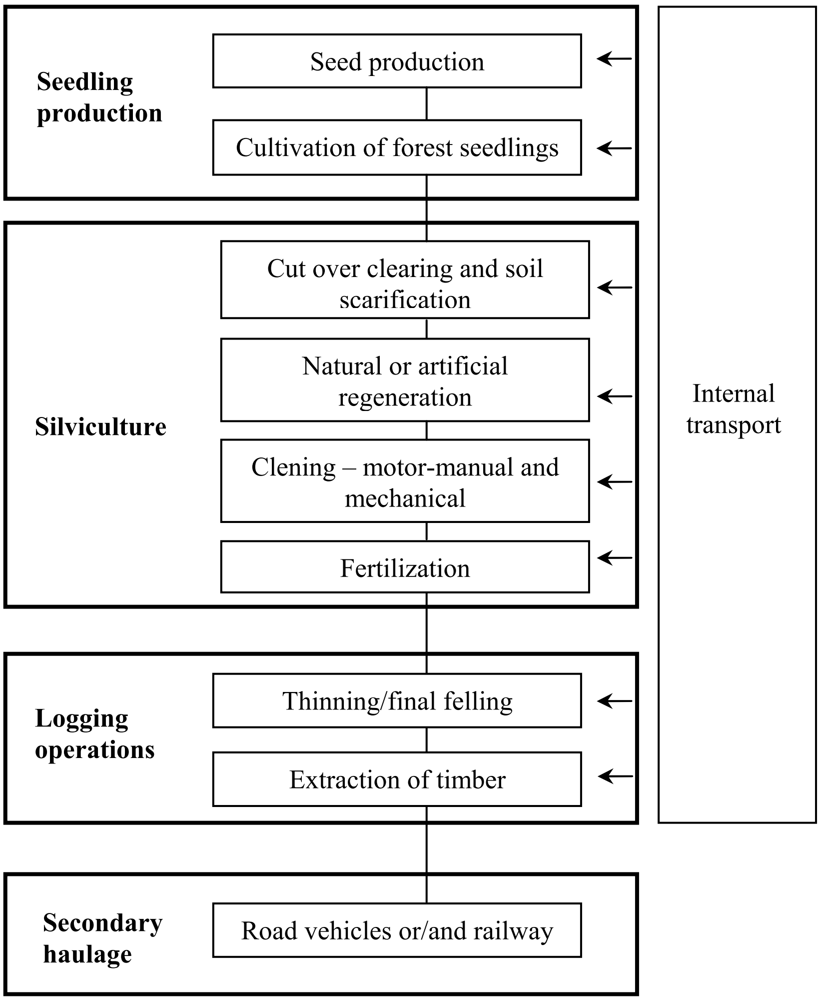

Figure 1. Forest operations in the forestry systems.

The data for northern and central Sweden were obtained from business units responsible for managing forest regions covering 700 000 ha and 350 000 ha, respectively, owned by a major forest organisation. The third area, comprising 335 000 ha in southern Sweden, was a region belonging to a private forest owner's association. Each of them annually produced about 1 million cubic metres industrial roundwood under bark (m^3 solid under bark, m^3 s.u.b.).

Logging in 1996-1997 was carried out by means of a fully mechanized dual-machine system employing the cut-to-length method, with secondary haulage being done by road or rail. Site-specific data related to the means of transport, energy requirements and use of ancillary materials were collected mainly as measurements or from company performance data.

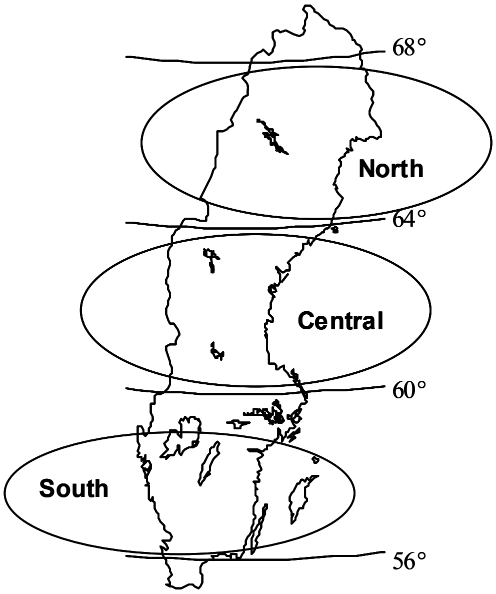

Figure 2. Locations of the regions.

