Temporal Climate Impacts of Using Willow and Logging Residues for District Heating in Sweden

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Abstract

Using bioenergy to replace fossil fuels has been adopted as a climate mitigation measure, since less greenhouse gases are expected to be released into the atmosphere. In Sweden, the share of bioenergy is relative high (about 23% of total consumption including peat), with a relatively large proportion originating from domestically produced forest biomass.

This thesis examined the climate impact of using two types of woody biomass (willow, logging residues) for district heating, using time-dependent life cycle assessment methodology. The climate impact of the wood-based energy systems was determined and compared with that of the fossil fuels coal and natural gas. The focus was on the temporal dynamics of carbon fluxes between soil, biomass and atmosphere.

Establishing willow on agricultural land provided the potential to sequester carbon from atmosphere to soil, giving a net cooling effect on global mean temperature. However, this effect was shown to be highly dependent on willow yield (*i.e.* productivity), with low yield potentially decreasing soil carbon content. Moreover, district heating from willow chips gave a lower warming effect than coal and natural gas, irrespective of yield.

Combustion of forest biomass in the form of logging residues also gave a lower warming effect than coal and natural gas. However, the climate benefits compared with natural gas were delayed by 15-20 years (depending on geographical location) due to the chemical composition of natural gas, which generates less greenhouse gas emissions than coal and logging residues during extraction and combustion. Nevertheless, when decomposition of unharvested forest biomass was included in the reference systems, bioenergy from logging residues had climate benefits compared with coal and natural gas.

Keywords: Temperature change, global warming, greenhouse gas (GHG), soil organic carbon (SOC), biogenic carbon, life cycle assessment (LCA), bioenergy, forest biomass, wood chips, short-rotation forestry

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The most common way people give up their power is by thinking they don't have any.

Alice Walker

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Hammar, T., Ericsson, N., Sundberg, C. & Hansson, P.-A. (2014). Climate impact of willow grown for bioenergy in Sweden. *BioEnergy Research* 7(4), 1529-1540. doi:10.1007/s12155-014-9490-0.

II Hammar, T., Ortiz, C., Stendahl, J., Ahlgren, S. & Hansson P.-A. (2015). Time-dynamic effects on global temperature when harvesting logging residues for bioenergy. *Submitted.*

Paper I is reproduced with the permission of the publisher.

The contribution of Torun Hammar to the papers included in this thesis was as follows:

I Developed the scenarios in cooperation with the co-authors. Performed the calculations and prepared the data presentation (figures and tables). Wrote most of the manuscript with input from the co-authors.

II Performed the LCA calculations and prepared the data presentation (figures and tables). Wrote most of the manuscript with input from the co-authors.

Abbreviations

AGTP	Absolute global temperature potential
AGWP	Absolute global warming potential
CRF	Cumulative radiative forcing
DH	District heating
DM	Dry matter
ER	Energy ratio
GHG	Greenhouse gas
GJ	Gigajoule (10^9 J)
GWP	Global warming potential
ha	Hectare (10^4 m^2)
HHV	Higher heating value
ICBM	Introductory carbon balance model
iLUC	Indirect land use changes
LCA	Life cycle assessment
LHV	Lower heating value
LUC	Land use change
MC	Moisture content
MJ	Megajoule (10^6 J)
RF	Radiative forcing
SOC	Soil organic carbon
SRCW	Short-rotation coppice willow

1 Introduction

An issue that has received much attention recently is how to provide the world's population with sufficient food and energy, while at the same time mitigating climate change. Although food security, energy security and climate change may seem to be three separate subjects, they are all interlinked within the planetary boundaries. The use of energy has increased greatly since the beginning of the industrial age. An increasing human population and a higher standard of living have created demand for greater quantities of land and energy for *e.g.* food production. This has led to emissions of the three major greenhouse gases (GHGs), carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4), mainly due to the use of fossil fuels (Ciais *et al.*, 2013). GHGs have the ability to trap heat in the atmosphere, giving rise to higher global mean temperature.

This human-induced temperature change has impacts on the Earth's ecosystems, which may change the living conditions to which we are accustomed. To mitigate climate change, different strategies have been suggested, one of which is replacement of fossil-based energy with bioenergy (Chum *et al.*, 2011). Using biomass for energy generates CO_2 emissions when it is combusted in the same way as fossil fuels, but the CO_2 originating from biomass (referred to as biogenic CO_2) was previously absorbed from the atmosphere and can be taken up again by plant regrowth. This has led to the assumption that bioenergy can be considered *carbon neutral*, *i.e.* having no impact on the climate, by giving rise to zero net emissions of CO_2.

The carbon neutrality concept is simplistic and overlooks several important factors (Haberl *et al.*, 2012). Producing biomass for energy purposes releases GHGs during the extraction and conversion phase, which affects the climate. Moreover, the time lag between the release of biogenic CO_2 and its uptake by plants has an impact on the atmospheric concentration, which needs to be considered. Furthermore, bioenergy requires land for producing biomass and increasing the share of bioenergy can lead to both direct and indirect land use changes.

To consider the above-mentioned aspects of bioenergy, the whole system needs to be studied. This can be done using life cycle assessment (LCA) methodology, which considers all emissions and use of energy during the entire lifespan of the studied system, including all processes and the production of inputs (Cherubini & Strømman, 2011). To include the temporal aspect of biogenic CO_2 fluxes (*i.e*. uptake due to growth and release due to combustion or decomposition), a time-dependent climate metric can be used in an LCA (Repo *et al.*, 2014; Zetterberg & Chen, 2014; Ericsson *et al.*, 2013; Levasseur *et al.*, 2012; Levasseur *et al.*, 2010).

Bioenergy accounts for about 10% of global energy consumption (IRENA, 2013; Don *et al.*, 2012), with the most common form of bioenergy (about 99% of total consumption) being solid biomass used for traditional purposes (*e.g*. heating and cooking) (Hallström *et al.*, 2011). The global demand for bioenergy is expected to increase in the future, partly due to climate change mitigation measures and energy security strategies (Hallström *et al.*, 2011). Bioenergy can be obtained from primary energy biomass (produced directly for energy purposes) or from residual biomass (*e.g*. forest residues, waste wood or residues from the agricultural sector).

In the Swedish energy system, about 53 TWh (2013 values) originate from domestically produced forest biomass, with logging residues accounting for about one-fifth. Short-rotation forestry grown directly for energy (mostly willow) accounts for a much smaller share (around 0.25 TWh in 2013) (Swedish Energy Agency, 2014b). However, short-rotation forestry such as willow has the potential to bind carbon from the atmosphere in the soil when grown on agricultural land (Ericsson *et al.*, 2013), which is interesting to study further.

2 Aim and structure

2.1 Overall aim

The overall aim of this licentiate thesis was to examine the climate impacts of bioenergy systems for producing district heating from willow or logging residues, with the focus on the temporal dynamic effects on global temperature. Specific objectives were to analyse:

- The carbon fluxes between soil, biomass and atmosphere when agricultural land is used for growing willow or forest is used for extracting logging residues for energy purposes, and the impact on the climate (Papers I and II)
- The climate effects of growing willow or extracting logging residues for energy purposes compared with using the fossil fuels coal and natural gas (Papers I and II)
- The influence of willow productivity, previous land use and the effect of a terminated willow cultivation on the climate impact (Paper I)
- The influence of different productivity and decomposition rates in three geographical locations on the climate impact of extracting logging residues for bioenergy (Paper II).

2.2 Structure of thesis

This thesis is based on two papers describing two different types of bioenergy systems in Sweden, one based on short-rotation forestry grown directly for energy and one based on residual forest biomass extracted from final felling. Paper I studied short-rotation coppice willow (SRCW) (*Salix* ssp.) grown on arable land, which generated a continuous supply of bioenergy (every 3-4 years). Paper II studied a long-rotation forest system based on Norway spruce

(*Picea abies*), where logging residues used for bioenergy were only extracted during final felling (first year of time frame). Both papers used the same methodology, time-dependent LCA, for evaluating the climate impact of the systems over time in terms of global temperature change. In both papers, two reference fossil systems were defined based on coal or natural gas. In addition, alternative land management systems were included within the system boundaries of the reference systems (Fig. 1).

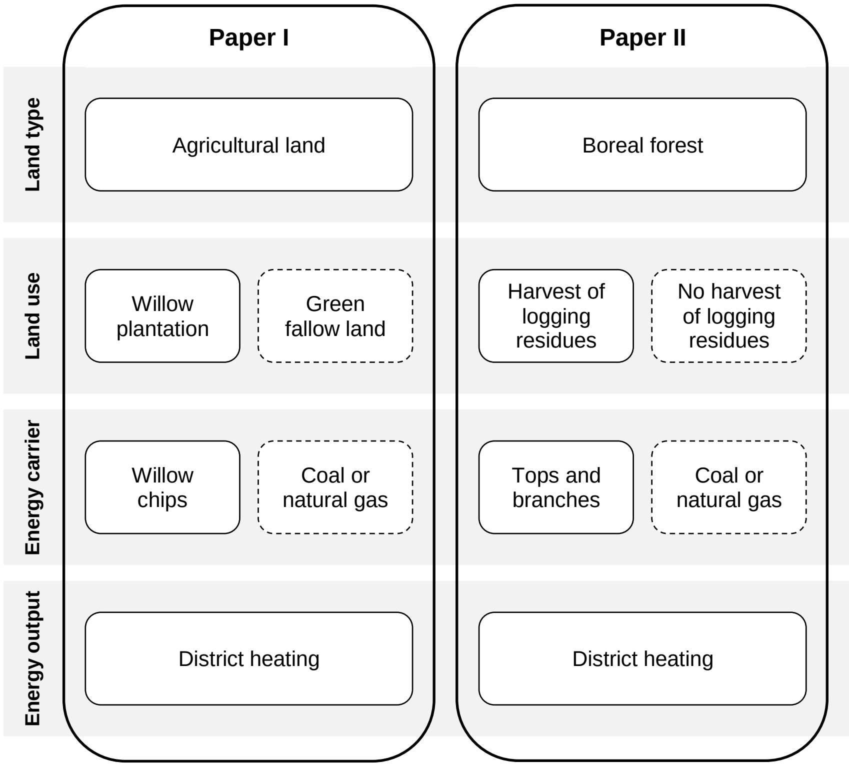

Fig. 1 The two different types of bioenergy systems studied in Papers I and II, both with the purpose of producing district heating from woody biomass. Dotted lines indicate land use and energy carrier in reference systems.

