Climate Impacts of Woody Biomass Use for Heat and Power Production in Sweden

Torun Hammar
Faculty of Natural Resources and Agricultural Sciences
Department of Energy and Technology
Uppsala

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Abstract

Global warming is a result of human-induced greenhouse gas emissions, primarily from fossil fuel use, but also from land use changes. To mitigate climate change, fossil fuel-based energy systems need to be replaced with alternative energy sources. Here bioenergy can play an important role, since this renewable fuel is considered to be carbon-neutral, meaning that no extra carbon dioxide (CO_2) is emitted to the atmosphere.

However, carbon-neutral is not the same as climate-neutral and, while the CO_2 from biomass use was once, and will again, be captured during plant growth, the temporary imbalance in the atmosphere can have consequences for the climate. Furthermore, bioenergy supply chains generally consume fossil fuels and producing biomass for energy requires land, which can lead to carbon stock changes.

This thesis examined the climate impact and energy performance of bioenergy from short-rotation coppice willow and long-rotation forest residues. Willow is a dedicated energy crop grown on agricultural land for energy, while forest residues (tops, branches and stumps) are a by-product harvested after final felling in conventional forests. A time-dependent life cycle assessment (LCA) method was used to capture the timing of greenhouse gas fluxes, including biogenic carbon (carbon stored in biomass and soil). In addition, a new method that combines time-dependent LCA with GIS mapping, and thus assesses the climate impact over a landscape, was developed.

The results showed that growing willow on former fallow land can give a negative climate impact (cooling effect) by sequestering carbon from the atmosphere in biomass and soil and by achieving high productivity, which is important for the final outcome. Initial soil organic carbon content was shown to have a large influence on future carbon stocks. Harvesting forest residues for energy gave a higher climate impact than harvesting willow, with forest stumps giving a slightly higher climate impact than tops and branches. Moreover, forest residues harvested in northern Sweden gave a slightly higher climate impact than forest residues harvested in the south. All bioenergy feedstocks studied gave a lower climate impact than hard coal and natural gas over time and the climate benefit of replacing these fossil fuels increased over time when studying continuous energy outtake (landscape perspective).

Keywords: bioenergy, LCA, willow, forest residues, temperature change, soil organic carbon, land use change, GIS

Author's address: Torun Hammar, SLU, Department of Energy and Technology,
P.O. Box 7032, 750 07 Uppsala, Sweden
E-mail: Torun.Hammar@slu.se

Allt stort som skedde i världen skedde först i någon människas fantasi.
Astrid Lindgren

Imagination is the highest form of research.
Albert Einstein

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.

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. *BioEnergy Research* 8(4), 1912-1924.

III Ortiz, C.A., Hammar, T., Ahlgren, S., Hansson, P.-A. & Stendahl, J. (2016). Time-dependent global warming impact of tree stump bioenergy in Sweden. *Forest Ecology and Management* 371, 5-14.

IV Hammar, T., Hansson, P.-A. & Sundberg, C. (2017). Climate impact assessment of willow energy from a landscape perspective: a Swedish case study. *GCB Bioenergy* 9(5), 973-985.

Papers I-IV are reproduced with the permission of the publishers.

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

I Developed the scenarios together 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 the manuscript with input from the co-authors.

III Prepared the life cycle inventory, performed the climate impact calculations and contributed to interpretation of the results. Assisted in writing the manuscript together with the co-authors.

IV Planned the study and scenarios in cooperation with the co-authors. Developed the simulation model and performed the calculations. Prepared the data presentation (figures and tables) and wrote the manuscript with input from the co-authors.

Abbreviations

AGTP	Absolute global temperature change potential
AGWP	Absolute global warming potential
CHP	Combined heat and power
CRF	Cumulative radiative forcing
DH	District heating
DM	Dry matter
ER	Energy ratio
GHG	Greenhouse gas
GIS	Geographical information system
GWP	Global warming potential
ha	Hectare (10^4 m^2)
HHV	Higher heating value
ICBM	Introductory carbon balance model
iLUC	Indirect land use changes
kWh	Kilowatt hour (3.6 MJ)
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

Climate change mitigation is one of today's greatest challenges, as noted in both research and policy discussions. There is consensus among the majority of researchers that the climate is warming and that the cause is human-induced greenhouse gas (GHG) emissions, primarily from fossil fuel use, but also as a result of land use change (Ciais *et al.*, 2013).

How to mitigate climate change has been debated intensively, and has resulted in *e.g.* the 'Paris agreement', where the member countries of the United Nations Framework Convention on Climate Change agreed on the urgent need to reduce GHG emissions in order to keep the global temperature rise below 2 °C and suggested that efforts should be made to keep the temperature rise to a maximum of 1.5 °C, compared with the pre-industrial age (UNFCCC, 2015). Several other energy and climate change mitigation targets have been adopted worldwide. In the European Union (EU), the renewable energy directive (RED) states that emissions of GHGs should decrease by 20% and that the amount of renewables should be 20% by 2020 (compared with 1990). The targets for 2030 and 2050 are higher and the ultimate goal is to have a 'carbon-neutral' society (European Commission, 2013).

Interest in bioenergy has intensified in recent decades due to increasing awareness of climate change issues and the ambition to decrease dependency on fossil fuels. Bioenergy is one option for a 'carbon-neutral' energy source, since the carbon dioxide (CO_2) released to the atmosphere through combustion was once, and will again, be taken up by plants through photosynthesis. The atmospheric lifetime of so-called 'biogenic carbon' is therefore much shorter than that of carbon originating from fossil energy that has formed over millions of years. Combustion of fossil fuels consequently adds additional CO_2 to the atmosphere, which has a warming effect on the climate. Bioenergy has the advantage that it only takes a year (annual crops), a few years (perennial energy crops) or around a hundred years (forest) to regrow, *i.e.* to remove CO_2 from the atmosphere.

Concerns regarding bioenergy have been raised, however. The production, distribution and use of biomass for energy emit more GHG emissions than solely the carbon stored in the biomass, since fossil fuels are consumed in the bioenergy supply chain. The use of land also strongly affects the GHG balance, both by affecting soil carbon stocks and through soil emissions from application of fertilisers. Furthermore, the time difference between uptake and release of biogenic carbon perturbs the atmospheric concentration of CO_2 for a certain time frame, which has implications for the climate.

To assess the climate impacts of bioenergy compared with fossil energy, a system perspective that considers the above-mentioned aspects is required. One method commonly used is life cycle assessment (LCA), which is a standardised method for assessing the environmental impacts of a product or service during its whole lifespan (ISO 14040, 2006; ISO 14044, 2006). This method is often applied to complex systems, even though the standard does not state how to handle issues such as land use change or biogenic carbon fluxes.

One more complexity with assessing the climate impact of bioenergy systems is the choice of spatial scale. Biomass production systems can vary greatly depending on geographical location (due to *e.g.* transport distances or prevailing climate) and site-specific conditions (*e.g.* soil texture and previous land use). Moreover, biomass production systems can vary greatly in harvest interval (*i.e.* rotation time). As a consequence, such systems can be assessed from two different perspectives: stand level (*i.e.* one field or forest stand) and landscape level (*i.e.* several fields or stands, which are harvested continuously for a yearly energy outtake).

In order to meet future climate and energy targets, alternative energy sources to fossil fuels are needed, for which bioenergy can play an important role. However, a better understanding is needed of how different types of bioenergy systems (*e.g.* short- and long-rotation forestry) affect the climate, both in terms of temporal aspects, *i.e.* timing of GHG fluxes (especially biogenic carbon) and spatial aspects, *i.e.* the scale (stand or landscape perspective), but also regarding the spatial variations within a landscape. Knowledge of these aspects can facilitate decision making by helping to identify types of bioenergy systems that should be prioritised to fulfil future energy demands while giving the highest climate change mitigation potential.

2 Aim and structure

2.1 Overall aim

The overall aim of this thesis was to improve understanding of the effects of increased domestic bioenergy supply in Sweden, in terms of climate impact and energy efficiency. The focus was on woody biomass used for heat and power production. Specific objectives were to analyse:

- The temporal climate impact when agricultural land is used for growing willow energy, with the focus on carbon fluxes between soil, biomass and atmosphere, the influence of willow productivity and the effect of terminating willow cultivation on the climate impact (Paper I).
- The temporal climate impact when extracting forest residues (tops, branches and stumps) for bioenergy, with the focus on carbon fluxes between soil, biomass and atmosphere, and the influence of different productivity and decomposition rates in different geographical regions (Papers II and III).
- The climate impact from a landscape perspective, *i.e.* considering yearly harvesting (Paper III), and of spatial variations in terms of geographical location and site-specific properties (Paper IV), and the potential to improve the climate impact when producing bioenergy from willow by selecting certain fields within a landscape (Paper IV).
- The climate effects of energy from willow or forest residues compared with using the fossil fuels hard coal and natural gas (Papers I-IV).

An additional aim was to assess the energy performance of the different bioenergy systems and to study how the above-mentioned factors could improve the energy efficiency of these bioenergy systems.

2.2 Structure of work

The four papers on which this thesis is based describe three different types of bioenergy feedstocks: (1) short-rotation coppice willow (*Salix* ssp.) grown directly for energy on agricultural land; (2) logging residues (tops and branches) extracted after final felling; and (3) stumps extracted after final felling. In Papers I and II, a stand perspective was applied to assess the temporal climate impact of willow (one field) and logging residues (single harvest from one forest stand), respectively. In Paper III, a stand perspective (single harvest) and a theoretical landscape perspective (identical stands for continuous harvest) were applied to assess the temporal climate impact of stump harvesting.

A time-dependent LCA methodology was applied in Papers I-III, which was further developed in Paper IV to allow for a 'real' landscape perspective, *i.e.* continuous harvesting and consideration of spatial variations within a real landscape (defined as a Swedish county) (Figure 1).

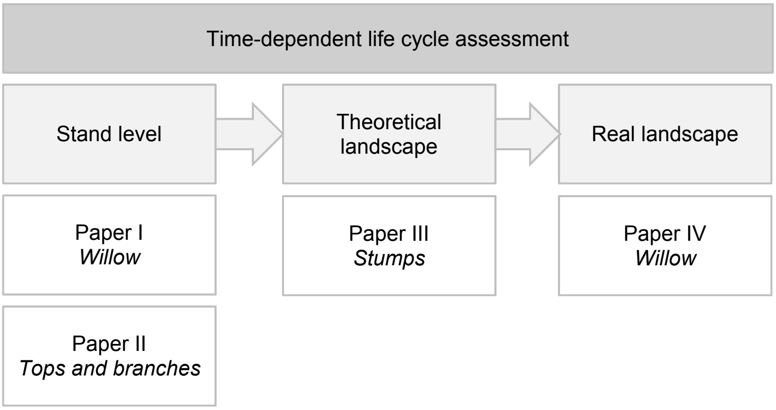

Figure 1. Structure of studies performed in Papers I-IV of this thesis.

3 Background

3.1 Global warming

The global energy balance is determined by the incoming solar radiation and the outgoing terrestrial radiation, where the difference is described as radiative forcing (Wm^{-2}). Greenhouse gases can absorb and re-emit longwave terrestrial radiation (also called infrared radiation) (Manning & Keeling, 2006), while short-wave radiation from the sun can pass through the molecular structure of these gases (Cubasch *et al.*, 2013). Consequently, as more GHGs accumulate, more energy is trapped in the atmosphere, which can lead to higher global mean surface temperature.

The atmospheric concentration of the three major anthropogenic GHGs (CO_2, nitrous oxide (N_2O) and methane (CH_4)) has increased by 40%, 20% and 150%, respectively, since the beginning of the industrial age in the mid-1700s. This increase has mainly been a result of human activities, primarily from use of fossil fuels for energy purposes, but also from land use changes (Le Quéré *et al.*, 2015; Berndes *et al.*, 2013; Ciais *et al.*, 2013). Climate records show that the atmospheric concentrations of these three GHGs are higher now than any time during the past 800 000 years, which points to an anthropogenic cause (Ciais *et al.*, 2013).

3.1.1 Sources of greenhouse gas emissions

Carbon dioxide fluxes

Carbon (C) is an essential building block for plants and trees and around half of the dry weight of biomass is carbon. Carbon dioxide is captured from the atmosphere by plant photosynthesis in the presence of sunlight. Some of this CO_2 is returned to the atmosphere through autotrophic (plant) respiration, while the remaining carbon is stored in biomass (referred to as biogenic carbon). This carbon may then be transferred to the soil pool by root turnover and litter fall, and back to the atmosphere again by heterotrophic respiration by decomposers (Chapin *et al.*, 2002).

Carbon is also a building block of fossil fuels, which have been formed when organic material has been trapped in sediments where anaerobic conditions have limited their decomposition. The formation of fossil fuels, *i.e.* oil, natural gas and coal, has taken a very long time, *e.g.* up to 50-500 million years for oil. Combustion of fossil fuels therefore releases CO_2 that has been stored in the ground for a very long time and increases the CO_2 concentration in the atmospheric cycle (Figure 2).

