Available online at www.sciencedirect.com
SCIENCE DIRECT
Journal of Cleaner Production 13 (2005) 33–42
Journal of Cleaner Production
www.elsevier.com/locate/jclepro

Energy use and environmental impacts of forest operations in Sweden

Staffan Berg *, Eva-Lotta Lindholm

Forestry Research Institute of Sweden, Uppsala Science Park, S-751 83 Uppsala, Sweden

Received 2 September 2002; received in revised form 4 July 2003; accepted 29 September 2003

Abstract

An inventory of energy use in forest operations in Sweden 1996 and 1997 comprises all operations including seedling production, silviculture, logging and secondary haulage to forest industries. Energy use in Swedish forestry was about 150–200 MJ/m^3 of timber, depending on the locality in Sweden. This inventory demonstrates much higher energy use for secondary haulage than was anticipated by earlier studies. In contrast to this, energy use in logging shows a slight decrease compared to the state of operations a decade earlier, possibly reflecting improvements in technology and management. Although secondary haulage operations account for the largest share of the energy used, logging and silviculture generate the highest levels of certain exhaust emissions. Emissions were either fuel-related (CO_2, SO_x) or engine-related (hydrocarbons, NO_x). Use of renewable fuels and improvements in engine design and the better adjustment of engines to forestry operations could decrease these kinds of emissions.

The emission of gases that contribute to climate change is very small compared to national emissions. Nevertheless, there is scope for a further decrease of this contribution. Timber is an interesting raw material for alternative fuels, thus enabling a better market prospect for such timber that does not meet the specifications of traditional forest industry.

Keywords: LCA; Forestry; Energy use

1. Introduction

There are several means available for studying environmental sustainability. Life cycle assessment (LCA) [1] is an often used comprehensive tool to evaluate the environmental impact of products or services. Its scope is the entire life cycle of a product, from the extraction of raw materials, through to manufacturing, use, and end of life. Data from life cycle inventories (LCI) of forest operations provide the forest industry with the input required for assessing its products. Since LCA came into wider application during the 1990s, efforts have been made to make progress with LCI in relation to forest operations with sufficient relevance and quality [2–6].

Many studies from the Scandinavian forestry sector [7–9] are based on deductions from, and transformation of, historical data that were not originally intended for LCA. A disadvantage here is the difficulty in achieving satisfactory control of the data quality. Furthermore, as these kinds of data are collected from national statistics, assessments are limited to a macro perspective. Recent studies with a machine-orientated approach, based on specific data collected for the purpose of LCA, are presented by Athanassiadis [10].

2. Background

The Swedish forest industry is a major producer and exporter of forest industry products. The industry relies on the vast forest resources that are at hand. There are some 30 million ha of forest and other wooded land, of which 21.2 million ha (55% of the total land area) are covered with forests available for wood supply,

* Corresponding author. Tel.: +46-18-188-500; fax: +46-18-188-600.

E-mail address: staffan.berg@skogforsk.se (S. Berg).

0959-6526/$ - see front matter
doi:10.1016/j.jclepro.2003.09.015

productive forest land [11,12]. The productive forest land is spread across northern and southern Sweden, with the greatest surface areas being predominant in the north, while the greatest volumes are attained in the south. This is a result of the south's higher growth rate (9 m^3/ha year) compared to the north (3–4 m^3/ha year). On a national level, the ownership of forest land is dominated by private owners, who own 48%, while companies own 40%. Companies predominate in the north, while private ownership predominates in the south [12]. This difference in land ownership distribution affects the average size of forest holdings but hardly has any effect on the management systems, as the private forest owners with small holdings co-operate under forest owners' associations, which means even they can benefit from economies of scale. There are other differences between the north and south with respect to population, infrastructure and terrain. The northern part of Sweden is sparsely populated, with a less developed road network than the south. The distance to industries is further, but unlike the south, forest operations in the north benefit from terrain that poses fewer technical problems, and from larger work sites.

The industrial round wood is transported to the pulp and paper industry and the saw milling industry. The forest industry not only uses the raw material for the preparation of products, but also uses black liquor, bark, chips and sawdust as an energy source for processing. A large part of the yearly harvest, over 40% [13,14], is used as an energy source, mainly within forest industries. Saw mills and pulp mills are net providers of energy to local communities [14,15].

3. Goal and scope

The main objectives of this study were to:

- Identify the most significant process in terms of input of energy and outputs of timber and emissions, the latter caused by energy use in forest operations, from seedling production through to the delivery of harvested timber to forest industries.
- Compare forestry in three parts of Sweden and highlight the differences between the forest operations.
- Provide inventory data concerning forest production to the forest industry for its LCA of forest products and services.

4. The system

The study included the Swedish technical system for the production of round wood from forest seedling production through to 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[4] regeneration, cleaning,[5] logging operations[6] and secondary haulage.[7] Other transport was also included: the transport of labor, machinery and supplies to forest work sites. These operations are broken down into unit processes (seedling production, silviculture, logging and secondary haulage) that form the system shown in Fig. 1. Three regional variations of the technical system were included. They were typical in line with the geographical location: northern, central and southern Sweden (Fig. 2).