Data on the operations in 1972 represent average values from all of Sweden and the operations they covered varied both in scale and the technology used. One particular system was used in small-scale forestry, whereas two other systems, involving differing methods, were used in large-scale operations. In Sweden the annual cut in 1972 amounted to 56.8 million cubic metres (Genfors & Thyr, 1976). Large-scale harvesting accounted for 63 percent of the cut, with small-scale forestry accounting for the rest. Motor-manual felling dominated in both large-scale and small-scale forestry, with only 2 percent of the cut being felled by mechanized methods. Mechanized limbing and bucking (17 percent) was also used in large-scale logging. Several methods of secondary transportation were used: road haulage, rail haulage, river driving and rafting.

The functional unit that all the data collected were related to was one cubic metre of solid wood under bark (m^3 s.u.b) delivered to the mill.

Paper III

In Paper III nine different scenarios for the secondary transport systems were compared (Fig. 3): involving lorry or lorry-and-train combinations using a variety of potential fuels/energy carriers, including diesel-oil, coal, hydropower, nuclear fuel and biofuels like ethanol (EtOH), methanol (MeOH) and Fischer-Tropsch Diesel (FTD) fuel. Three kinds of electricity were included in the scenarios: the Swedish average electricity mix, Swedish hydro-electric (a “green” alternative) and coal-generated electricity (Swedish marginal electricity).

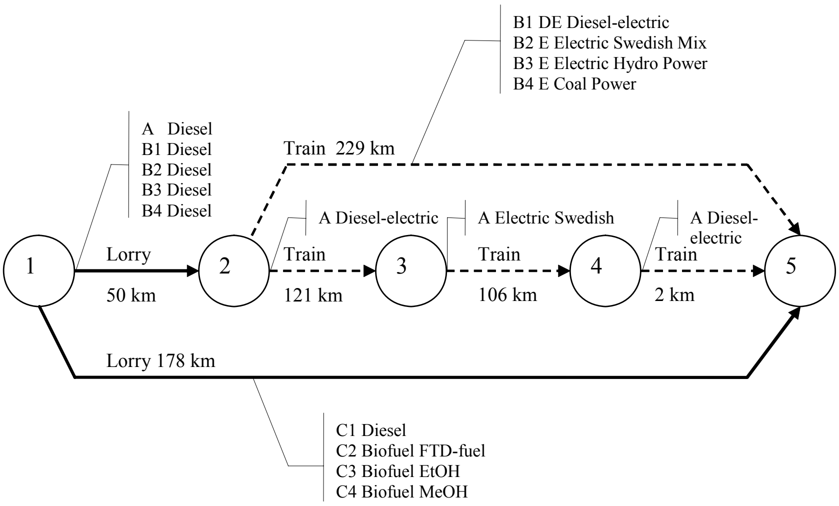

Figure 3. The transport scenarios. A is the base scenario - the current transport solution - and B1-C4 are the alternative scenarios.

The system's functional unit was the transport of 100 000 cubic metres of solid wood under bark (m^3 s.u.b.) from the forest in north-western Sweden to a timber terminal on the eastern coast of Sweden. In order to evaluate the different fuels, the total efficiency of each complete system was considered, from the extraction of energy carriers to their use.

Inventory data

In all of the studies (I-III), the energy requirements were related to the material and energy use in each of the unit processes in the systems. The system boundaries were set to encompass the extraction and production of material and energy carriers going into the system. System outputs were roundwood and calculated emissions into the air, water and soil. The emissions released were related to appropriate environmental impact categories (Global warming, Acidification, Eutrophication and Photochemical Ozone Creation) and the potential environmental impact of each scenario was calculated based on indicators used by the Swedish Environmental Management Council (2000).

The studies did not consider the production of capital goods (machinery and buildings); transport of energy carriers or ancillary material from the production sites to the forest management region; the assimilation of CO_2 by the trees; pesticide leakages at nurseries; or the environmental effects of the ecosystems which, at that time, were not measurable using the LCA methodology, such as damage to the production system, biodiversity or aesthetic, cultural and recreational amenities.