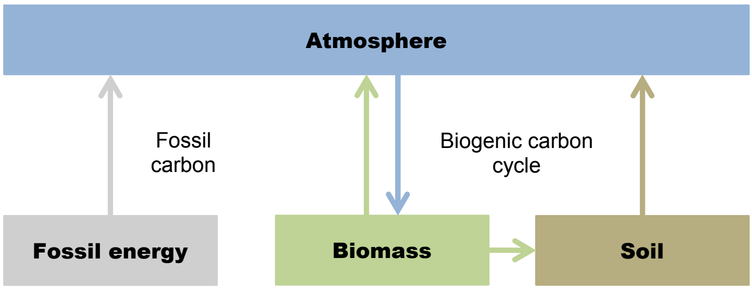

Figure 2. Simplified diagram of biogenic and fossil carbon fluxes between atmosphere, biomass and soil (excluding oceanic fluxes).

Combustion of biomass generates CO_2 emissions, but the time frame for biomass regrowth, *i.e.* uptake of CO_2, is relatively short (a year for annual crops to around 100 years for boreal forest). The concept of biogenic and fossil carbon has been introduced to distinguish between the two sources. Furthermore, the assumption has been made that bioenergy can be considered carbon-neutral (Wiloso *et al.*, 2016). 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).

Soils also contain large fractions of carbon (around three times more than in the global vegetation) (Smith *et al.*, 2008), and land use management can play an important role for the carbon balance. In boreal and temperate regions such as Europe, most of the carbon stock is generally found in the soil pool, while in subtropical and tropical regions such as South America, most carbon is found in biomass (Köhl *et al.*, 2015). In Europe, around 29% of all forest carbon is found in aboveground biomass, while 54% is in the soil (the remaining carbon is found in belowground biomass (7%), dead wood (1%) and litter (9%)) (Forest Europe, 2015).

To mitigate climate change, emissions of GHG must be decreased, but the uptake of carbon can also be increased. Carbon sequestration in the terrestrial biosphere can be increased by two measures; either by increasing net photosynthesis (*e.g.* by establishing forest or other measures to increase net primary production) or by decreasing the decomposition rate (*e.g.* by changes in management) (Cederberg *et al.*, 2012).

Methane emissions

Methane can originate from both fossil and biotic sources, in the same ways as carbon. A large proportion of global methane emissions comes from agriculture, primarily from ruminants. Methane is also the main component of natural gas and can leak to the atmosphere during the production and distribution of this fuel. Methane leakage also occurs during coal mining and it is released when combusting both fossil fuels and bioenergy (Saunois *et al.*, 2016). Methane is a stronger climate agent than CO_2, *i.e.* it has a higher impact on the radiative balance when emitted to the atmosphere. However, the mean lifetime is much shorter (12.4 years) and the gas partly decays into CO_2, which gives an additional warming effect. There are also indirect effects of CH_4 emissions on both tropospheric and stratospheric ozone and stratospheric water vapour, which gives rise to additional warming (Myhre *et al.*, 2013b).

Nitrous oxide emissions

Nitrogen (N), like carbon, is essential for plant growth and most nitrogen is taken up via the root system. Reactive nitrogen is therefore the main component of mineral fertilisers (together with phosphorus (P) and potassium (K)), which are applied in agriculture and in some cases also in forestry. The application of nitrogen fertiliser, and inputs of plant litter, can lead to N_2O emissions from soil by microbial processes. The emissions occur directly (through nitrification) or indirectly (through denitrification) and the magnitude is affected by several factors (*e.g.* soil temperature, moisture content, management), which makes it highly variable (IPCC, 2006). Nitrous oxide is also released by incomplete fuel combustion. This gas has a higher ability to absorb and remit terrestrial radiation than CO_2 or CH_4, *i.e.* it is a stronger greenhouse gas. It has a mean lifetime of 121 years and has indirect effects on the atmospheric CH_4 concentration (Myhre *et al.*, 2013a; Prather & Hsu, 2010).

3.2 Bioenergy in a Swedish context

3.2.1 Present state

The share of bioenergy in Sweden is comparatively high from a global perspective, accounting for around 22% (81 TWh) of the total energy use (including peat) (Swedish Energy Agency, 2016). Most of the bioenergy is used in industry, but some is used for producing district heating and other energy carriers (Figure 3).

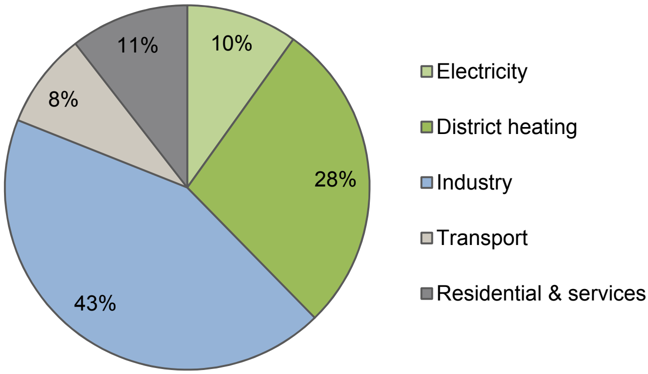

Figure 3. Bioenergy use divided per sector, 2014 (Swedish Energy Agency, 2016).

Biomass from forestry is the main bioenergy resource, where unprocessed wood is the largest fraction, followed by black liquor, which is a residual product used internally in paper and pulp mills (Swedish Energy Agency, 2016) (Figure 4).

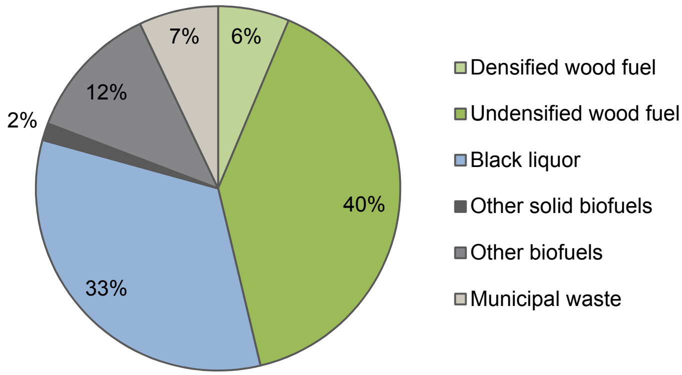

Figure 4. Bioenergy use divided per fuel category, 2014 (Swedish Energy Agency, 2016).

The use of fossil energy for heat and power production is relatively low in Sweden and the use of coal, in contrast to the global trend, has decreased in recent decades, partly as a result of national CO_2 taxes (Di Lucia & Ericsson, 2014). The use of coal and coke comprised about 4% of final energy use in 2014, which was somewhat higher than the use of natural gas (2%) (Swedish Energy Agency, 2016). Globally, however, coal accounts for around 29% of primary energy consumption (compared with 24% for natural gas) (British Petroleum, 2016).

3.2.2 Biomass potential

Forests cover a major proportion of Sweden, occupying nearly 70% of the land area (Matthews *et al.*, 2014; Statistics Sweden, 2013). Agricultural land comprises only around 8%, with pastures occupying one-sixth of agricultural land (Statistics Sweden, 2013). In Sweden today, the combined biomass potential from forest and agricultural land is estimated to be 40-50 TWh per year more than the current use, when considering technical, ecological and economic restrictions (Börjesson *et al.*, 2013). In a global perspective, the technical biomass potential has been estimated to range from less than 50 million TJ yr^{-1} to more than 1000 million TJ yr^{-1} by 2050, with assumptions regarding sustainability restrictions playing a major role in reported variations (Creutzig *et al.*, 2015). Besides increasing the extraction of biomass, improving the energy efficiency of existing systems can make more biomass available. In the following sections, the biomass potential of agricultural land and forests in Sweden is described in more detail.

Agricultural land

Using agricultural land for bioenergy production raises the question of whether cropland should be used for producing food or energy. One way to avoid competing with food or feed production is to only utilise land currently unused, *e.g.* long-term fallow, marginal land or degraded land currently not used. 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 clear how large this potential is, but there are around 2.6 million ha of cropland in Sweden, of which around 0.5% is energy forestry and 5.1% is temporary and permanent (minimum 3 years) fallow (in 2014) (Statistics Sweden, 2015) (Figure 5). This indicates that the current area of dedicated energy crops can be increased.

Establishing perennial energy crops on agricultural land can also give positive effects by increasing the soil organic carbon content through higher carbon input from leaf and root litter, and decreased soil disturbance (Rytter *et al.*, 2015; Cederberg *et al.*, 2012; Djomo *et al.*, 2011).

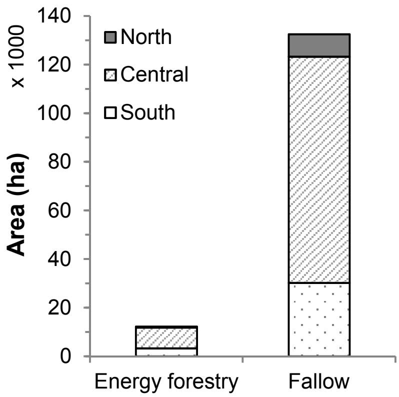

Figure 5. Energy forestry and fallow land in Sweden, 2014 (Statistics Sweden, 2015).

Forest land

Swedish forests are dominated by conifers (*e.g.* *Pinus sylvestris* (Scots pine) and *Picea abies* (Norway spruce)) (Statistics Sweden, 2013) and the forest biomass is primarily used for timber and pulp wood, while leftover branches and tree tops are often left in the forest to decompose, or harvested for energy purposes. Using residual biomass from forestry is one way to increase the domestic bioenergy supply in Sweden, since around 20-30% of a tree consists of tops and branches and around 20% is stumps (Norway spruce).

The bioenergy potential of forest residues is limited by the demand for wood products. However, only around one-third of the total available logging residues (tops and branches) are utilised (around 9.7 out of 27.6 TWh in 2012) and, since stump removal is not an established forest practice in Sweden, stumps are currently extracted to a very small extent (only about 0.3 TWh), mainly for research purposes (Staffas *et al.*, 2015).

The economic profitability of transporting forest residues long distances is a limiting factor, which can be a problem since the majority of Swedish forests are located in the north of the country, while the largest energy need is in the south (Figure 6).

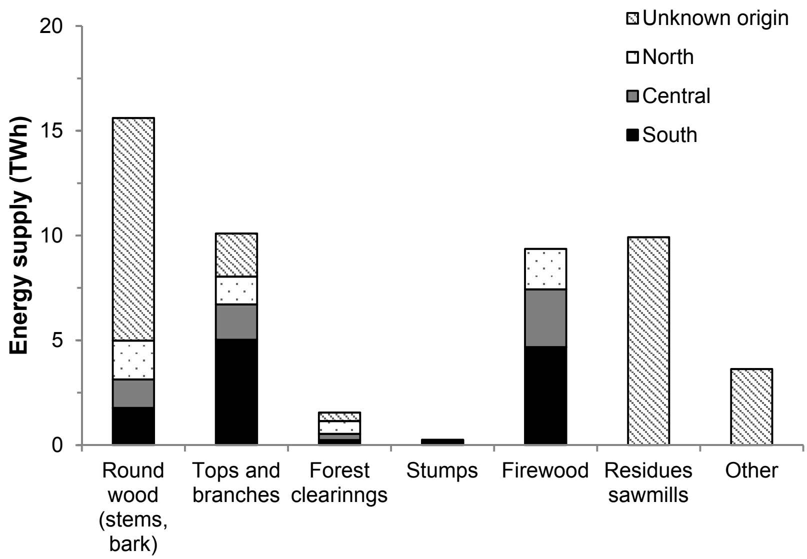

Figure 6. Production of unprocessed wood fuel in Sweden, 2014. 'Other' includes by-products from industry, clearings and residues from gardens and parks. Reproduced from Swedish Energy Agency (2015).

Concerns about removing additional forest biomass, especially stumps, include the risk of biodiversity loss (de Jong & Dahlberg, 2017), nutrient removal and the potential negative impact on future forest productivity. To limit the risk of decreased forest productivity, restrictions regarding how much residues may be extracted from the total amount of final felling in Sweden have been suggested (maximum 80% for tops and branches, 30% for stumps) (de Jong *et al.*, 2017). Moreover, ash should be returned to the forest site and needles should be left on-site, where possible, to avoid nutrient removal and acidification (de Jong *et al.*, 2017).

Estimates of the bioenergy potential from forest residues by 2030 vary from around 20 to 34 TWh per year for tops and branches and 0 to 15 TWh per year for stumps, depending on different assumptions regarding economic and ecological limitations (Pöyry, 2013; de Jong *et al.*, 2012; Gustavsson *et al.*, 2011).

3.3 Climate impact assessment of bioenergy systems

3.3.1 Life cycle assessment

Life cycle assessment (LCA) is a method for evaluating environmental impacts from a systems perspective, *i.e.* the whole lifespan of a product or service. This includes the use of natural resources for producing inputs, the utilisation phase and waste management. The LCA approach in its earliest form was originally developed from energy analysis in the 1960s, but the method has evolved greatly since then, as new environmental problems have been recognised through the years. The method was standardised in the 1990s, which was further updated in 2006. According to ISO 14040/44, LCA is made up of four iterative phases (ISO 14040, 2006; ISO 14044, 2006):

- Definition of goal and scope
- Life cycle inventory (LCI)
- Life cycle impact assessment (LCIA)
- Interpretation of results

The first phase involves defining the system boundaries, certain environmental impacts, characterisation models and a functional unit, which is a quantitative measure of the function of the system to which all emissions are related. If the system is multifunctional, *i.e.* has more than one output product or service, or if recycled materials are used, then allocation methods are required, which should be described in this phase.