5. Inventory

This study relied on data from forest operations carried out over one full year, in 1996 or 1997, in three different areas in Sweden. The data were collected from forest management regions in northern Sweden, 700,000 ha, and central Sweden, 350,000 ha. Each one comprised a business unit with its own responsibilities within a large forest industry organization. The third area, comprising 335,000 ha in southern Sweden, was a region belonging to a private forest owner's association. Each of them produced annually about 1 million m^3 industrial round wood under bark (cubic metre solid under bark, m^3 s.u.b.). The data collection involved identification of the total timber flow from the area to several industry facilities, such as pulp mills, sawmills, etc. and keeping track of the machines, manpower, hired services and other resources used in order to achieve this production. The data came from the management regions' operating statistics and business accounts, including data from contractors[8] hired by them. In case contractors did not report to the company, the authors collected data about fuel consumption and production from the contractors' book keeping. The fuel use could be related to both operations performed and the harvested volume. Thus, for each year, the data reflected all activities, from the

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

[2] Soil scarification: loosening up the top soil or breaking up the forest ground, as 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 end-point by road vehicle or railway.

[8] Contractors were hired for some of the unit processes, i.e. cleaning, scarification and logging operations (harvesters and forwarders).

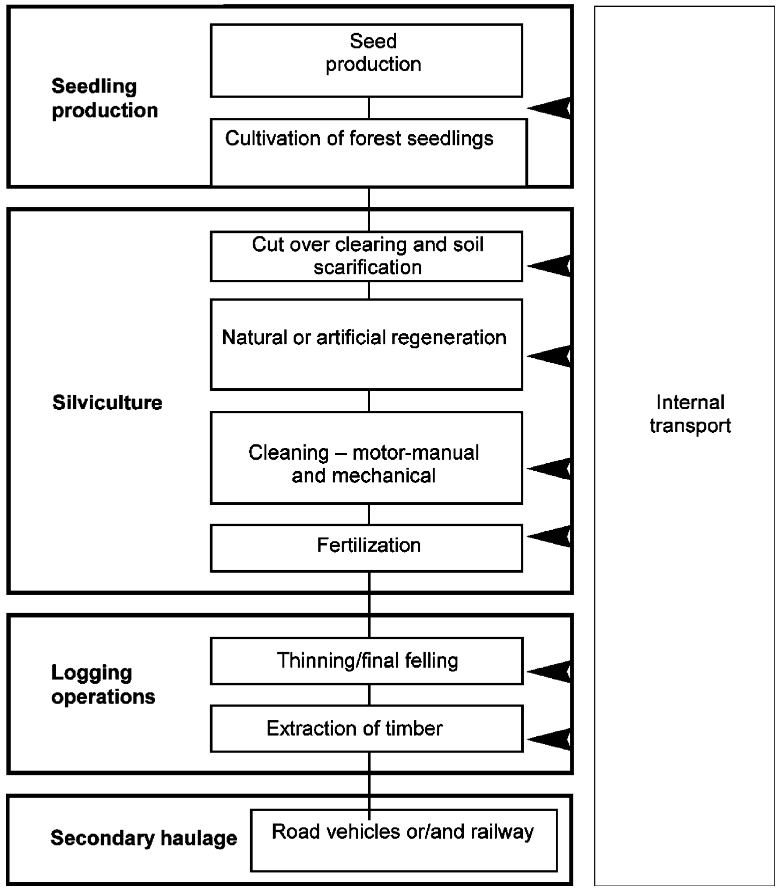

Fig. 1. Unit processes (boxes and text in bold) and their comprising forest operations. Internal transports are allocated to unit processes.

regeneration of a harvested area through to logging as thinning and final felling and timber transport. The harvested area, thinning and final felling together, was 14,600 ha in the north, 6300 ha in the central region, and 5500 ha in the south.

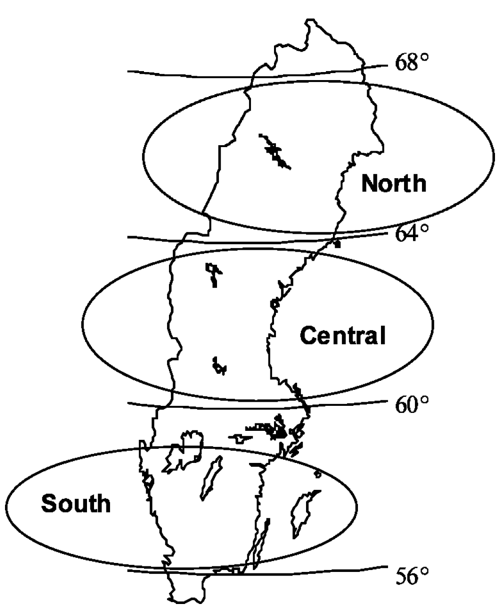

Fig. 2. Locations of the regions.

Collected data were classified into four groups depending on origin:

A Specific measurement from follow-up routine, treated with a measured factor, e.g. area multiplied with consumed amount of fuel per hectare.
B Specific measurement treated with other constant, e.g. calculation of used quantity of engine oil based on measured fuel consumption with the aid of a technical specification for engine oil per litre of fuel.
C Local averages based on measurements, e.g. mean transportation distance in a region. Technical specifications (for machinery used) such as energy consumption per unit (e.g. ton km).
D General averages, e.g. total energy use for transportation by railway.

The data are presented in Table 1.