Results

Energy use

The results indicated that energy use in the total system of 1997 (147–200 MJ) was lower than in the mechanized system of 1972 (236 MJ), but of roughly the same magnitude as in the motor-manual systems of that time (156–177 MJ), Table 2. Transporting timber to the industrial sector (secondary haulage) accounted for the largest energy requirements in both 1997 and 1972 (47-56 percent), except for the mechanized system of 1972, where logging operations required the most energy (60 percent). The remaining energy used in the systems in 1997 and the motor-manual system in 1972 was divided between logging operations (33-40 percent), silviculture (2-16 percent) and seedling production (1-6 percent). In the mechanized system of 1972, secondary haulage accounted for 35 percent of the total energy requirements, silviculture 3 percent and seedling production 1 percent.

Table 2. Energy requirements for each operation in forestry, 1972 and 1997.

Forestry systems MJ/m^3 s.u.b.	Seedling Production	Silviculture	Logging	Secondary Haulage	Sum
Northern Sweden, 1997	5.3	16	65	113	200
Central Sweden, 1997	8.5	15	66	99	187
Southern Sweden, 1997	9.0	3.5	57	77	147
Large-scale mechanized, 1972	1.6	7.8	142	84	236
Large-scale motor-manual, 1972	1.6	7.8	63	84	156
Small-scale motor-manual, 1972	1.6	28	64	84	177

In 1997, the kind of cutting operation (final felling or thinning) had a greater influence on energy use per m^3 s.u.b than the geographical area of operation, Table 3.

Table 3. Energy requirements in cutting operations, 1997.

MJ/m^3 s.u.b.	Final felling	Thinning
Northern Sweden, 1997	32	44
Central Sweden, 1997	32	60
Southern Sweden, 1997	27	40

The energy requirements per hectare for silviculture after final felling were higher in southern and central Sweden than in northern Sweden, Table 4. Cleaning used more energy in the south (430 MJ per ha) than in both the central region (300

MJ per ha) and the north (230 MJ per ha). In contrast, the energy used in soil scarification was highest in the central region (1560 MJ per ha), followed by the south (1240 MJ per ha) and the north (1050 MJ per ha).

Table 4. Energy requirements per hectare in silvicultural operations, 1997.

MJ/hectare	Cleaning	Soil scarification
Northern Sweden, 1997	230	1050
Central Sweden, 1997	300	1560
Southern Sweden, 1997	430	1240

Secondary haulage accounted for more than 50 percent of the energy used in Swedish forestry in 1997. In fact, its energy demands were higher in 1997 than in 1972 (Table 2), since road haulage had increased and, possibly, haulage distances were longer in 1997 than in 1972. River driving and rafting, which consumed very low amounts of external energy, accounted for 30% of the timber transport in 1972, Table 5.

Table 5. Energy use in secondary haulage to the mill, 1972 and 1997.

Forestry systems MJ/m^3 s.u.b.	Road	Rail, Electricity	Rail, Diesel	Floating	Rafting	Total
All systems 1972	76	3.0		0.1	4.0	84
Northern Sweden, 1997	98	10	4.9			113
Central Sweden, 1997	91	8.3				99
Southern Sweden, 1997	77					77

The results from the analyses of the timber transport systems presented in Paper III showed that both primary and process energy requirements were lower for rail scenarios (A-B3) than for road (lorry) transport scenarios (C1-C4), except for the train powered by electricity from coal power scenario (B4), Table 6. It should be emphasized that the primary energy uses in scenario B2 (train, Swedish power mix, with a small diesel lorry component) would have been higher if the conversion losses (heat) from nuclear power had been included. In addition, the renewable energy fraction was higher in scenarios involving lorry transport based on biofuels (scenarios C2-C4) than in the railway transport scenarios.

Table 6. Primary energy, process energy, energy efficiency (process energy/primary energy), the renewable component of primary energy and the process/fossil energy input ratio.

Scenario	Primary energy TJ	Process energy TJ	Energy efficiency, %	Renewable part of primary energy, %	Process energy/ fossil energy input, %
A	11.7	10.7	91	18	111
B1	12.9	11.5	89	0	89
B2	12.7	9.6	76	19	121
B3	10.2	9.6	94	44	169
B4	25.9	9.6	37	0	37
C1	17.7	15.7	89	0	89
C2	36.0	15.7	47	97	1357
C3	35.2	15.7	49	96	1246
C4	30.5	15.7	56	96	1343

Emissions from and environmental impacts of the forestry systems

In the forestry systems in 1997, logging and silviculture generated more emissions of greenhouse gases and other potentially damaging gases such as carbon monoxide (CO), hydrocarbons (HC), dinitrogen oxide (N_2O), nitrogen oxides (NO_x) and sulphur oxides (SO_x) than secondary transport, although secondary transport accounted for the greatest part of the energy used, Table 7. Timber transport accounted for the greatest part of the emissions of carbon dioxide (CO_2), particles and methane (CH_4).