In the second phase, data are collected for all processes included in the system boundaries. The data are related to the functional unit and later used to assess the environmental impacts of the system. To assess climate impact, several metrics can be used, where 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 4.5.2).

In the last phase the results are interpreted, usually by performing some type of sensitivity or uncertainty analysis. This phase can also involve additional optional steps; normalisation, valuation and grouping (Baumann & Tillman, 2004).

3.3.2 Key methodological issues

The LCA methodology is continuously evolving as a result of new complex systems and questions (McManus & Taylor, 2015). One of these challenges is how to assess bioenergy systems, and more specifically how to include biogenic carbon stock changes due to *e.g.* land use changes. The following sections describe some key issues when performing LCA of bioenergy systems that are relevant to this thesis. Other aspects not included here that are under discussion are *e.g.* albedo and biodiversity (Teixeira *et al.*, 2016; Bright *et al.*, 2012).

Land use change

Land use change (LUC) has been recognised as a contributing cause of climate change, primarily as a consequence of expansion of urban areas into agricultural land and expansion of agricultural land into grassland, savannah and forests (UNEP, 2014). Including potential negative land use effects is therefore important when assessing bioenergy systems, as is considering alternative uses of the biomass or land (*i.e.* a reference system) and both short-term and long-term effects (Helin *et al.*, 2014; Lamers & Junginger, 2013).

Direct land use change (dLUC) may in turn 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 land use change elsewhere (Berndes *et al.*, 2013). Direct land use change is calculated based on natural sciences where the place of land or region is known. Indirect land use change, on the other hand, can occur in any part of the world controlled by market reactions. Modelling indirect land use change is therefore very complex and requires economic models. Even though indirect land use change has been discussed and pointed out as a potential negative aspect of bioenergy, there is so far no consensus on how to incorporate it in LCA (Finkbeiner, 2014).

Climate metrics and the importance of time

As mentioned, LCA is often used to study the climate impact of bioenergy systems and the default climate metric is global warming potential during a period of 100 years (GWP_{100}). This is a normalised metric, meaning that the warming potential of one gas with a specific atmospheric lifetime is normally related to that of CO_2 during a set time frame. In other words, gases that will remain in the atmosphere for varying time frames (a few years to infinite) are grouped together (Cherubini *et al.*, 2016).

Alternative climate metrics have been developed during the past decade with the aim of better handling the time issue (Levasseur *et al.*, 2016). Absolute global temperature change potential (AGTP) (also referred to as ΔT_s) is an absolute climate metric that describes the impact at a specific point in time, and not as a relationship between two gases during a certain time frame (Ericsson *et al.*, 2013; Myhre *et al.*, 2013a). The metric thus considers the timing of greenhouse gas emissions and also continues down the cause-effect chain to temperature (Figure 7). Since temperature change is further down the cause-effect chain, uncertainties are higher compared with GWP (which is based on radiative forcing). Another metric that has been used in LCA of bioenergy is the global temperature potential (GTP), which describes the AGTP for one gas relative to another at a specific point in time.

Examples of other climate metrics are global sea level rise potential (GSP), global precipitation change potential (GPP) and climate change impact potential (CCIP). Levasseur *et al.* (2016) points out that several climate metrics and time horizons can be used in an LCA to better display uncertainties and impacts of choice of metric, which would then increase the transparency. For instance, even though GWP has limitations, this metric can be valuable for comparability purposes, since it is the most common method used in earlier studies.

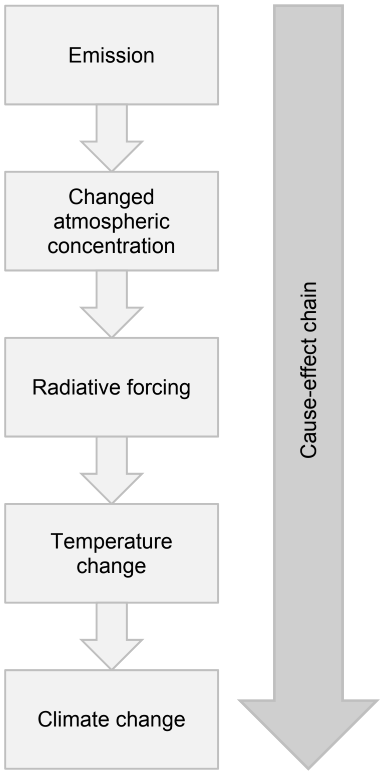

Figure 7. Simplified cause-effect chain of greenhouse gas emissions on climate (reproduced from Levasseur *et al.* (2016))

The choice of time frame for the inventory analysis also plays an important part for 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.

Stand versus landscape perspective

Besides the timing issues related to bioenergy systems, the choice of spatial scale is also important. In bioenergy assessments, a division between stand level and landscape level is often made (Lamers & Junginger, 2013). A stand perspective only studies the dynamics of *e.g.* one forest stand with equal age distribution or one hectare of agricultural land under site-specific growing conditions. Drawing general conclusions from these types of assessments may be misleading, since spatial variations are overlooked (*e.g.* in terms of initial carbon stocks, site-specific conditions influencing productivity and decomposition, and transport distances to energy facilities). Therefore, the landscape perspective concept has been developed to include the dynamics of a whole landscape, and to enable modelling of a bioenergy system with an even energy outtake (independent of rotation time).

However, there are different definitions of a landscape and some studies have made a division between 'true' or 'real' landscape and a theoretical or hypothetical landscape (Cintas *et al.*, 2016). A theoretical landscape refers to a landscape made of identical stands of different ages (to distribute energy output over time, *i.e.* continuous harvest), while a real landscape describes the actual conditions in a specific region. The size of a landscape can also vary greatly between studies (Englund *et al.*, 2017).

3.3.3 Previous LCA of solid bioenergy

Life cycle assessments of willow systems have revealed low global warming potential or even negative effects (*i.e.* cooling) when including soil carbon (*e.g.* Zetterberg & Chen, 2015; Ericsson *et al.*, 2013; Heller *et al.*, 2003). For willow, *e.g.* Whittaker *et al.* (2016) calculated a global warming potential of 6.8 g CO_2-eq MJ^{-1} willow biomass when excluding soil organic carbon and around -2.8 g CO_2-eq MJ^{-1} when including soil carbon.

Previous LCAs on using forest biomass for energy have generally shown 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 MJ^{-1} (excluding biogenic carbon) in previous studies (Zetterberg & Chen, 2015; Jäppinen *et al.*, 2014; Repo *et al.*, 2015; Gode *et al.*, 2011; Lindholm *et al.*, 2011).

The time-dependent climate impact of woody biomass use has also been assessed previously, *e.g.* to study different end uses of short-rotation coppice willow and different wood pellet systems (Porsö, 2017; Ericsson, 2016).

4 Method

4.1 Overview

All studies described in Papers I-IV of this thesis were performed using a time-dependent LCA method, which can be divided into four modelling steps (described in following chapters):

(1) Biogenic carbon fluxes
(2) Emissions from supply chain
(3) Energy conversion
(4) Climate impact assessment

The method was further developed in Paper IV to allow for a real landscape perspective, *i.e.* include all fields in a region while considering the specific properties and location of each field:

(5) Landscape modelling

The region of Uppsala was used as study region in Papers I and IV, while three Swedish regions (southern, central and northern Sweden) were studied in Papers II and III (Figure 8). Two functional units were used in the papers: (1) hectare of land (ha); and (2) megajoules of heat produced (MJ heat). The life cycle assessments conducted were performed using Microsoft Excel 2010 (Papers I-III) and MATLAB (version R2012b, The MathWorks, Inc., Natick, MA, USA) (Paper IV).

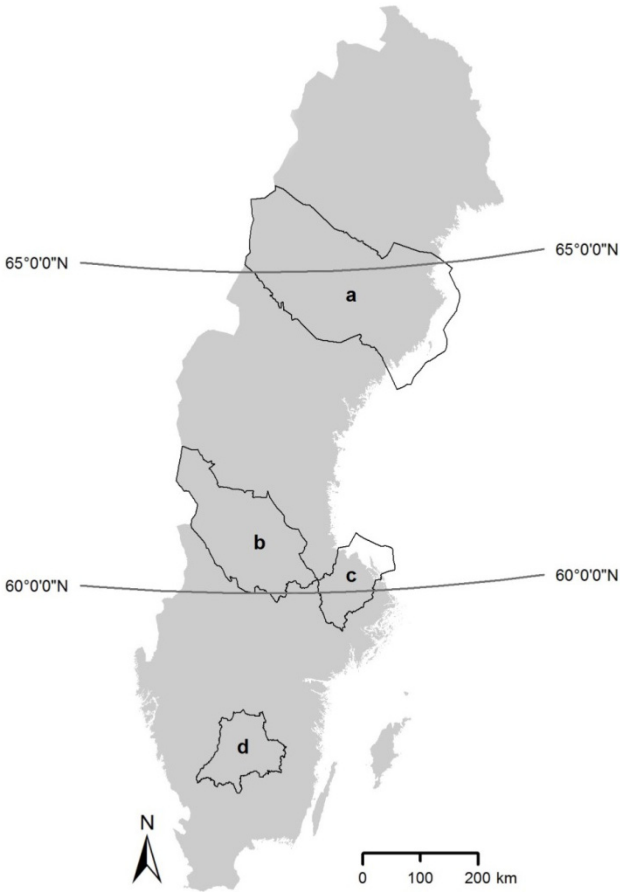

Figure 8. Map of Sweden showing the regions studied in Papers I-IV, representing: a) Västerbotten (north); b) Dalarna (central); c) Uppsala; and d) Jönköping (south). Background map: Overview map 1:1 000 000 © Lantmäteriet.

4.2 Biogenic carbon fluxes

Biogenic carbon fluxes were modelled somewhat differently for the forest biomass (tops and branches, and stumps) and willow. Since the goal was to study the climate impact of increased use of biomass for energy (‘forward looking’ perspective), and the future forest productivity was assumed to be unaffected by the harvesting of forests residues, only the fate of carbon stored in the residual biomass was considered. The carbon uptake due to forest growth was instead allocated to the production of timber and pulp wood.

Willow, on the other hand, is a dedicated energy crop, and therefore both carbon sequestered from the atmosphere by net primary production (*i.e.* biomass growth) and the decomposition of residues were included. In the next two sections, the biogenic carbon modelling of the two types of systems is further described. No indirect land use changes were included and a forward looking perspective was applied, *i.e.* only GHG fluxes occurring from the start of the time frame onwards were included.

4.2.1 Carbon dynamics of willow grown on agricultural land

The biogenic carbon fluxes for the willow systems (Papers I and IV) were divided into standing biomass (stems, leaves, roots) and soil organic carbon (SOC) (Figure 9). The standing biomass was modelled based on net primary production from Rytter (2001) and a set yield level.

The soil organic carbon balance of willow was modelled by the Introductory Carbon Balance Model (ICBM), which is designed for agricultural soils (only mineral soils were studied). 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 that enters the old pool is described by a humification factor. In addition, the young pool is separated into two sub-pools, one which considers the carbon input from aboveground biomass (leaves) and the other the belowground biomass (fine roots, coarse roots and stumps). The model incorporates external factors, such as weather and soil type, that affect the decomposition rate. The total SOC content is the sum of the old pool and the two young pools (Andrén *et al.*, 2004). The biogenic carbon fluxes for an alternative land use (reference land use), which was defined as green fallow (cut yearly without biomass removal), were also modelled in this thesis (Papers I and IV).

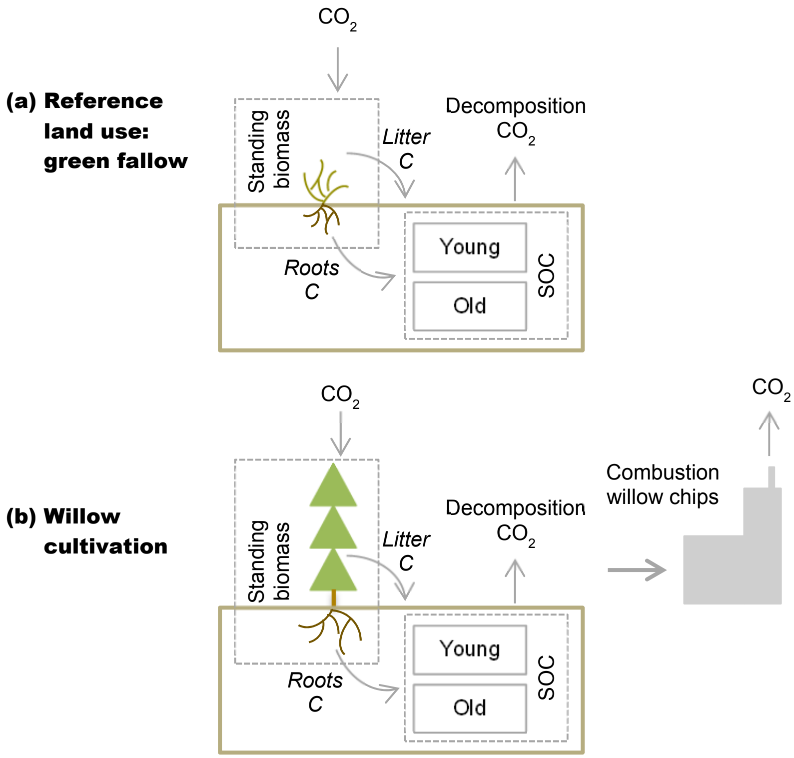

Figure 9. Biogenic carbon fluxes in (a) reference land use green fallow and (b) the willow system. Standing biomass refers to living biomass in the form of stems, branches, roots and stumps. The standing biomass is either harvested for bioenergy or enters the soil pool in the form of aboveground litter (leaves) or belowground biomass (root turnover). The soil pool is divided in a young carbon pool and an old carbon pool, which together make up the soil organic carbon content.