3 Background

3.1 The Earth system

3.1.1 Greenhouse effect

The energy balance on Earth is determined by the incoming solar radiation and the outgoing terrestrial radiation, described as the radiative forcing (Wm^{-2}) (Fig. 2). The fraction of solar radiation reflected back to space from the Earth's surface is referred to as the albedo effect (~0.3) (Betts & Ball, 1997). GHGs can absorb and remit longwave radiation (also called infrared radiation) (Manning & Keeling, 2006), at the same time as shortwave radiation from the sun can pass through the gases (Cubasch *et al.*, 2013). This means that when more GHGs are released more energy will remain in the atmosphere, which can lead to higher global mean surface temperature.

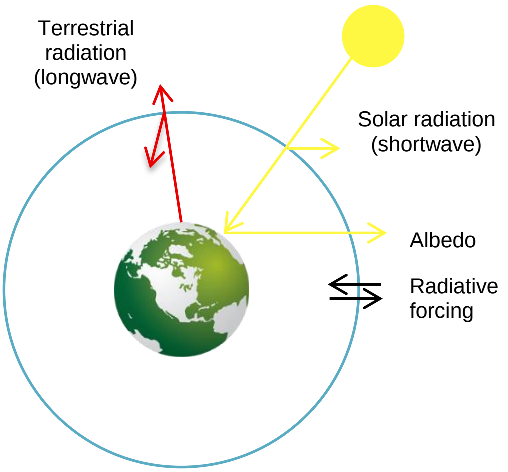

Fig. 2 Simplified diagram of the radiative balance of the Earth, where the circle represents the atmospheric boundary (tropopause).

3.1.2 Temporal dynamics of emissions

The release of GHGs changes the concentrations in the atmosphere. Depending on the gas involved, these emissions affect the atmospheric concentration for varying periods of time, since CO_2, N_2O and CH_4 have different atmospheric residence times. CH_4 and N_2O decay with average residence times of 12.4 and 121 years, respectively (Myhre *et al.*, 2013b). On the other hand, CO_2 remains in the atmosphere until it is taken up by oceans or terrestrial ecosystems. A large proportion of the emitted CO_2 can stay in the atmosphere for centuries or millennia (Archer *et al.*, 2009). According to Joos *et al.* (2001), about half of the anthropogenic CO_2 remains in the atmosphere, while the rest is taken up by oceans (Khatiwala *et al.*, 2012) and by the biosphere.

3.1.3 Biogenic carbon

Carbon is fundamental for plant growth since it is needed for the process of photosynthesis. A fraction of the CO_2 captured by plants is returned to the atmosphere through autotrophic (plant) respiration. The remaining carbon stored in the biomass (referred to as biogenic carbon) can transfer to the soil pool by root turnover and litter fall, and back to the atmosphere by heterotrophic respiration by decomposers (Fig. 3) (Chapin *et al.*, 2002).

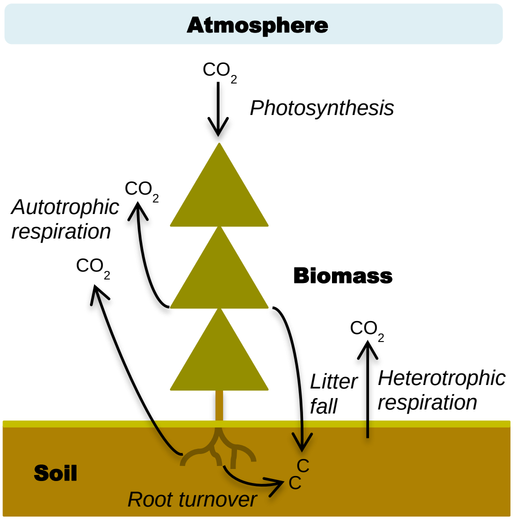

Fig. 3 Simplified diagram of biogenic carbon fluxes between atmosphere, biomass and soil due to photosynthesis and respiration.

The carbon stored in the biomass can also be released by combustion, which releases the carbon earlier in time compared with the slower process of decomposition. Soil respiration increases with increasing temperature, so higher global mean temperature could lead to higher CO_2 emissions from soil (Schlesinger & Andrews, 2000).

Burning biomass for energy emits CO_2 in the same way as when fossil fuels are combusted. The difference between fossil fuels and biomass is that the CO_2 originating from biomass has been captured from the atmosphere recently (relative to fossil fuels) and can be taken up again by plant regrowth (except following *e.g.* permanent deforestation). This has led to the assumption that bioenergy can be considered carbon neutral. However, although the net CO_2 emissions from combustion to regrowth may be zero, the time period between CO_2 release and uptake can differ widely. This time gap brings a temporary change in the atmospheric concentration, which is especially important to consider in wood-based bioenergy systems with long rotation periods (Lamers & Junginger, 2013).

3.2 Human activities

The atmospheric concentrations of the three major GHGs (CO_2, N_2O and CH_4) have all increased (by 40%, 20% and 150%, respectively) since the beginning of the industrial age in the mid-1700s. The increase has mainly been a result of human activities such as use of fossil fuels for energy purposes and land use changes (Berndes *et al.*, 2013; Ciais *et al.*, 2013). The majority (91%) of the emissions can be attributed to the use of fossil fuels (together with cement production), while the remaining 9% originate from land use changes (Le Quéré *et al.*, 2014). Climate records show that the atmospheric concentrations of the three GHGs are higher now than at any time during the past 800 000 years, which points to an anthropogenic cause (Ciais *et al.*, 2013).

3.2.1 Energy use

Among fossil fuels, coal is the largest emitter of CO_2 globally (Swedish Energy Agency, 2014a) and this fuel demonstrated the greatest increase of all fossil fuels in 2013, accounting for about 30% of global energy consumption (British Petroleum, 2014). The use of natural gas also increased in that year, although the increase was below the historical average, representing about 23.7% of global energy use (British Petroleum, 2014).

In Sweden, the use of coal has not followed the global trend. Instead, coal consumption has decreased in recent decades, partly as a result of national CO_2 taxes (Di Lucia & Ericsson, 2014). The use of natural gas has been relatively low in Sweden, only accounting for about 3% of total annual energy use in 2011 (Swedish Energy Agency, 2014a). Instead, the share of bioenergy is comparatively high, accounting for around 23% of total energy use (including peat) (Swedish Energy Agency, 2014a), with forest biomass comprising a large proportion (Björheden, 2006). According to an assessment in 2004, about half the total forest biomass extracted in Sweden is used for energy (Nilsson, 2004). Part of the biomass is used for producing district heating (DH), with about 38% of DH produced from wood fuel (logging residues, energy forest, recycled wood *etc*.) in 2011 (Swedish Energy Agency, 2014a).

3.2.2 Land use

Land is a finite resource and the amount of land used for crops globally has increased due to higher demand for food, fuel and fibres, and also as a result of land degradation and an increase in urbanisation (UNEP, 2014). Globally, about half of the world's population now lives in urban areas and, with the expected increase in global population in the future, the trend for urbanisation is also expected to increase (Hallström *et al.*, 2011). Land use change (LUC) has been recognised as a contributing cause of climate change and is primarily the result of expansion of urban areas into agricultural land and expansion of agricultural land into grassland, savannah and forest (UNEP, 2014). Direct LUC may cause indirect land use changes (iLUC), when *e.g*. arable land is changed from food production to non-food production although the food demand still remains, which leads to additional LUC elsewhere (Berndes *et al.*, 2013).

In a global perspective, the land area used for crops has been expanding since the 1960s (Hallström *et al.*, 2011), with the harvested area having increased by around 23.6% since then. In Europe, the trend is different and a large share of domestic animal feed production has been replaced by imported products grown elsewhere (UNEP, 2014). According to an assessment by Hallström *et al.* (2011), around 2% of global cultivated land is used for growing biofuels, but the largest share (62%) is used for growing products for human consumption directly and for animal feed production (33%). According to Don *et al.* (2012), the share of arable land used for bioenergy is somewhat higher in Europe (about 3%).

It has been pointed out that Sweden has more arable land than is currently used for food or feed production. This unused land could be used for growing energy crops, *e.g*. short-rotation forestry, without displacing food production (González-García *et al.*, 2012). It is not certain how large this potential is, but in Sweden about 6.7% of total arable land is under temporary or permanent fallow (Statistics Sweden, 2013a). According to estimates, the amount available globally is around 29% (Hallström *et al.*, 2011).

The most common form of short-rotation forestry in Sweden is willow, which is grown on about 12 000 ha of Swedish land (Aronsson *et al.*, 2014; Hollsten *et al.*, 2013; Don *et al.*, 2012). In Europe, short-rotation coppicing energy crops are grown on approximately 50 000 ha of land (Don *et al.*, 2012).