Table 7. Estimated emissions per cubic metre of round wood in the 1996-97 systems.

Substance	Silviculture & logging	Secondary haulage
Carbon monoxide (CO) g/m^3s.u.b.	23.1	6.33
Hydrocarbons (HC) g/m^3s.u.b.	5.14	3.10
Methane (CH_4) g/ m^3s.u.b.	0.476	0.534
Dinitrogen oxide (N_2O) g/ m^3s.u.b.	0.566	0.313
Nitrogen oxides (NO_x) g/ m^3s.u.b.	71.9	50.5
Particles g/ m^3s.u.b.	0.420	0.971
Sulphur oxides (e.g. SO_2) g/ m^3s.u.b.	0.475	0.015
Carbon dioxide (CO_2) kg/ m^3s.u.b.	5.86	6.66

Global impact - Climate change

The results of the Climate Change impacts category, shown in Table 8, correlate with their energy requirements (Table 2). The northern region had the largest impact per cubic metre, closely followed by the central region. The southern region's impact was considerably lower than that of the other regions. Of the various unit processes, secondary haulage had greater potential impact than logging, silviculture and seedling production, due to the high energy demands of the secondary haulage (Table 2), which was mainly met by fossil fuels. Silviculture and seedling production operations had greater impacts in the central and northern regions than in the southern region (Table 8).

Table 8. Results of the climate change impact characterisation.

Climate change GWP (100 yr) kg CO_2-equivalents/m^3 s.u.b.	North	Central	South
Seedling production	386	562	599
Silviculture	1 720	1 730	299
Logging operations	5 880	5 910	5 100
Secondary haulage	9 510	8 370	7 060
Total	17 496	16 572	13 058

Regional impacts - Acidification, Photochemical Ozone Creation and Eutrophication

The potential impact of Photochemical Ozone Creation is shown in Table 9. Secondary haulage had the largest impact, followed by logging operations. Silviculture and seedling production operations collectively accounted for 13-15 percent of the total impact in the north and central regions, while in the south the figure was only 7 percent.

Table 9. Characterization results for Photochemical Ozone Creation Potentials, POCP.

POCP, ethene-equivalents/m^3 s.u.b.	North	Central	South
Seedling production	0.4	0.6	0.6
Silviculture	2.4	2.4	0.5
Logging operations	7.4	7.5	6.5
Secondary haulage	10.7	9.3	7.9
Total	20.9	19.8	15.5

The results of the eutrophication and acidification impact analyses showed similar patterns (Tables 10 and 11). In both categories, logging operations had the largest potential impact in the south and central regions, accounting for about 50 percent of the total impacts. In the north, the contributions made to the eutrophication and acidification impacts by logging and secondary haulage were similar, 45-47 percent. The impacts of silviculture and seedling production were small in both categories.

Table 10. Characterization results for acidification.

Acidification, mol H^+/m^3 s.u.b.	North	Central	South
Seedling production	0.1	0.1	0.1
Silviculture	0.2	0.2	0.1
Logging operations	1.8	1.9	1.6
Secondary haulage	1.9	1.7	1.4
Total	4.1	3.9	3.2

Table 11. Characterization results for eutrophication.

Eutrophication, g O_2/m^3 s.u.b.	North	Central	South
Seedling production	15	14	13
Silviculture	62	79	12
Logging	454	461	389
Secondary haulage	449	389	331
Total	980	943	745

Potential environmental impact of the transport scenarios

Paper III examined the effects of using different types of process energy. The secondary transport systems that depended largely on electric train transport had low environmental impacts, except for the systems based on electricity generated from coal, Table 12. The systems based on biofuel had low Global warming and Photochemical Ozone Creation impacts.

Table 12. Potential environmental impacts of the transport scenarios.