The forest management's needs in terms of forest tree seedlings were met by nurseries. Data for forest seedling production are outlined by Aldentun [16] in a study of four forest tree nurseries in Sweden. The seedlings produced were containerized forest tree seedlings

Table 1
Input of fossil fuel, electricity and fertilizers (N) to three forest regions: north, central and south

	North					Central					South				
	Diesel, m^3	Petrol, m^3	Engine oil etc. and hydr. oil, m^3	Electricity, GW h	Data origin: fuel/eng. oil/hydr. oil	Diesel, m^3	Petrol, m^3	Engine oil etc. and hydr. oil, m^3	Electricity, GW h	Data origin: fuel/eng. oil/hydr. oil	Diesel, m^3	Petrol, m^3	Engine oil etc. and hydr. oil, m^3	Electricity, GW h	Data origin: fuel/eng. oil/hydr. oil
Seed production and cultivation of forest seedlings[a]	145	1.09		0.291	B/–/–	163	1.02		0.605	B/–/–	225	0.58		0.549	B/–/–
Soil scarification and cut-over clearing	221		2.04[b]		A/B/B	77		0.76[c]		A/B/B	68		1.12[d]		B/B/B
Natural or artificial regeneration						(Included in "Not allocated")									
Manual	20 (*4010 ha*)		0.04[e]		A/B/–	(*1793 ha*)						19.4 (*1804 ha*)	0.039[e]		B/B/–
Mechanized	24 (*387 ha*)		0.24[f]		A/B/B	16 (*249 ha*)		0.155[g]		A/B/B					
Cleaning															
Motor manual		24.5	0.27[e]		B/B/–		23.55	0.471[e]		B/B/–		13.41	0.13[e]		A/B/–
Mechanized						10		0.1[d]		A/B/-					
Fertilization	1.6[h]		0		A/B/–	32.33[i,j]		0.36		A/C/–					
Logging total	2075		129.8[k]		A/C/C	1670		52.9[l]		A/C/C	1633		149.22[m]		B/C/C
Secondary haulage	3423		4.79[n]		B/B/C	2412		3.38[n]		C/C/C	2416		5.05[o]		A/B/C
Road vehicles															
Diesel electric railway	173				C/–/–										
Electric railway				3.409	D/–/–				2.075	D/–/–					
Total	3596		4.79	3.409		2412		3.38			2416		5.05		C/C/C
Not allocated		280	0.56[e]		C/C/–	131	119	1.8[e]		C/C/–					
Total sum	6038	306	138	3.700		4511	144	60	2.680		4342	34	156	0.549	
Volume of timber solid m^3 s.u.b. cut	1,167,700					936,900					1,100,000				
Volume timber solid m^3 s.u.b. transported	1,234,615					1,131,309					1,100,000				

[a] Input according to Aldentun [16: Table 2]: north—Kilåmon (100%, 2300 pl/ha), central—Lugnet (50%, 3200 pl/ha) and SörAmsberg (50%, 3200 pl/ha), south—Lugnet (50%) and Hillet (50%).
[b] Engine oil 0.7; hydr. oil 1.34.
[c] Engine oil 0.25; hydr. oil 0.51.
[d] Engine oil 0.52; hydr. oil 0.6.
[e] Engine oil.
[f] Engine oil 0.08; hydr. oil 0.16.
[g] Engine oil 0.055; hydr. oil 0.1.
[h] 72.62 tons of N.
[i] Air jet fuel 30.0.
[j] 192.58 tons of N.
[k] Engine oil 61.2; hydr. oil 68.6.
[l] Engine oil 22.9; hydr. oil 30.
[m] Engine oil 113.64; hydr. oil 35.58.
[n] Engine oil 1.4‰; hydr. oil 3×10^{-10} of diesel.
[o] Engine oil 3.38; hydr. oil 1.67.

that were cultivated with spacing appropriate to field requirements at outplanting, from 400 seedlings/m^2 in the south to almost 1000 in the north.

Data from forest operations and seedling production put together give an estimate of the amounts of fuel, electricity, and ancillary materials used in each unit process in 1996 (north) and 1997 (central and south).

6. System boundary

Energy requirements related to the material and energy use were collected for each of the unit processes in the systems. The system boundaries were set to encompass the extraction and production of all energy carriers and ancillary materials of the system. System outputs were round wood, waste and calculated emissions into the atmosphere (air), water and soil.

It was not possible to find data concerning energy use for production and transport of pesticides [16]. No specific data were found for fertilizer used in seedling production and forestry. However, the energy use for production of nitrogen was evaluated according to [17]. The leakage of nitrogen into the ground water after applying fertilizer to forest stands [18] and nurseries [19] was included. According to Athanassiadis et al. [20], about 40% of the lubricants used by the harvesters and forwarders leached into the ground, while the rest was collected as hazardous waste and transported to an incineration plant for energy generation.

The study did not include the production of capital goods (machinery and buildings), transport of energy carriers and ancillary material from the production industry to the forest management region, the assimilation of CO_2 by the trees, pesticide leakage at nurseries, or the environmental effects of the ecosystems which, at that moment, were not measurable using the LCA methodology, such as damage to the production system, biodiversity, and the nutrient cycle.

