Energy Use and Environmental Impact of Roundwood and Forest Fuel Production in Sweden

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Doctoral Thesis
Swedish University of Agricultural Sciences
Uppsala 2010

Acta Universitatis agriculturae Sueciae
2010:40

ISSN 1652-6880
ISBN 978-91-576-7453-1

Print: SLU Service/Repro, Uppsala 2010

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Abstract

The increasing awareness of climate change issues, unstable fossil fuel prices and concerns about energy security are leading to a rising demand for forest products. If meeting this demand involves increased harvesting it is essential to employ efficient systems that allow sustainable forest management. This thesis examines the environmental performance of the Swedish forestry system and potential opportunities to improve this system. The focus was on roundwood and forest fuel procurement and timber transport, which were evaluated using a Life Cycle Assessment perspective. To evaluate the greenhouse gas savings from forest fuel, the dynamics of soil carbon stocks and the potential to replace fossil fuel were examined.

Production of roundwood and forest fuel required little external energy and emitted low greenhouse gas emissions. About 3% of the inherent energy available in roundwood and 2-5% of that in forest fuel, logging residues and stumps was required in forest fuel production. More energy was required in northern Sweden than in southern Sweden, mostly due to higher energy use in transport operations. Secondary transport of roundwood and forest fuel comprised about 50% of energy use, which could be decreased by reducing the road transport distance by modal changes, e.g. between lorry and train, increasing the loading factor, decreasing the fuel requirements of vehicles and using an energy carrier with good environmental characteristics.

There were great greenhouse gas savings when forest fuel, stumps and logging residues, replaced fossil fuel. Important factors when assessing the greenhouse gas savings from forest fuel, were the efficiency of the end use, type of fossil fuel substituted, allocation method, site productivity, intensity of the harvesting and bioenergy source (stumps or logging residues).

Increasing the use of forest products and forest fuel may decrease energy use and emissions of greenhouse gases if fossil fuel and petrochemical-intensive products can be substituted. However, this can have other environmental impacts, indicating potential conflicts between different environmental areas.

Keywords: life cycle assessment, forest fuel, transport, roundwood.

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To Lisa and Anton

Contents

List of Publications

This thesis is based on the following papers, which are referred to in the text by their Roman numerals:

I Berg, S. & Lindholm, E-L. (2005). Energy use and environmental impacts of forest operations in Sweden. *Journal of Cleaner Production* 13(1), 33-42.
II Lindholm, E-L. & Berg, S. (2005). Energy requirement and environmental impact in timber transport. *Scandinavian Journal of Forest Research* 20(2), 184 - 191.
III Lindholm, E-L., Berg, S. & Hansson, P.-A. Energy efficiency and the environmental impact of harvesting stumps and logging residues. (Accepted for publication in *European Journal of Forestry*)
IV Lindholm, E-L., Stendahl, J., Berg, S. & Hansson, P-A. Greenhouse gas balance of harvesting stumps and logging residues in Sweden. (Manuscript)

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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 Berg and Lindholm. Berg and Lindholm jointly wrote the paper.

For Paper II, the modelling was planned by Berg and Lindholm, Lindholm constructed the model, analysed and interpreted the results. Lindholm wrote the paper with input from Berg.

For Paper III, the modelling was planned by Lindholm together with Berg. Lindholm carried out data collection with input from Berg. Lindholm constructed the model, analysed and interpreted the results. Lindholm wrote the paper with input from the co-authors.

For Paper IV, the modelling was planned by Lindholm together with the co-authors. Lindholm modelled the forest growth and calculations of the litter input to the soil model, and Stendahl was responsible for the soil carbon simulation. Lindholm analysed and interpreted the results. Lindholm wrote the paper with input from the co-authors.

Abbreviations

C	Carbon
CO_2	Carbondioxide
EtOH	Ethanol
FTD	Fischer Tropsch Diesel
GHG	Greenhouse gas
LCA	Life Cycle Assessment
MeOH	Methanol
PE	Primary Energy
SOC	Soil Organic Carbon

1 Introduction

1.1 Background

One of the key elements of global ecosystems is forests, which cover about one-third of the Earth's land area (FAO, 2005). Forests fulfil many environmental functions such as providing habitats for a variety of plant and animal species, protecting soil and water, and improving air and water quality. Forests are also an important economic resource for millions of workers, contractors and forest owners and therefore contribute to economic growth, jobs and wealth. Furthermore, forests provide renewable energy and biomass if sustainably managed.

The world's forests are also a major and dynamic reservoir for carbon and therefore play a substantial role in the global carbon cycle (Nabuurs *et al.,* 2007; Shvidenko *et al.,* 2005). Thus, one of the key options in solving the challenge of mitigating climate change is forest management. Mitigation options include reducing emissions from deforestation, preventing forest degradation, enhancing the sequestration rate in existing and new forests and in forest products, providing wood fuels as a substitute for fossil fuels, and providing wood products for more energy-intensive materials.

In 2007, total global roundwood removal (including traditional fuelwood) was 3 billion m^3, of which the firewood component was estimated to amount to almost half the removed wood (FAO, 2005). Between 1960 and 2000, industrial roundwood harvesting increased by 60% and is expected to continue increasing, but at a slower rate (Sampson *et al.*, 2005). In Sweden, gross felling increased by about 50% between 1960 and 2009 (Swedish Forestry Agency, 2009a). Although the depressed global financial market in recent years has led to decreased demand for wood products, the demand for wood energy has remained buoyant

(UNECE/FAO, 2009). This is a cause of the structural change in the forest industry towards increased production and consumption of wood energy, a change driven by government policies on seeking renewable energy sources (UNECE/FAO, 2009).

In Sweden, the use of wood fuel has increased from 47 TWh to 100 TWh in less than 30 years (Swedish Forest Agency, 2009a). Today the proportion of renewable energy used in Sweden is 43.3% (183 TWh in 2006) with wood fuel contributing with 23% of the total (Swedish Energy Agency, 2008). There are several reasons for the increased used of bioenergy in Sweden, among the most important of which are the expansion of district heating, increased use of forest by-products as energy in forest industries and the implementation of CO_2 taxes on emissions from fossil fuels in 1991 (Lunnan *et al.,* 2008; Björheden, 2006). In an international and national perspective, there have been a multitude of policies to stimulate the use of renewable fuels for environmental reasons and to increase energy security by diversifing the energy portfolio and protecting the market against unstable fossil fuel prices and availability.

More recently, the EU has committed to a 20% reduction in greenhouse gas (GHG) emissions, a 20% increase in energy efficiency and 20% of energy from renewable sources by 2020 (EU, 2009). The target for renewable energy is complemented by national targets, which for Sweden is 49% renewable fuels. Furthermore, the Swedish government has proposed increasing harvesting of roundwood and forest fuel from the Swedish forests (Anon, 2008a).

The EU also has a 10% target for energy from renewable energy sources in the transport sector (EU, 2009). In Sweden, the share of biofuels in road traffic in 2007 was about 4% (Swedish Energy Agency, 2008). Today, energy use in transport makes up 26% of total final energy consumption in Sweden (Eurostat, 2009). The transport related to forestry is substantial, making up about 23% of all domestic road transport in Sweden (SIKA, 2009).

Overall, the increasing demand for bioenergy and wood products is likely to lead to more intensive forest harvesting. Therefore, concerns are being raised about the environmental risks of the substantial governmental targets for renewable fuels. In this context, it is essential to have efficient systems that provide sustainable forest management. This thesis deals with some of the environmental concerns and possible ways to reduce these in the Swedish forestry system.

1.2 Forestry in Sweden

The land area of Sweden is 41 million hectares of which 22.7 million is classed as productive forest land, while according to the international definition the total forest area is just over 28 million hectares (Swedish Forest Agency, 2007). Thus forests cover more than half the land area in Sweden, which makes forest and forestry an important part of the Swedish lift and of the national economy.

About 50% of Swedish forests are owned by private, small-scale forest owners, forest companies own around 25% and the State and other public organisations own around 24% (Swedish Forestry Agency, 2009a). Small-scale forest ownership dominates in southern Sweden, while forest companies, the state and public ownership dominate in northern Sweden. This difference in land ownership affects the average size of forest holdings but has little effect on the management systems, as private forest owners with small holdings often co-operate under forest owners' associations, which means they can benefit from economies of scale.

Since the 1920s, the growing stocks in Swedish forest have increased by over 68% owing to changes in land use and improved silviculture. Many of the forests in central and southern Sweden were established on abandoned agricultural land during the 20th century. Today the growing stocks are increasing by about 120 million m^3 every year (Swedish Forestry Agency, 2009b)

Conifers dominate in Swedish forests, as about 80% the total standing volume is Norway spruce (*Picea abies* (L.) Karst.) (41%) and Scots pine (*Pinus silvestris* L.) (38%). Birch (*Betula* sp.) is the most common of the deciduous species, making up 12% of the standing volume. The length of a stand rotation is 60-100 years for conifers in the south of Sweden and 80-130 years in the north. The major explanations for the difference are climate and soil fertility variations, as the site fertility class in Sweden decreases strongly from south to north. The forest land is mostly on glacial till soils (75%), although some is on sedimentary soils (15%) (Swedish Forest Agency, 2009b). This is because farmers have always preferred fine-textured sedimentary soils for agriculture. In parts of Sweden, the land is hilly but not to the extent that it creates problems for forest machinery. However, the large amount of wetlands can cause problems with bearing capacity when the ground is not frozen.

The Swedish Forestry Act of 1994 gives equal importance to production goals and nature conservation goals. Forest owners have a great responsibility for achieving these goals, and characteristics of natural forest must be part of the managed forest. This means that in practice, forestry should consider the impacts of various forestry operations on the environment to fulfil the forestry act. Nature reserves are also an important part and approximately 10% of the land area in Sweden is protected by some kind of nature conservation legislation. Of that, about 5% is forest land concentrated in northern Sweden. However, within the forest certification systems, forest owners voluntarily set aside forest areas for nature conservation, which amounted to about 1.2 million hectares in 2008.

The net felling volume in 2008 was 69 million cubic meters solid (m^3 solid) timber excluding bark, of which 32.6 million m^3 was saw logs, 30 million m^3 was pulpwood, 5.9 million m^3 was fuelwood and other assortments accounted for 0.5 million m^3 (Swedish Forestry Agency, 2009a). The harvest of logging residues is about 7 TWh and there is barely any stump harvesting (Svensson, 2008). There is still a large potential of forest biomass not being used, estimated by the Swedish Forest Agency to be in the range of 16-25 TWh for logging residues (tops and branches), 21 TWh for stumps and about 2.2 TWh for small trees (late cleaning and early thinnings) (Svensson, 2008).

However, a large part of the harvested roundwood is ultimately used as energy, in internal processes or sold externally. It has been estimated that 45-50% of the harvest from Swedish forests was used as energy during the 1990s (Johansson, 2008; Nilsson, 2006; Eriksson, 1991). Today, there is evidence of a structural change in the Swedish forest market towards a larger proportion of the harvest being used as energy (Anon., 2010a).

1.3 Forestry and the environment

In Sweden, the current trend is towards more intensive forest management and intensified forest harvesting through whole tree harvesting and stump harvesting. The first probably involves increased productivity, which could be achieved through tree improvement programmes and intensified forest management operations including increased fertilisation, shorter rotations, *etc.* The focus in this thesis is on intensified forest harvesting, i.e. whole tree harvesting and stump harvesting.

Logging residues (branches and tops) have a high concentration of nutrients compared with the stemwood and thus removing these from the growing site could create a nutrient deficit in the soil, which could lead to gradual acidification and overall nutrient depletion of the soil. This could have effects on growth and long-term fertility (Swedish Energy Agency 2006; Burger, 2002). Returning wood ash to these forest sites could counteract the acidification, although it will take some time before this is done on a sufficient scale. However, wood ash could also have direct and indirect effects of fauna, flora and fungi in soil and watercourses downstream (Swedish Energy Agency, 2006). In additionally, ash does not contain nitrogen, which governs the growth rate in most Swedish forests. In southern Sweden, high anthropogenic deposition of nitrogen may compensate for nitrogen losses through logging residues extraction. However, in northern Sweden nitrogen deposition is lower, so extraction of nitrogen-rich logging residues could reduce growth (Egnell *et al.*, 1998). Fertilisation could counteract this reduction (Jacobson, 2001), although this may have other direct and indirect environmental consequences (Anon., 2007a). However the extraction of logging residues could facilitate pre-scheduled site preparation and regeneration, *e.g.* a shorter period of fallow, which could compensate for the reduced growth (Swedish Energy Agency, 2006).

Stumps contain relatively low concentrations of nutrients. In an environmental impact assessment on stump harvesting conducted in Sweden the conclusion was that stump harvesting might not cause any serious depletion of soil nutrient reserves (Egnell *et al.*, 2008). However, there are indication that stumps may retain nitrogen (N) after harvesting and even serve as a N pool, thus potentially reducing N leaching and serving as source of N for the next generation (Palviainen *et al.,* 2010). Furthermore, Zabowski *et al.* (2008) found a decline in mineral soil N content (-20%), mineral soil carbon (-20%) and forest floor depth (-24%) 22-29 years after stump removal in five stands with varying soils in the states of Oregon and Washington. Hope (2007), on the other hand, found major changes in the forest floor rather than in the mineral soil when comparing stump harvesting with no mechanical treatment of the soil at three sandy loam sites in British Colombia. The results showed significantly lower nutrient content in the forest floor 10 years after stump harvesting, which was caused by accelerated decomposition of surface organic matter according to Hope (2007).