About 30% of the Earth's land surface is covered by forest (Hallström *et al.*, 2011; Parikka, 2004). The total forest area decreased in the period 1990-2005, mainly due to deforestation of tropical forests. However, boreal forest area increased during the same period (FAO & JRC, 2012). Sweden has a relatively large share of forest land (about 70% of total land area) (Matthews *et al.*, 2014; Statistics Sweden, 2013a), dominated by conifers (*e.g. Pinus sylvestris* and *Picea abies*) (Statistics Sweden, 2013a). Forest biomass is primarily used for timber and pulp wood, while leftover branches and tree tops are left in the forest to decompose, or harvested for energy purposes.

3.3 Global warming – assessment and mitigation

The increase in GHGs in the atmosphere since the beginning of the industrial age has had a large influence on the radiative balance on Earth. Shortwave solar radiation has entered the atmosphere at the same time as more longwave radiation has been absorbed and remitted by GHGs. This has led to a human-induced global mean surface temperature rise on Earth (Cubasch *et al.*, 2013). Increased awareness regarding the possible consequences of this rise has led to the development of strategies for mitigating human-induced climate change.

3.3.1 Strategies for mitigating climate change

In order to mitigate climate change, the European Union (EU) has decided on joint energy targets, referred to as the '20-20-20' targets, which declare that compared with 1990, by the year 2020:

(1) GHG emissions in the EU should be decreased by 20%
(2) Renewable energy consumption should increase to 20%
(3) There should be a 20% improvement in the EU's energy efficiency

The EU has also agreed on higher mitigation targets for the years 2030 and 2050 (European Commission, 2013).

Sweden has decided on higher mitigation targets related to the energy sector, namely: (1) to decrease GHG emissions by 40% and (2) for 50% of energy consumption to come from renewable sources, also by the year 2020 (compared with 1990) (Swedish Energy Agency, 2014a). In addition, Sweden has set the target of zero net emissions of GHGs by the year 2050 (Swedish

EPA, 2012). To evaluate whether renewable energy sources, such as bioenergy from woody biomass, decrease emissions according to the climate mitigation targets, LCA methodology can be used for analysing the bioenergy systems.

3.3.2 General framework of life cycle assessment

Life cycle assessment is a standardised method (ISO 14040/44) for assessing the environmental impact of a system during its entire time frame (ISO, 2006a; ISO, 2006b). The general framework consists of four stages:

(1) Goal and scope definition
(2) Life cycle inventory analysis
(3) Life cycle impact assessment
(4) Interpretation of the results

The goal and scope definition stage includes drawing the boundaries of the studied system, which outlines the processes included. It also involves defining a reference system for comparison. A functional unit for quantifying the performance of the system is then defined. It can be either an input-based unit (*e.g.* hectares of land used) or an output-based unit (*e.g.* MJ of heat produced). The functional unit works as a reference to which all process flows are related.

In the life cycle inventory stage, data on all relevant inputs and outputs during the entire time frame are collected. These data are related to the functional unit and later used to assess the environmental impacts of the system (Baumann & Tillman, 2004).

In the third phase, life cycle impact assessment, several environmental impact categories can be studied (*e.g.* eutrophication, acidification or biodiversity), but the most common impact category when studying bioenergy systems is the impact on climate. To assess the climate impact, several impact indicators can be used. However, the most common method is to describe the impact in terms of emitted CO_2-equivalents (CO_2-eq) and the potential to cause global warming (see further description of *Global Warming Potential* in section 4.3.2).

3.3.3 Attributional and consequential approaches

In addition to the general framework, life cycle assessment can be separated into attributional LCA (ALCA) and consequential LCA (CLCA), depending on the aim of the study (Brander *et al.*, 2009). ALCA is used to evaluate the direct implications of a product or service and does not consider indirect effects. ALCA can be used *e.g.* when the purpose is to compare two products or to identify which parts of the system give the largest impact, *i.e.* potential hotspots (Brander *et al.*, 2009).

If the purpose of the study is to assess the effects of a decision leading to both direct and indirect effects, an CLCA should be used (Finnveden *et al.*, 2009). CLCA is change-orientated and considers the market effects of a change in production level. This makes the approach more relevant for policy making, although the inclusion of economic modelling can increase the degree of uncertainty. Another difference between the two types of LCA is that ALCA generally uses average data, while CLCA uses marginal data.

3.3.4 Assessing bioenergy

Previous studies of bioenergy have shown that carbon fluxes between the soil, biomass and atmosphere play an important part in climate impact assessment (Buchholz *et al.*, 2014; Repo *et al.*, 2014; Helin *et al.*, 2013; Lindholm *et al.*, 2011). Fargione *et al.* (2008) concluded that policies should take into account the net GHG emissions, including emissions due to LUC and carbon sequestration. One way of assessing the impact of LUC is to use the change in soil organic carbon (SOC) content as a measure of soil quality (Milà i Canals *et al.*, 2007). To capture the dynamics of biogenic carbon fluxes, a time-dependent climate metric can be used in an LCA (Zetterberg & Chen, 2014; Ericsson *et al.*, 2013; Levasseur *et al.*, 2012).

The choice of time frame plays an important part in the interpretation of the results. For example, a 'forward-looking' perspective, which focuses on future carbon stock changes from the present time onwards, can be used when studying bioenergy from forest biomass. Alternatively, previous carbon stock changes can be considered, if it is assumed that carbon stored in *e.g.* forests today is due to previous decisions and that burning the forest biomass today would only emit previously captured carbon. Helin *et al.* (2013) concluded that from a climate change mitigation perspective, the forward-looking perspective is more relevant.

To put the climate impact of a bioenergy system into perspective, an alternative use of the biomass or land should be defined (*i.e.* a reference system) (Lamers & Junginger, 2013). It is important to consider the biogenic CO_2 balance in both the bioenergy system and the reference system, including short-term and long-term effects of the land uses (Helin *et al.*, 2014).

Another methodological choice to consider is the assumption of scale. Bioenergy systems can be studied either from a stand perspective or from a landscape perspective (Lamers & Junginger, 2013). The stand perspective only considers the dynamics of *e.g.* one hectare of forest or agricultural land, while the landscape perspective includes the dynamics of a whole landscape.

3.3.5 Previous studies of bioenergy

Life cycle assessments of willow systems have revealed low global warming potential or even negative effects (*i.e.* cooling) when including SOC changes (*e.g.* Zetterberg and Chen (2014); Ericsson *et al.* (2013); Heller *et al.* (2003). Analyses of willow have also shown positive values compared with other energy crops, in terms of cost and energy efficiency (Börjesson, 2006; Heller *et al.*, 2003). However, this is based on the assumption that willow chips can be sold for the same price as wood chips, which has not been the case in the past (Aronsson *et al.*, 2014). Börjesson (2006) also concluded that willow yield is an important factor for the overall performance of the willow system, and the practical results for willow plantations have not lived up to the high yield expectations in the past (Dimitriou *et al.*, 2011).

Previous LCAs on using forest biomass for energy have generally shown a higher global warming potential compared with willow, since extracting forest residues does not contribute to increasing the carbon content in the soil, unlike the willow system. The global warming potential of wood chips has been shown to be in the order of 1-10 g CO_2-eq per MJ (Jäppinen *et al.*, 2014; Repo *et al.*, 2014; Zetterberg & Chen, 2014; Gode *et al.*, 2011; Lindholm *et al.*, 2011). However, comparing LCA results is problematic since the system boundaries usually differ, as do the choice of data and functional unit.

4 Method

4.1 System description

This thesis is based on two papers, one studying willow and one logging residues (branches and tree tops) of Norway spruce. In both papers, reference systems were defined based on alternative land use and use of an alternative energy carrier for producing the same amounts of district heating. A stand perspective was applied in both papers, which means that only one hectare of agricultural land (Paper I) or one forest stand (Paper II) was considered.

Time-dependent LCA methodology was used in both papers to study two impact categories; climate impact and energy performance. An ALCA approach was applied and the analysis was limited to the direct effects of extracting biomass for energy. Average data were used for assessing GHG emissions and energy use in the bioenergy production chains and in their reference systems.

4.1.1 Short-rotation forestry

The short-rotation coppice willow system studied in Paper I included all processes from site preparation to direct combustion of willow chips at a DH plant (Fig. 4). The willow system had an assumed rotation period of 25 years and a coppice cycle of 3-4 years depending on scenario, which meant that the willow was harvested every 3-4 years after establishment until the plantation was broken up after 25 years, followed by replanting. The willow system was assumed to be located in south-eastern Sweden (59°51′N, 17°38′E), which is one of the regions with the largest share of energy forestry in the country (Statistics Sweden, 2013b).