The functional unit, which all the data collected were related to, was 1 m^3 s.u.b. delivered to the mill. Inputs and outputs were allocated to this volume. For calculation of energy content of timber and transports, reference to dry matter is necessary. The basic density of the round wood, 399 kg/m^3, comprised the density values for Scots pine, Norway spruce and birch species from [21], which were weighted according to the mean annual felling for 1993–1998 in Sweden. The net calorific value was 19.2 MJ/kg of dry matter (dm) [22].

7. Technology and the representativeness of data

Site-specific data for the means of transport, energy requirements and ancillary material use were collected mainly in the form of measurements and company performance data from the forest management regions and nurseries. The LCI data for fuels used in the systems came basically from Frischknecht et al. [23]. Requirements for petrol, diesel and electricity in unit processes were included according to [24]. Lubricants were approximated as having the same LCI values as petrol. Electricity supply was taken from the Swedish grid mix [25] when used in Sweden, and from the European mix [26] for processes outside Sweden.

Cargo ships, ferries and road vehicles transported ancillary materials for seedling production. The technology used in the diesel engines in harvesters and forwarders and the petrol engines in cars and power saws was of branch standard. According to Hallonborg [27], the average age of harvester and forwarder machines in Swedish forestry was 10 years, while for haulage rigs in Sweden the same average age was 3 years. Representative emission factors (CO, NO_x, HC) for the forestry machinery used came from a Swedish study of tractors and forestry machines[9] [28], and for other emissions according to "heavy truck" in [24]. In the north, timber was transported to the industrial sector via a combination of road vehicles, electric and diesel–electric trains. In the central region, transport was carried out by road vehicles and electric trains, and in the south only road vehicles were used. General emission factors from the Network for Transport and the Environment [29] were used for diesel truck engines, petrol and diesel cars, ships and ferries. The truck engines were to Euro 2 standard. The fuel used was Environmental class 2 for diesel and petrol, as per the Swedish environmental classification [30]. The average loading factor[10] for the timber trucks was 57% in the south and 50% in both the central and northern regions. The loading factor of 50% was due to haulage entailing transporting a full load one way and coming back empty on the return journey. Table 2 shows the various vehicles and technical devices used in the systems.

8. Results

The energy use required to produce 1 m^3 s.u.b. of timber wood was 200 MJ in northern Sweden, 187 MJ in the central region, and 147 MJ in southern Sweden (Fig. 3). This included all unit processes, from seedling

[9] For harvesters and forwarders work moments, in Table 10 of [28], "transport 1" and "transport 2" represent driving in forest and "lastning (*loading*)" represents crane work. A harvester is supposed to use the crane 80% of time and drive 20%. The corresponding values for forwarders are 77% and 23%. For tractor work during fertilizing, the average of "transport 1" and "transport 2" was used. Scarification and mechanized planting used values for "stubbearbetning på åker (*cleaning of stubblefields*)", also according to Table 10 in [28].

[10] Distance driven with a full load (100%) per round trip.

Table 2
Vehicles and technical devices used in the systems

Unit	Used in unit process	Source
Bulk carrier ship coaster	Transport of ancillary materials	[26]
Truck (Euro 2)	Seedling production; secondary haulage	[29]
Oil heating	Seedling production	[31]
Tractor	Seedling production	[24,28]
Helicopter	Silviculture	[32]
Harvesters and forwarders	Logging operations	[24,28]
Petrol car	Silviculture	[33]
Diesel car	Silviculture	[29]
Power saw	Silviculture	[34]
Train—diesel and electric	Transport of logs	[29]
Electricity—Swedish mix and European mix	Seedling production; electric train	[25,26]

production through to secondary haulage and delivery to the industrial site. The energy carrier used was predominantly diesel, but petrol and electricity also had some significance (Table 1). Forestry machinery was powered using fossil fuels. Of the total energy needed to produce 1 m^3 s.u.b. of wood, about 0.1% was renewable energy, which was derived from the Swedish electricity mix.

One cubic metre of timber contains about 7700 MJ. This means that the energy used for getting the timber to the mill, less than 200 MJ, comprises less than 3% of the inherent energy that is available in the timber. This relationship is quite favourable compared to, for example, refined fossil oil for some market applications. Frischknecht et al. [23] estimated that the proportion of feedstock energy used is 5% after refining and 20% for use in a diesel–electric locomotive, for example.

Of the total amount of energy used, transporting timber to the industrial sector (secondary haulage) accounted for the largest energy requirement, with 56% (113 MJ) of the total energy being used in the north, 53% (99 MJ) in the central region, and 53% (77 MJ) in the south (Fig. 3). The remaining energy use was divided between logging operations, silviculture and seedling production, with silviculture needing only 8% in the north (16 MJ), 7% in the central region (15 MJ), and 2% (3 MJ) in the south. Corresponding energy use for seedling production is 5, 9 and 9 MJ, respectively.

In logging operations, the energy use comprised about 30% of the total in the north and central regions (66 and 65 MJ), and 40% in the south (57 MJ). The kind of cutting operation (final felling or thinning) had larger influence on energy use per m^3 s.u.b than geographical area of operation. Forwarders and harvesters in the various management regions had similar fuel consumption per volume of harvested timber. The final felling needed less energy per volume of timber (32 MJ/m^3 in the north, 32 MJ/m^3 in the central region, and 27 MJ/m^3 in the south) compared to thinning (44 MJ/m^3 in the north, 60 MJ/m^3 in the central region, and 40 MJ/m^3 in the south). Extension, forwarding of timber to forest roads, used 31–34 MJ/m^3 s.u.b. in thinning and 22–27 MJ in final felling.