4.2.2 Carbon dynamics of forest residues

Management of the forest stands (Papers II and III) was modelled by the stand-wise version of the Heureka Forestry Decision Support System (Heureka) (Wikstrom *et al.*, 2011). Heureka consist of several models that can be used for simulating biomass functions and decomposition. The decomposition of organic material was modelled using the Q model, which requires the supply of fresh litter as an input parameter. Different biomass fractions are decomposed differently depending on quality.

An updated version of the Q model was used for simulating the SOC changes, which included decomposition of old organic material (Ortiz *et al.*, 2013; Rolff & Ågren, 1999). The decomposition of old material was assumed to be unaffected by the removal of forest residues. The county-wise calibration of the Q model (Ortiz *et al.*, 2011) was used for parameterisation of each forest stand (Papers II and III).

The forest planning tool INGVAR was used to design a forest system representing conventional forest management of Norway spruce (*Picea abies*) in Sweden (Papers II and III) (Jacobson, 2008). To represent forest stands located in three climate zones (scenarios South, Central and North in Papers II and III), 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). Three forest management practices were assessed (Papers II and III):

(a) No harvesting of forest residues
(b) Harvesting of tops and branches at final felling
(c) Harvesting of stumps at final felling

Stumps would normally not be harvested without first harvesting tops and branches, but to separate the effect of stump harvesting, the results were presented as three isolated management choices (Paper III). The initial soil organic carbon content was assumed to be unaffected by the different management practices and was thus the same for the three options (Figure 10). The net land use effect of a forest management option was calculated as the yearly difference in biogenic carbon fluxes between the reference land use, *i.e.* (a) no harvesting of forest residues, and the management option, *i.e.* either (b) harvesting of tops and branches or (c) harvesting of stumps. This resulted in negative emissions in years when the carbon emissions from alternatives (b) are (c) were lower than in (a).

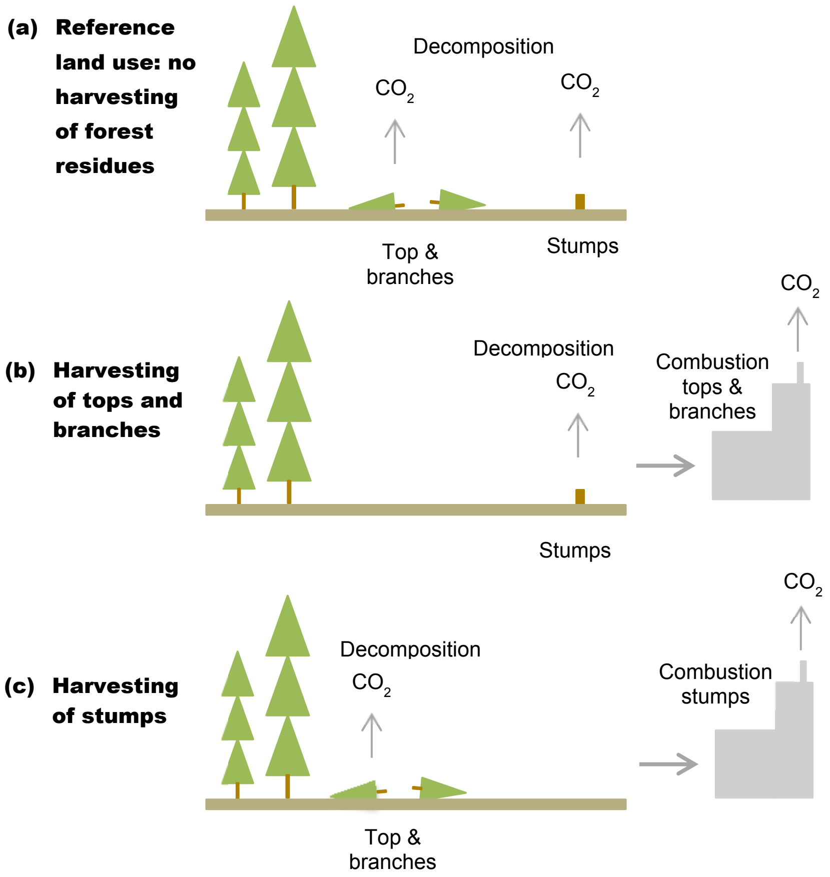

Figure 10. Biogenic carbon fluxes in a forest system: (a) without harvesting of forest residues (reference system); (b) including harvesting of tops and branches for bioenergy; and (c) including harvesting of stumps for bioenergy. The net biogenic carbon effect for the two forest scenarios (harvesting of tops and branches or harvesting of stumps) is the difference between (a) and (b) and (a) and (c), respectively.

4.3 Supply chains

Besides biogenic carbon fluxes from land use, greenhouse gas emissions and energy consumption from all included processes in the supply chains were calculated (Figure 11).

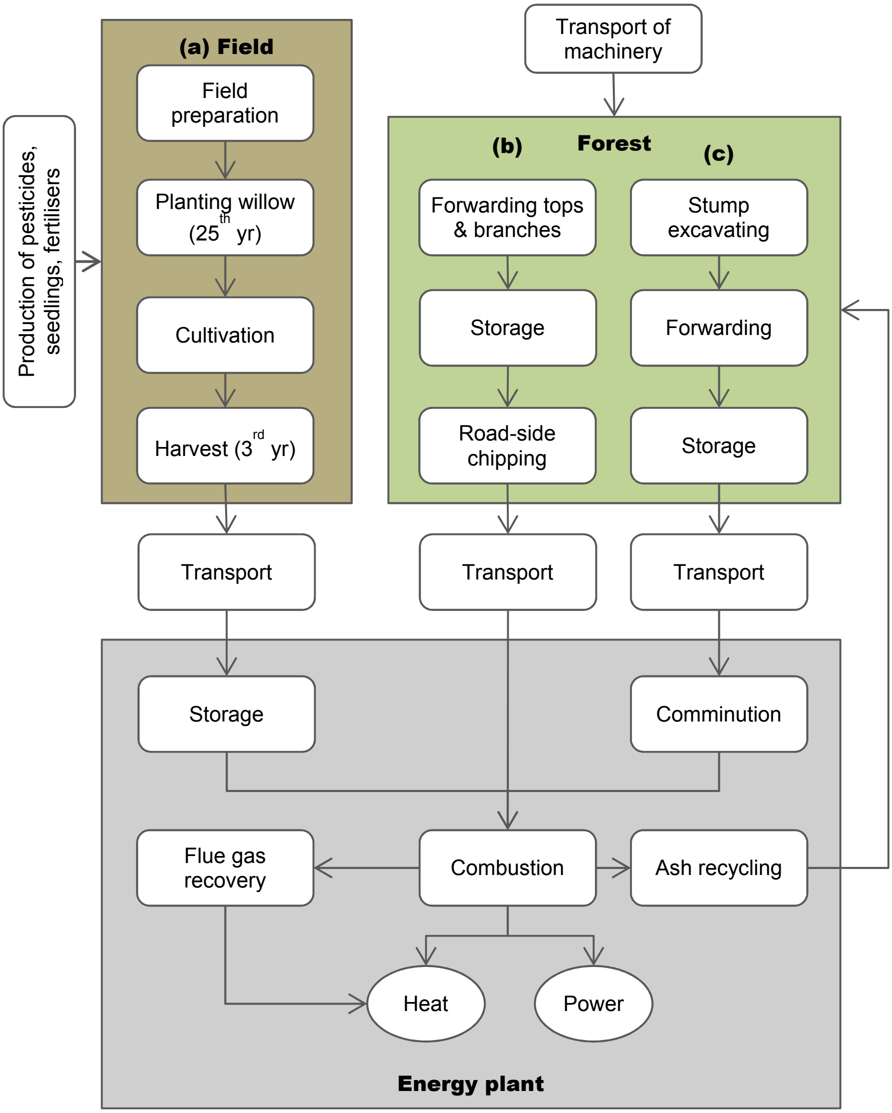

Figure 11. Flowchart describing the supply chains of (a) willow; (b) forest tops and branches; and (c) forest stumps harvested for heat and power production (only heat was produced in Papers I-III).

4.3.1 Field operations

Growing willow on agricultural land for bioenergy was studied in Papers I and IV, where the same supply chain was assumed in both studies (aside from transport distance). The field was first assumed to be prepared mechanically by weed harrowing and chemically by application of pesticides. Willow seedlings were then planted and grown for three years, after which the first harvest took place during winter time, when the ground generally has a higher carrying capacity. The willow was thereafter regrown and harvested by direct chipping in a three-year cutting cycle for a period of 25 years (in total eight harvests per rotation period), before the plantation was broken up and new seedlings planted. The willow yield level was set to 20 Mg dry matter (DM) ha^{-1} for the first harvest and 30 Mg DM ha^{-1} for the subsequent harvests in the base scenarios, levels which were varied in sensitivity analyses (Papers I and IV).

During one rotation, nitrogen fertiliser was applied in years 3-25, where the amount was calculated based on yield level, so that equal amounts of nitrogen were applied as removed by harvesting (and nitrogen leaching). Phosphorus and potassium were applied every third year. Energy use and emissions from production and application of the fertilisers were included in the system boundaries (Fossum, 2014; Nilsson & Bernesson, 2008; Börjesson, 2006). The willow chips were transported to the energy facility for storage and combustion within 30 days, with an assumed dry matter loss of 3% (Jonsson & Jiris, 1997).

N_2O soil emissions

The application of nitrogen (both from mineral fertilisers and contained in biomass entering the soil) was assumed to give rise to N_2O emissions, which were calculated using default values (Table 1):

$$N_2O_{direct} = EF_N \cdot (N_{applied} + N_{litter} + N_{roots}) \cdot \frac{44}{28} \quad (1)$$

$$N_2O_{indirect} = N_{applied} \cdot (F_A \cdot EF_D + N_{leached} \cdot EF_L) \cdot \frac{44}{28} \quad (2)$$

where $N_{applied}$ is the nitrogen applied by mineral fertilisers and N_{litter}, N_{roots} and $N_{leached}$ is the nitrogen contained in the aboveground and belowground biomass entering the soil and nitrogen lost by leaching, respectively. The nitrogen is converted to N_2O by a fraction of $\frac{44}{28}$. The N_2O soil emissions were also calculated for the reference land use green fallow, following the same methodology.

Table 1. *Parameters used for calculating nitrous oxide (N_2O) emissions by Eqs. (1) and (2)*

Parameter	Value	Unit	Description
$N_{leached}$	0.30[b]	kg N kg^{-1} applied N	Nitrogen lost by leaching
EF_N	0.01[a,b]	kg N_2O-N kg^{-1} N	Direct emissions from applied nitrogen
EF_D	0.01[a,b]	kg N_2O-N kg^{-1} NH_3-N	Emissions from volatilisation and re-deposition
EF_L	0.0075[a,b]	kg N_2O-N kg^{-1} leached N	N_2O emissions due to nitrogen leaching
F_A	0.012[a]	kg NH_3-N + NO_x-N kg^{-1} applied N	Fraction of applied nitrogen emitted as ammonia

[a]IPCC (2006), [b]Ahlgren *et al.* (2009).

4.3.2 Forest operations

Tops and branches (Paper II) and stumps (Paper III) were assumed to be harvested separately after final felling. Emissions and use of energy occurring before and during final felling were allocated to the production of timber and pulp wood. At each site, 70% of the forest residues were assumed to be harvested (Table 2).

Table 2. *Yield levels for single harvest of forest residues in the three regions of Sweden (Papers II and III)*

Region	Vegetation zone	Rotation period (yr)	Yield (Mg dry matter ha^{-1})	
			Tops and branches	Stumps
South	Hemiboreal	70	47.9	59.0
Central	Southern boreal	90	35.3	37.9
North	Northern boreal	120	33.5	32.9

Tops and branches were assumed to be forwarded with an average forwarder to the roadside for storage. The biomass was thereafter chipped by a truck-mounted grinder and transported to the energy facility. The stumps were excavated and also forwarded to the roadside for storage. The stumps were thereafter loaded on a truck for transport to the energy facility, where the biomass was comminuted by a stationary crusher (Table 3). All forest residues had an assumed storage time of eight months, with a storage loss of 1% per month (Filbakk *et al.*, 2011).

Forest soils generally cause lower N_2O emissions than the more productive soils in agriculture. However, the effect of harvesting forest residues on soil N_2O is unclear and was therefore not included in this thesis.

Table 3. *Inventory data for forest residues (h_{15} includes pauses shorter than 15 min, DM = dry matter, w.b. = wet weight basis)*

	Value	Unit
Top and branches		
Forwarding		
Diesel use	10.8[a]	h_{15}^{-1}
Time	8.4[b]	minutes Mg DM^{-1}
Chipping		
Diesel use	3.05[c]	litre Mg DM
Losses	3.6[d]	%
Stumps		
Excavating		
Diesel use	20.2[d]	litres h^{-1}
Time	2.9[d]	Mg DM h^{-1}
Forwarding		
Diesel use	11[d]	litres h_{15}^{-1}
Time	7.40[d]	Mg DM h^{-1}
Transport		
Loading	4.7[d]	litres $load^{-1}$
Unloading	1.7[d]	litres $load^{-1}$
Basic density	0.430[e]	Mg net DM m^{-3}
Load space	145[e]	m^3
Comminution		
Electricity consumption	3.6[d]	MJ Mg^{-1} (w.b.)
Losses	3.6[d]	%

[a]Brunberg (2013), [b]Eliasson and Lundström (2013), [c]Eliasson *et al.* (2012), [d]Lindholm *et al.* (2010), [e]Eriksson *et al.* (2014).