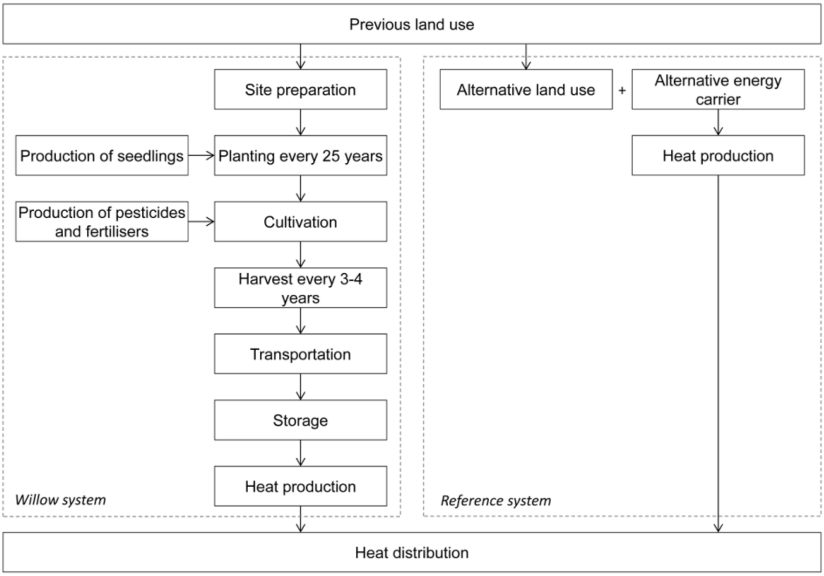

Fig. 4 Process flowchart describing the willow system established on agricultural land to produce district heating, and the reference system including an alternative land use and energy carrier. Dashed lines indicate system boundaries.

Seven scenarios were defined in Paper I to study the impact of productivity in terms of yield level and use of improved clones, previous land use and the effect of terminating willow cultivation (Table 1).

Table 1. *Description of the short-rotation coppice willow (SRCW) scenarios studied in Paper I (LU = land use, DM = dry matter)*

Name	Yield level (1st harvest, subsequent harvests) (Mg DM ha^{-1})	Coppice cycle (yr)	Previous land use	Time frame SRCW system (yr)
Base scenario	20, 30[a]	3	Green fallow	50
Previous LU1	20, 30[a]	3	Ley	50
Previous LU2	20, 30[a]	3	Annual Crops	50
Terminated cultivation	20, 30[a]	3	Green fallow	25 (followed by green fallow)
Improved clone	20, 30 (10% increase each rotation)	3	Green fallow	50
Low yield	10, 17[b]	4	Green fallow	50
High yield	30[c],42[d]	3	Green fallow	50

[a]Hollsten *et al.* (2013). [b]Mola-Yudego and Aronsson (2008). [c]Guidi *et al.* (2013). [d]Heller *et al.* (2003).

Three types of former agricultural land (green fallow, ley and annual crops) were assumed to be transformed into willow plantation. As the reference system, coal or natural gas was assumed to be used for producing the same amount of DH during the same period and green fallow was assumed as an alternative land use.

Production and application of mineral fertilisers and pesticides were included within the boundaries of the willow system. The amount of nitrogen (N) applied with fertilisers was based on the amount of N removed from the willow system through stem harvesting and leaching (Table 2).

Table 2. *Amount (kg ha^{-1}) of nitrogen applied with mineral fertilisers during each coppice cycle for three willow scenarios: Base, Low yield and High yield*

	Base scenario	Low yield	High yield
First coppice cycle	130	50	190
Subsequent coppice cycles	190	70	270

Emissions of N_2O from soil were calculated based on default values and were assumed to be released through three different pathways: (1) direct emissions from N application; (2) indirect emissions from N leaching; and (3) indirect emissions from ammonia volatilisation and re-deposition (Ahlgren *et al.*, 2009; IPCC, 2006). Nitrogen applied with residual biomass was handled in the same way as N applied with fertilisers. The amount of potassium (K) and phosphorus (P) was assumed according to Börjesson (2006).

4.1.2 Long-rotation forestry

In Paper II, the impact of extracting logging residues from one forest stand for bioenergy purposes was studied. The logging residues system included all processes from the forwarding of residues to the combustion of wood chips at a DH plant and the recycling of ash to recover nutrients (Fig. 5). Emissions and energy use taking place before and during final felling were allocated to the production of timber and pulp wood.

In the reference system, the alternative land management was defined as leaving the logging residues in the forest to decompose. The two fossil fuels coal and natural gas were assumed as alternative energy carriers. The same amount of heat was assumed to be produced as in the bioenergy systems.

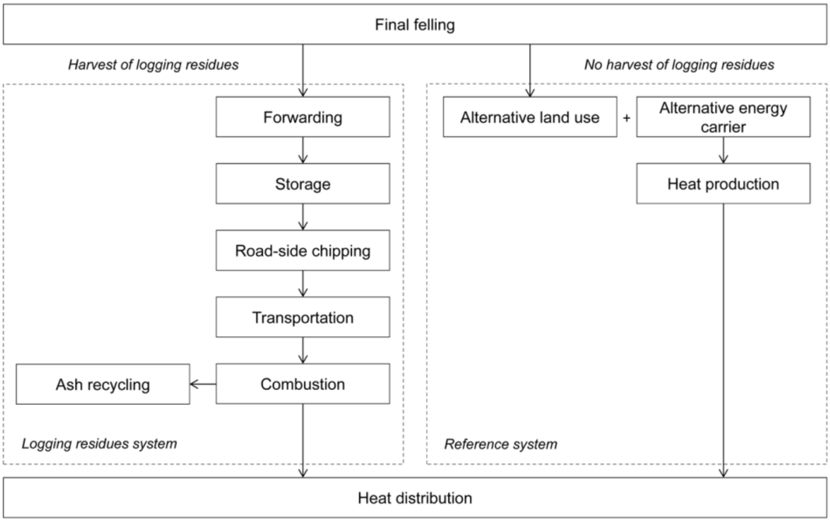

Fig. 5 Process flowchart describing the bioenergy system and corresponding reference system, *i.e*. harvesting or not harvesting logging residues (alternative land use). An alternative energy carrier for producing district heating was assumed in the reference system. Dashed lines indicate system boundaries.

Three forest scenarios were defined in Paper II based on forest location, with the aim of studying the impact of different climate conditions in three boreal vegetation zones (South, Central, North) in Sweden (Table 3). The three forest stands were assumed to be located in regions with varying growing conditions and decomposition rates, and varying transportation distances and forest sizes. The time frame was set to 50 years following final felling for all three forest stands.

Table 3. *Description of the South, Central and North forest scenarios studied in Paper II (DM = dry matter)*

Name	Vegetation zone	Region	Latitude	Yield level (Mg DM ha^{-1})	Rotation period (yr)
South	Hemiboreal	Jönköping	60° N	47.9	70
Central	Southern boreal	Dalarna	61° N	35.3	90
North	Northern boreal	Västerbotten	64° N	33.5	120

Soil N_2O emissions were assumed to be unaffected by the harvesting of logging residues, and were therefore not included in the analysis. Emissions factors for the production and distribution of the fossil fuels were assumed according to Uppenberg *et al.* (2001b) and the combustion-related emissions according to Paulrud *et al.* (2010).

4.2 Carbon balance modelling

The second phase of an LCA (*i.e.* life cycle inventory) involves collecting data for GHG fluxes, including SOC changes. For this, two types of carbon balance models were used; one adapted for arable land (ICBM) and one for forest soils (Heureka and Q model). The models were calibrated for Swedish conditions.

4.2.1 ICBM

The Introductory Carbon Balance Model (ICBM) was used in Paper I for modelling SOC changes. The model assumes that the carbon stored in plant litter first enters a young soil pool, where a fraction returns to the atmosphere while the rest moves on to an old soil pool. The fraction which enters the old pool is described by a humification factor. In addition, the young pool is separated into two sub-pools, one of which considers the carbon input from aboveground biomass (leaves and branches), while the other considers the belowground biomass (fine roots, coarse roots and stumps). The model incorporates external factors such as weather and soil type which affect the decomposition rate. The total SOC content is the sum of the old pool and the two young pools (Andrén *et al.*, 2004).

4.2.2 Heureka and Q model

In Paper II, the stand-wise version of the Heureka Forestry Decision Support System (Heureka) was used for modelling the living biomass of the forest stands (Wikstrom *et al.*, 2011). An updated version of the Q model was used for simulating the SOC changes, which included the decomposition of old organic material (Ortiz *et al.*, 2013; Rolff & Ågren, 1999). The county-wise calibration of the Q model was used for the parameterisation of each forest stand (Ortiz *et al.*, 2011).

The forest planning tool INGVAR was used to design a forest system representing conventional forest management of Norway spruce in Sweden (Jacobson, 2008). To represent the three chosen forest locations (scenarios South, Central and North in Paper II), average data on site productivity and understory vegetation were retrieved from the Swedish National Forest Inventory (SLU, 2014b) and the Swedish Forest Soil Inventory (SLU, 2014a).

4.3 Climate impact assessment

The third phase of an LCA involves assessing the environmental impacts of the studied system based on the life cycle inventory. In this thesis, the climate impact and energy performance were assessed. The climate impacts can be calculated using different climate impact indicators. The same time-dependent method for assessing the climate impact was used in Papers I and II.

4.3.1 Radiative forcing

The energy balance on Earth is described by the radiative forcing (RF), which is measured in Wm^{-2} at the top of the troposphere. GHGs have different characteristics, which makes them unevenly strong climate agents. The magnitude of impact a particular GHG has on the energy balance is described by its radiative efficiency, which measures the impact of one unit change in the atmospheric concentration of the gas on the energy balance (IPCC, 2007). The radiative efficiency (ΔF) is calculated based on the background concentration of the gas in ppmv (parts per million by volume) (Table 4). The radiative efficiency of gas x can be converted from volume (ΔF_v) to mass, measured in kg gas (ΔF_m), by:

$$\Delta F_m = \Delta F_v \cdot \left(\frac{M_A}{M_x} \cdot \frac{10^6}{T_M}\right) \quad (1)$$

where M_A is the mean molecular weight of air (28.96 kg $kmol^{-1}$), M_x is the molecular weight of gas x and T_M is the total weight of the atmosphere ($5.15 \cdot 10^{18}$ kg) (Shine *et al.*, 2005) (Note: ΔF can also be referred to as RE or A_x).