Scenarios	Global warming tonne GWP	Acidification kmol H^+	Eutrophication ktonne O_2 potentials	Photochemical ozone creation potentials (POCP) ethene-equivalents
A	808	236	58	938
B1	1100	347	87	1290
B2	526	110	26	541
B3	468	106	25	535
B4	1630	229	42	591
C1	1440	300	70	1610
C2	118	251	68	378
C3	129	253	68	390
C4	121	251	68	380

Discussion

Energy use

The total energy used per cubic metre in the Swedish forestry system in 1997 was consistent with amounts used elsewhere in Europe, as reported for instance by Knechtle (1997), Schweinle (1996), Schweinle and Thoroe (2001) and Wegner (1994). However, the results also revealed that energy use in logging operations in Sweden is low compared with operations in continental Europe, Table 1.

The energy used in secondary transport is of the same order of magnitude as for certain areas in continental Europe, despite a number of adverse factors, such as the harsh climate and smaller tree sizes in Sweden. A favourable factor is that Swedish timber-transporting vehicles are allowed to carry larger weights than their counterparts in continental Europe. In Sweden gross weights of up to 60 metric tonnes per vehicle are permitted, thus allowing them to carry higher payloads. Another advantageous factor is that small-scale forestry concerns use large-scale transport solutions. In general, large-scale logging is also applied in small-scale forestry.

Logging

Despite the advances in technology that occurred between 1972 and 1997, the amount of energy used in both large- and small-scale motor-manual operations in 1972 (63 and 64 MJ/m^3, respectively) was roughly the same as in the northern and central mechanised systems in 1997 (66 and 65 MJ/m^3). Exceptions to this were mechanized operations in 1972 (142 MJ/m^3) and logging in the south in 1997 (57 MJ/m^3). The improvements between 1972 and 1997 can be largely explained by the advent of more efficient machines thanks to improvements in engine and machine design, operational logistics, productivity and operational efficiency. In 1972, mechanized logging was in its infancy and single-function machines were used for operations such as felling, limbing, bucking and extraction (Silversides & Sundberg, 1988). In contrast, by the 1990s, logging had become fully mechanized, the most common logging system comprising a harvester (a single-grip or two-grip machine), which felled, limbed and bucked the trees, and a forwarder that extracted the timber and took it to the roadside. Advances in technology led to the introduction of machines that were both more efficient and more sophisticated, resulting in a step up from mechanization to automation (Vestlund, 2005).

Logging could be improved by adapting machine operations to the conditions in specific stands. Large harvesters use more energy than small machines, but use less energy (per unit volume of timber) when processing large trees than smaller machines do when processing small trees. An imbalance in this respect (*i.e.* use of large harvesters to process small trees) is a possible explanation for the high energy use in thinning for the central region in 1997, Table 3.

It is difficult to predict how logging operations will be improved in the future. However, it would be possible to reduce fuel consumption in forwarding through expanding and increasing the load-bearing capacity of the forest-road network. Other potential improvements include installing longer knucklebooms on harvesters (Hallonborg & Nordén, 2001) and optimizing route planning with GPS (Arvidsson *et al.* 1999). Use of combined harvester-forwarders, known as a ‘harwarders’, might also help reduce fuel consumption since they carry out work otherwise done by two machines and thus less machine movements are required. The drawback is that cutting and forwarding capacities would be reduced, but the benefits of hardwarders are estimated to be greater than their drawbacks in thinning since the volume harvested per hectare in thinning operations is low.

Silviculture and seedling production

The results in Table 2 indicate that the energy used in silviculture and seedling production increased between 1972 and 1997, possibly due to the use of more supposedly advanced technology and more intensive silvicultural treatments. In 1972, bare-root seedlings were predominantly used, but the situation was reversed in the 1990s, when container seedlings became the most widely used. Container-seedling systems use more fossil energy than bare-root systems.

The wide difference in energy use between silvicultural systems in 1997, which accounted for 2–15 percent of the total energy used, was largely due to two factors. Firstly, it was difficult to include all internal transport movements. Transport movements in silvicultural work involve considerable energy usage and it was difficult to identify and specify all relevant transport movements. Secondly, organisational differences in large-scale and small-scale forestry affect internal transport movements. In Sweden, companies (large-scale) predominate in the north, while private ownership (small-scale) predominates in the south (National Board of Forestry, 2005). In southern Sweden the private woodlot owners usually perform silviculture activities themselves, while they hire contractors for logging and secondary transport. So, in small-scale forestry, the forest owners manage all the internal transport movements themselves. In their daily work they combine transport related to forestry with transport for other purposes, e.g. private transport or transport related to agriculture. The energy use in internal transport related to forestry might therefore be insignificant. On the other hand, in large-scale forestry in northern and central Sweden and for logging in the south, internal transport movements are organised in larger structures and are therefore also easier to distinguish.