Intensified forest harvesting causing increased soil disturbance and decomposition of organic matter might be important, since soil organic matter is important due to its effect on the soil structure, moisture-holding capacity, cation-exchange capacity and soil biota (Burger, 2002; Brady *et al.,* 1990), all of which affect the growth of roots and soil organisms. Increased soil disturbance and decomposition of organic matter could also lead to nutrient leaching, with subsequent eutrophication of rivers and lakes and deterioration of aquatic habitat quality. However, increased harvesting of nutrient-rich forest residues in particular, could decrease the leaching of nutrients (Swedish Energy Agency, 2006).

All use of heavy machinery in the forest can cause tracks and soil compaction. These deteriorate the soil structure, which could cause lower growth (Burger, 2002; Hakkila, 1989). The risk of soil compaction is greater when harvesting logging residues and stumps since logging residues are used as foundation/bedding in strip-roads and the larger roots of the stumps reinforce the soil which limits compaction (Egnell, 2009).

Maintaining the biodiversity of forest ecosystem is important in order to resist change or to recover following disturbance. Biodiversity is a wide definition which includes diversity within species, among species and of ecosystems. In Sweden, forestry was intensified during the 20th century, and today almost all forests are managed rationally. Thus, today it is forest management activities that control the occurrence and amounts of valuable objects in a biodiversity perspective, and not the natural forest dynamics (Swedish Energy Agency, 2006). Many qualities of a natural forest have therefore been reduced, such as areas of old forest, mature forest with a large deciduous component and the quantity of dead wood (Anon., 2010b). Until now, the amount of dead wood in Swedish forest has been reduced as an effect of efficient forest management together with a reduced proportion of old-growth forest, but also in order to prevent forest fires, providing fire wood and control damage by insects. In northern Sweden, it has been shown that the amount of dead wood is about 30% of that in unmanaged forests, while in central and southern Sweden it is only about 2-3% (Dahlberg & Stokland, 2004). About 20-25% of the forest species in the boreal region are dependent on dead wood (Siitonen, 2001), and in Sweden 54% of red-listed forest species are associated with dead wood (Dahlberg & Stokland, 2004). Intensified harvest from the forest ecosystem of logging residues and stumps would decrease the amount of dead wood even more. Although there are predominantly trivial forest species that are related to logging residues (Rudolhi, 2007), it has been shown that the extraction may both reduce and damage remaining woody debris (Rudophi & Gustafsson, 2005). The harvest of logging residues may also result in reduced amounts of other nature consideration objects such as high stumps and retention trees although the situation could be improved by educating forest workers (Gustafsson & Weslien, 2004). Stumps are a man-made substrate that has increased during the 20th century but it may still be important to species that are dependent on dead wood when other dead wood substrates are lacking (Egnell *et al.*, 2008; Rudophi, 2007).

1.4 Forestry and the carbon cycle

In the global carbon cycle there are five principal carbon (C) pools, the oceanic, geological, pedological (soil), biotic and atmospheric (Fig 1). There are interconnections between these pools, which are both natural and human-induced. Although the flux of CO_2 from fossil fuels greatly increased during 20th century, the flux of CO_2 between the soil and the atmosphere is estimated to be 10-fold greater (Schils *et al.,* 2008). Nevertheless, the annual flow of C to and from the atmosphere is rather small in comparison with the pool in the soil, 2500 Pg. It is important to emphasise that small changes in such a significant pool could have dramatic impacts on global carbon budget and the concentration of CO_2 in the atmosphere.

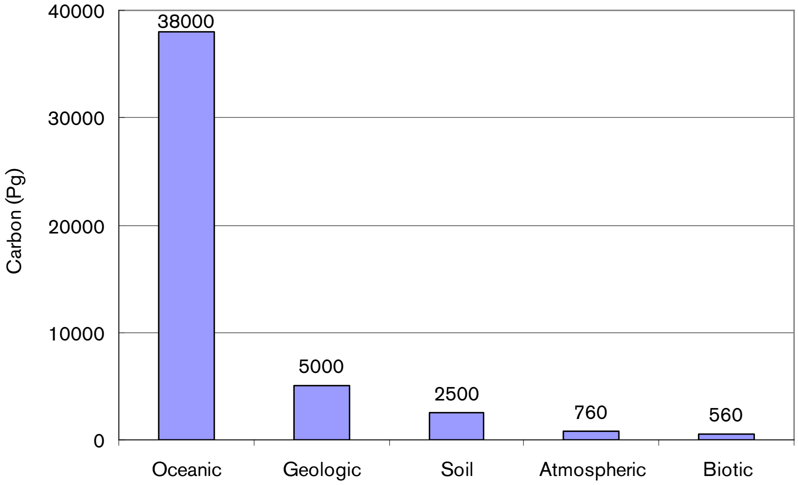

Figure 1. Principal global carbon pool expressed in Pg (10^{15} g) (Lal, 2004).

1.4.1 Forest management and carbon sequestration

Forestry can affect net CO_2-emissions either by increasing or decreasing carbon stocks in biomass, soil and products, or by supplying biofuels to replace fossil fuels and energy-intensive materials. Studies on forest management have shown that the rotation length, fertilisation regime and intensity of harvesting affect the carbon stock and the potential to replace fossil fuel (Eriksson *et al.*, 2007; Eriksson, 2006; Liski *et al.*, 2001). In general, forest store most carbon when they remain undisturbed (unmanaged) and are allowed to grow to maturity (Eriksson *et al.*, 2007; Jandl *et al.*, 2007; Kirschbaum, 2003), whereas using wood for bioenergy necessitates wood removal from the forest and thereby lowers on-site carbon storage (Eriksson *et al.*, 2007; Kirschbaum, 2003).

Nevertheless, sequestration of carbon is limited because the carbon stock becomes saturated and can be released to the atmosphere if the forest is disturbed, whereas using biomass for direct substitution of fossil fuels or fossil fuel-intensive materials provides a permanent and cumulative reduction in GHG emissions (Eriksson *et al.*, 2007; Kirschbaum, 2003). This indicates that in the long time horizon, the largest sustained mitigation will be generated by sustainable forest management strategies aimed at maintaining or increasing forest carbon stocks, while producing an annual yield of timber, fibre or energy from the forest (Nabuurs *et al.,* 2007).

1.4.2 Forest management and effects of the soil carbon pool

In forest, the carbon pool in forest soils is balanced by carbon inputs from plant residues and other organic matter, and the release of C due to decomposition, erosion and leaching. Forestry practices such as thinning and final felling result in a changed microclimate, since removal of the tree canopy leads to increased soil temperature and water content, which favour biological activity, resulting in enhanced organic matter decomposition (Jandl *et al.*, 2007; Pumpanen *et al.*, 2004).

After thinning, the microclimate returns to the previous conditions unless the thinning intervals are short and intensities are high (Jandl *et al.*, 2007). In both heavily thinned stands and in final fellings, the annual litter input is reduced. With thinning this is very temporary, while with final felling it remains low until a new generation of trees has developed.

Final fellings removes more biomass, disturbs the soil and changes the microclimate more than thinning operations. During the first year following harvest and regeneration operations, soil carbon losses due to decomposition may exceed uptakes from aboveground vegetation. Studies on the carbon balance of young forest stands show that these change from being a carbon source to being a sink at an age of about 15 years (Karjalainen, 1996; Karjalainen & Asikainen, 1996; Liski *et al.*, 2001). The soil carbon balance after harvest is the net effect of the increased decomposition rate and the amount of organic matter added to the soil as logging residues (Pumpanen *et al.,* 2004). The degree of soil disturbance is also important for the soil carbon balance, since it determines the long-term carbon balance (Jandl *et al.,* 2007).

Intensifying the harvest from forests by outtake of forest fuels such as residues and stumps may reduce the soil carbon content compared with conventional timber production. This is a consequence of four effects:

- Increased removal of biomass directly reduces organic matter additions to the soil (Cowie *et al.,* 2006; Ågren & Hyvonen, 2003; Ericsson, 2003; Schlamadinger *et al.*, 1997).
- Increased removal of biomass has a negative effect on the soil nutrient balance, leading to loss of productivity unless these nutrients are replaced (Walmsley & Godbold, 2010; Cowie *et al.*, 2006; Richardson *et al.*, 2002).
- A decline in soil carbon stock directly affects plant productivity, since soil organic matter is important for soil fertility (Cowie *et al.* 2006).
- If harvesting involves soil disturbance, the degree of disturbance affects the soil carbon balance (Jandl *et al.,* 2007; Hope, 2007; Johansson, 1994).

However, the increased mobilisation of nutrients in relation with soil disturbance could promote rapid establishment and thus favour production of biomass in the new forest vegetation and stand (Johansson, 1994), resulting in an accumulation of carbon which might balance the losses (Jandl *et al.*, 2007).

2 Objectives

In the long-term perspective, the demand for forest products as a resource in the forest industry and in the energy sector will continue to increase. The drivers for this are increasing awareness of climate change issues, unstable fossil fuel prices and concerns about energy security. However, if the purpose of increasing the use of forest products is to reduce pressure on the environment, it is important that the production system is designed in a way that minimises the total environmental burden.

The overall aim of this thesis work was to improve our knowledge of the forestry system in order to identify opportunities to reduce the energy use and environmental impact of the system. The specific objective was to produce quantified and reliable information on the environmental impact and internal energy use for the Swedish forestry in order to allow fair comparisons between forest products and other materials.

Four studies were conducted to evaluate this issue by:

- Describing the forestry system up to the late 1990s and identifying the most significant forestry processes in terms of energy and material inputs and outputs of roundwood production and a few related environmental impacts (Paper I).
- Analysing future possible secondary transport scenarios in order to identify approaches that could reduce the use of energy and environmental impacts of the timber transport system (Paper II).
- Describing the Swedish forest fuel system and identifying the most significant processes in terms of energy balance and a few related environmental impacts (Paper III).
- Analysing the total greenhouse gas balance of forest fuel (residues and stumps) including the carbon stocks in forest soils and the potential to substitute fossil fuel (Paper IV).

3 Methodological approach

In each of Papers I-IV, a Life Cycle Assessment (LCA) perspective was adopted, *i.e.* the studies were not intended to be complete LCAs according to ISO 14 040 standards, but applied an LCA perspective (ISO, 2006a, 2006b). Papers I, II, and III focused on energy use in the systems and a few related environmental impacts, from the extraction of energy and production through to combustion. In Paper IV, the dynamics of carbon in forest soil related to harvested forest fuel and the potential to substitute fossil fuel were examined.

3.1 Life Cycle Assessment – the methodology

LCA is a tool that addresses the environmental aspects and potential impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (*i.e.* from cradle-to-grave). Initially, LCA was developed as a learning and decision support tool for companies and industrial sectors. The first LCAs conducted (1969-1972) were studies on waste and packaging materials focusing on effects on natural resources and the environment. Shortly after that came the oil crisis in 1973, which fuelled the interest in further LCA studies, although, the focus changed to the energy part of the analysis (Baumann & Tillman, 2004). Application of the LCA procedure and methodological discussions developed the technique and in 1997, the first standard for LCA (ISO 14 040) was issued by the International Organization for Standardization (ISO, 1997).

The holistic environmental scope that LCA provides on products is useful in order to avoid problem-shifting, for example from one phase of the life cycle to another, from one region to another or from one environmental concern to another (Finnveden *et al.,* 2009). This comprehensive scope has made LCA a central concept for policy-making in public government and for environmental management in industry (Baumann & Tillman, 2004) and in the scientific community (Cherubini *et al.,* 2009). The LCA tool can be used to identify energy and materials used and waste and emissions released to the environment, and to prioritise and target actions to minimise negative environmental impacts. Other uses are in environmental labelling, *e.g.* Environmental Product Declaration (EPD) and Carbon Footprinting.

An LCA includes four phases:

1. Definition of the goals and scope of the LCA. In this phase the system boundaries are also described and the functional unit defined. The functional unit is a quantitative measure that reflects the functions of a product (or service). It is the unit to which all inflows and outflows of the system are related in the study.
2. Inventory analysis, consisting of gathering data concerning inputs of energy and resources and outputs of emissions and products resulting from each process in the production chain.
3. Life cycle impact assessment, in which the results are evaluated to clarify 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 processes.
4. Interpretation of results and identification of components that have the most significant environmental impacts.

3.1.1 Consequential versus attributional LCA

There are two main types of LCA, accounting (attributional) and change-orientated (consequential). The change-orientated LCA reflects the effects of a change, which is often due to a decision or rule. The accounting LCA, on the other hand, focuses on describing the environmental impact a product may be responsible for. In other words, the change-orientated LCA looks forward in time, while the accounting LCA is retrospective. The accounting type LCA is well-suited to different types of eco-labelling, while the change-orientated LCA is more suited to product development, building design and process choices, since these fields involve choices between different options (Baumann & Tillman, 2004).