4.3.3 Transport

The diesel consumption for transportation was calculated in the same way for all papers, assuming fuel consumption of 0.58 litre km^{-1}, which is the average consumption for a vehicle with a full loading rate of 54% of the transport distance and a load weight of 34 Mg (Andersson & Frisk, 2013). The transport distances were assumed based on previous studies (Paper I), average transport distances in Swedish forestry (Papers II and III) and actual distances in the study region (Paper IV) (further described in section *4.6.1 Data retrieval and GIS mapping*) (Table 4).

Table 4. *Transport distances (km) in the supply chain*

	Distance	Description
Willow		
Paper I	30	One-way
Paper IV	3-96 (43)	One-way transport distance between fields and energy plant, average in brackets
Forest residues		
Paper II and III	120.2, 122.6, 144.6[a]	Round-trip for south, central and north Sweden

[a]Based on Andersson and Frisk (2013).

4.4 Energy conversion

The biomass was assumed to be transported to a district heating plant (Papers I-III) or a combined heat and power plant (Paper IV). The energy performance of the bioenergy systems was determined by calculating 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):

$$\mathrm{ER} = \frac{E_{out}}{E_{in}} \quad (3)$$

The primary energy use was calculated using a primary energy factor of 1.09 MJ MJ^{-1} for diesel consumption (Gode *et al.*, 2011) and 1.5 MJ MJ^{-1} for electricity (SOU, 2008). The energy output depends on the specific properties of each fuel and the conversion efficiency.

4.4.1 Fuel properties

The amount of energy produced from different fuels depends on their properties, which for solid biofuels vary with biomass assortment, storage time and processing. In general, half of fresh biomass consists of water, while the remaining fraction (dry matter) consists of around 50% carbon, 6% hydrogen, 40% oxygen, 0.5% nitrogen and a non-combustible part, *i.e.* ash (Lehtikangas, 1999). The reference fossil energy sources, natural gas and hard coal, mainly consist of methane and carbon, respectively, which affects the emissions at combustion (Figure 12).

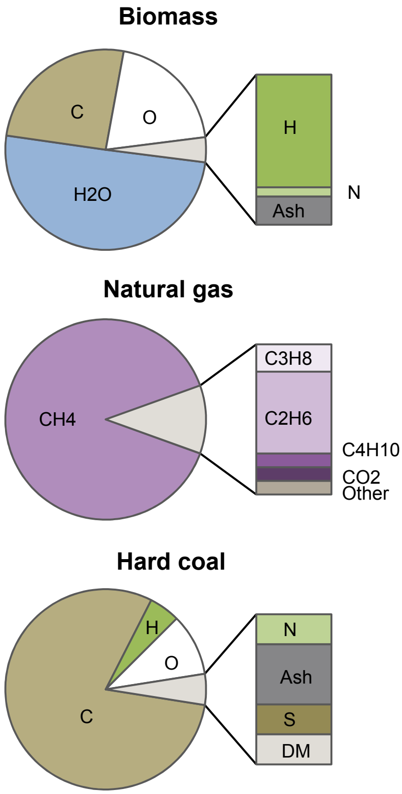

Figure 12. Typical fuel properties for biomass, natural gas and hard coal (C = carbon, O = oxygen, H_2O = water, H = hydrogen, N = nitrogen, S = sulphur, CH_4 = methane, C_3H_8 = propane, C_2H_6 = ethane, C_4H_{10} = butane, CO_2 = carbon dioxide, DM = dry matter).

The total energy content in biomass without considering heat losses from water condensation is referred to as the higher heating value (HHV) (Table 5). The lower heating value (LHV) can be calculated as:

$$LHV_{MC} = (HHV - 2.45 \cdot 0.09 \cdot H_2) \cdot (1 - \frac{A}{100}) - 2.45 \cdot \frac{MC}{100 - MC} \quad (4)$$

where LHV_{MC} is the theoretic heat gained from wood chips excluding water condensation heat, 2.45 is the latent heat of water vaporisation at 20 °C (MJ kg^{-1}), A is the ash content, 0.09 represents 1 part hydrogen and 8 parts oxygen in water, and H_2 is the hydrogen content (6% assumed) (Lehtikangas, 1999).

Table 5. *Biomass fuel properties. HHV = higher heating value, DM = dry matter, MC = moisture content, LHV = lower heating value*

	Tops and branches	Stumps	Willow
HHV (MJ kg^{-1} DM)	20.8[a]	20.5	19.9
Ash (%)	1.5	3	1.5
MC (%)	45	30	50
LHV (MJ kg^{-1} DM)	17.2	17.6	15.8

[a]Nilsson *et al.* (2012).

Combusting biomass generates emissions of N_2O and CH_4 in addition to CO_2, as a result of incomplete combustion. Emission factors were used for combustion emissions in all papers (Table 6).

Table 6. *Greenhouse gas emissions from different fuels (g MJ^{1} fuel) (Gode et al., 2011) (CHP = combined heat and power)*

	Biomass	Hard coal		Natural gas	
	Combustion	Production & distribution	Combustion CHP	Production & distribution	Combustion CHP
Fossil carbon dioxide	-	4.15	106	5.53	56.8
Methane	0.011	0.56	0.01	0.275	0.001
Nitrous oxide	0.006	$2.35 \cdot 10^{-5}$	0.00127	$2.59 \cdot 10^{-12}$	0.0001

4.4.2 Efficiencies and allocation

Both the district heating plant (Papers I-III) and the combined heat and power plant (Paper IV) were assumed to be equipped with flue gas condensation recovery. With flue gas recovery, some of the energy lost by water vaporisation can be recovered in the form of heat, which increases the conversion efficiency for biomass and natural gas. This means that the total conversion efficiency can be more than 100% (Table 7).

Table 7. *Conversion efficiencies used for the combined heat and power plant in Paper IV. Separate production efficiencies were used for calculating heat allocation factors.*

	Separate production[a]			Combined production[b]		
	Biomass	Hard coal	Natural gas	Biomass	Hard coal	Natural gas
Heat	78	80	82	55	55	45
Power	33	44	53	30	30	40
Flue gas recovery				20	0	10
Total efficiency				105	85	95

[a]EU (2011), [b]Börjesson *et al.* (2010).

Since both heat and power were generated in Paper IV, the impact was allocated between the two products to gain the same functional unit as in Papers I-III (*i.e.* MJ heat). An energy efficiency allocation method (Martinsson *et al.*, 2012) was applied, which is described by:

$$\alpha_h = \frac{\frac{Q_h}{\eta_h}}{\frac{Q_h}{\eta_h} + \frac{Q_p}{\eta_p}} \tag{5}$$

where α is the allocation factor, Q is the energy produced from combined heat (h) or power (p) production, and η is the conversion efficiency for separate production of power and heat (excluding flue gas recovery) (Table 8).

Table 8. *Allocation factors (%) for heat and power calculated using conversion efficiencies from Table 7 and Eq. 5.*

	Biomass	Hard coal	Natural gas
Heat	44	50	42
Power	56	50	58

4.5 Climate impact assessment

The third phase of an LCA involves assessing the environmental impacts, in this thesis climate impact, of the system under study, based on data collected in the life cycle inventory. The climate impacts can be calculated using different climate metrics. Global warming potential (GWP) and absolute global temperature change potential (AGTP), which are both based on radiative forcing, were used in all studies in this thesis.

4.5.1 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 (~10 km altitude). Greenhouse gases 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 that one unit change in the atmospheric gas concentration has 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 9). The radiative efficiency of gas x can be converted from volume (ΔF_v) to mass, measured in kg gas (ΔF_m), by:

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

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 9. *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. Indirect effects of N_2O on CH_4 are also included. (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	2.78	$3.58 \cdot 10^{-13}$

Greenhouse gases have different perturbation lifetimes, *i.e.* residence times in the atmosphere (Figure 13). The RF of gas x is described by:

$$RF_x = \Delta F_{m_x} \cdot R_x \qquad (7)$$

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 concentration decreases.

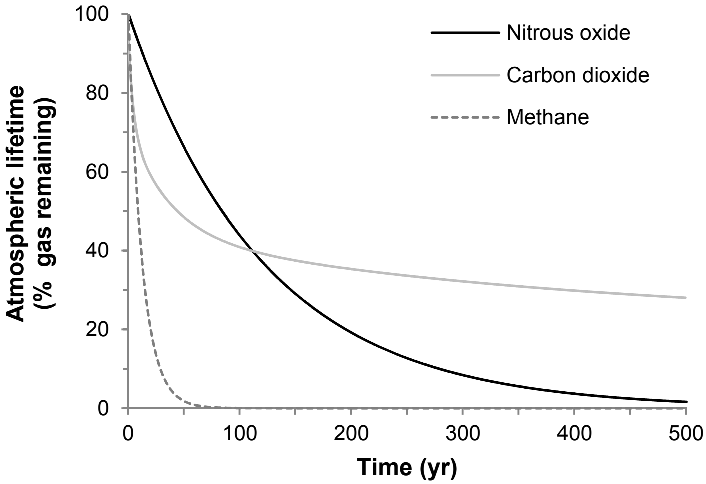

Figure 13. Fraction remaining in the atmosphere after pulse emission of nitrous oxide, carbon dioxide and methane at year zero, calculated based on Myhre *et al.* (2013a).

For N_2O and CH_4, the mean atmospheric 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. 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 (Joos *et al.*, 2001).

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 t:

$$CRF_x = \int_0^H RF_x(t) \quad (8)$$

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

4.5.2 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:

$$AGWP_x = CRF_x \quad (9)$$

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):

$$GWP_x(H) = \frac{AGWP_x(H)}{AGWP_{CO_2}(H)} \quad (10)$$

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, fossil CH_4 and N_2O is 1, 28 and 26, respectively (Myhre *et al.*, 2013b).

4.5.3 Temperature response

The cumulative radiative forcing 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 of a unit pulse emission, referred to as absolute global temperature potential (AGTP) by the IPCC, is described by (measured in degrees K kg^{-1} gas):

$$AGTP_x(H) = \int_0^H RF_x(t) R_T(H-t)dt \quad (11)$$

i.e. a convolution between the radiative forcing (RF) and the climate response function (R_T) due to a unit change in radiative forcing (1 Wm^{-2}) from a pulse emission of gas x (Myhre *et al.*, 2013a). The surface temperature response of a unit change in RF due to pulse emissions of CO_2, N_2O and CH_4 is dependent on the atmospheric lifetime of the gases (Figure 14).

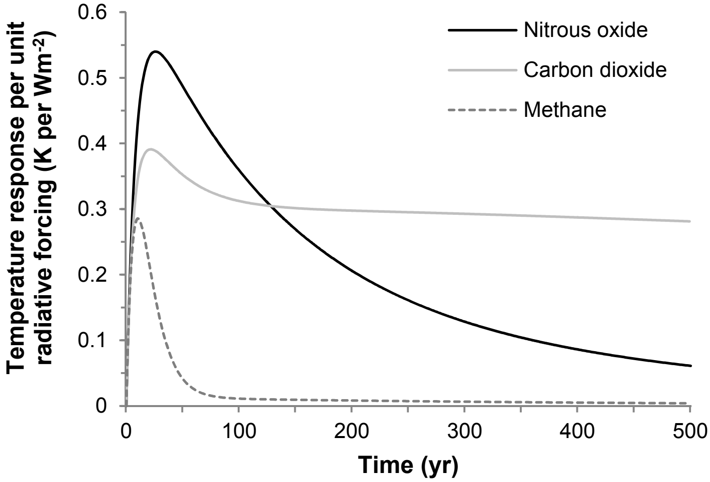

Figure 14. Surface temperature response after a pulse emission of 3 Pg nitrous oxide, 570 Pg carbon dioxide and 5 Pg methane leading to one unit change in radiative forcing (1 Wm^{-2}), calculated based on Myhre *et al.* (2013a) and Joos *et al.* (2013).

The total global surface temperature response *(ΔT)* of the system under study is then the sum of the temperature responses of all greenhouse gas emissions (E) during the studied time horizon (H) (measured in degrees K):

$$\Delta T(H) = \sum_x \int_0^H E_x(t)\, AGTP_x(H-t)dt \quad (12)$$

where t is the time of emission and x is the gas (CO_2, CH_4 and N_2O).

4.6 Landscape modelling

The additional model steps in Paper IV included data retrieval for all fields in the study region (Uppsala County, Figure 8), geographical information system (GIS) mapping and time-dependent LCA of each individual field in the studied landscape. These steps are further described in the following sections.