The higher energy usage per cubic metre in the northern than in the southern region is due to the growth rates and, thus annual harvests, being lower in the former than in the latter region. For a given amount of round wood, the requisite area for silvicultural work operations per year was three times higher in the north (16 200 ha per million cubic metres) than in the south (4 900 ha). In contrast, the energy required per hectare for silviculture after final felling was higher in southern and central Sweden due to the more difficult work conditions, Table 4.

Secondary transport

Current EU policy (European Parliament, 2001) to promote renewable fuels makes it important for the forestry sector to consider the scope for using renewable fuels. The results in Table 6 revealed that fossil energy accounted for just 3-4 percent of the primary energy in the fuel cycles where biofuels supplied 100 percent of the process energy (scenarios C2-C4), indicating that about 96 percent of the fossil energy could be replaced with bioenergy by substituting diesel with biofuel for road transport.

Research on timber haulage (Forsberg 2002) suggests that there are many ways of decreasing the energy demands in secondary road haulage, such as reducing the transport distance, adjusting the load factors, using better route-planning systems, improving the standard of roads (widening them, and improving their curve geometry and surfaces), adopting more fuel-efficient driving techniques and using the best available transport carrier.

Using better route-planning systems could increase the load factor, which is an expression of the size of the return cargo. For timber transport in 1997, the road vehicles' loading factor was 50 percent in the north and central regions, and 57 percent in the south. An analysis of the loading factor variation demonstrated that arbitrarily increasing the load factor to 70 percent in all three management regions would decrease the energy requirement for timber transport by about 19-26 percent, Fig. 4. This would cause an overall reduction in the total energy used in timber production of 10-14 percent.

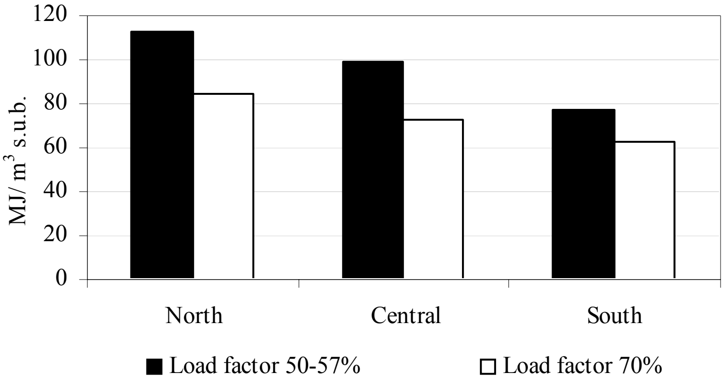

Figure 4. Energy requirements of secondary haulage with different load factors.

Other ways of reducing the energy requirements for timber transport include teaching lorry drivers fuel-efficient driving techniques (Forsberg & Löfroth 2002). According to the cited study, the fuel use in lorries could be reduced by 10 percent if the drivers were better educated.

Emissions from and environmental impact of the forestry systems

Emissions of sulphur and substances that have a global warming effect are linked to the fuel use. Emissions could be reduced by improving engine designs in order to enhance fuel combustion and cleaning of exhaust emissions, and adjusting the engines to suit the forest operations. Changing fuels from fossil fuels to renewable fuels would also decrease the emissions of sulphur and substances that have a global warming effect.

Climate change has a global impact, and the main emissions that cause global warming are CO_2, N_2O, CH_4 and various forms of CFCs. In all the scenarios the substances with global warming effects that were most abundantly released were CO_2, followed by N_2O and CH_4. The CO_2 emissions were related to the fossil energy components of the fuel input, and could be decreased by changing the process energy sources.

Incomplete combustion of fuels or lubricating oil results in hydrocarbon (HC) emissions. Chainsaws and power saws used in silvicultural operations are equipped with two-stroke engines, which emit large amounts of hydrocarbons. Magnusson et al. (2000) found that the output of unburned fuel due to scavenging losses from two-stroke engines amounts to about 22 percent of the fuel consumed. Enhancing the fuel combustion, or the cleaning of exhaust emissions, would decrease emissions of hydrocarbons in silvicultural operations.