In consequential LCA, only the part of the system that is affected by the change needs to be studied. Accounting LCA, on the other hand, seeks for completeness and uses average data to reflect the actual physical flows, while marginal data are used in change-orientated LCA to reflect the consequences.

There is also a type of LCA based on Input-Output (IO) analyses, which originates from the field of economics. IO tables are often used in national accounts and states the trade between sectors. Environmental impacts can be included in IO analyses by including average resource use and relating the data to emissions coefficients. These analyses can estimate upstream environmental impacts generated throughout a supply chain of an average product although the precision could be poor (Finnveden *et al.*, 2009). In a Hybrid-LCA, IO-LCA and the traditional LCA (process-LCA) are combined by estimating the main processes in detail using process-LCA and far upstream flows connected to the main processes using IO-analyses (Finnveden *et al.*, 2009). Since IO-LCA and hybrid LCA contain average data, they are applicable for accounting LCA.

3.1.2 The flexibility of LCA methodology

Different LCA studies on the same process often give different results due to the use of differing data sets (including data sources and ages) and methodologies. There is no single method for conducting LCA. The ISO standards on LCA (ISO, 2006a; ISO 2006b) create a framework but only provide requirements and guidelines and do not specify the application of these to specific products or services. Many methodological choices depend on the goal, subject and intended use of the study (ISO, 2006a) and the LCA results very much depend on the assumptions made. Since LCA can be used in many different applications, the requirement of the methodology is also different and the LCA method flexible. There are mainly four critical choices/factors in the LCA methodology that determines the outcome of an LCA study (Cherubini *et al.,* 2009; Baumann & Tillman, 2004);

- Definition of functional unit
- System boundaries and allocation procedure
- Type of data used
- Impact assessment methodology.

Besides the factors mentioned above, other factors are especially important when undertaking studies on bioenergy, such as the type of feedstock sources, conversion technologies, end-use technologies, and the reference energy system with which the bioenergy chain is compared (Cherubini *et al.,* 2009).

3.1.3 LCA and land use change

In sectors such as forestry and agriculture, land use is often substantial and could lead to different environmental impacts, both negative and positive. The list of possible impacts is broad, *e.g.* impacts on biodiversity, soil quality and biotic production potential. Although the research about land use in LCA has been extensive, there is still no common methodology to evaluate land use in LCA due to a lack of consensus within the field of LCA (Finnveden *et al.*, 2009; Milà i Canals *et al.*, 2007). Land use and forestry are further discussed in section 6.5 of this thesis.

In recent years, the issue of direct and indirect land use when producing biofuel has been on the agenda in the scientific community (Brandao *et al.,* 2010; Börjesson, 2009; Cherubini *et al.,* 2009; Gnansounou *et al.,* 2009) and policy makers. In fact, the EU Directive on the promotion of renewable energy presents methods to evaluate carbon stock change due to land use change (EU, 2009).

Direct land use includes those impacts that occurs on the land that is used, whereas indirect land use (or leakage) is for example when expanded production of bioenergy leads to displacement of food and feed production into new cropping land previously not cultivated. Several studies have shown the importance of including land use in greenhouse gas balances of bioenergy (*e.g.* Searchinger *et al.,* 2009; Fargione *et al.*, 2008; Wihersaari, 2005). Fargione *et al.* (2008) identified the most extreme land use change, *i.e.* biofuel production systems that required the conversion of native ecosystems to biofuel production. The results show that by converting rainforest, peat-lands, savannah, or grasslands to produce biofuels in Brazil, Southeast Asia and the United States, the amount of CO_2 released is 17-420 times more than the annual GHG reductions that these biofuels would provide by substituting fossil fuels (Fargione *et al.*, 2008).

The reference land use is important when assessing land use issues, since the land use studied must be compared against a baseline. Authors differ regarding choice of reference land use. Gnansounou *et al.* (2009) argue that previous land use should be used as the reference when the land previously stored carbon *e.g.* forests or grassland. When the same land was previously used for other purposes, an alternative land use should be the reference. Brandão *et al.* (2010), who estimated the SOC degradation due to different land uses (bioenergy cultivation) used the potential level of SOC if land had been left undisturbed as the reference situation. In contrast, Mila i Canals *et al.* (2007) believe that the reference situation for attributional LCA should be the natural relaxation in an ecosystem and in a consequential LCA it should be an alternative land use.

There is no common methodology for how to assess carbon emissions related to land use change in GHG balances of biofuels. However, there seem to be two different ways of calculating the effects on organic carbon in the system depending on the object of the assessment. A number of studies that assess the effect of different forest management alternatives on carbon sequestration in forest ecosystems and products calculate mean carbon stocks over a time period (often one rotation) (Eriksson *et al.*, 2007; Liski *et al.*, 2001; Schlamadinger & Marland, 2001; Nabuurs, 1996; Schlamadinger *et al.,* 1997). The reason cited was that this could be deemed suitable for a landscape where all stands have been managed according to the chosen practice, with an equal area being managed each year (Liski *et al.,* 2001; Palosuo *et al.*, 2001).

Other studies that assess the GHG emissions due to direct land use change use a stock change approach (Cherubini *et al.*, 2009; Gnansounou *et al.* 2009; Bergsma *et al.*, 2006). This approach is based on the IPCC Guidelines, where a stock change perspective is provided and this change in soil C should be divided by the plantation life-time (IPCC default value: 20 years) (IPCC, 2006). The result is the annual change in soil carbon stocks. Similar methodology is used in the European Union Directive on the promotion of the use of energy from renewable sources, which states that changes must be spread (annualised) equally over 20 years or until the crop reaches maturity, whichever is earlier (EU, 2009). In a method developed for the Dutch government to calculate the emissions of GHG from biofuels and bioenergy Bergsma *et al.* (2006) states that changes should be distributed over the lifetime of the plantation.

3.1.4 Case studies of roundwood

The new focus on ecological evaluation of products, production processes and services that evolved during the 1990s 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 Switzerland (Knechtle, 1999). In Sweden and Finland, Karjalainen and Asiakainen (1996) and Berg and Karjalainen (2003) presented data on energy use and related emissions from forest operations. Schwaiger and Zimmer (2001) compared fuel consumption and GHG emissions from forest operations in Europe. Michelsen *et al.* (2008) conducted a hybrid LCA of Norwegian forestry and presented emissions related to timber production. Gonzáles-Garcia *et al.* (2009) compared Spanish and Swedish forest production and supply of pulpwood.

According to a number of European forestry studies over the past decade (Table 1), the energy use in silviculture and logging ranges from less than 60 MJ per m^3 timber up to 270 MJ per m^3. Secondary haulage accounts for 90-223 MJ, raising total energy use to a level of 180-395 MJ per m^3. Energy use has been shown to be higher in exceptionally difficult terrain (Wegner, 1994), in long-distance haulage of pulpwood (Gonzáles-Garcia *et al.,* 2009; Michelsen *et al.,* 2008) and when silviculture is highly mechanised and the use of chemicals is high (Gonzáles-Garcia *et al.*, 2009).

Table 1. *Studies on energy use in forest operations (MJ m^{-3})*

	Silviculture and logging	Secondary haulage	Total
Germany, saw logs, spruce (transport distance 50 km) (Schweinle, 1996).	135	92	227
Switzerland, mechanised logging (Knechtle, 1999).	91	-	-
Switzerland, motor-manual logging (Knechtle, 1999).	111	-	-
Germany, (transport distance 50 km) (Wegner, 1994).	62	125	187
Norway (hybrid LCA 3 scenarios from best to worst depending on transport distance) (Michelsen *et al.,* 2008)			Best 48 Average 162 Worst 390 [1]
Spain (Gonzáles-Garcia *et al.*, 2009)	116+155=271	124	395
Sweden (Gonzáles-Garcia *et al.*, 2009)	12+136	223	370

[1] Assuming that the energy content in diesel is 35.3 MJ per litre.

3.1.5 Case studies of forest fuel

A number of studies have used LCA, or similar techniques, to examine the GHG balance of forest bioenergy systems (Näslund-Eriksson & Gustavsson. 2008; Eriksson *et al.*, 2007; Wihersaari, 2005; Palosuo *et al.*, 2001; Börjesson, 1996) (Table 2). These studies, mainly based on data from the literature, have shown that transportation of forest fuel dominates the primary energy use (PE) in many forest fuel systems (Cowie, 2007; Näslund-Eriksson & Gustavsson, 2008). Wihersaari (2005) who used data from Palosuo *et al.* (2001) on impact on soil carbon, assessed forest supply chains in Finland, and estimated the total GHG impact to be 15-17 g CO_2-eq per MJ fuel. The decrease in soil carbon dominated, comprising about 75% of total emissions. This corresponded to a decrease in SOC of 1.7 tonnes C per ha which represents the average carbon stock within the 100 year rotation.

In an assessment of different forest management alternatives, the decrease in soil carbon when harvesting stumps and residues, calculated as the (running) mean over one rotation, was estimated to be 0.05 tonnes C per ha and year (Eriksson *et al.*, 2007). The differences between studies can be explained by different background data, system boundaries and calculation method.

Table 2. Studies on energy use and greenhouse gas emissions from forest fuel procurement

	Collection, chipping and transport	CH_4 and N_2O from burning	Ash recirculation/ Fertilisation	CO_2 emission from decreasing soil C	Total
Finland, tops and branches (transport distance unknown) (Wihersaari, 2005)					
g CO_2-eq/MJ_{fuel}	1.1-1.9	2	0.1/1.9	11.1-12.5	14.8-17
MJ/MJ_{fuel}					0.019-0.026
Sweden (Näslund-Eriksson & Gustavsson, 2008)					
- tops and branches (transport distance unknown)					
g CO_2-eq/MJ_{fuel}				-	1.0-1.5
MJ/MJ_{fuel}					0.013-0.018
- stumps (transport distance unknown)					
g CO_2-eq/MJ_{fuel}				-	1.8
MJ/MJ_{fuel}					0.023
Sweden, tops and branches (transport distance 50 km) (higher value for 1996 and lower value for 2015) (Börjesson, 1996)					
MJ/MJ_{fuel}					0.026-0.038

4 Roundwood production and secondary transport

4.1 System description: Forest production of roundwood

Paper I 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 Figure 2. Paper I relied on data from forest operations carried out over one full year *i.e.* data from 1996 and 1997 representing typical forest management regions in northern, central and southern Sweden (Figure 3).

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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 topsoil 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 haulage: The transport of timber from landing to the endpoint by road or rail.

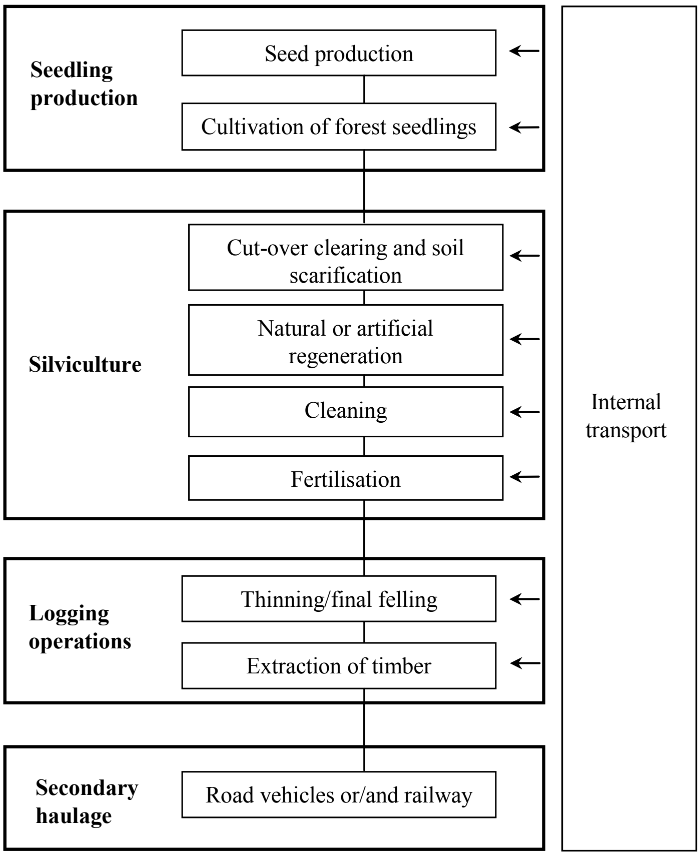

Figure 2. Forest operations in the forestry systems studied in Paper I.

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 owners' association. Each of these produced about 1 million cubic metres industrial roundwood under bark (m^3 solid) annually.

Logging in 1996-1997 was carried out by means of a fully mechanised dual-machine system employing the cut-to-length method, with secondary haulage being made 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.

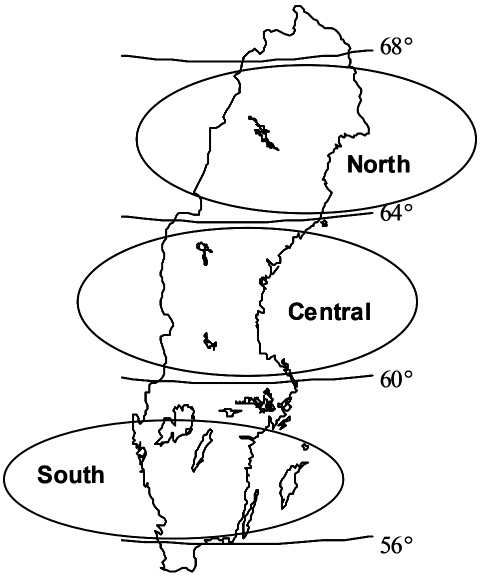

Figure 3. Locations of the regions studied in Paper I.