Table 4. *Radiative efficiency (ΔF) of carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) after a unit change in the atmospheric concentration by volume (ΔF_v) and mass (ΔF_m). Calculated based on background concentrations from Hartmann (2013). Values for CH_4 include indirect effects on tropospheric and stratospheric ozone and stratospheric water vapour. (ppmv = per parts per million by volume)*

	ΔF_v (Wm^{-2} $ppmv^{-1}$)	ΔF_m (Wm^{-2} kg^{-1})
CO_2	0.01	$1.76 \cdot 10^{-15}$
CH_4	0.60	$2.11 \cdot 10^{-13}$
N_2O	3.0	$3.85 \cdot 10^{-13}$

GHGs have different perturbation lifetimes, *i.e.* the time before they decay in the atmosphere. The RF of gas x is described by:

$$RF_x = \Delta F_{m_x} \cdot R_x \tag{2}$$

where R_x is the fraction of gas x still remaining in the atmosphere after a unit emission. The yearly RF of a pulse emission will thus change over time as the gas is decaying. For N_2O and CH_4, the perturbation lifetime is based on simple decay functions (Joos *et al.*, 2013; Myhre *et al.*, 2013a), while the CO_2 decay function is more complex since the gas does not decay chemically in the atmosphere (Fig. 6). Instead, CO_2 is taken up by oceans and the terrestrial biosphere and the atmospheric lifetime also depends on future CO_2 concentrations (Cherubini *et al.*, 2011). The perturbation lifetime of CO_2 was modelled by the Bern carbon cycle model in Papers I and II (Joos *et al.*, 2001).

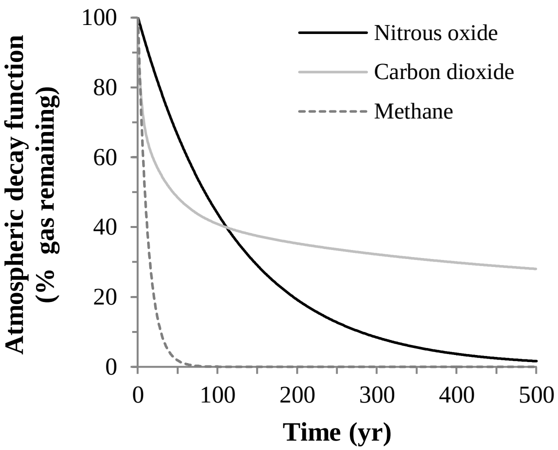

Fig. 6 Fraction remaining in the atmosphere after pulse emission of nitrous oxide, carbon dioxide and methane at year zero, calculated based on Myhre *et al*. (2013a).

The cumulative radiative forcing (CRF) of gas x is expressed as the integrated RF during the time horizon H due to a pulse emission of the gas at year zero:

$$CRF_x = \int_0^H RF_x(t) \tag{3}$$

Cumulative radiative forcing is also referred to as the absolute global warming potential (AGWP).

4.3.2 Global warming potential

Global warming potential (GWP) is a climate metric commonly used in LCA to assess climate impact (Cherubini & Strømman, 2011). The metric describes the radiative efficiency of a gas relative to CO_2. The AGWP of gas x is described in the same way as the CRF:

$$AGWP_x = CRF_x \tag{4}$$

The GWP of gas x is the AGWP for that gas relative to the AGWP for CO_2 during time horizon H (Joos *et al.*, 2013):

$$GWP_x(H) = \frac{AGWP_x(H)}{AGWP_{CO_2}(H)} \tag{5}$$

The GWP is measured in CO_2-eq and commonly calculated based on a 100-year time frame (denoted GWP_{100}). According to the latest Intergovernmental Panel on Climate Change (IPCC) report, the GWP_{100} for CO_2, CH_4 and N_2O is 1, 28 and 265, respectively (Myhre *et al.*, 2013b).

4.3.3 Temperature response

The CRF does not consider the inertia of the Earth, *i.e.* delays in climate processes which mean that the climate does not change immediately when the radiative balance is altered. These delays can be taken into account using a temperature response function. The temperature response (ΔT_s in Papers I and II), referred to as absolute global temperature potential (AGTP) by the IPCC, is described by:

$$AGTP_x(H) = \int_0^H RF_x(t) R_T(H - t) dt \tag{6}$$

i.e. a convolution between the RF and the climate response function (R_T) due to a unit change in RF from a pulse emission of gas x (Myhre *et al.*, 2013a). The surface temperature response ΔT_s of a unit change in RF due to pulse emissions of CO_2, N_2O and CH_4 is dependent on the perturbation lifetime of the gases (Fig. 7).

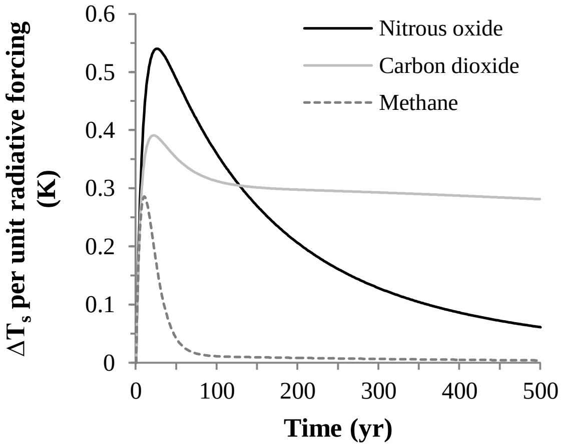

Fig. 7 Surface temperature response (ΔT_s) after a pulse emission of 3 Pg nitrous oxide, 570 Pg carbon dioxide and 5 Pg methane leading to one unit change in radiative forcing (1 Wm^{-2}), calculated based on Myhre *et al*. (2013a) and Joos *et al*. (2013).

4.4 Energy Performance

The energy performance of the bioenergy systems was determined by the energy ratio (ER), which is defined as the ratio between the energy output (E_{out}) and the primary energy use (E_{in}) (Djomo *et al.*, 2011):

$$\mathrm{ER} = \frac{E_{out}}{E_{in}} \tag{7}$$

The energy output depends on the heating value and the moisture content of the biomass and the efficiency of the combustion process. It is also dependent on whether latent heat lost by water vaporisation can be recovered by flue gas condensation.

Flue gas condensation was assumed in Papers I and II by using two different approaches. In the willow system, a higher heating value (HHV) of 19.9 MJ per kg DM was assumed to include latent heat recovery. In the logging residues system, a lower heating value (LHV) on a dry weight basis of 19.2 MJ per kg DM was assumed (Lindholm *et al.*, 2010; Paulrud *et al.*, 2010) and, to account for flue gas condensation, the conversion efficiency was set to 106% (Uppenberg *et al.*, 2001a). The LHV was adjusted for a moisture content (MC) of 45%.

5 Results and discussion

5.1 Biogenic carbon dynamics

5.1.1 Short-rotation forestry

In Paper I, the climate impact of growing willow on agricultural land was assessed. The establishment of the willow plantation on former green fallow land increased the SOC content, since more carbon entered the soil pool from leaf litter and root turnover (Fig. 8a). This effect was enhanced by the assumption of a higher yield level (~50% higher), since the carbon input from both aboveground and belowground biomass was increased (Fig. 8c). As a result, more carbon was stored in the soil and more energy was gained from higher harvest levels, which was able to replace more fossil energy. A low yield (~50% lower) showed the opposite effect and released carbon from the soil to the atmosphere (Fig. 8b). However, using willow for bioenergy instead of the two fossil alternatives coal or natural gas was shown to be a better climate mitigation option, irrespective of yield level.

When willow was assumed to be established on land formerly used for annual crops or ley (instead of green fallow), the outcome was only affected to a small degree. These two alternative previous land uses gave a higher initial SOC content and consequently the SOC increase from planting willow was lower. However, this difference was found to be marginal.

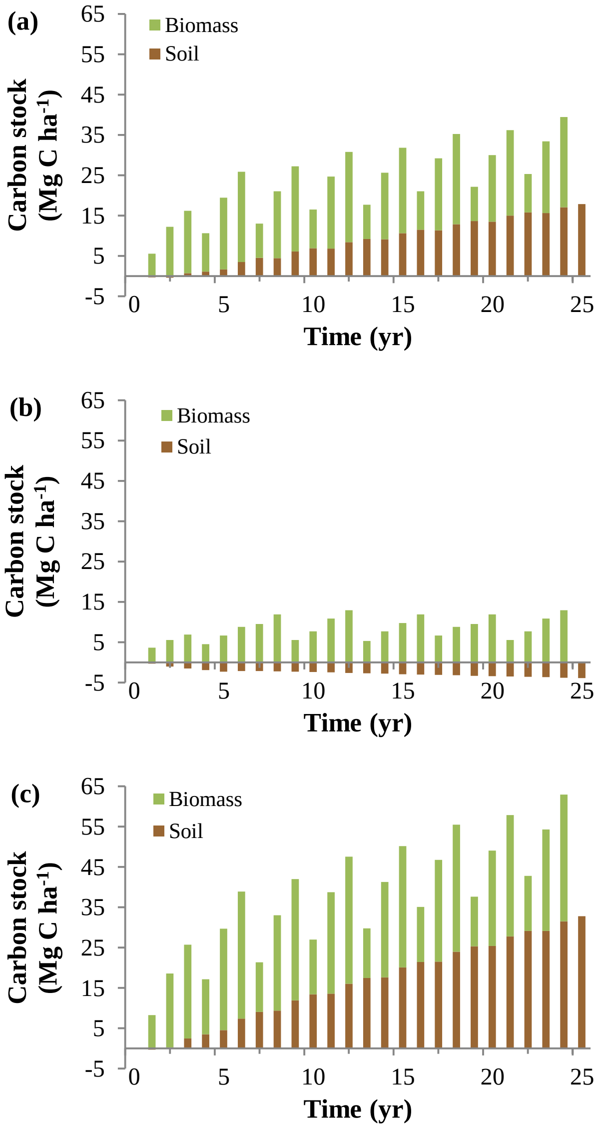

Fig. 8 Carbon (C) stored in willow biomass (stems, leaves, roots) and soil each year during 25 years of cultivation on agricultural land previously used as green fallow in (a) the Base scenario, (b) the Low yield scenario and (c) the High yield scenario. Net change compared with baseline year zero (previous land use), *i.e.* negative values indicate decreased carbon stock and positive values increased carbon stock compared with the previous land use. Carbon in litter was assumed to enter the soil pool with a one-year delay.