In Fig. 4, energy use per hectare is shown per management region for cleaning and scarification. Due to adverse work conditions, the energy required per hectare in silviculture after final felling was higher in southern and central Sweden, which gives another interpretation of energy use shown in Fig. 3, where the result is related to harvested volume timber. Cleaning used more energy in the south (430 MJ/ha) than in the central region (300 MJ/ha) or the north (230 MJ/ha). In addition, for soil scarification, the use was highest in the central region (1560 MJ/ha), followed by the south (1240 MJ/ha) and the north (1050 MJ/ha).

A contributing factor to high energy use per cubic metre in the north is lower growth and consequently smaller harvests each year. For a certain amount of round wood, the requisite area for work operations in silviculture, listed in Fig. 1, per year is three times greater in the north, 16,200 ha/million m^3 compared to the south, 4900 ha.

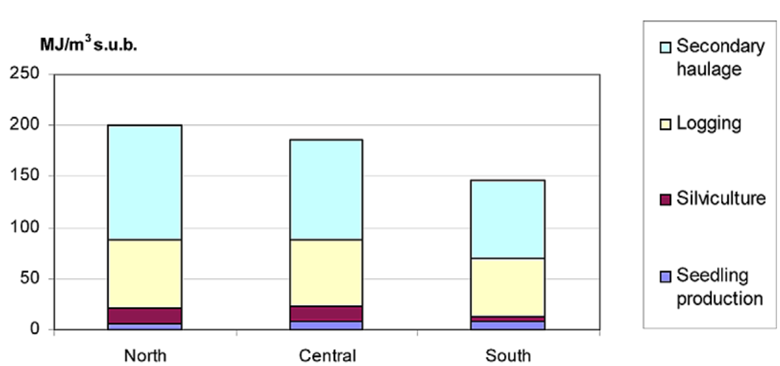

Fig. 3. Energy requirements in three different forestry management regions.

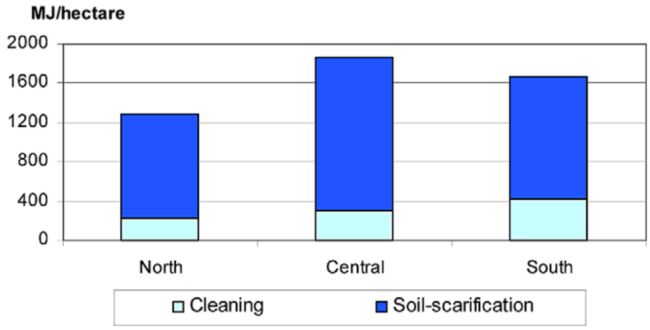

Fig. 4. Energy requirements per hectare of silviculture in the three different management regions.

The energy used for the secondary transport of timber depends on the distance, the possible return cargo (expressed by loading factor), and the type of road and vehicle. For timber transport, the vehicles' loading factor was 50% in the north and central regions, and 57% in south. An analysis of the loading factor variation demonstrates that an arbitrary chosen load factor of 70% in all three management regions would decrease the energy requirement in timber transport by about 19–26% (Fig. 5). This would cause an overall decrease of the total energy used in timber production of 10–14%.

Although transporting timber to the industrial sector accounted for the greatest part of the energy used, logging and silviculture together generate the majority of certain exhaust emissions, such as carbon monoxide (CO), hydrocarbons (HC), dinitrogen oxide (N_2O), nitrogen oxides (NO_x) and sulphur oxides (SO_x) (Table 3). Timber transport accounted for the greatest part of the emissions of carbon dioxides (CO_2), particles and methane (CH_4).

9. The impact assessment

The environmental impacts were evaluated by category indicators as climate change, acidification, eutrophication, and photo-oxidant formation, according to the Swedish Environmental Management Council [35].

9.1. Global impacts—climate change

The characterization results for climate change, shown in Table 4, correlate with the result for the energy requirement (Fig. 3). 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 the largest potential impact compared to logging, silviculture and seedling production. This was caused by secondary haulage's major energy need (Fig. 3). The energy demand was mainly met by using fossil fuels. Silviculture and seedling production operations had a larger impact in the central and northern regions than in the southern region (Table 4).

9.2. Regional impacts—acidification, photo-oxidant formation and eutrophication

The potential impact of photo-oxidant formation is shown in Table 5. Secondary haulage had the largest impact, followed by logging operations. Silviculture and seedling production operations together made up 13–15% of the total impact in the north and central regions, while in the south the figure was only 7%.

The eutrophication and acidification impact categories both show a similar pattern of results (Tables 6 and 7). In both categories, logging operations showed the largest potential impact in the south and central regions, about 50%. In the north, the contributions made to the eutrophication and acidification impacts by logging and secondary haulage were similar, 45–47%. The impacts of silviculture and seedling production were small in both categories.