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

4.2 System description: Secondary transport solutions

Secondary transport of timber has been shown to dominate the energy use in the timber supply chain in many countries (Schwaiger & Zimmer, 2001). This was in line with the results from Paper I and therefore a case study was conducted to evaluate the efficiency and related environmental performance of different timber transport solutions in Paper II. Nine different scenarios for the secondary transport systems were compared (Figure 4): involving lorry or lorry-and-train combinations using a variety of potential fuels/energy carriers, including diesel-oil, coal, hydropower, nuclear fuel and biofuels such as 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).

The system's functional unit was the transport of 100 000 m^3 solid from the forest in north-western Sweden to a timber terminal on the east coast of Sweden.

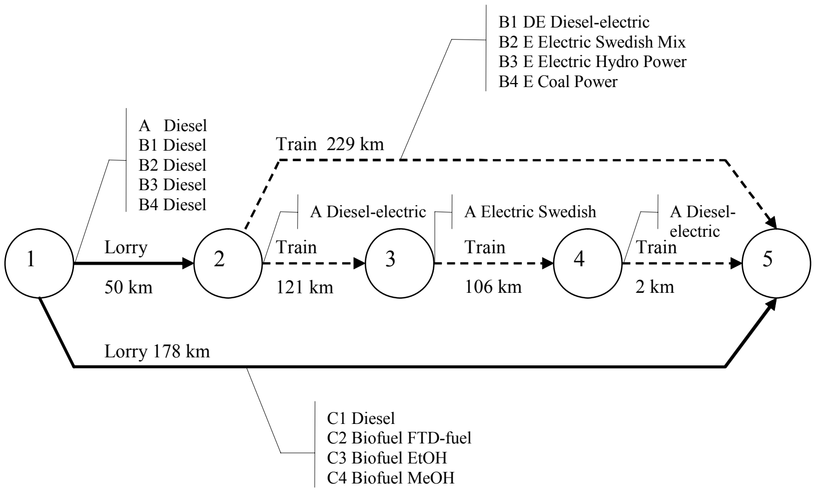

Figure 4. Transport scenarios used in Paper II. A is the base scenario - the current transport solution - and B1-C4 are the alternative scenarios.

4.3 Results

4.3.1 Energy use

The energy use in the Swedish forestry system of 1996-1997 was 147-200 MJ per m^3 solid or 172-240 MJ per m^3 solid in primary energy[8] (Figure 5). One cubic meter of wood contains about 7700 MJ, which means that the energy requirements to produce the wood were about 3% of the inherent energy that is available in the timber. The forestry system in northern Sweden required more energy compared with the system in southern Sweden. Transporting timber to the industrial sector (secondary haulage) accounted for the largest primary energy requirements (49-57%). The remaining energy used in the systems in 1997 was divided between logging operations (33-40%), silviculture (2-16%) and seedling production (1-6%).

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[8] Assuming that 1.16 MJ of primary energy (PE) per MJ diesel and the corresponding figure for Swedish electricity is 1.79 MJ (Paper III).

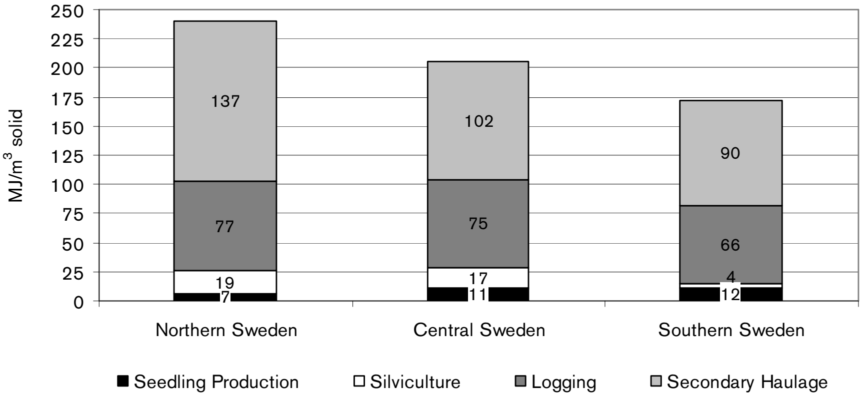

Figure 5. Primary energy requirements (MJ per m^3 soild) for each operation in the Swedish forestry systems studied in Paper I.

The energy use per m^3 solid was larger for thinning than for final felling, indicating that the kind of cutting operation (final felling or thinning) had a greater influence on energy use per m^3 solid than the geographical area of operation (Table 3).

Table 3. *Energy requirements (MJ per m^3 solid) in logging operations in Paper I*

	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. This is because of more difficult work conditions in southern Sweden. 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).

The results from the analyses of the timber transport systems presented in Paper II 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) (Figure 6). It should be emphasised 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. At the same time, there was no recovery of low-grade heat from the biofuel production which in the future might be produced in combination with other production processes to optimise the use of energy. 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.

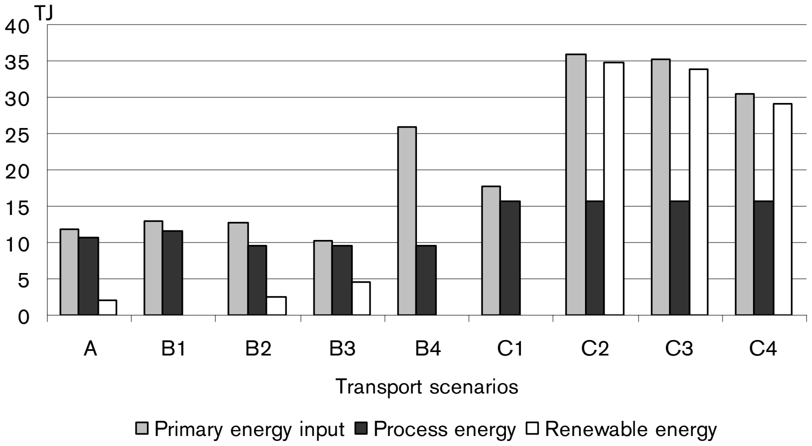

Figure 6. Requirements of primary, process energy and renewable energy (TJ) in the scenarios studied in Paper II.

4.3.2 Environmental impacts of the forestry system

Paper I showed that the roundwood procurement system in the north had the largest impacts in all categories, closely followed by the central region. Of the various unit processes, secondary haulage had greater potential global warming (GWP) and photochemical ozone creation (POCP) impact than logging, silviculture and seedling production (Figure 7).

The results of the eutrophication and acidification impact analyses showed similar patterns. In both categories, logging operations had the largest potential impact in the south and central regions, accounting for about 50% of the total impacts. In the north, the contributions made to the eutrophication and acidification impacts by logging and secondary haulage were similar, 45-48%.

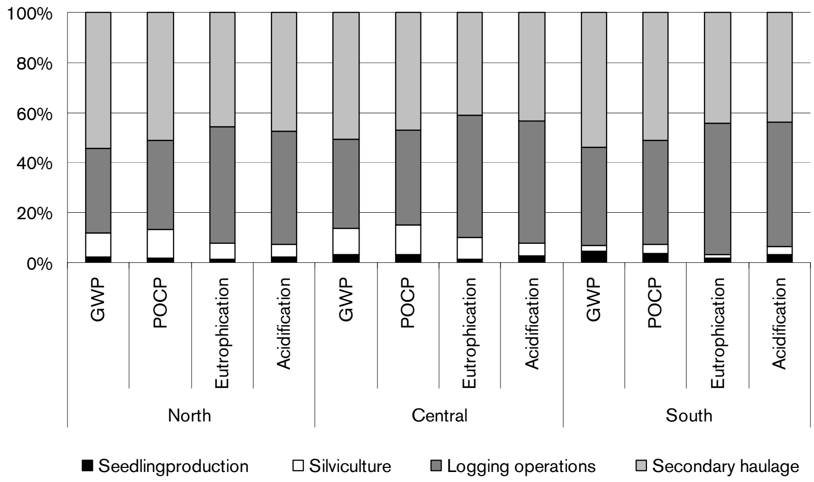

Figure 7. Potential environmental impact of the roundwood systems studied in Paper I.

4.3.3 Environmental impact of the transport scenarios

The analyses of the timber transport scenarios in Paper II showed that scenarios depending largely on electric train transport (scenarios B2 and B3) had low environmental impacts, except for the systems based on electricity generated from coal (scenario B4) (Figure 8). The systems based on biofuel had low global warming and photochemical ozone creation impacts, but high impact of acidification and eutrophication. The environmental impacts were high in all scenarios depending largely on diesel (scenarios A, B1 and C1).

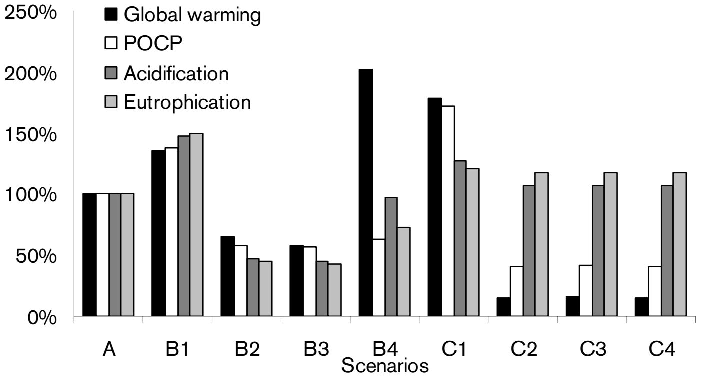

Figure 8. Potential environmental impact of the transport scenarios studied in Paper II when all systems are related to the base scenario A.

4.4 Discussion

The results in Paper I showed that the energy used to produce roundwood is only 3% of the inherent energy that is available in the timber, which is favourable compared with other materials. The results also indicated that forest operations in northern Sweden use more energy and have a higher potential environmental impact per cubic metre than those in central and southern Sweden. This is largely due to longer transport distances in the northern region but also to lower tree growth rate. Of the energy use in all regions, about half is used in secondary transport from forest to industries.

The total energy used per cubic metre in the Swedish forestry system presented in Paper I was consistent with amounts used elsewhere in Europe, as reported for instance by Schweinle (1996) and Wegner (1994). However, the results also revealed that energy use in silviculture and logging operations in Sweden is low compared with operations in continental Europe *e.g.* in Spain (Gonzáles-Garcia *et al.;* 2009) and Finland (Berg & Karjalainen, 2003). The major explanation is the degree of mechanisation, which is low in Swedish silviculture operations compared with Spain and Finland (Gonzáles-Garcia *et al.*, 2009; Berg & Karjalainen, 2003). The use of energy-intensive chemicals is also higher in Spain than in Sweden. One explanation for the higher energy use in Finnish silviculture is that more forest drainage work is carried out there, which explains the higher rate of mechanised silvicultural operations (Berg & Karjalainen, 2003). In logging, the situation is quite the contrary, since it has been shown that Sweden is one of the countries with the highest rate of mechanisation in logging (harvesting and forwarding) operations (Berg & Karjalainen, 2003; Schwaiger & Zimmer, 2001). The explanation is that in general, large-scale logging is also carried out in small-scale forestry.

Further improvements in logging operations could include 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 (Table 3).

A contributing factor to the higher energy usage per m^3 in the northern region than in the south is the growth rates, and thus annual harvests, which is lower in the north. For a given amount of roundwood, the requisite area for silvicultural work operations per year was three times higher in the north (16 200 ha per million m^3) than in the south (4 900 ha per million m^3). In contrast, the energy required per ha for silviculture after final felling is higher

higher in southern and central Sweden due to the more difficult work conditions.

The energy used in secondary transport in Sweden (Paper I) 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 on longer vehicles than their counterparts in continental Europe. In Sweden, gross weights of up to 60 metric tonnes per vehicle and a vehicle length of 24 m are permitted, compared with a gross weight of 40-44 tonnes and a length of 19 m in continental Europe, thus allowing the Swedish vehicles to carry higher payloads. Another advantageous factor is that small-scale forestry in Sweden use large-scale transport solutions.

The results from the timber transport scenarios in Paper II revealed that the transport alternatives including railway were more efficient than options relying exclusively on road vehicles. The potential environmental impacts were also low in the scenarios involving electric trains, except for trains powered with coal power. This was due to higher energy efficiency of conversion when generating electricity compared with producing biofuels. Nuclear power and hydro-electric power generation caused almost no combustion emissions such as those produced in scenarios involving the combustion of diesel oil, coal or biomass. 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 the study.

In the scenarios where biofuels dominated the process energy, fossil energy accounted for only 3-4% of the primary energy in the fuel cycles compared with 65-100% in the other scenarios. Current EU policy (EU, 2009) to promote renewable fuels makes it important for the forestry sector to consider the scope for using renewable fuels.