When willow cultivation was assumed to be terminated after one rotation period (25 years) and the land converted back to green fallow, the sequestered carbon in the soil was slowly released back to the atmosphere (Fig. 9). However, the SOC content was still above the initial level 75 years after termination of the willow plantation.

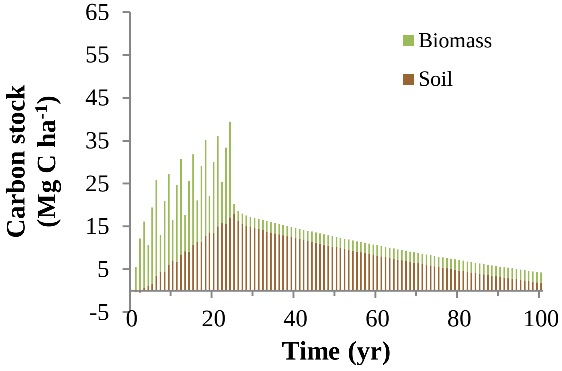

Fig. 9 Carbon (C) stored in standing willow biomass and soil (years 1-25) followed by green fallow (years 26-100) (terminated cultivation scenario in Paper I). Dead biomass was assumed to enter the soil pool with a one-year delay.

5.1.2 Long-rotation forestry

In Paper II, logging residues from managed forests were assumed to be either extracted and combusted for energy or left in the forest to decompose. When the residues were assumed to be combusted, the biogenic carbon stored in the biomass was released immediately, while when the residues remained in the forest, the biogenic carbon was released to the atmosphere over a longer period. The length of this period was found to be dependent on the geographical location of the forest stand (Fig. 10).

The accumulated biogenic carbon emissions when harvesting logging residues (compared with not harvesting) were smallest in the South climate zone of Sweden (2.0 Mg C ha^{-1} difference) (Fig. 10a). In the Central (Fig. 10b) and North zones (Fig. 10c), the difference between harvesting and not harvesting was higher (2.9 and 3.1 Mg C ha^{-1}, respectively).

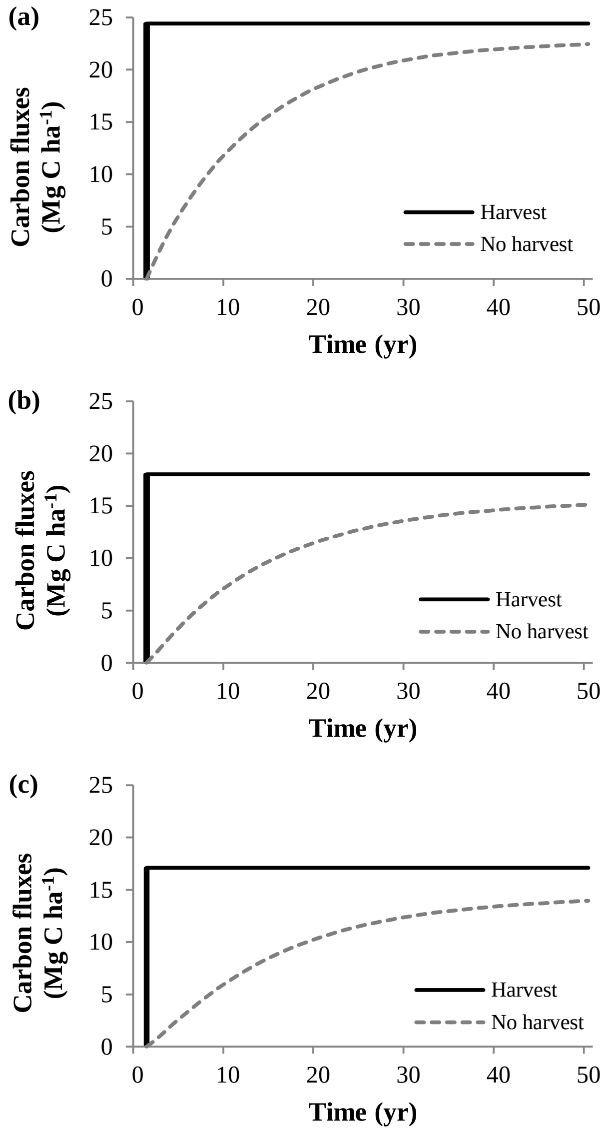

Fig. 10 Accumulated biogenic carbon (C) emissions entering the atmosphere when logging residues were harvested (Harvest, = biomass combustion) or not harvested (No harvest, = litter decomposition) in the (a) South, (b) Central and (c) North zones of Sweden during 50 years following final felling.

The difference in timing of CO_2 emissions between combustion and decomposition was shortest in the South zone of Sweden. In the colder regions of Sweden (Central and North forest stands), the remaining forest biomass worked as a carbon sink for a longer time when the residues were not harvested. However, leaving the logging residues meant that an alternative energy carrier had to be used, which in this case was assumed to be coal or natural gas.

5.2 Global warming potential

5.2.1 Short-rotation forestry

The global warming potential of the willow production system was about 10 g CO_2-eq per MJ heat (base scenario), including all emissions of non-biogenic GHGs (Table 5). The carbon sequestration effect gave a negative GWP (-15 g CO_2-eq per MJ heat) when considering only the biogenic carbon fluxes from the willow plantation. The total GWP of the willow system was thus about -5.0 g CO_2-eq per MJ heat. However, when the difference between the willow cultivation and the alternative land use (green fallow) was included, the GWP was slightly lower, since the reference land use released CO_2 (around 2.3 g CO_2-eq per MJ heat) during the 50-year time frame.

Table 5. *Global warming potential (GWP, g CO_2-eq MJ^{-1} heat) of the willow system (Base scenario, Paper I) calculated based on accumulated greenhouse gas fluxes during a 50-year time frame. The production chain includes greenhouse gas emissions from all processes included in the system boundaries, excluding biogenic carbon from litter decomposition, soil organic carbon changes and biomass combustion*

	Willow system	Reference system I Coal	Reference system II Natural gas
Production chain	10	150	60
Biogenic carbon	-15	2.3	2.3

The lowest GWP was found for the high willow yield scenario (-9 g CO_2-eq per MJ heat), while the low yield scenario gave the highest GWP (18 g CO_2-eq per MJ heat), including SOC changes in the willow system.

5.2.2 Long-rotation forestry

The global warming potential of the production chain for harvesting logging residues was around 3.4 g CO_2-eq per MJ heat (South forest scenario, Paper II) (Table 6). Harvesting logging residues released more biogenic carbon than the reference case of not harvesting (10 g CO_2-eq per MJ heat difference) during the 50 years following final felling.

Table 6. *Global warming potential (GWP, g CO_2-eq MJ^{-1} heat) of the logging residues system (South scenario, Paper II) calculated based on accumulated greenhouse gas fluxes during a 50-year time frame. The production chain includes greenhouse gas emissions from all processes included in the system boundaries, excluding biogenic carbon from litter decomposition, soil organic carbon changes and biomass combustion*

	Logging residues system	Reference system I Coal	Reference system II Natural gas
Production chain	3.4	150	60
Biogenic carbon	340	330	330

The Central and North forest stands gave similar GWPs for the production chain as the South forest stand. However, the difference in biogenic carbon between harvesting and not harvesting logging residues was higher (about 20 g CO_2-eq per MJ heat).

5.3 Time-dependent temperature change

5.3.1 Short-rotation forestry

The soil carbon dynamics in the willow plantations (Fig. 8) showed net uptake of carbon in the base scenario and the high yield scenario, and net loss of carbon in the low yield scenario. The SOC changes were found to have a strong influence on the overall climate impact of the bioenergy systems and the CO_2 uptake due to carbon sequestration even exceeded the GHGs emitted in the production chain, which gave a cooling effect (Fig. 11a).

In addition to the climate benefit of sequestering carbon in the soil, higher yield was also able to replace larger quantities of fossil fuel, enhancing the mitigation potential of substituting fossil fuel with willow chips. The largest substitution effect was achieved when replacing coal (Fig. 11b), followed by natural gas (Fig. 11c).