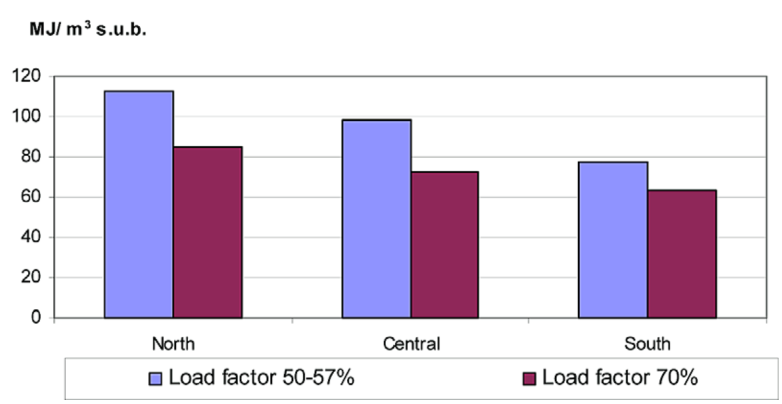

Fig. 5. Energy requirements of secondary haulage with different load factors.

Table 3
Estimated emissions per cubic metre (s.u.b.) of round wood

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

Table 4
Characterization results for climate change, kg CO_2 equivalents/m^3 s.u.b.

Climate change GWP (100 years), CO_2 equivalents/m^3 s.u.b.	North	Central	South
Seedling production	386	562	599
Silviculture	1720	1730	299
Logging operations	5880	5910	5100
Secondary haulage	9510	8370	7060
Total	17,110	16,010	12,459

Table 5
Characterization results for photo-oxidant formation, POCP/m^3 s.u.b.

Photochemical ozone formation, POCP/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	20.5	19.1	14.8

Table 6
Characterization results for acidification,. mol H^+/m^3 s.u.b.

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 7
Characterization results for eutrophication, g O_2/m^3 s.u.b.

Eutrofication, 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	965	929	732

10. Discussion

The results from this study indicate that forest operations in northern Sweden uses more energy per cubic metre than in central and southern Sweden; also, about half of the energy use per cubic metre in Swedish forestry is provided for secondary haulage from forest sites to industries. Unless heavy investments in infrastructure are made, very little can be done to decrease the actual distances from forest to industry. There is, however, scope for enhancing the payload per distance driven on each round trip. At the time the study was conducted, it was common for road vehicles to make return trips unloaded, which theoretically entails a loading factor of 50%. To attain a higher loading factor, the use of better route planning systems is suggested [36]. If such measures are applied, there might be a significant effect: e.g. an arbitrary chosen increase of loading factor to 70% results in a total energy use reduction of 10–14% from nursery to industry. Other ways of lowering the use of energy in road transport are to improve the standard of the present rough forest roads (road width, curvature and better surfacing/ foundation) and the driving style (“soft” driving, i.e. heavy eco driving) [36].

A major leap forward in logging operations is difficult to anticipate. Some improvements are possible through adjusting fuel consumption to the energy requirement for felling, limbing and bucking of timber. This implies a correct application of machine operations to stand conditions. Larger harvesters use more energy, but when processing large trees the energy use is less than when smaller machines process small trees. An imbalance in this respect (that is, large harvesters processing small trees) is a possible explanation for the high energy use in thinning for the central region. Major progress in forwarding might occur if load bearing capacity is increased or if the forest road network is expanded. The latter will bring about other environmental costs during construction, and a long-lasting loss of biodiversity due to decreased land quality in the areas the roads run through.

Climate change has global impact, and the emissions that cause global warming are CO_2, N_2O, and CH_4, as well as different forms of CFCs. In this study, CO_2 was the most abundant emission with a global warming effect, followed by N_2O and CH_4. The northern region had the largest energy use, and since fuel combustion releases CO_2, the highest CO_2 emission to the atmosphere from this region. Applied on all forest operations in Sweden during one year, the level of ca 15 kg CO_2 equivalents/m^3 sums up to modest national emissions of ca 0.3 Tg C a^{-1}, a very insignificant contribution compared to Swedish national emissions from fossil fuels (18.9 Tg C a^{-1}) [37].

The photo-oxidant formation impact category was affected by hydrocarbon emissions, which are formed due to the incomplete combustion of fuels. Table 5 shows that the northern system had the largest impact in terms of photo-oxidant formation. Here too, this is due to the higher energy use in the northern system. Enhanced fuel combustion, or the cleaning of exhaust emissions, would improve the results in this category. Chainsaws and power saws are equipped with two-stroke engines due to their high power to weight ratio. Magnusson et al. [38] found that the output of unburned fuel due to scavenging losses from two-stroke engines is about 22% of the fuel consumption.

In terms of the acidification impact category, emissions of sulphur oxides (SO_x) and nitrogen oxides (NO_x) made the greatest contribution. Both compounds originate from fuel combustion, although sulphur is released from the fuel, while NO_x is created in the combustion process. In Sweden, the sulphur content of fuels decreased greatly during the 1980s and 1990s due to new legal requirements, which have decreased the amount of SO_x released during fuel combustion processes. NO_x is formed in the combustion process in engines, and the higher the temperature, the more the NO_x formed. In a petrol engine, it is possible to reduce NO_x emissions in a catalytic converter, but in a diesel engine measures have to be taken in relation to the combustion process, which is much more difficult.

Eutrophication is the consumption of oxygen in the water ecosystem, caused by the mineralization of organic material that has been produced from emitted nutrients, for example phosphorous and nitrogen. As was also the case with acidification above, the northern region shows the highest eutrophication impact. The NO_x emissions created in the combustion process contributed the most to this category.