Paper II shows that it is easy to identify transport solutions that should be avoided since energy efficiency is low and potential environmental impact is high. Such solutions are those that include the use of coal power and diesel fuel. The most optimal scenarios with regard to energy and environmental impact seem to be the electric train using Swedish mix electricity or hydropower. However, the lorry scenarios with biofuel use almost no fossil energy, which might be important in the future when the fossil energy resources are limited. The results from Paper II emphasise the energy carrier, fossil or renewable, rather than the technical transportation means itself.

5 Forest fuel

5.1 System description

In Paper III and IV, seven different procurement chains for forest fuel in Sweden were compared in a case study (Figure 9). The systems differed with respect to their geographical location, technology, resource use (stumps and logging residues), biological production potential and harvesting intensity. In Paper III, the focus was on the primary energy input (PE) in the technical system and the related environmental impact, whereas in Paper IV the focus was on the greenhouse gas (GHG) balance of forest fuel, including direct land use change, determined as annual changes in soil carbon stock. The reference land use was the alternative land use, *i.e.* conventional forest management with no harvest of logging residues or stumps. Different time periods were used in the evaluation: (i) 20 years, (ii) one rotation, and (iii) two rotations (240 years) in northern Sweden and three rotations (231 years) in southern Sweden. The last was used in order to even out different rotation times when comparing northern and southern Sweden. A fallow period of two years after each rotation period was included.

Two functional units were used: 1 MJ dry matter (DM), the estimated lower heating value of fuel chips from logging residues or stumps from final felling delivered to the energy plant (Paper III); and 1 MJ of electricity generated from forest fuel, stumps or logging residues (branches and tops) (Paper IV). The systems studied started in the forest after final felling and ended when the wood chips had been comminuted and delivered to the energy plant.

Logging residues and stumps were assumed to be harvested from artificially regenerated stands dominated by spruce (*Picea abies* (L.) Karst.). Two different geographical locations in Sweden were studied, north (64°N) and south (57°N). The stands were more productive than average in the study areas, with a natural potential production of 8.9 m^3 per ha and year in southern Sweden and 4.2 m^3 per ha and year in the north. In southern Sweden, one stump and three logging residue supply chains were examined, including chipping of residues at the roadside, bundling of residues and handling of loose residues all the way to the end-use facility. In northern Sweden, the supply chains included one stump and two logging residue supply chains, namely loose residues and bundles (Figure 9).

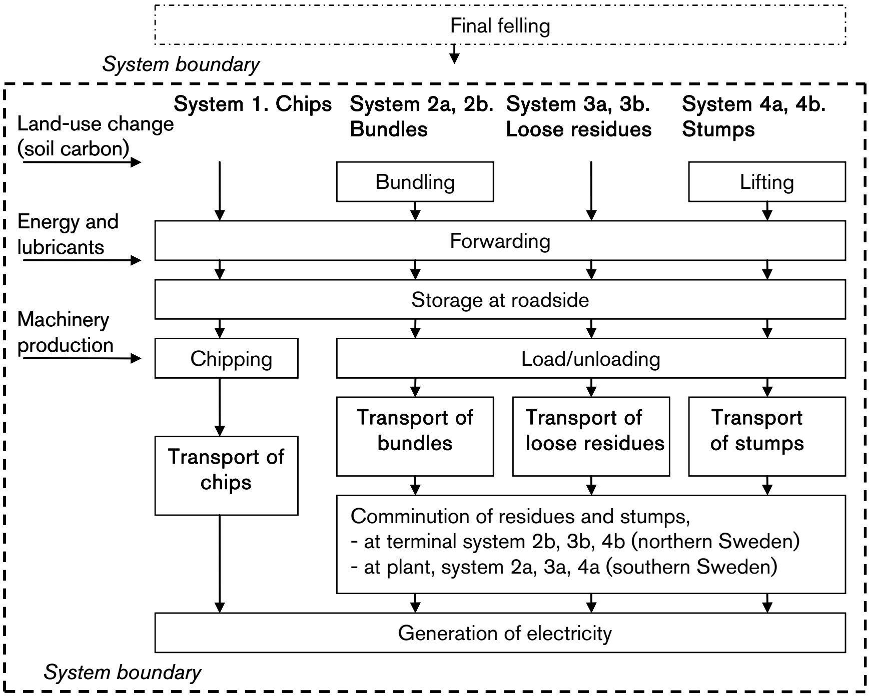

Figure 9. Flowchart of the forest fuel systems in southern (1, 2a, 3a, 4a) and northern (2b, 3b, 4b) Sweden (Paper III and IV).

The analysis was mainly based on the collection of representative average values from the literature. However, data were also collected from bioenergy companies in southern and northern Sweden in order to obtain information on the structure of the forest fuel procurement chains and specific transportation data (*i.e.* load size, moisture content and distances). These data were derived from operating statistics and were therefore representative of the forest fuel systems in those companies.

5.1.1 Modelling biomass production and soil carbon dynamics

In Paper IV, the focus was on the GHG balance of forest fuel and the dynamics of carbon in forest soil were considered. Two independent models were used to simulate the development of the stand and the soil organic carbon including decomposing litter (SOC). A forest growth model, ProdMod, estimated the biomass production and a forest soil model, the Q-model, estimated SOC development.

ProdMod is an empirical model based on experimental data basically driven by site quality and stand density and was originally constructed to simulate growth from first thinning to final felling of a stand (Ekö, 1985). The Q-model is a mechanistic model of the decomposition of soil organic matter based on the continuous quality theory of Ågren and Bosatta (1998). It simulates the development of the SOC by assuming that the quality of the material deteriorates gradually as the dead organic matter degrades. Five different managment strategies were modelled for both southern and northern Sweden. These differed with regard to harvesting intensity and harvested resource. In addition, there was a reference strategy with no harvest of forest fuel. Finally, the effect of substituting fossil fuel, *i.e.* coal and natural gas, with forest fuel, for generating power was estimated as GHG savings in Paper IV. The assumed efficiency of generating power in condensing power plants was 58% for natural gas and 47% for coal, while forest fuel was assumed to be used in a combined heat and power (CHP) plant with efficiency of 29.6% for electricity and 110% for heat. Allocation of the environmental impact associated with the generation of electricity in the CHP plant was 52% based on the alternative generation method provided by the International EPD Consortium. The GHG emissions when generating power were estimated to be 106 g CO_2-eq per MJ electricity (381 kg CO_2-eq per MWh) with natural gas and 217 g CO_2-eq per MJ electricity (783 kg CO_2-eq per MWh) with coal.

5.2 Results

5.2.1 Energy balance

The primary energy (PE) used to produce chips from logging residues and stumps was 2-5% of the harvested energy in the forest fuel (0.021-0.049 MJ per MJ chips) (Figure 10) (Paper III). In general, the PE to produce 1 MJ of forest fuel chips from residues was higher in northern Sweden than in southern, mostly due to the greater PE use in transportation. However, due to the fact that transport was via terminals in northern Sweden, the greater

PE required for comminution and the increased work associated with loading and unloading also had an effect. The non-bundled logging residue systems in southern Sweden (systems 1 and 3a; Figure 10) had the lowest PE input.

The PE used for transportation dominated in the logging residue systems that produced chips from bundles and loose residues (systems 2a, 2b, 3a and 3b; Figure 10). In contrast, in the stump systems, the energy use was dominated by stump lifting. In system 1, where residues were chipped at the forest roadside, the PE input was approximately equal for comminution and transportation, each requiring about 35% of the PE used.

To evaluate the energy efficiency of the forest fuel production system, the energy balance (output energy/input energy ratio) was calculated, (Figure 10). The most efficient systems were systems 1 and 3a in southern Sweden, generating 38-48 times more energy than was used. The residue system in northern Sweden (2b, 3b) and the stump systems in both southern and northern Sweden (4a, 4b) generated only about 50-70% of that, *i.e.* 21-27 times more energy than was used.

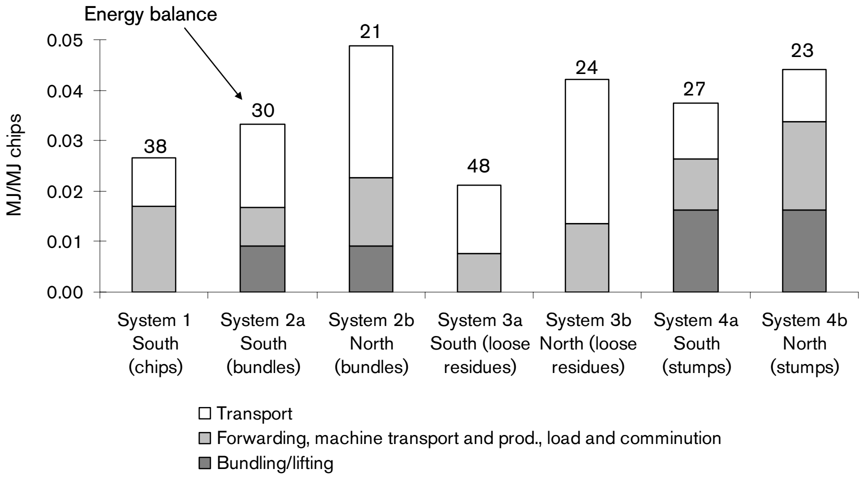

Figure 10. Primary energy (PE, MJ per MJ chips) for different processes per FU and energy balance for the systems studied in Paper III.

5.2.2 Effect on soil carbon when harvesting forest fuel

Paper IV showed that harvesting of stumps and residues resulted in larger losses of SOC and decomposing litter in the beginning of each rotation period compared with the reference scenario (Figure 11). However, by the end of each rotation period the difference was small. The decrease in SOC as stock changes due to harvest of forest fuel depended on the time period applied, harvesting intensity, geographical location and resources harvested (stumps or logging residues) (Figure 12). A short time period, 20 years, resulted in a higher decrease in SOC than the longer time periods (one to three rotations). Furthermore, in the short time perspective of 20 years, the decrease in SOC was larger in northern Sweden than in southern Sweden and stump harvest resulted in a larger decrease in SOC compared with logging residues.

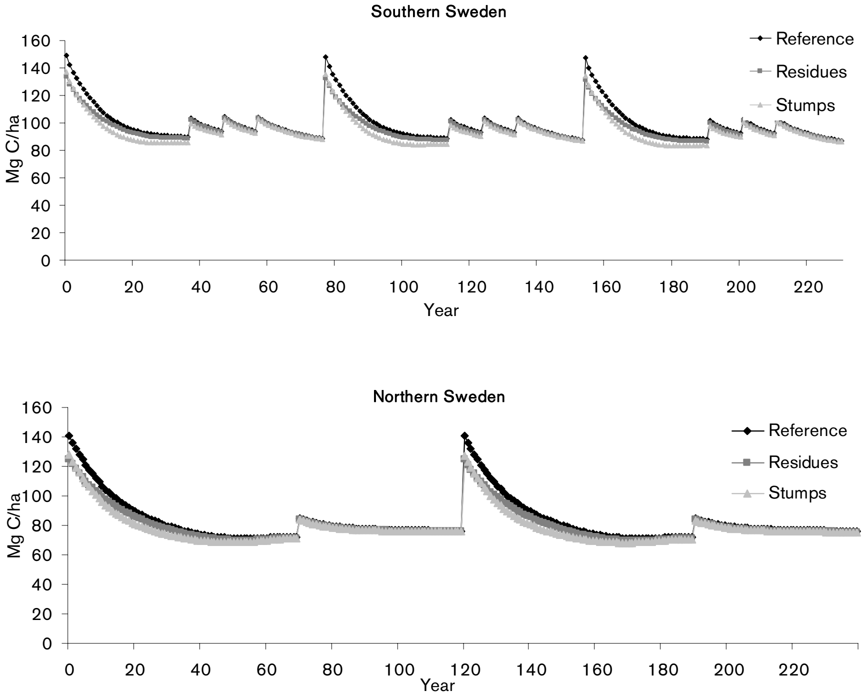

Figure 11. Dynamics of soil organic carbon including decomposition litter (SOC) in southern and northern Sweden for the reference and average harvest of logging residues and stumps studied in Paper IV.

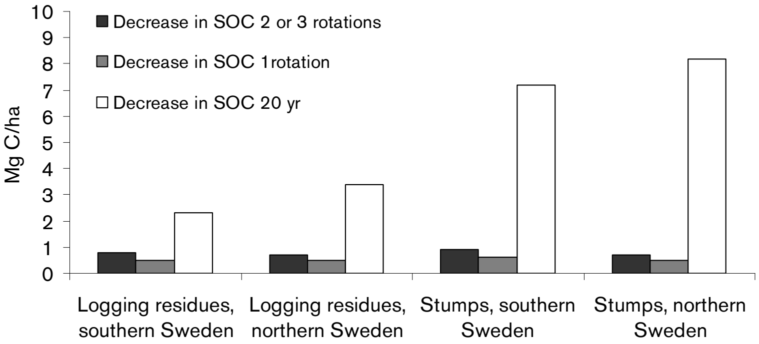

Figure 12. Decrease in soil C per hectare as stock change due to harvesting of stumps and logging residues in relation to different time periods.

5.2.3 Greenhouse gas balance of the forest fuel system

In Paper IV, the decrease in SOC was shown to be the most important process in the GHG balance of forest fuel in the time perspective of one rotation (Figure 13). In the total time perspective all processes evaluated were important for the GHG balance. The GHG emissions were lower from forest fuel systems in southern Sweden compared with those in northern Sweden except for the stump system in southern Sweden in the perspective of one rotation.