Both sulphur oxides (SO_x) and nitrogen oxides (NO_x) originate from fuel combustion. Although sulphur is released from the fuel, the major source of NOx is oxidation of atmospheric nitrogen. In Sweden, the sulphur content of fuels has declined greatly during the last 25 years due to new legal requirements, and consequently the amounts of SO_x released during fuel combustion processes have fallen. The formation of NO_x is enhanced by high temperatures, pressures and oxygen availability. It is possible to reduce NO_x emissions by using a catalytic converter.

The scenarios that depended on electric trains had low environmental impacts (Table 12), due to the processes used to generate electricity. Nuclear power and hydro-electric power generation caused no combustion emissions, such as those produced in scenarios involving the combustion of diesel oil, coal or biomass. Emissions formed in the hydro and nuclear power energy cycles arise from additional energy carriers used in power processing. However, hydro-electric and nuclear power generation was associated with other types of environmental problems; for example damage to the ecosystem due to dams and mining, which were not evaluated in this study.

Data quality

The quality of the data used in studies like those presented in Papers I-III depends on their source, the period they relate to, and their relevance to the technical system studied. The use of different data sources caused variation and uncertainty. In the study described in Paper I, the collected data were site-specific, covering all forest operations carried out over a full year, from management regions´ operating statistics and business accounts, including data from contractors hired by them. The facts that the data were site-specific and that metadata (data of data) were presented indicate that the data quality was good.

Earlier studies on the Scandinavian forestry sector (Berg, 1995, Karjalainen & Asikainen, 1996, Berg, 1997) were based on deductions from, and transformation of, historical data that were not originally intended for LCA, which makes it difficult to control the quality of the data satisfactorily. Furthermore, since these kinds of data are collected from national statistics, assessments are limited to a macro perspective.

In Paper II, two different kinds of data-sets were compared; site-specific data from Paper I and macro data from the 1970s (national statistics and general data on energy consumption by forestry machines). Since the study had these limitations the results could only provide indications of the major differences between the systems, as in Paper II. Nevertheless, the most important criterion was fulfilled, i.e. the system boundaries were the same in all systems; all forest operations carried out during a single year from seedling production through to secondary transport.

The study in Paper III was site-specific, but the energy consumption values originated from different sources. In addition, some of the data were related to future scenarios, for example, the production values of biofuels from Ahlvik & Brandberg (2001) were related to possible future scenarios of 2012. Nevertheless, I believe that such an approach gives realistic indications of the potential for biofuels in comparison to conventional fuels. The study could be used to identify scenarios that should be avoided since their energy efficiency was low and their potential environmental impact was high.

There are also various criteria that have not been investigated in the studies, for example the cost of the systems. Many other environmental and social aspects were also ignored, since they were beyond the scope of the studies.

Conclusions

Genfors & Thyr (1976) compared Swedish forestry between 1956 and 1972 and found that its energy demands had risen three-fold during the intervening period. The main reasons for this were the mechanization of logging operations and the increased use of road vehicles for the secondary haulage of timber. Since then there have been major technological advances. The results in this thesis illustrate the improvements that have been made in forest operations in general, and logging in particular. Increased mechanization since 1972 has not resulted in a rise in total energy use; in fact, it has led to more energy-efficient logging machines, from motor-manual and early mechanised systems, to current machines that are on the verge of automisation.

In contrast, energy use in silviculture has increased, possibly due to the use of more supposedly advanced technology and more intensive silvicultural treatments. The same is also true for secondary haulage because of the greater use of road vehicles and longer haulage distances.

The most important forest operation to improve in the future is secondary haulage since it accounts for about 50 percent of the energy demands in forestry. Continuous progress is being made to decrease the energy demands of secondary haulage by improving the standard of roads and logistics, including a switch from road to rail transport, the development of lighter transport carriers and the adoption of more fuel-efficient driving techniques.

In the studies underlying this thesis some of these improvements were evaluated by calculating the effects of different transport and process energy scenarios. The results did not unambiguously identify environmentally optimal scenarios. However, it was easy to identify scenarios that should be avoided since their energy efficiency was low and potential environmental impact high, including those involving heavy use of coal power and fossil diesel.

The results showed that in biobased-fuel cycles the greenhouse gas emissions are about 95 percent lower than in corresponding fossil fuel cycles and, as discussed above, they involve little fossil energy. Given the expected future scarcity of fossil fuels, and potential consequences of global warming, it could be advantageous for the forest sector to both produce and use a renewable fuel, since it could increase the overall value of forest products and have a low environmental impact.

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