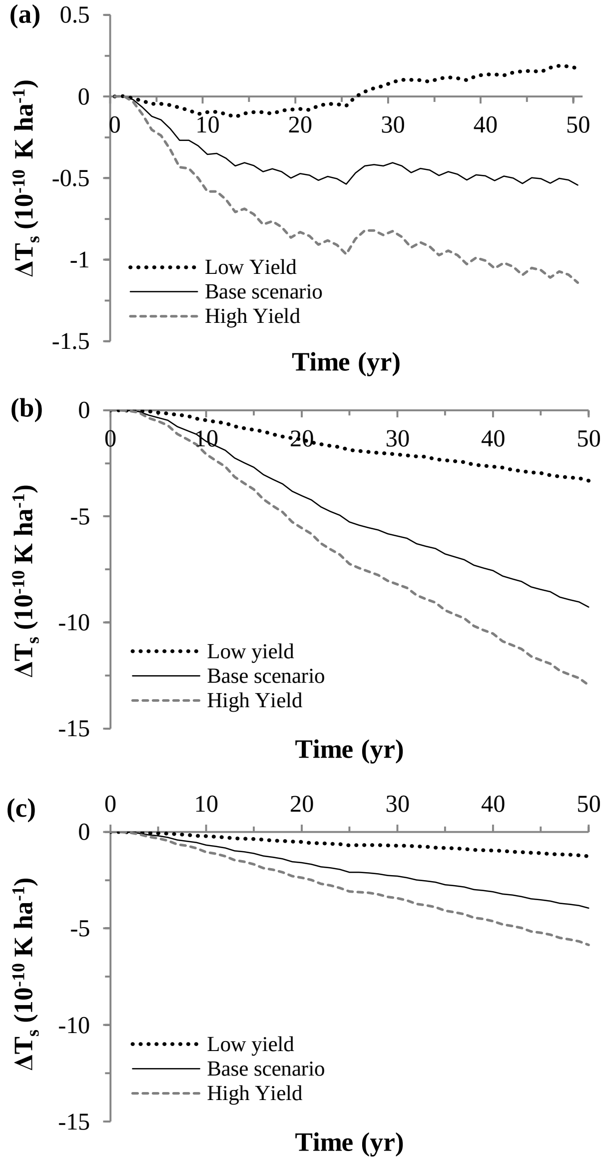

Fig. 11 Time-dependent temperature change (ΔT_s) for three assumed willow yield levels (Low yield, Base and High yield scenarios in Paper I) (a) including all processes in the willow production chain, soil organic carbon changes and emissions related to biomass combustion (excluding substitution effects), (b) the substitution effect on replacing coal and (c) the substitution effect on replacing natural gas. Note different scale in (a).

5.3.2 Long-rotation forestry

When only biogenic carbon fluxes were considered, harvesting forest biomass initially gave high temperature responses at all three forest locations compared with the reference scenario of not harvesting (Fig. 12). The warmer climate in southern Sweden gives better productivity and faster litter decomposition compared with central and northern Sweden, which have a colder climate and shorter growing season. Consequently, more biomass can be extracted in southern parts of the country. Since more biomass was extracted in the South scenario, the temperature response from biomass combustion was also higher per hectare compared with the Central and North scenarios. In the case of not harvesting, the South forest stand also emitted more CO_2 from litter decomposition. The difference in warming potential between harvesting and not harvesting logging residues was thus smallest in the South.

Paper II showed that harvesting logging residues for bioenergy gave a lower climate impact compared with leaving the biomass in the forest and instead using coal or natural gas for energy. Replacing coal gave a direct cooling effect, while replacing natural gas gave a temperature cooling effect after 15-20 years depending on forest location (Fig. 13).

The climate impact of using logging residues for energy can be calculated based on different functional units, *e.g.* per hectare of forest land or per unit of energy. The climate benefits of harvesting residues in the South of Sweden compared with the North were higher on a per hectare basis than on an energy basis (Fig. 13). This was due to the higher biomass extraction level and faster decomposition when the biomass remained in the forest. An energy-based functional unit may be more relevant when studying residual biomass, since the primary forest biomass (used in the pulp and paper industry and the sawmill industry) will be produced from the land regardless of whether the logging residues are extracted or not.

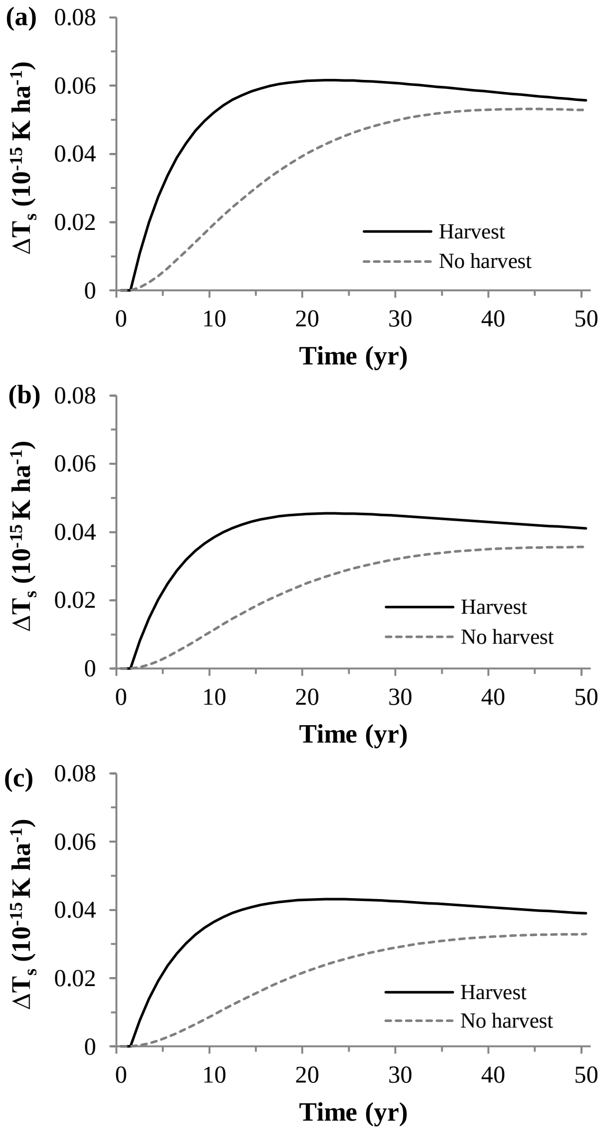

Fig. 12 Time-dependent temperature change (ΔT_s) when logging residues were harvested (Harvest = combusted) or not harvested (No harvest = decomposed) in (a) South, (b) Central and (c) North Sweden (Paper II) during 50 years following final felling.

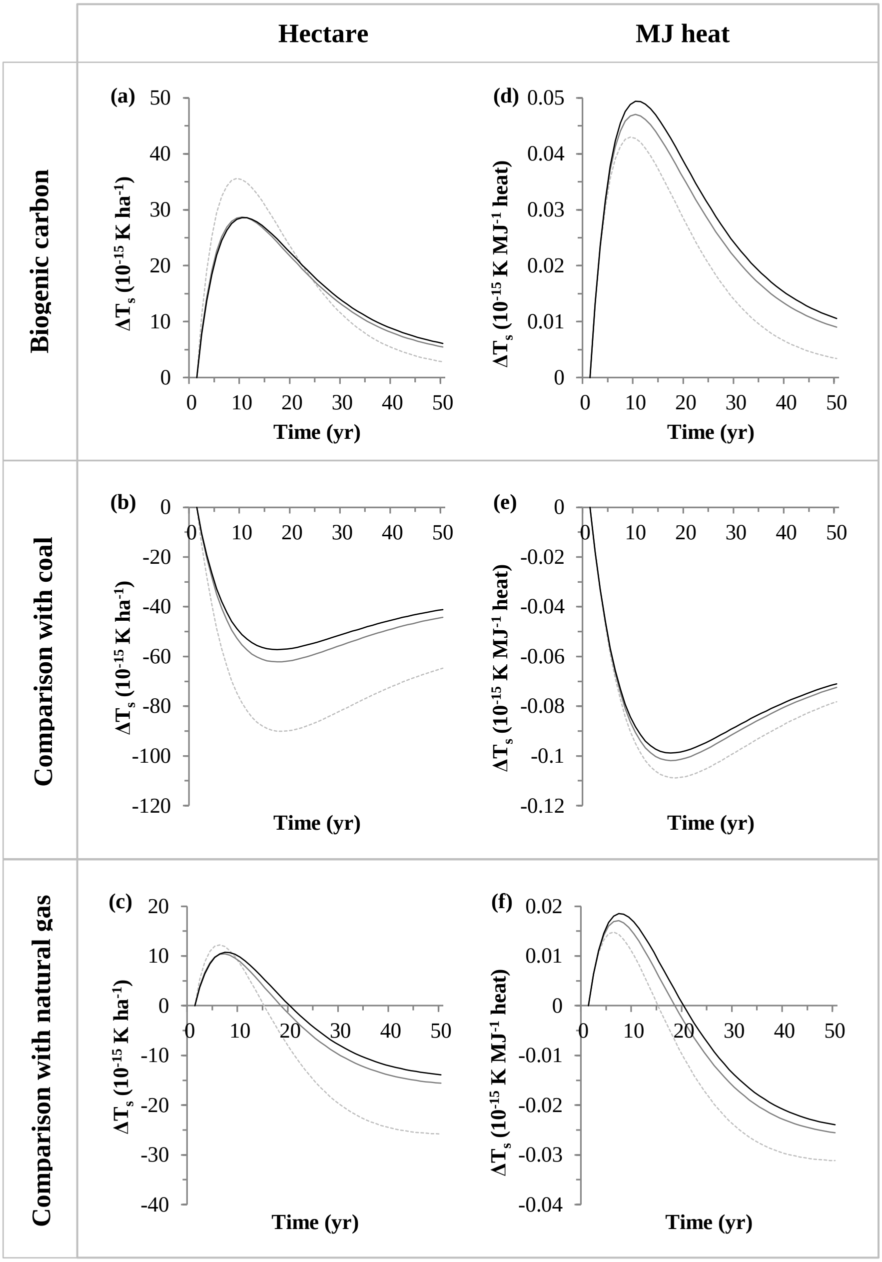

Fig. 13 Time-dependent temperature change (ΔT_s) when logging residues were harvested in South (----), Central (——) and North (——) Sweden. Difference between harvesting and not harvesting, calculated based on two functional units; per hectare (a-c) and per MJ district heating produced (d-f). (a, d) Only including

emissions of biogenic carbon, (b, e) the temperature effect when coal was replaced and (c, f) the temperature effect when natural gas was replaced (Paper II)

5.4 Energy ratio

The energy performance assessment showed that the energy ratio was higher for the forest systems than the willow systems (Table 7), *i.e*. less energy was needed for converting forest biomass into DH compared with willow, which requires more energy for machinery and production of inputs (*e.g*. fertilisers).