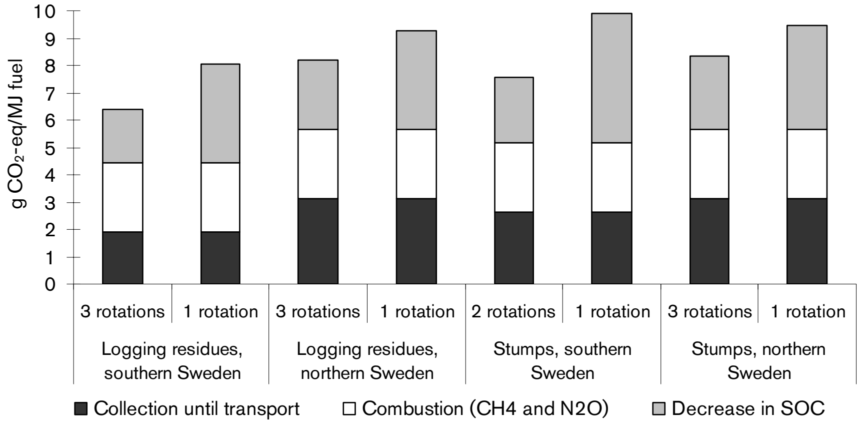

Figure 13. Emissions of GHG (g CO_2-eq per MJ fuel) with different time periods applied in Paper IV.

In Paper IV the emissions of GHG when generating electricity from forest fuel were estimated to 11-16 g CO_2-eq per MJ power in the long time perspective (one to three rotations) and 14-18 g CO_2-eq per MJ power in the perspective of one rotation (Paper IV). The GHG savings were estimated to 83-95% when forest fuel replaced fossil fuels (coal and natural gas) were estimated (Figure 14). The GHG savings were greater when the substituted fossil fuel was coal (199-207 g CO_2-eq per MJ electricity) rather than natural gas (88-95 g CO_2-eq per MJ electricity) and the savings were greater in the total time perspective than for one rotation, although the difference was small.

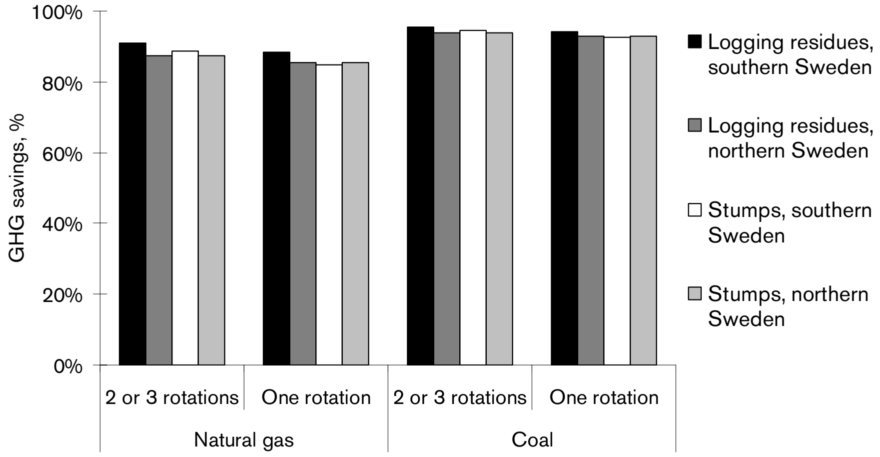

Figure 14. GHG savings when forest fuel substitutes fossil fuel (natural gas and coal), time perspective two or three rotations and one rotation.

5.3 Discussion

5.3.1 Energy balance

The primary energy requirement for harvesting forest fuel, logging residues and stumps, was 2-5% of the inherent energy according to the results in Paper III. These figures are quite favourable compared with fossil energy such as diesel oil, which requires about 15% of the inherent energy (Anon., 2007b).

In the forest fuel systems considered, the PE use varied due to all three main factors examined, *i.e.* technical system, geographical location and the forest resource harvested. The forest fuel systems in northern Sweden generally required more PE than similar systems in southern Sweden. The explanations were the long transportation distance, higher moisture content of residues and low load factor in the northern systems. Moreover, diesel-powered comminution at terminals in northern Sweden resulted in higher use of PE than the electrical engines used in most systems in the south. In addition, the use of terminals for processing and transfer created increased handling and transportation and thus increased PE use in the northern systems.

In northern Sweden the difference in PE use was small between the three systems, loose residues, bundles and stumps. In southern Sweden, on the other hand, residue comminuted at the roadside (system 1) and loose residues (system 3a), were identified as more efficient systems than the systems involving bundled residues and stump systems. The system with logging residues comminuted at the roadside (system 1) is the dominant supply chain in Sweden and one possible explanation for its low energy use was the greater experience of that systems and thus better optimisation of its productivity by operators.

The technique for lifting stumps dates from the 1970s, representing the early mechanisation of forestry. This might explain why it dominated the PE use (systems 4a and 4b). The scenario analysis in Paper III also showed that the stump system was most sensitive to changed harvesting levels; bundles were affected less, while loose residues were quite insensitive to different levels.

In the bundle supply system, the energy use in bundling process was substantial although in Paper III there were many ways identified to improve the supply chain, *i.e.* the bundling process at forest site but also bundle transport. When first designed, the bundling system was intended to make use of standard timber vehicles for transporting logging residues (Glöde, 2000). As yet, this has not been realised and the bundles are transported in container vehicles. In Paper III, the PE was higher for bundles (systems 2a and 2b) than for loose materials (system 3a and 3b). This was probably because operators have little practical experience of the bundle system and do not fully utilise the better load capacity when transporting bundles. This was especially true in northern Sweden, where the load size for the secondary transportation of bundles was shown to be low (Paper III), with a similar level to that for loose material. In addition, the bundles were transported only a short distance to a terminal for comminution. The data used in Paper III relate to the transportation of bundled materials during a short period of field testing, so it was not possible to make use of the potential positive aspects of the system.

Furthermore, integrating forest fuel harvest into timber procurement has been suggested by Glöde (2000). This involves an integrated harvester for forest fuel and timber in which the stem is processed over a platform onto which the tops and branches fall for automatic compaction into bundles. It has also been argued that large-scale systems including comminution at the plant are necessary for a competitive bundle system (Hakkila, 2004).

In the future, good logistics and control of transportation will be important, since the majority of PE use and environmental impact in the bundling and other residue supply systems occur during transport.

5.3.2 Greenhouse gas balance

An increased use of forestry resources by removal of logging residues and stumps is likely to affect the soil carbon stocks due to decreased organic matter input to the soil. However, with respect to the sustainable use of forests, the GHG savings from the use of forest fuel, stumps and logging residues, will outweigh this stock decrease.

There was large variation in the decrease in SOC between the time periods, since the SOC and decomposing litter varied greatly within the rotations due to the large input of litter at thinning and harvesting, which was followed by rapid initial decomposition. This caused a strong decrease in SOC stocks for the short time period (20 years) in comparison with the reference. In the long time perspectives, continued harvest of biomass and fossil energy substitution will shift soil carbon stocks towards a new equilibrium at a lower level (Wihersaari, 2005; Schlamadinger *et al.,* 1997). However, if the effect of the soil C and decomposing litter is limited, and biomass is harvested from sustainably managed forest, using forest fuels to replace fossil fuels can provide permanent and cumulative reductions in GHG emissions.

Paper IV concluded that important factors when assessing soil organic carbon stock change are the time horizon used, site productivity, harvest intensity and the bioenergy source (stumps or logging residues). Furthermore, when assessing the substitution effect of the forest fuel with respect to the mitigation of climate change, the efficiency of the end-use, allocation method between heat and power and the type of fossil fuel substituted are also important. This is consistent with a number of previous reports, for instance Schlamadinger & Marland (1996) and Cherubini *et al.* (2009) who concluded that in order to gain GHG savings when using biomass for fossil energy substitution, a high growth rate and a high efficiency of product harvesting and use are required.

Faster decomposition rates in southern Sweden explain why decrease in SOC was smaller in southern Sweden than in the north in the short time perspective (20 years). The decrease in SOC was higher for the stump systems than for the logging residues systems in the 20-year perspective since the decomposers are initially limited by the physical dimensions of the stumps, resulting in a lag phase in the decomposition before the decomposers have completely invaded the stumps. In the long time perspective, when the stumps were completely invaded by decomposers, the change in SOC was similar for the logging residues and stump systems. Logging residues systems in southern Sweden showed lower GHG emissions per MJ than the systems in northern Sweden, since the decrease in SOC was lower per MJ forest energy due to larger yields per year (total time period) and lower GHG emissions from fossil energy use during collection until transport.

The decreases in soil carbon related to harvesting stumps might be larger than indicated in Paper IV, since that study did not include the soil disturbance occurring when lifting the stumps. Soil disturbance could cause increased decomposition of organic matter resulting in release of carbon and other nutrients. These negative effects of soil disturbance may be a matter of concern for nutrient cycling and long-term productivity on poor sites (Zabowski *et al.,* 2008; Jandl *et al.*, 2007; Johansson, 1994) and for the GHG balance of stumps. This is further discussed in section 6.2 of this thesis.

However, the increased mobilisation of nutrients in connection with scarification and stump harvesting could promote rapid establishment and thus favour production of biomass in the new forest vegetation and stand (Johansson, 1994), resulting in an accumulation of carbon which might balance the losses (Jandl *et al.*, 2007). This factor was not included in the estimates reported in Paper IV.

Nevertheless, it is important to clarify the effect of stump harvesting on nutrient losses, long-term productivity of sites and soil organic matter content. A decrease in SOC is important not only for GHG balance, but also due to its effect on the soil structure, moisture-holding capacity, cation-exchange capacity and soil biota (Burger, 2002; Brady *et al.,* 1990), all of which affect the growth of roots and soil organisms. One solution could be to use a harvesting technique that gives more moderate effects on the soil and roots, thereby minimising the effect on SOC.

5.3.3 Other environmental impacts and conclusions

Intensifying the forestry system by harvesting residues and stumps may have other environmental consequences such as acidification and loss of biodiversity. The value of stumps as a resource for biodiversity is not fully known, but the fact that there is a deficit of coarse woody debris in Swedish forests increases the potential value of stumps for biodiversity. The challenge is to harvest stumps without having a significant effect on biological diversity.

Overall, with respect to the sustainable use of forests, the use of forest fuels (logging residues, *i.e.* tops and branches and stumps) will mitigate global warming. However, there is a risk that the reduction in SOC was underestimated in the stump harvesting systems studied in Paper IV, as the effect of soil disturbance *per se* was not included. It is probable that the choice of stump lifting technique could determine the net effect of the GHG balance. Furthermore, the primary energy requirement when harvesting forest fuel, logging residues and stumps, is low, only 2-5% of the inherent energy in the fuel, which is favourable compared to fossil fuels. Nevertheless, there are possibilities to improve the systems, since both stumps and bundle residue systems are currently relying on immature technologies.

6 General discussion

6.1 Potential improvement of forest procurement systems

Technological development in the Swedish forestry system has been great during the past 30-40 years. In the 1970s, mechanisation was in its infancy. Single-function machines were used for all logging operations in mechanised logging, *i.e.* felling, limbing, bucking and extraction (Anon., 1997). However, the energy use per cubic meter roundwood in the Swedish forestry system has decreased and in 1990s it was lower overall than that in the mechanized system of 1970s (Lindholm & Berg, 2005). In fact, there have been improvements in all processes from engine and machine design, operational logistics, productivity and operational efficiency leading to more energy-efficient logging processes. The overwhelming goal has been to increase the productivity in order to be competitive on the global market.

The system used today in Sweden for roundwood procurement is in principle the same as the system from the late 1990s presented in Paper I although there have been developments, mainly focusing on the use of information technology (IT). Examples of IT applications are vehicle computers, decision support tools for optimising different processes using geographical and positioning systems (GIS, GPS), online internet applications and information transfer over mobile phones (Kollberg, 2005). Decision support tools have been developed for a number of different processes such as machine logistics in the forest, timber haulage, road improvement, considering nature conservation measures, *etc.* (Jacobson *et al.*, 2008; Frisk & Rönnqvist, 2006; Frisk, 2005; Forsberg, 2003; Höglund, 2000). In addition, computers in vehicles have made remote troubleshooting and failure repair possible, which has raised the level of utilisation, and leading to improved productivity (Kollberg, 2005). Some of these factors have probably led to decreased energy use, although it is difficult to estimate the scope since there have been many but small improvements.

6.1.1 Future potential developments in forest procurement system

The future potential of different solutions is difficult to predict although looking into the future, there are mainly two issues that might bring changes to Swedish forestry technology; new machine technology and a structural change towards increased production of forest fuel.

Firstly, the increased demand for forest fuel gives both possibilities and challenges. The greatest possibility is probably the fact that the increased harvest from each stand means that the resources used could be allocated across more products. Obviously, one challenge is to develop efficient and flexible procurement systems, another is to handle the sustainability of the forestry system, *i.e.* challenges such as nutrient cycling, biodiversity and soil quality.