4.6.1 Data retrieval and GIS mapping

Information regarding agricultural land use in the study region was needed to determine which fields were available for willow plantation, defined as current fallow land according to Swedish statistics. This information and data on soil texture and soil organic matter (SOM) were obtained from the Swedish Board of Agriculture. The initial SOM was needed as the starting value for modelling soil organic carbon fluxes under willow cultivation. Data were available for 880 measurement points in the Uppsala region and the SOM for each field was defined as the SOM value at the closest measurement point. The soil carbon model was also adapted for the specific soil texture by changing the external factor parameter (r_e) in the ICBM model. Fields smaller than 2 ha were excluded from the study according to Swedish management recommendations (Hollsten *et al.*, 2013). The willow yield was assumed to be constant for all fields in the base scenario (same levels as in Paper I), which was varied in a scenario analysis.

In total 2083 fields were studied, corresponding to about 9800 ha (Figure 15). The biomass was assumed to be transported to an energy plant located in Uppsala after harvesting (Figure 15). Transport distances between each field and the energy plant located in Uppsala were retrieved using road network data from the Swedish Transport Administration (Trafikverket, 2016) (Table 4). The fields were mapped out and all retrieved information was linked, which was done using the ArcGIS product (ArcMap version 10.3, Esri) (Paper IV).

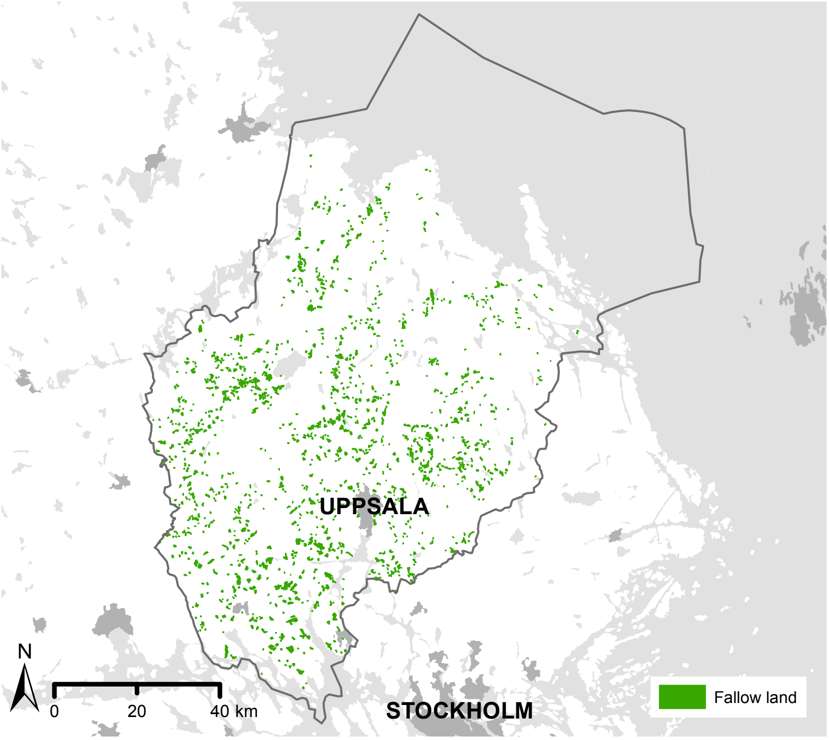

Figure 15. Map of fields in Uppsala County included in thesis (Paper IV). Crop and field information © Swedish Board of Agriculture; background map: Overview map 1:1 000 000 © Lantmäteriet.

4.6.2 Time-dependent LCA and landscape model

The next step of the landscape model was to apply the time-dependent LCA method to each field in the study region to assess the climate impact and energy balance. The information retrieved from the GIS mapping was used as input for modelling biogenic carbon fluxes, emissions from the supply chains and energy balances for all fields identified. For continuous willow energy production (due to a three-year cutting cycle), all willow fields in the region were randomly divided into three groups, which were harvested in sequence (Paper IV).

By using this combined method, selection could be made of fields that gave the most beneficial climate response and highest energy efficiency. The result could be expressed either for each field individually, or as the combined effect over the whole landscape.

5 Results

5.1 Biogenic carbon dynamics

5.1.1 Willow systems

The biogenic carbon dynamics of a willow stand were divided into standing biomass (stems, leaves and roots) and soil organic carbon (Paper I). Willow has a higher carbon uptake in standing biomass than the reference land use fallow (higher biomass growth), which affects the soil organic carbon development over time. A higher input of carbon via leaf litter and root turnover can build up the soil carbon pool (Figure 16). During a 25-year period (corresponding to one willow rotation), both the standing biomass and soil pool were shown to increase under willow cultivation (Figure 16a), while the soil pool was shown to decrease under fallow land (Figure 16b). Thus the net effect of establishing willow was slightly higher than solely the carbon increase in the willow plantation (Figure 16c).

Higher willow productivity increased the amount of aboveground and belowground biomass, which gave a larger carbon input to the soil. High willow productivity thus increased both the standing biomass and the soil pool, *i.e.* more CO_2 was removed from the atmosphere. Conversely, low willow productivity gave decreased uptake from the atmosphere and a smaller build-up.

When willow cultivation was terminated after one rotation period (25 years) and the land was under fallow once again, the carbon sequestered in the soil was slowly released back to the atmosphere. The carbon storage is thus temporary. However, after a 100-year period, the soil organic carbon content of the terminated willow plantation was still higher than that in the reference land use of only green fallow (Figure 17).

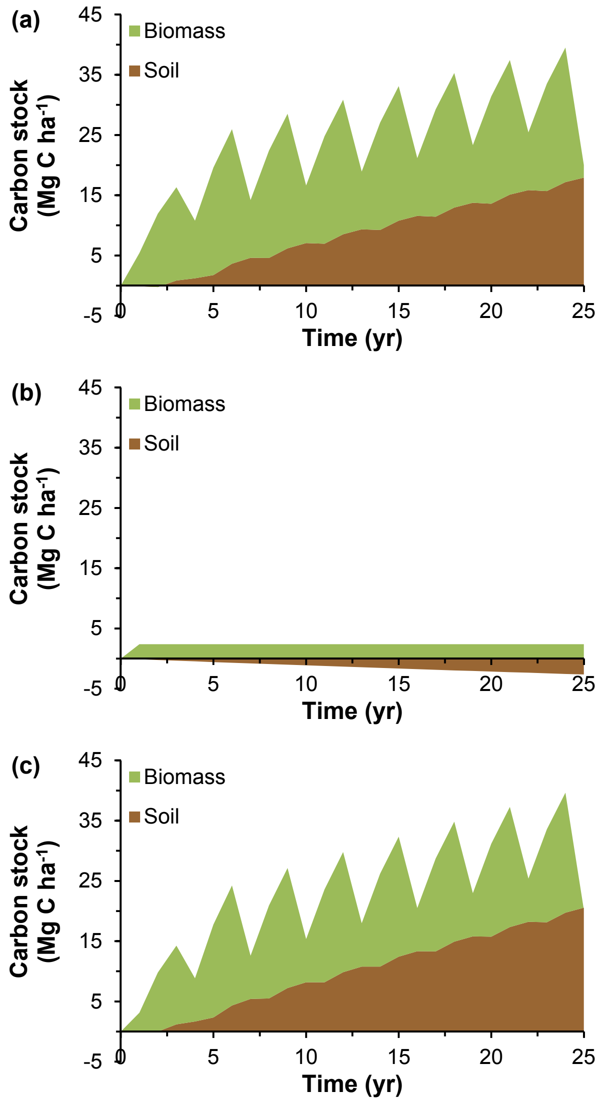

Figure 16. Carbon stock in (a) willow biomass (stems, leaves, roots) and soil during 25 years of cultivation on agricultural land previously used as green fallow; (b) reference land use green fallow; and (c) net effect of the two land uses, *i.e.* yearly difference between willow and green fallow. Carbon stocks are expressed in relation to baseline year zero, *i.e.* negative values indicate decreased carbon stock and positive values increased carbon stock compared with the initial value. Carbon in litter was assumed to enter the soil pool with a one-year delay. Values are modelled for one field (Paper I, base scenario).

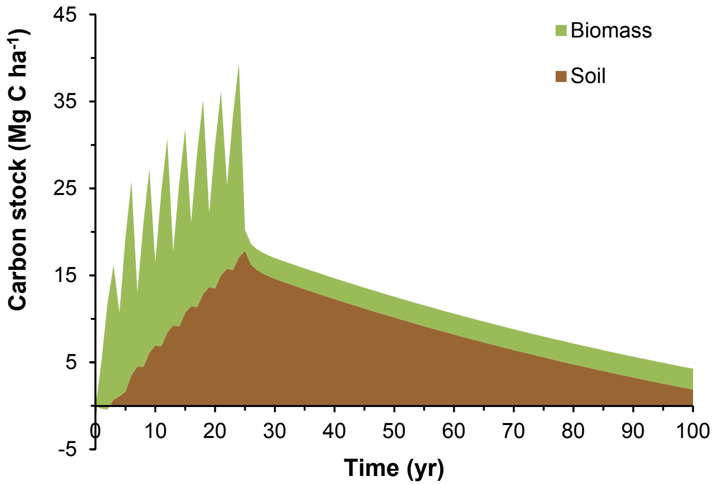

Figure 17. Carbon stock in a 25-year willow rotation followed by 75 year of green fallow (scenario 4 in Paper I). Biomass includes stems, leaves and roots.

The biogenic carbon dynamics of growing willow on all available fields in a landscape (Uppsala County) varied greatly with initial soil carbon content (Figure 18). The initial soil carbon content was within the range 19.5-447 Mg C ha^{-1}, with an average of 114 Mg C ha^{-1} (Paper IV). The carbon stock in standing biomass and soil after one willow rotation varied from 54 to 400 (average 130) Mg C ha^{-1}. Fields with initially low carbon content showed a build-up of soil carbon, while fields with a high initial soil carbon showed a decline. The average carbon change in all fields during one willow rotation was a build-up of 20 Mg C ha^{-1} on average (soil and standing biomass) (Figure 18a).

The reference land use green fallow displayed a decline for almost all fields during the same time frame, with an average loss of 9 Mg C ha^{-1} (Figure 18b). The net effect of growing willow on current fallow land in Uppsala County was thus on average a carbon build-up of 29 Mg C ha^{-1} during a 25-year period (one willow rotation), including both standing biomass and soil organic carbon (Figure 18c).

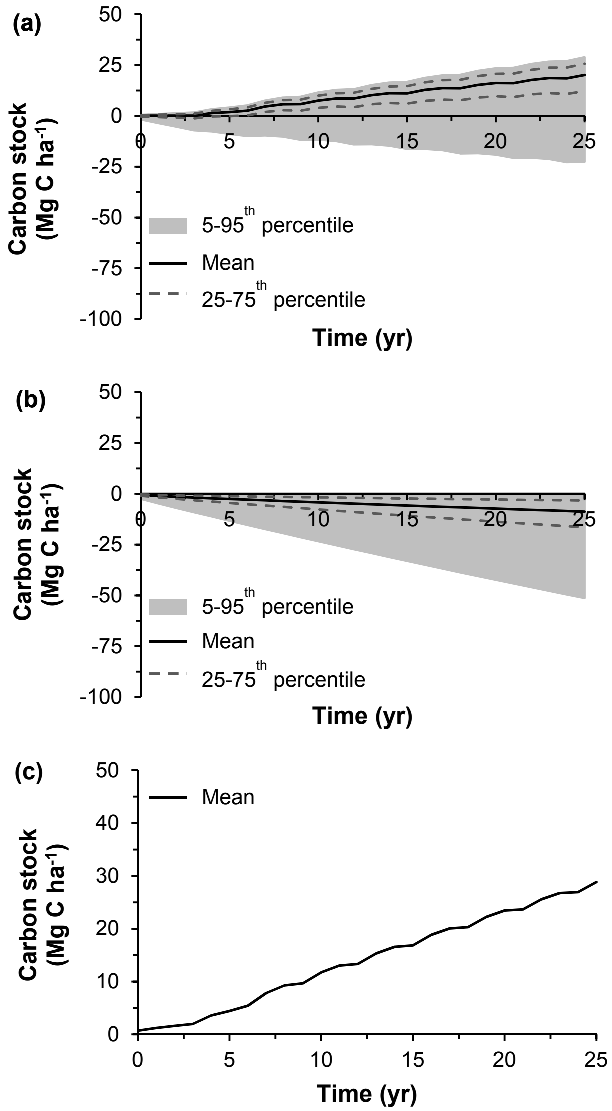

Figure 18. Carbon stock development (biomass and soil) of (a) willow fields, (b) the reference land use green fallow and (c) the net land use (*i.e.* difference between the land uses) during a 25-year period (base scenario in Paper IV). Carbon stocks are expressed in relation to baseline year zero, *i.e.* negative values indicate decreased carbon stock and positive values increased carbon stock compared with the initial value (N = 2083).

5.1.2 Forest residues

The biogenic carbon balance in the forest stands varied with climate zone (Papers II and III). Forest stands in southern Sweden had higher productivity, due to a warmer climate and longer growing season. Due to the resulting higher biomass input from residues, carbon stocks were thus higher after final felling than for northern regions (Figure 19). Harvesting tops and branches removed from the forest site carbon that would otherwise decompose over time, and stump harvesting removed additional carbon, *i.e.* carbon stocks were lowest after harvesting stumps (Papers II and III). The carbon stored in the biomass also decomposed faster in warmer climate zones, which meant that the net effect of harvesting forest residues was smaller in the south of Sweden than in the north. The differences between the three management options (no harvesting, harvesting of tops and branches, harvesting of stumps at clear-cut) decreased over time, and were very small after one rotation period (70-120 years).