Table 7. *Energy ratio (ER) of bioenergy systems (MJ MJ^{-1})*

	ER
Willow (low yield, base scenario, high yield)	20, 26, 27
Logging residues (south, central, north)	45, 44, 43

Depending on growing conditions and management, the amount of land used for producing the same amount of biomass varied in both bioenergy systems. The land required for producing one GJ of DH from logging residues depended on the geographical location of the forest, with more land being needed in northern Sweden due to lower productivity and a longer rotation period.

5.5 General discussion

5.5.1 Impact of site-specific conditions

Growing willow on unused arable land has been suggested as a climate mitigation strategy. Paper I confirmed that willow cultivation has the potential to bind carbon from the atmosphere that outweighs the GHGs released in the production chain, and thereby provide climate benefits. However, the carbon sequestration effect was shown to be dependent on stand productivity, with low willow yield possibly resulting in decreased carbon stocks. Soil conditions vary depending on site and can be important for willow productivity (Alriksson, 1997), since poor soil quality has been cited as one possible reason for low willow yields in the past (Dimitriou *et al.*, 2011). If marginal land with low soil quality is used for willow cultivation, the soil carbon sequestration effect may be non-existent. However, using fertile land could potentially displace food production, which can lead to indirect land use changes and potentially undesirable climate effects elsewhere. Obtaining high yield is not only important from a climate perspective, but is also crucial for the profitability of willow production (Lindroth & Båth, 1999). Drawing general conclusions from a study based on site-specific data is problematic, but the results can highlight important factors. Paper I showed that irrespective of the soil carbon sequestration effect, all willow systems had a climate mitigation effect compared with the two fossil energy systems, coal and natural gas.

In Paper II, regional differences in the biogenic carbon cycle were shown to influence the overall temperature response. Lamers and Junginger (2013) concluded that regional differences in the biogenic carbon cycle add complexity to policy making. However, Paper II showed relatively small geographical differences per unit energy produced.

5.5.2 Soil N_2O emissions

An uncertain factor when modelling GHG emissions from willow cultivation is N_2O emissions from soil. For instance, previous studies of willow have shown that the amount of N leached from willow plantations is comparatively low (Dimitriou *et al.*, 2012; Heller *et al.*, 2003), which means that the indirect N_2O emissions from N leaching could have been overestimated in Paper I. However, the sensitivity analysis performed in Paper I showed that the indirect N_2O emissions from N leaching and the direct emissions from N application only affected the overall climate impact to a small degree.

One potential uncertainty in Paper II was the omission of N_2O emissions from forest soil. The N_2O losses from forest soils are generally lower than those from agricultural soils, since the latter commonly use the most productive soils. It is not clear how harvesting of logging residues will affect the N_2O emissions from soil (Swedish Energy Agency, 2009), which makes it difficult to include such emissions in an LCA.

5.5.3 Fossil reference system

In Papers I and II, the climate impact of fossil reference systems based on natural gas and coal were compared with that of the two bioenergy systems. Natural gas has a lower climate impact than coal due to differences in chemical composition. Natural gas also generates less GHG emissions than logging residues during combustion. However, the biogenic CO_2 released by combusting the logging residues would also be released by decomposition in the case of not harvesting. This was demonstrated in Paper II, where the climate benefits of logging residues compared with natural gas were delayed by 15-20 years, while the climate benefits compared with coal were immediate.

The sensitivity analysis performed in Paper II showed that the emissions factors used for the fossil fuels have a relatively high impact on the climate benefits of the bioenergy system. There are variations in the composition of both natural gas and coal. In this thesis, emission factors based on conventional natural gas were used. Unconventional natural gas (*i.e.* shale gas) generates higher GHG emissions (Howarth *et al.*, 2011), which may shorten the delay in climate benefits. There are also different types of coal, among which brown coal generates higher GHG emissions than *e.g.* bituminous coal (Hayhoe *et al.*, 2002). Published emissions factors for coal generally do not specify which type of coal the calculations are based on, which adds uncertainty to the assessment.

5.5.4 Methodological choices

Including biogenic carbon fluxes in LCAs have been shown to be important for the overall results, as also shown in this thesis. Depending on the system boundaries, different parts of the carbon cycle may be accounted for. In Paper I, both the uptake and the release of carbon were included, while in Paper II only the release of carbon was considered. This was because Paper I studied primary crop production, while Paper II only studied the use of residual biomass. The carbon uptake due to tree growth was therefore allocated to the timber and pulp wood production.

The choice of functional unit has importance for the interpretation of the results. In Paper II, the two functional units used (hectare and energy output) influenced the result of the analysis, especially in a short time frame. For that reason, it is important to choose a functional unit suited to the aim of the study, and to be aware of the variety of possible interpretations.

Global warming potential is commonly used as a climate impact indicator in LCA. However, attention has been drawn to several disadvantages with the climate metric, *e.g.* the risk of misinterpretation by policymakers, the use of arbitrary time horizons and the omission of the time aspect (Fuglestvedt *et al.*, 2003). If only GWP had been used in this thesis, the temporal dynamics of the biogenic carbon cycle would have been overlooked. In Paper II, the GWP of logging residues was lower than that of natural gas and the delayed climate benefit was not revealed, whereas it was revealed when using the temperature change metric. The temperature change metric thus has advantages when assessing bioenergy from long-rotation forestry.

Using temperature change as the climate metric also takes into account delays in climate processes due to the inertia of the Earth. Zetterberg and Chen (2014) found that using temperature change as the climate metric added around five years to the payback time (compared with using cumulative radiative forcing) of logging residues relative to natural gas. However, one disadvantage with using temperature change is that adding one more calculation step in the climate model also increases the uncertainty level. GWP can thus be useful in some cases, for instance when only assessing the impact of different production chains where the emissions are released on a yearly basis. It can also be useful for discovering emission hotspots.

The two papers included in this thesis were performed using an attributional LCA approach, which do not consider the potential indirect effects arising from increased consumption of bioenergy. To assess the overall implication of a higher biomass extraction level, a consequential LCA approach may be more relevant. However, the bioenergy systems studied in this thesis were assumed to utilise land or biomass that was currently not being used, *i.e*. there were no indirect land use changes. However, an increased share of bioenergy could lead to other indirect effects, *e.g*. loss of nutrients and a subsequent decline in future productivity, or competition for biomass with the forest industry.

6 Conclusions

The main conclusions regarding short-rotation forestry are as follows (Paper I):

- Growing willow on former arable land has the potential to increase the carbon content in both aboveground and belowground biomass and thereby give a cooling temperature effect
- The magnitude of this carbon sequestration effect is highly dependent on willow stand productivity, which makes management of the willow plantation important
- The carbon sequestration effect is temporary, so terminating willow cultivation may release the captured carbon back to the atmosphere. However, both the short-term and long-term effects are still beneficial for mitigating climate change.

The main conclusions regarding long-rotation forestry are as follows (Paper II):

- Bioenergy from logging residues has a lower climate impact than the fossil fuel alternatives coal (direct mitigation effect) and natural gas (delayed mitigation effect)
- Faster decomposition rates in southern Sweden give a shorter time lag until the bioenergy system achieves climate benefits compared with natural gas
- There are relatively small regional differences between forest sites in the south, centre and north of Sweden in terms of climate impact per unit of energy produced.

The overall conclusions of the work reported in this licentiate thesis are that:

- Using a time-dependent climate metric in an LCA is a useful way of capturing the temporal dynamics effects of biogenic carbon fluxes between soil, biomass and atmosphere in both a short-term and long-term perspective
- If only GWP had been used as a climate metric, the delayed climate effects observed in this thesis would not have been revealed.

7 Future research

Converting the fossil fuel-dependent society we have today towards a more biobased economy may require more efficient bioenergy systems. The resulting higher demand for biomass could lead to intensified forest management in the future. Different aspects of forest management should therefore be the subject of further study, *e.g.* the impact of shorter rotation periods, increased harvesting levels, fertilisation or afforestation of unused land.

Land use changes due to increased bioenergy extraction can influence the Earth's climate system in more ways than releasing greenhouse gases. Altering the land cover may also cause changes in albedo (reflected solar radiation) and perturb the evapotranspiration (latent heat flux) (Levasseur *et al.*, 2012; Müller-Wenk & Brandão, 2010). These two aspects may be relevant to include in LCA of bioenergy systems.

Another uncertain factor is N_2O emissions from forest soils and how harvesting logging residues might affect these emissions. Incorporating N_2O modelling in LCA of forest soil would be useful.

To draw more general conclusions that could be used for policy making, a wider perspective that includes indirect effects of land use changes and market effects should be used. This could be done by applying a consequential LCA perspective on a larger scale.

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