Expressed in terms of the volume of timber harvested, silviculture operations only have a minor impact on effect categories. However, contrary to other forest operations, some silviculture operations, such as seedling production and early stand establishment measures, have been performed in the same area for many years. Regional effects such as acidification and eutrophication are important. The leakage of nutrients and emissions from nurseries are significant environmental aspects.

As a difference to other studies [7,9], in which general data from official statistics were collected [12], this study relied on data specifically collected from forest areas that delivered 1 million m^3/year annually. Also, contrary to other studies data were classified according to its origin. Data in this study emerge to a high degree from measured data or calculated local averages. To the authors' opinion this have improved the estimates for secondary haulage, whereas earlier studies of silviculture and logging already relied on sound data as it came from field studies or research within companies. Its quality was checked by various users of this information.

Results from earlier studies of Swedish forestry [7] is difficult to compare in detail due to different definitions of unit processes. It is however, evident that present study gives a higher estimate of emissions from secondary haulage. Results from [7] give a lower estimate of CO_2 equivalents/m^3 s.u.b (3.6 kg) compared to 7–10 kg in present study. Present study includes seedling production, which was not covered in [7 or 9]. Data from [7] gives a energy use of 91 MJ m^3 in silviculture and logging together, whereas present study as average for similar areas gives a magnitude of about 85 MJ, ca 90 when seedling production is included.

Energy use in silviculture and logging vary less. A lower energy use concerning logging in the present study might be the effect of improvements in logging machinery and technique, whereas differences in silviculture rather reflect difficulties in data gathering or a variation in time caused by extension in space and intensity. It is difficult to tell if this is caused by differences in data quality per se or due to local circumstances in this study compared to the general approach applied in [7].

There are differences in data collection and definitions between [7] and present study, the former representing national averages and the latter three individual cases. This contributes to the variation between results. However, according to the judgment of the authors, this study presents a realistic contemporary level compared to results from [7], especially with respect to secondary haulage.

The environmental impact evaluated in this study here is caused by the use of fossil fuels. A changeover of the fuels used in forest operations to renewable energy sources is an option that holds interesting prospects, as forest companies work with timber, which is renewable if sustainable forestry is implemented. The high return of inherent energy in timber compared to energy use in forest management makes timber a very interesting energy carrier. As it is renewable in sustainable forest operations, timber processed to alternative fuels [39] is an interesting renewable alternative to consider in situations where nuclear power or fossil energy is being targeted for reduction or phasing out. This entails a prospect of better market position for timber that does not meet the quality specifications of forest industry.

References

[1] Swedish Standards Institution. Environmental management—life cycle assessment—principles and frame work (ISO 14040: 1997). Svensk Standard SS-EN-ISO 14040. 2001.18 p.

[2] Berg S. Methods for environmental assessment of forestry operations—an overview. Forest and society: the role of research. XIX IUFRO World Congress 2000, Sub-Plenary Sessions vol. 1. International Union of Forestry Research Organisations; 2000.

[3] Heinimann HR. Ökobilanzierung von forstlichen Produktionssystemen—Beziehungen zu Umweltmanagementsystemen und Übersicht über das methodische Konzept. Schweiz Z Forstwes 1999;150(3):73–80.

[4] Richter K. Life cycle assessment of wood products. In: Frühwald A, Solberg B, editors. Life cycle analysis—a challenge for forestry and forest industry. EFI Proceedings No. 8. 1995, p. 65–74.

[5] Knechtle N. Materialprofile von Holzerntesystemen—Analyse als Grundlage für Ökoinventare. Schweiz Z Forstwes 1999; 150(3):81–7.

[6] Schweinle J. Analyse und Bewertung der forstlichen Produktion als Grundlage für weiterführende forst- und holzwirtschaftliche Produktlinien—Analysen. Mitteilungen der Bundesforschungsanstalt für Forst- und Holzwirtschaft, No. 184. Hamburg: Kommissionsverlag Buchandlung Max Wiedebusch; 1996 [September].

[7] Berg S. The environmental load of fossil fuels in Swedish forestry—an inventory for a LCA. In: Frühwald A, Solberg B, editors. Life cycle analysis—a challenge for forestry and forest industry. EFI Proceedings No. 8. 1995, p. 53–65.

[8] Berg S. Some aspects of LCA in the analysis of forestry operations. J Cleaner Prod 1997;5(3):211–7.

[9] Karjalainen T, Asikainen A. Greenhouse gas emissions from the use of primary energy in forest operations and long-distance transportation of timber in Finland. Forestry 1996;68(3):215–28.

[10] Athanassiadis D. Resource consumption and emissions induced by logging machinery in a life cycle perspective. Doctoral thesis, Acta Universitatis Agriculturae Sueciae, Silvestria, 143, Swedish University of Agricultural Sciences, Department of Silviculture, Section of Forest Technology. 2000.

[11] TBFRA 2000. The UN-ECE/FAO temperate and boreal forest resource assessment 2000, vol. I. Main report. New York, Geneva: United Nations; 1999.

[12] Anon. Skogstatistisk Årsbok (Yearbook of forest statistics Jönköping (Sweden): National Board of Forestry; 2001.

[13] Sundberg U, Silversides R. Analysis Operational efficiency in forestry vol. 1. Dordrecht, Boston, London: Kluwer Academic Publishers; 1988 [219 p.].