Secondly, there is potential for new technological development. Hardwarders (combined harvester-forwarder) will lead to lower fuel consumption, since they carry out work otherwise done by two machines (Bergkvist, 2007; Bergkvist *et al.*, 2003) and also eliminate the loading work with knucklebooms. 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 thinnings, since the volume harvested per hectare in thinning operations is low. Other machine systems are different semi-automatic (unmanned) systems designed for use in final felling, *e.g* a system comprising an unmanned harvester which is controlled remotely by one or more manned forwarders that are directly loaded. One study estimated that fuel consumption could be reduced by more than 20% by this system, mainly due to elimination of the loading work with knucklebooms (Bergkvist *et al.*, 2006). Other alternatives are autonomous wood shuttles (Hallongborg, 2003), which have been deemed to have the best ability to compete with the current harvester system (Hellström *et al.*, 2009). However, there are challenges to be dealt with, since the automatic system is an integrated system and thus all machines are dependent on each other (Lindroos, 2010). If one machine breaks down the other will also be affected and in the worst case standing idle. Major research efforts are still required, especially in the field of obstacle avoidance, before autonomous forest vehicles are ready for end users (Hellström *et al.*, 2009).

The forest fuel assortments could also involve great technological development in which the most promising might be integrated harvest of both roundwood and forest fuel. The concept is that the base machine in roundwood logging would simultaneously harvest residues, for example bundle the logging residues. This would eliminate at least one machine and thus less machine movements would be required. If the harvest of bundles is successfully integrated into timber harvest and the following secondary transportation, the potential to decrease energy use in forest fuel production could be substantial (Bergkvist, 2009).

The dominant supply chain of logging residues in Sweden is comminution at the roadside in the forest and subsequent transportation of wood chips, which was shown to be an efficient system in Paper III. Nevertheless, the flexibility is limited since it is an integrated system, meaning that each machine in the system is dependent on the previous one. One possibility to increase the flexibility in the whole system is bundling of residues, since drying and storing of bundles can be done in a variety of places, making the system more flexible and less vulnerable (Paper III). Bundling of forest fuel makes it more uniform to handle and allows better load capacity in forwarding and secondary transportation. As the harvest of forest fuel is expected to increase, and thus also the transport distances, flexible systems and good transport characteristics will be important.

6.1.2 Future potential developments in forest secondary transport

The forest sector is responsible for about 23% of all domestic road transport in Sweden (SIKA, 2009). Secondary transport is the process with highest energy requirements and environmental impacts in the procurement chains of both roundwood and forest fuel (Papers I and III). According to the findings in this thesis, the potential exists to improve the forestry transport systems by reducing the road transport distance, increasing the loading factor, decreasing the fuel requirements of each transport vehicle and using an energy carrier with good environmental characteristics. Potential solutions involve using better decision support tools for route-planning, modal changes (*e.g.* between lorry, train and ship for long-distance transport), adopting more fuel-efficient driving techniques, using the best available transport carrier and also choosing the best type of fuel or energy carrier.

Modal changes, between lorry and train, open up the possibility of longer transport distances with limited energy requirements and low environmental impacts (Paper II). Modal changes also involve terminals, an important factor to increase the flexibility of the forest fuel system, since terminals entail characteristics such as security of delivery, possibilities to use large-scale comminution and the potential to increase the quality of fuel since the operations (storage and comminution) take place in a controlled environment (Johansson *et al.*, 2006). The drawback is that the use of terminals creates increased handling and transportation. However, there are potential ways to improve logistics and operations in terminals (Enström, 2009).

It is also possible to improve the transport carrier, both by increasing the possible load and by lowering fuel consumption. In Sweden a roundwood rig that is longer (30 m) and has a heavier gross weight (90 tonnes) than conventional rigs (24 m and 60 tonnes) has been tested (Löfroth & Svensson, 2008). It is estimated that this would decrease fuel consumption and CO_2 emissions by 20-25%. Other improvements in secondary haulage of timber and forest fuel could be prioritising road improvements, which could lower fuel consumption and decrease the dependence on season in Swedish forestry (Frisk & Rönnquist, 2006).

Finally, it could enable better market prospect for the forest industry to change over to renewable energy sources as forest companies work with roundwood and forest fuel, which is renewable if sustainable forestry is implemented.

6.2 Greenhouse gas savings from the use of forest fuels

The vast resource of forest in Sweden has an important role to play in mitigating climate change by enhancing sequestration rate in existing forests and providing wood fuels as a substitute for fossil fuels and wood products for more energy-intensive materials. The annual national yield increment in Sweden is 120 million m^3 of stemwood and the gross felling was 85 million m^3 in 2008 (Swedish Forest Agency, 2009a). This means that the Swedish forest is an annual carbon sink, estimated at about 18 million tonnes CO_2 in 2008 (Anon., 2009b). The total carbon stocks in Swedish forest biomass are estimated to be about 4300 millions tonnes CO_2 (1180 million tonnes C) (Anon., 2008c), while the soil carbon stock are about twice that, *i.e.* 7000 million tonnes CO_2 (1900 million tonnes C) (Alriksson et al., 2002).

The annual increment is mainly due to improved forest management during the 20th century and also changes in land use. Nevertheless, there is potential to improve forest management in order to increase the biomass production by different forest management regimes (Eriksson, 2006). The yield increments presented above indicates that there is a large potential source of forest biomass that is not being used. Today, about 7 TWh of logging residues are harvested and the Swedish Forest Agency estimates the maximal potential for primary forest fuel, including ecological and technical restrictions, to be 16-25 TWh per year from logging residues (tops and branches) and 21 TWh per year from stumps (Svensson 2008). In the recommendation from the Swedish Forest Agency for stump harvest, it was estimated that a realistic potential in the near future is in the range of 1.3-2.6 TWh, which corresponds to 5-10% of the annual final fellings (Swedish Forest Agency, 2009c).

If it is assumed that this amount of biomass is used to generate electricity, it would give about 2-7 TWh electricity from logging residues and 0.3-6 TWh electricity from stumps (Table 4). This corresponds to about 1-10% of the Swedish electricity production in 2008 (129 TWh). The GHG savings would be 0.6-4 million tonnes CO_2 if natural gas was substituted or about twice that if coal was substituted. In relation to the total GHG emissions in Sweden (64 million tonnes for 2008), this is about 1%-14%.

Table 4. *Effects of forest fuel as decrease in SOC, electricity produced and GHG savings if substituted with natural gas and coal power power*[9].

Harvest	Decreased in SOC	Electricity produced	GHG savings	
TWh	10^6 tonnes CO_2	TWh	Natural gas, 10^6 tonnes CO_2	Coal, 10^6 tonnes CO_2
Logging residues				
7	0.091	1.9	-0.62	-1.4
16	0.21	4.3	-1.4	-3.2
25	0.32	6.8	-2.2	-5.0
Stumps				
1.3	0.024	0.35	-0.12	-0.25
2.6	0.044	0.70	-0.23	-0.51
21	0.36	5.7	-1.9	-4.1

However, these GHG savings are only valid in the time horizon of 75 years in southern Sweden. If shorter time commitments are to be fulfilled, using forest fuel would result in a lower GHG savings when substituting fossil energy. However, most of the logging residues and stumps would degrade anyway, but at a slower pace than when used as an energy source. In the long time perspective, continued harvest of biomass and fossil energy substitution will shift the soil carbon stock towards a new equilibrium on a lower level.

In Paper IV showed that harvest of logging residues results in a decrease in soil C of about 0.5-0.8 tonnes C per ha in the long time perspective,

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[9] Calculations based on figures in Paper IV, decrease in soil is for stumps and logging residues in southern Sweden, one rotation (75 years). GHG savings includes the whole fuel cycle.

while the corresponding value for stumps is 0.5-0.9 tonnes C per ha. The average soil carbon pool in Sweden is 82 tonnes C per ha[10] (Olsson *et al.*, 2009), indicating that the harvest of logging residues and stumps would decrease soil C by about 0.6-1% in a long time perspective. In relation to the total soil carbon pool in Sweden of 7000 million tonnes CO_2 (1900 million tonnes C) (Alriksson *et al.*, 2002), the decrease in soil C from forest harvesting is small (0.09-0.3 million tonnes CO_2 for logging residues and 0.02-0.4 million tonnes CO_2 for stumps; Table 4).

However, the decrease in soil C might be larger when harvesting stumps, since the calculations did not include the effect of soil disturbance occurring when lifting the stumps, as discussed in Paper IV. This implies that the GHG savings from stumps may not be as large as estimated in Table 4. There is a lack of published literature on the effect of soil disturbance related to stump harvesting on the soil carbon content. However, Zabowski *et al.* (2008) showed an extended decrease in mineral soil C 22-29 years after stump harvesting. Hope (2007) also found a substantial decrease of soil C 10 years after stump harvesting, but only in the forest floor and the impact was larger with more intensified soil disturbance. According to Hope (2007), there was a reduced content of C in forest floor of 10 tonnes C per ha 10 years after stump harvest[11]. On the other hand, there was an increase in soil C of 3.5 tonnes C per ha in the mineral soil. In total, this equals a net loss of 6.7 tonnes C per ha (25 tonnes CO_2 per ha). Assuming that this is also valid for Swedish soils and that it is caused by increased mineralisation and release of CO_2 into the atmosphere, this figure is only slightly lower than the decrease in soil C due to stump harvest a the time perspective of 20 years (Figure 12). This would have a substantial impact on the GHG balance of stumps as a fuel. However, this only gives a short-term perspective. Örlander *et al.* (1996) studied long-term effects (70 years) on soil scarification on sandy sites and concluded that total soil C was 6-41% lower on scarified sites compared with control sites. This indicates that the effects of soil disturbance from stump lifting might be long-lasting although specific to individual sites.

It has also been shown that the impact of soil disturbance on the soil C content will vary with the intensity of the treatment (Walmsley & Godbold, 2010; Jandl *et al.*, 2007; Johansson, 1994). Furthermore, good establishment and production of biomass in the new forest vegetation and stand is important, since this result in an accumulation of carbon which might

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[10] The average soil organic content in Swedish Podsol soils which cover 60% of the forest land area in Sweden.

[11] Total C year 10 in Table 5 (Hope, 2007).

balance the losses (Jandl *et al.*, 2007). Thus, the overall GHG savings from logging residues could be substantial in a long time perspective. However, for stumps it is probable that the choice of stump lifting technique could determine the net effect of the GHG balance, as was concluded in Paper IV.

6.3 Efficient use of a limited resource

Today, wood fuels contribute almost 25% of the final energy use in Sweden (Swedish Energy Agency, 2008). The majority of wood fuel is produced and used by the forest sector. District heating sector is another substantial user. The question is what the most efficient use of forest fuel and roundwood is? Even though the biomass resource is large and renewable, at least in Sweden, it is limited and the competition for forest resources is increasing, so the use of forest biomass needs to be efficient in both environmental and energy security aspects.

Paper IV showed that the GHG emissions were 6-10 g CO_2-equivalents per MJ forest fuel or 11-18 g CO_2-equivalents per MJ electricity. This is about 6- to 10-fold lower than for electricity generated from natural gas and 12- to 20-fold lower than for coal power. Furthermore, the GHG savings were 83-95% depending on time perspective and type of fossil energy. The results in this thesis also show that both roundwood and forest fuel require low inputs of external energy: Paper I showed that about 200 MJ of energy were required to produce one m^3 of timber at the end of the 1990s. One m^3 of timber contains 7700 MJ, which means that only about 3% of the inherent energy available in the timber is required to produce the timber. The corresponding figure for primary forest fuel, logging residues and stumps, is 2-5% (Paper III). These figures should be compared with fossil energy *e.g.* diesel oil, which requires about 15% of the inherent energy (Anon., 2007b).

Wood products have also been shown to be favourable later on in the production chain, since they require less energy and emit less GHG emissions than alternatives such as steel, concrete and gypsum (Sathre, 2007; Gustavsson *et. al.*, 2006; Petersen & Solberg, 2002). Wood products in particular are less fossil energy-intensive, since by-products are used as an energy source in sawmills and pulpmills. This was shown in a study of wooden glulam beams which were compared with a steel alternative for the roofing construction at the Gardermoen Airport in Norway (Petersen & Solberg, 2002). Wooden beams required 6- to 12-fold less fossil fuels than the steel beams. In fact it has been shown that more energy is produced in the form of residues from forest, processing, construction and demolition than is needed for wood material processing (Sathre, 2007). The greatest reduction in GHG emissions when using wood products is gained when wood products substitute other materials such as concrete and steel rather than substituting fossil energy directly (Gustavsson *et al.*, 2006; Petersen & Solberg, 2002). The explanation is the cascading effect where wood first replaces fossil-intensive material and then in final waste treatment is incinerated to replace fossil energy.

It is difficult to give any general answer regarding which bioenergy or wood product system is the most favourable, since many key issues are site-specific and there are several uncertainties involved. Furthermore, there might be a trade-off between the two goals, the reduction of GHG and oil dependency. One study has shown that options that replaces a high proportion of electricity (coal power) lead to large reductions in CO_2 emissions, while replacing motor fuels leads to a reduction in oil dependency (Joelsson & Gustavsson, 2010). Other studies have shown that using biomass in combined heat and power (CHP) leads to greater reduction in GHG emissions per unit biomass compared with using it in transportation fuels (Joelsson & Gustavsson, 2010; Gustavsson *et al.*, 2007; Wahlund *et al.*, 2004). This is because the energy losses are greater when converting biomass into vehicle fuels than when producing heat and power.