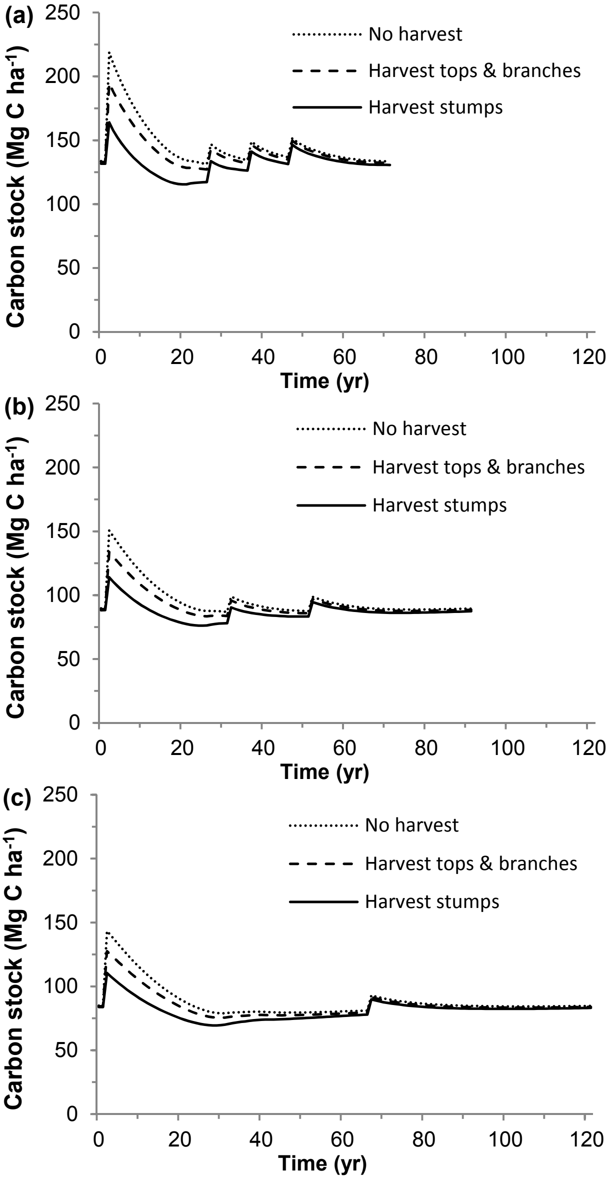

Figure 19. Carbon stock development in forest stands (not including standing biomass) located in three Swedish regions; (a) South; (b) Central; (c) and North, under three forest management practices: no harvesting of residues; harvesting of tops and branches; or harvesting of stumps (after removal of tops and branches) at final felling (Papers II and III). The increased carbon stock in the beginning is from final felling, and the following smaller inputs are carbon in residues from thinning.

5.2 Energy performance

Besides biogenic carbon dynamics, the use of fossil energy in the supply chains gave rise to greenhouse gas emissions. The total energy use during one rotation period was higher for willow than for forest residues, while stump harvesting had a higher fossil energy use than harvesting of tops and branches (Figure 20).

The production and use of mineral fertilisers were the processes requiring the most primary energy use in the willow supply chain, followed by harvesting, chipping and transport (Paper IV). In the forest supply chains (both for tops and branches, and stumps), the transport component required most energy (Papers II and III). The excavation of stumps was also very energy intense.

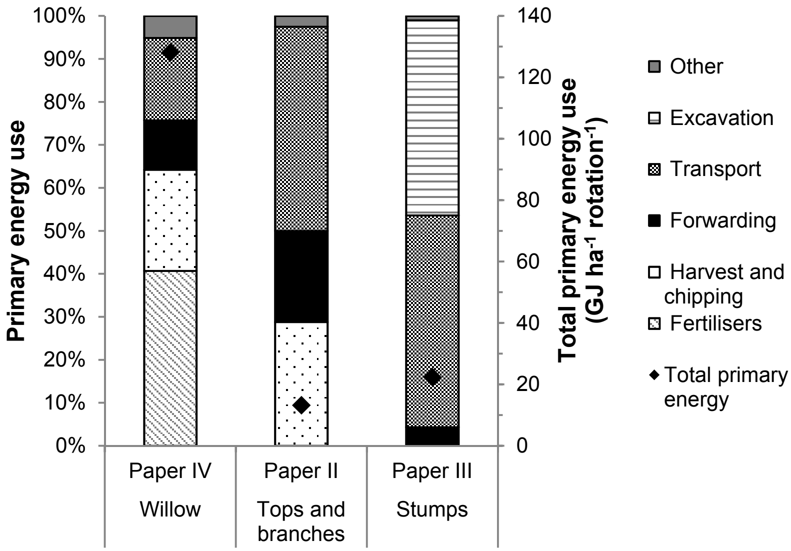

Figure 20. Left axis: Distribution of primary energy use in supply chains for willow (Paper IV, average transport distance in base scenario) and forest residues (tops & branches and stumps) (Central scenario in Papers II and III). Right axis: Total primary energy use during one rotation period (25 years for willow and 90 years for forest residues, *i.e.* central Sweden).

Due to the high energy use (and lower biomass extraction), willow gave the lowest energy return per unit of primary energy use, around 25-30 MJ MJ^{-1}, which was also dependent on yield level (Paper I) and transport distance (Paper IV) (Figure 21). The energy ratio for harvesting forest residues was higher, especially for tops and branches, which gave an energy ratio of around 42 for a single harvest in central Sweden (Paper II), compared with stumps where the corresponding value was around 33 (Paper III). The energy ratio was somewhat lower for northern Sweden, due to longer transport distances, and was higher for the southern forest stand, due to shorter transport distances.

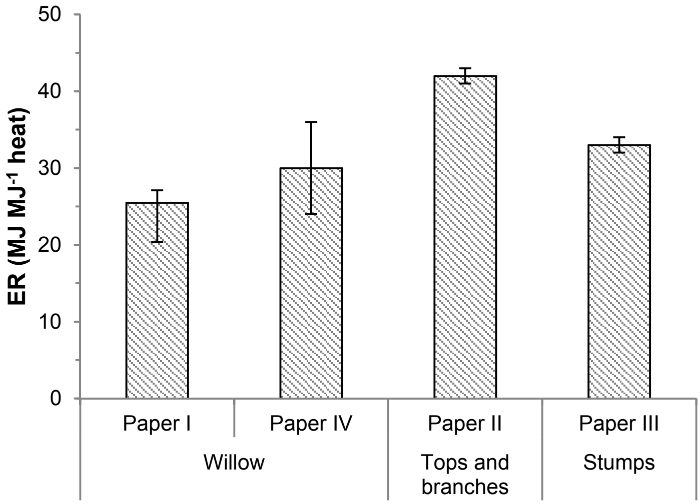

Figure 21. Average energy ratio (ER, energy output per unit primary energy used) for willow and forest residues (tops & branches and stumps). Based on forest system located in central Sweden (Papers II and III). The ER for willow varied with yield level (Papers I-IV) and transport distance (Paper IV).

5.3 Climate impact

The analysis of biogenic carbon dynamics showed that willow can sequester CO_2 from the atmosphere to the standing biomass and soil pool, and thereby give a net uptake of CO_2 (Papers I and IV). Harvesting forest residues will not give an uptake of CO_2, but will merely move the emissions to earlier in time (relative decomposition) (Papers II and III). From a biogenic carbon perspective, willow thus has benefits over forest residues. However, the energy analysis showed that forest residues require less fossil energy and give a higher energy return than willow. In the next sections, the climate impact of biogenic carbon fluxes and of use of fossil energy in the supply chains is calculated by the two climate metrics global warming potential and temperature response.

5.3.1 Global warming potential

Since global warming potential (GWP) converts all emissions into CO_2-equivalents for a set time period, the choice of time frame plays an important role for the results, particularly for biogenic carbon fluxes that can vary greatly in time. This has a particular impact for conventional forests, where biogenic

CO_2 fluxes occur over a long time frame. Dividing the results into fossil-based emissions from supply chains and biogenic carbon emissions is therefore helpful for interpreting the results (Figure 22).

The GWP_{100} for the supply chain of willow was between 7.2 and 10.2 g CO_2-eq MJ^{-1} heat (Paper IV and I, respectively). This was higher than for forest residues, which was around 3.5 g CO_2-eq MJ^{-1} for tops and branches and 4.2 g CO_2-eq MJ^{-1} for stumps harvested in central Sweden (Papers II and III). Adding emissions for biogenic carbon fluxes (during a 50-year time frame) gave a negative GWP for willow (due to carbon sequestration) of around -4.8 to -8.2 g CO_2-eq MJ^{-1} heat (net land use) (Paper I and IV, respectively). Forest residues did not give a cooling effect, since no CO_2 was captured from the atmosphere. The total warming potential, including supply chains, was around 22 g CO_2-eq MJ^{-1} heat for tops and branches, and around 33 g CO_2-eq MJ^{-1} heat for stumps (50 years after a single harvest in central Sweden) (Papers II and III). This value would have been higher if a shorter time frame had been used, and lower with a longer time frame.

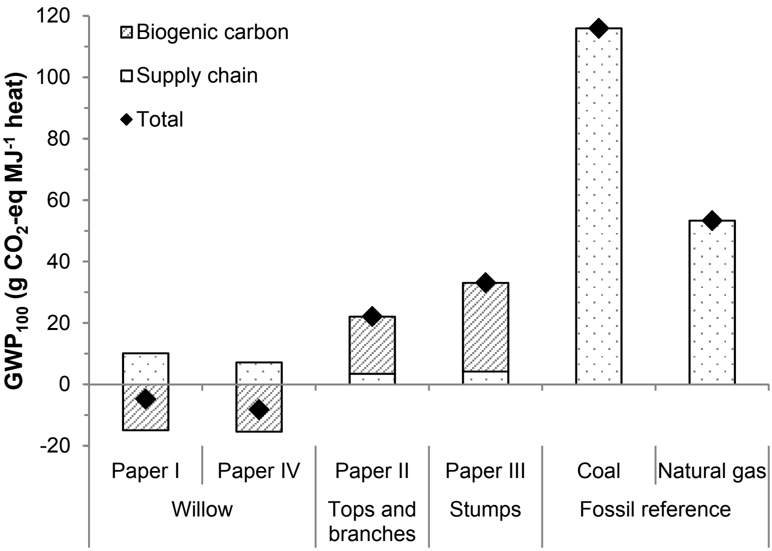

Figure 22. Global warming potential (GWP_{100}) for willow and forest residues (tops & branches and stumps) calculated based on accumulated greenhouse gas fluxes during a 50-year time frame (single harvest, Papers II and III). Values represent average for base scenario (Papers I and IV) and central forest scenario (Papers II and III). Supply chain includes greenhouse gas emissions from all processes included in system boundaries, excluding biogenic carbon fluxes from litter decomposition, net soil organic carbon changes and biomass combustion. Net soil organic carbon is the difference between bioenergy land use and reference land use (*i.e.* green fallow or no harvesting of forest residues). Fossil reference fuel data are from Paper IV (*i.e.* heat allocated values).

The GWP_{100} of the two fossil reference fuels, hard coal and natural gas, was much higher than for all types of biomasses, both when including and excluding biogenic carbon fluxes. Coal had a higher warming potential than natural gas, which was due to the composition of the fuels (Figure 12) and emissions differences during the production and distribution of the fuels (Table 6).

5.3.2 Temperature response

In contrast to global warming potential, the temperature response metric shows the absolute effect over time. For the same reasons as the global warming potential, the temperature response of willow energy was negative (*i.e.* cooling effect) when including biogenic carbon fluxes. This cooling effect was enhanced with higher willow productivity, since more CO_2 was captured from the atmosphere (Figure 23).

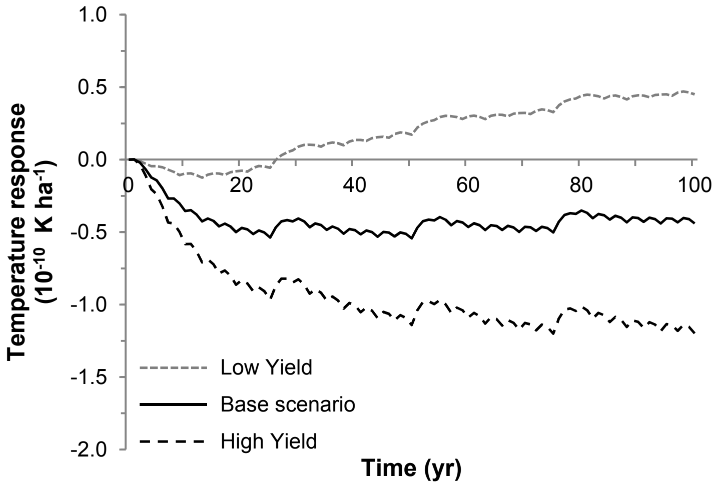

Figure 23. Temperature response for willow energy with different yield levels (scenarios 1, 6-7 in Paper I).

Low willow productivity (~60% lower yield during one rotation period) decreased the uptake and could even give a warming effect over time, but the net effect of substitution of fossil coal was still negative (*i.e.* a cooling effect) (scenario 6 in Paper I) (Figure 24). Terminating the willow plantation after one rotation (25 years) gave a cooling of the temperature even after 100 years (partly due to coal substitution during the first 25 years and partly due to carbon sequestration) (scenario 4 in Paper I).