[14] Nilsson PO, Lönner G, editors. Energi från skogen. Uppsala: Swedish University of Agricultural Sciences; 1999 [SLU kontakt 9].

[15] Norén J, Jarnehammar A. Miljöbedömning av Trähus 2001—bakgrundsfakta. Trätek. Rapport P 0105010. Stockholm: 2001 [in Swedish].

[16] Aldentun Y. Life cycle inventory of forest seedling production—from seed to regeneration site. J Cleaner prod 2002;10:47–55.

[17] Montfoort J. Produktie van stikstoft kunsmest [Production of nitrogen for fertilizers]. RIVM rapport 773006147, RIVM 1995. 20 p. Available through Sima Pro Database PRé Consultants B.V.

[18] Westling O, Nohrstedt H-Ö. Environmental impact assessment of STORA SKOG's fertilization programme, Part 2, Assessment. Report B1219e. Aneboda: Swedish Environmental Research Institute; 1995.

[19] Hannerz M, Rosenberg O. Näringsutnyttjande och läckage vid praktisk plantodling. Arbetsrapport nr. 2001. SkogForsk (The Forestry Research Institute of Sweden). p. 480 [in Swedish].

[20] Athanassiadis D, Lidestav G, Wästerlund I. Fuel, hydraulic oil and lubricant consumption in Swedish mechanized harvesting operations, 1996. J Forest Eng 1999;10(1):7.

[21] Karjalainen T. Dynamics of the carbon flow through forest ecosystem and the potential of carbon sequestration in forests and wood products in Finland. Research notes 40. University of Joensuu, Faculty of Forestry; 1996. 478 p.

[22] Anon. Energifakta, energiinnehåll och densitet för bränslen. Stockholm (Sweden): AB Svensk Energiförsörjning; 1998 [In Swedish].

[23] Frischknecht R, et al. Ökoinventare von Energiesystemen. Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. Energiewirtschaftliche Grundlagen. Bundesamt für Energiewirtschaft; 1996.

[24] Uppenberg S, Almemark S, Brandel M, Lindfors L-G, Marcus H-O, Stripple H, et al. Bakgrundsinformation och Teknisk bilaga. Miljöfaktabok för bränslen, Del 2. IVL rapport B 1334B-2. Stockholm: 2001. 172 p.

[25] Anon. LCA inventory tool (LCAiT) version 2.1. Software programme. Chalmers Industriteknik (CIT) Ekologik; 1996 [Using data from Brännström-Norberg et al. Life-cycle assessment for Vattenfall's electricity generation. Summary report. Stockholm: Vattenfall; 1996].

[26] Frees N, Pedersen Weidema B. Life cycle assessment of packaging systems for beer and soft drinks. Energy and transport scenarios. Technical report 7. Miljöprojekt nr. 406. Denmark: Ministry of Environment and Energy; 1998.

[27] Hallonborg, U. Personal communication. The Forestry Research Institute of Sweden; 2001.

[28] Hansson P-A, Burström A, Norén O, Bohm M. Engine emissions from agricultural tractors and forestry machines. Report 232. Department of Agricultural Engineering, Swedish University of Agricultural Science; 1998 [in Swedish, abstract in English].

[29] NTM (the Network for Transport and the Environment). Version 2000-05-30 [1 June 2001].

[30] Swedish Environmental Protection Agency (EPA). Available from:www.naturvardsverket.se/dokument/teknik/trafik/trafikdok/mkbensin.htm. Version 2001-05-10 [1 July 2002].

[31] Swedish Environmental Protection Agency (EPA). Miljöanpassad effektiv uppvärmning och elanvändning—20 °C men hur? Rapport Naturvårdsverket nr. 4526. 1998 [in Swedish].

[32] Swedish Civil Aviation Administration (SCAA). Available from: www.emis.ffa.se/lfv/swe/action.lasso [23 August 2002].

[33] Arnäs P-O, Blinge M, Bäckström S, Furnanader Å, Hovelius K. Livscykelanalys av drivmedel—en studie med utgångspunkt från svenska förhållanden och bästa tillgängliga teknik. Meddelande 95. Göteborg (Sweden): Department of Transportation and Logistics, Chalmers University of Technology; 1997 [in Swedish, abstract in English].

[34] Holmgren K. Katalysatorfunktion i tvåtaktsmotorer. SMP (The Swedish Machinery Testing Institute); 2000 [in Swedish].

[35] Swedish Environmental Management Council (EPA). Requirements for environmental product declarations—EPD, an application of ISO TR 14025 type III environmental declarations. MSR 1999:2. 2000.

[36] Forsberg M. Transportsamordning Nord—analys av returtransporter. Arbetsrapport SkogForsk nr. 529/2003. 30 p.

[37] Commission of the European Communities. Third communication from the European Community under the UN Framework Convention on Climate Change. SEC. 2001. 2053. 213 p.

[38] Magnusson R, Nilsson C, Andersson K, Andersson B, Rannug U, Östman C. Effect of gasoline and lubricant on emissions and mutagenicity of particles and semivolatiles in chain saw exhaust. Environ Sci Technol 2000;34(14):2918–24.

[39] Vägverket. Systemeffektivitet för alternativa drivmedel. Olika drivmedel och drivsystem/motorer i ett livscykelperspektiv 2012. Ecotraffic publikation 2001. 2001, p. 39 [61 p.].