The efficiency in reducing GHG emissions is also highly dependent on which the fossil fuel replaced. In Paper IV, the reduction in GHG emissions was much greater when replacing coal than when replacing natural gas. However, replacing coal power does not reduce oil dependency, which is of particular concern for the transport sector. Electric vehicles, where the electricity is generated from renewable energy and second generation biofuels could reduce oil use and GHG emissions. The second generation biofuels are based on lignocellulosic (woody) raw material, which has greater potential to reduce GHG emissions and oil dependency compared with the first generation biofuels, which are based on agricultural raw materials, *e.g.* ethanol and RME. This is because the energy efficiency of conversion is higher, but also because of lower external inputs when producing lignocellulosic materials, *e.g***.** biomass from forest, short rotation forest and residues such as straw than when cultivating wheat, maize, sugarcane or rapeseed. Other advantages of second generation fuels are that the resource base of woody material is much larger and the competition with food crops is smaller in most cases.

A promising technique for secondary generation fuels is the gasification-based concept, since many resources could be used to efficiently produce a variety of energy carriers that could be used for a array of purposes, *e.g.*

synthetic fuels (DME, methanol, hydrogen), city gas, gas turbines (electricity), substitution of oil and coal, replacement of industrial oil burners and production of other chemicals. There is particular potentials in black liquor gasification in pulp mills, which has been shown to reduce oil dependency and GHG emissions (Joelsson & Gustavsson, 2010; Gustavsson *et al.*, 2007).

Black liquor gasification is an example of the promising bioenergy refinery or bioenergy combined concept, with integrated production of several energy carriers. The integrated production results in a higher overall energy efficiency than when each energy carrier is produced individually. Another advantage of the combined system is the flexibility to produce high quality energy carriers such as liquid fuels and electricity, while at the same times making use of low grade heat for which the demand is limited in many places.

Overall, the production of forest products and forest fuel requires little external energy and also emits low GHG emissions. The resource of forest biomass is limited and has to be processed into products and energy in an efficient and environmentally friendly manner. There is no single best way of using the forest resource, as this depends on the objective. What is clear is that forest biomass will probably play an important role in our future energy supply. The increasing demand for renewable energy opens up new possibilities for the forest industry to integrate production of pulp and renewable energy. This could contribute to decreasing the fossil energy use and the GHG emissions.

6.4 Conflict between different environmental objectives

It should be born in mind that even though products from the forest may be related to both low GHG emissions and low fossil energy use compared with fossil energy and other alternatives, *e.g.* steel, concrete and gypsum, they may cause other environmental impacts, as described in section 1.3. This indicates that there could be a conflict between different environmental areas. In Sweden there are 16 national environmental quality objectives, of which four are largely related to forest management; *i.e.* Reduced Climate Impact, Sustainable Forests, Zero Eutrophication and Natural Acidification Only. Reduced Climate Impact could be met by reduced use of fossil energy, more energy-efficient technology and an increased use of renewable energy. The latter could partly be solved with increased use of wood products and wood fuel which indicates more intensively managed forests and intensified harvesting. Although this would maximise the production of roundwood and wood fuel, it might have impacts on other quality objectives. The challenge is to find the balance between these different environmental objectives. The solution might be to have areas with more intensively managed forests and other areas with more protected forests, although this is not compatible with the current Swedish Forestry Act.

6.5 Limitations of LCA in relation to land use

The LCA methodology is promoted as a holistic environmental tool for use in order to avoid problem-shifting in product systems. In practice, however, some relevant impacts are seldom included in LCA since there is a lack of consensus within the field of LCA (Milà i Canals *et al.,* 2007). These include *e.g.* the effects of land use on the flora and fauna and on soil productivity, which are difficult to assess in an LCA. As a result, there is a lack of credibility for LCA that is particularly significant in land-demanding sectors such as agriculture, forestry, mining, fishery, housebuilding and industry.

There are mainly three factors that are essential when it comes to impacts from land use. First, LCA focuses on flows and for many of the impacts related to land use there is no flow character and consequently no clear input or output characteristics (Udo de Haes, 2006). Second, in LCA, time is often considered by setting an arbitrary time interval, which is often a 100-year perspective. The reason is that LCA is basically a time-unspecific method (Finnveden *et al.*, 2009; Milà i Canals *et al.,* 2007; Hellweg *et al.,* 2003). There is often no information about the product system's extension in time or the temporal course of emissions (Finnveden *et al.*, 2009). Third, in the inventory part of LCA, data are aggregated, often referring to a small unit without any information about the geographical location of the product system. LCA consequently operates on mass loads representing a share of the full emission output from the process, without considering when and where the emissions take place (Finnveden *et al.,* 2009). Neglecting the receiving environment and the time perspective is problematic when dealing with LCA related to forestry, where both production and environmental impacts appear gradually, *e.g.* changes in carbon stocks and impacts on biodiversity. The conclusion is that LCA reveal the potential contribution to different environmental impacts but do not reflect the actual impact. One way to get around this is a more site-specific assessment. The drawback is that this is not always practical since it requires more data.

There have been a few attempts to assess the impacts of land use on ecological systems (Muys & Quijano, 2001; Köllner, 2000; Lindeijer, 2000; Baitz *et al.,* 1998). Nevertheless, the sets of indicators are seldom checked aginst a consistent framework (Milà i Canals *et al.,* 2007) and the experiences of using and comparing the different methods are limited (Finnveden *et al.* 2009). Milà i Canals *et al.* (2007) propose to using impacts on land quality by assessing the land occupation and transformation originating from Baits *et al.* (1998) and further developed by Lindeijer *et al.* (2002). The proposal is to determine in the life cycle inventory (LCI) wether the process intervention is land transformation or occupation, which is later on assessed for the related impacts in the life cycle impact assessment (LCIA) (Milà i Canals *et al.,* 2007). Land quality is represented by different parameters depending on the specific impact parameters, for example biodiversity, biotic production and soil quality. According to Milà i Canals *et al.* (2007) there is a need for extended work to define such impact indicators.

In the context of land use in forestry, land occupation is problematic since the landscape in our forest today is a result of past forest management, including some of the environmental impacts. Forest management activities are continually being developed and many of the new environmental effects of raw material extraction only appear gradually (Weslien *et al.,* 2009), so it is not possible to compile these through direct observation.

The greatest challenge is probably to find suitable parameters to include biodiversity since the definition of biodiversity as stated in the Convention on Biological Diversity is very wide: "the variability among living organism from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems" (Anon., 1992). Such a wide definition makes biodiversity difficult to deal with quantitatively, which is demanded by the LCA methodology.

The main environmental impacts of forestry are related to land use *i.e.* biodiversity, soil quality, *etc.*, which are not covered here, a weakness in this thesis. One way to get around this could be to combine LCA with other environmental system analysis tools such as Environmental Impact Assessment and Environmental Risk Assessment. However, the difficulties with assessing biodiversity in a quantitative manner remain, as do the delayed environmental effects of forest management activities.

7 Conclusions and final remarks

In this thesis, the Swedish forestry system was studied in a life cycle perspective. Opportunities to reduce the energy use and environmental performance were identified. The results presented here improve our understanding of the system and could be used to compare forest products with other materials and energy carriers. In general, the conclusions from the Papers I-IV were:

- Both roundwood and forest fuel require low input of external energy. Only about 3% of the inherent energy available in the timber is required to produce the timber. The corresponding figure for primary forest fuel, logging residues and stumps, is 2-5%.

- With respect to the sustainable use of forests, there are large greenhouse gas savings from the use of forest fuel, stumps and logging residues.

- Important factors for the GHG balance of forest fuel and possible GHG savings when substituting fossil energy were:
  (*i*) efficiency of the end use
  (*ii*) type of fossil fuel substituted
  (*iii*) allocation method between heat and power
  (*iv*) bioenergy source (stumps or residues)
  (*v*) site productivity
  (*vi*) harvesting intensity.

- In short time perspectives, the decrease in SOC was large, due to the fact that logging causes large input of litter followed by fast initial decomposition. This causes a strong decrease in SOC stock for short time intervals (20 years) when harvesting forest fuel in relation to a reference with no harvesting of forest fuel.

- For stumps, there is a possibility that the reduction in soil organic carbon was underestimated in the study, since the effect of soil disturbance *per se* was not included. The choice of technique when lifting stumps could determine the net effect of the greenhouse gas balance.

- Swedish forestry systems in northern and central Sweden require more energy than those in southern Sweden per cubic meter roundwood harvested due to longer transport distances and lower growth rates in northern and central Sweden.

- Forest fuel procurement systems in northern Sweden require more energy per MJ forest fuel than those in southern Sweden due to the greater energy use in transportation (longer transport distance, low load factor, high moisture content) and in terminals (diesel-powered comminution, loading and unloading).

- About half the energy used in procurement chains for both timber and forest fuel goes to secondary haulage (transporting). For roundwood, often little can be done to decrease the actual distance from forest to industry in Sweden, unless there are heavy investments in infrastructure. However, the energy use and environmental impact of transportation can be minimised by reducing the road transport distance by modal changes (lorry to train), increasing the loading factor, decreasing the fuel requirements of each transport vehicles and using an energy carrier with good environmental characteristics.

- The energy use is higher in systems with bundled logging residues than in systems with loose materials. The energy use in bundling systems can be decreased by improving the harvesting system, both on-site and utilising better load capacity when transporting bundles.

- The energy use in secondary transport of timber in Sweden is of the same order of magnitude as for continental Europe, despite the harsh climate, long transport distances and smaller tree sizes. This is because Sweden uses longer vehicles and larger gross weight, and consequently larger payloads, and small-scale forestry in Sweden uses large-scale transport solutions.

- Energy use in silviculture and logging is low in Sweden compared with some other countries in Europe due to the low degree of mechanisation in Swedish silviculture and the high degree of mechanisation in logging, since large-scale logging is generally also applied in small-scale forestry.

- Modal changes in transportation of forest products, between lorry and train, could allow longer transport distances with limited energy requirements and low environmental impacts.

8 Future research

In a future with increasing demand for bioenergy, harvesting intensity will have to increase in forestry. If this means that the use of artificial fertiliser is more common, there will be nitrous oxide emissions (N_2O) from soil which have been shown to have a large impact on the greenhouse gas balance. Most LCA-studies that include N_2O use default emission factors published by IPCC (2006), since these emissions are otherwise difficult to determine. Theoretically, emissions of N_2O evolve from fertiliser application and decomposition of organic material, but these might be cancelled out by a decrease in N_2O with increased forest fuel harvesting because N is removed from the forest site with the forest fuel. Therefore, both field measurements and a LCA of the impact of N_2O on the greenhouse gas balance of different forest products are necessary.

In Paper IV, the effect on soil carbon was only simulated and for stump harvest the simulation did not include the impact on soil carbon due to soil disturbance when lifting the stumps. This effect of soil disturbance thus needs to be further investigated through field measurements and through theoretically determing the effect on the greenhouse gas balance of the stumps in both a short- and long time perspective.

As the demand for bioenergy increases, it might be interesting to have other forest management regimes. It might be profitable to increase the forest fuel assortments and harvest longer tops and higher stumps. In Paper I-IV, each assortment, roundwood and forest fuel, was individually investigated. It would be interesting to integrate these products and investigate different methods for allocation between the different products, including the effect on soil C but also the impact of different management practices and procurement systems.

There is currently no consensus in the LCA community on how to treat land use so further evaluation is needed of methods proposed for different types of land uses and geographical (climate) areas.

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Acknowledgement

A large number of people have in different ways contributed to my work on this thesis. First of all, I would like to thank my associate supervisor Staffan Berg, for guiding me, sharing his knowledge, giving critical constructive comments and for fruitful discussion about research, military history, literature, you name it! Per-Anders Hansson, my supervisor, thank you for your support and for guiding me through the research area.

Thanks to former colleagues at Skogforsk and especially to Henrik von Hofsten, Eva Ring, Ulf Sikström, Lars Högbom, Folke Pettersson, Mikael Frisk, who always had good answers to my sometimes odd questions. I would also like to thank all present and former colleagues at the Department of Energy and Technology, especially to Carina, Serina and Annika for valuable talks. To my stump friends Erik Anerud and Raida Jirjis, thanks for help with data and good stump discussions. Berit, Majsan and Sven thanks for practical support and for making the department a nice place to work in. I would also like to thank Johan Stendahl for interesting collaboration. Monika Strömgren and Magnus Lindgren thank for your help and engagement. Åke Nordberg scrutinised the first version of this thesis in a very honourable manner. Excellent linguistic editing of this thesis was conducted by Mary McAfee.

To all my friends and especially to Helena, Ullen and Ullebulle, thanks for always being there when I need you! Ylva, for our good discussions about what's important in life! My parents, thanks for all your support. To Erik, Anton and Lisa, thanks for love and for making my life worth living!

The work in Paper III and IV was carried out as part of the Stump Research Programme at the Swedish University of Agricultural Sciences. It was funded by the Swedish Energy Agency and the Swedish University of Agricultural Sciences.