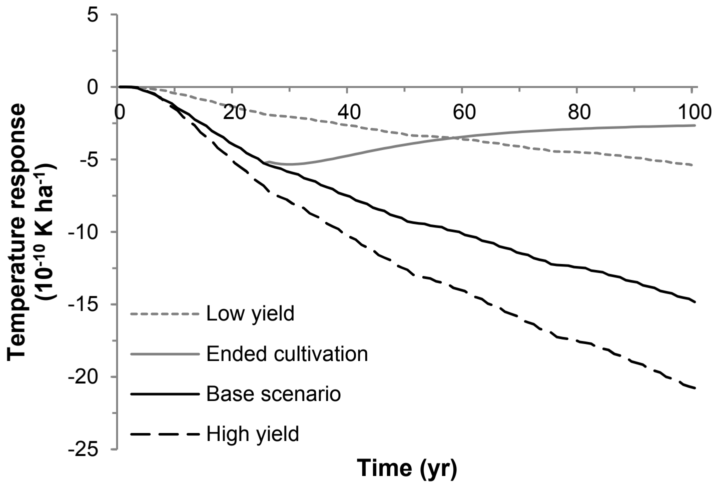

Figure 24. Temperature response for willow energy when substituting hard coal for heat production (scenarios 1, 4, 6-7 in Paper I).

Besides willow productivity, the initial soil carbon content had a large impact on the temperature response (Figure 25a). The landscape analysis showed that fields with high starting values showed a carbon stock decrease over time, while fields with lower initial carbon content gave a build-up of carbon (Paper IV). However, most fields displayed increased carbon stocks over time.

When considering the net land use effect (*i.e.* difference compared with green fallow), the variation in temperature responses for the individual fields was relatively small (Figure 25b). This was due to lower carbon build-up (or larger decrease of soil organic carbon) under fallow land than willow cultivation (assuming constant yield for all fields).

The final temperature response of willow energy harvested from all fields (*i.e.* a landscape perspective) was around $-6 \cdot 10^{-16}$ MJ^{-1} heat when considering the net land use effect, and around $-2 \cdot 10^{-16}$ MJ^{-1} heat when only including the willow land use (after 100 years) (Figure 25c).

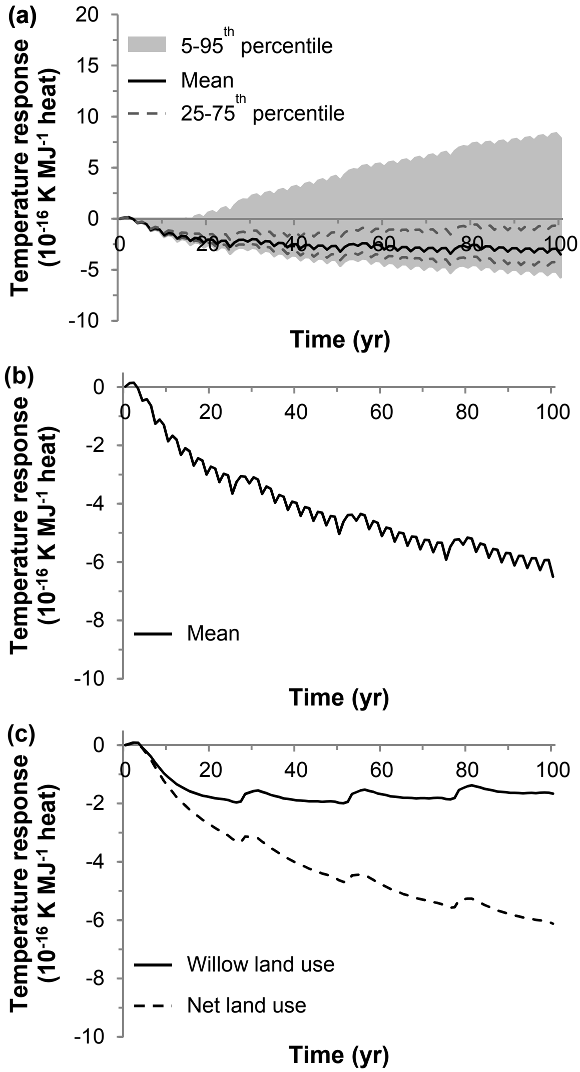

Figure 25. Temperature response of (a) each willow field in Uppsala County when only including biogenic carbon fluxes from willow cultivation, (b) each willow field in Uppsala County when including net land use effect, *i.e.* difference compared with green fallow, and (c) the combined effect of willow energy from the landscape, including either biogenic carbon fluxes from willow cultivation or net land use effect. All figures include temperature response of fossil greenhouse gas emissions from supply chains (N = 2083) (Paper IV).

Mapping the final temperature response of willow energy (year 100) displayed the influence of transport distance (when including the net land use effect, *i.e.* difference compared with green fallow) (Figure 26). However, as mentioned previously, transport made a relatively small contribution to the overall climate impact.

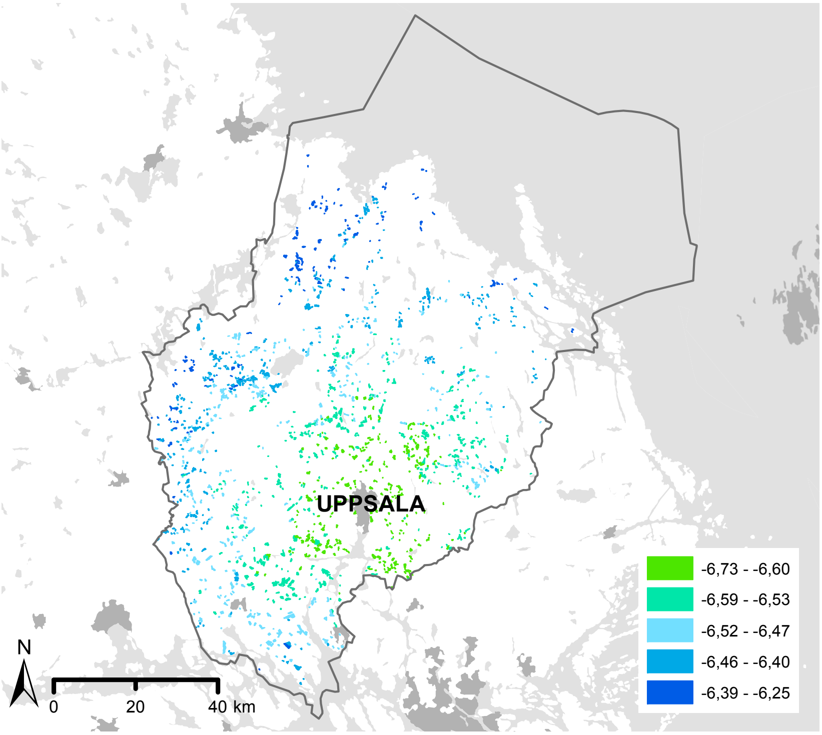

Figure 26. Final temperature response (year 100) of willow energy from the individual willow fields, calculated based on net land use effect (*i.e.* difference compared with green fallow), including fossil greenhouse gases from supply chains (Paper IV). Background map: Overview map 1:1 000 000 © Lantmäteriet.

Willow productivity was assumed to be constant for all fields, but to study the influence of yield variations (due to varying soil texture or other site-specific growing conditions), a random yield variation of ±20% was tested. This affected the temperature response of the individual fields, but the average temperature response over the whole landscape was affected to a very small degree (Figure 27).

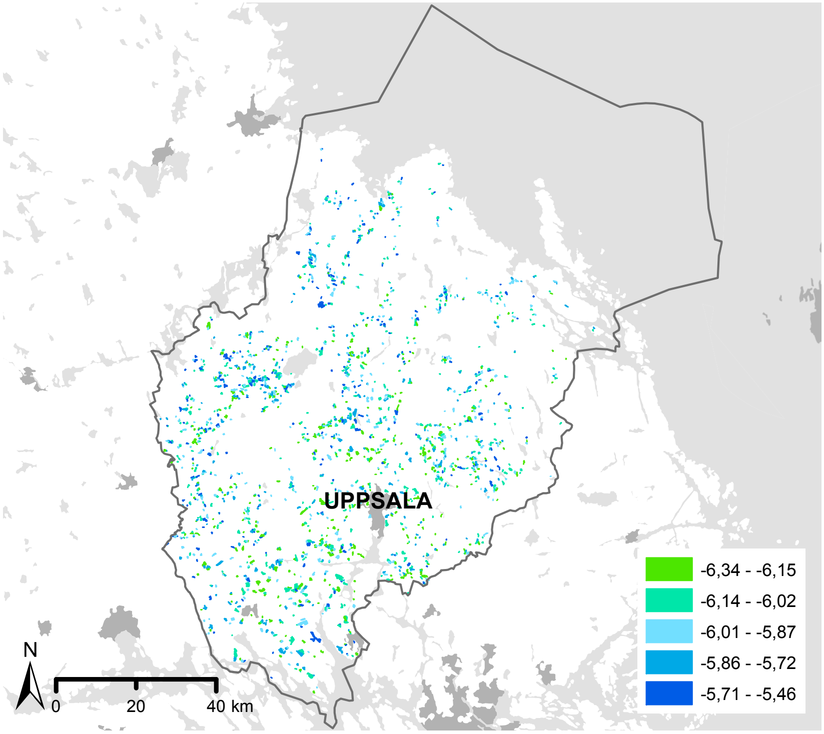

Figure 27. Final temperature response (year 100) of willow energy from the individual willow fields, calculated based on net land use effect and random yield level, including fossil greenhouse gases from supply chains (Paper IV). Background map: Overview map 1:1 000 000 © Lantmäteriet.

By selecting the best performing fields, higher climate change mitigation potential per MJ heat was reached, which consequently affected the total amount of heat supplied. The result varied depending on whether the net land use effect was considered, or only the biogenic carbon dynamics under willow cultivation (Figure 28).

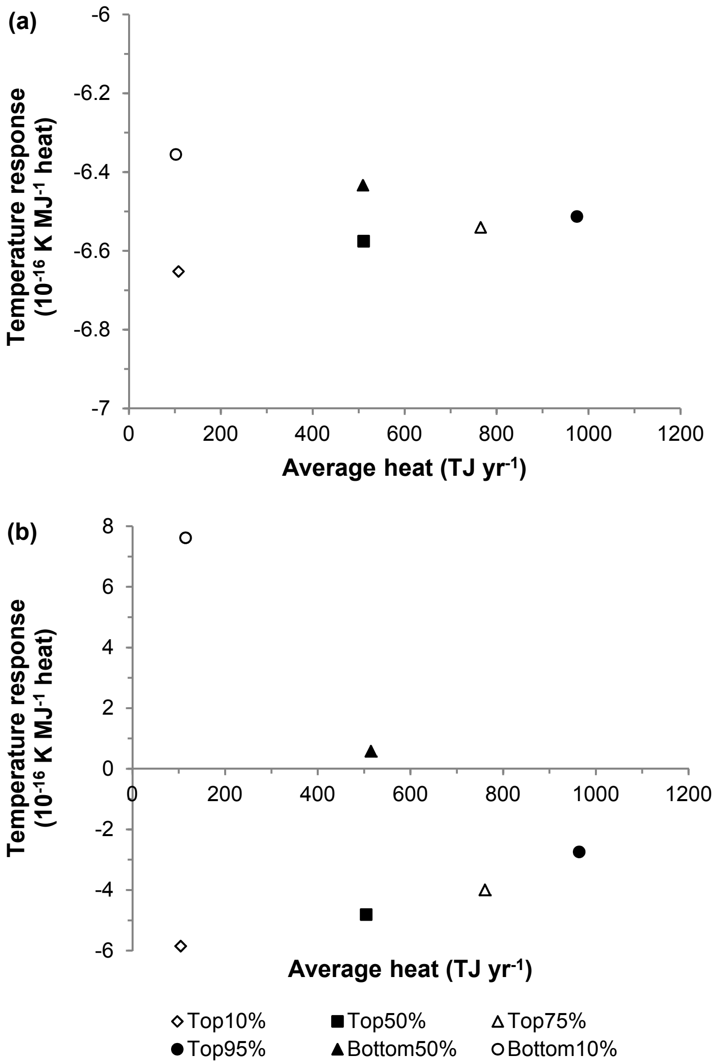

Figure 28. Final temperature response after 100 years of utilising willow energy harvested over a landscape and average heat produced per year when considering: (a) willow supply chains and the net land use effect, *i.e.* the difference between willow and the reference land use green fallow; or (b) willow supply chains and willow land use. The diagrams show the effect when selecting the best performing fields (top 10-95%) and worst performing fields (bottom 10-50%) in terms of climate impact (note scale differences) (Paper IV).

The temperature response of forest residues showed a warming effect for both tops and branches and stumps. At single harvest (year one), the temperature response peaked at around $0.5 \cdot 10^{-16}$ K MJ^{-1} heat after about one decade, and thereafter decreased over time (Figure 29). The net effect of harvesting forest residues for energy was calculated as the yearly difference between biomass combustion (harvesting in year one) and decomposition (no harvest). This gave an initial pulse emission of biogenic CO_2 followed by negative emissions (due to the 'avoided' decomposition emissions). This (together with the decay of methane and nitrous oxide in the atmosphere) gave a final temperature response of around $0.06 \cdot 10^{-16}$ K MJ^{-1} heat after one rotation period (90 years, central Sweden).

The temperature response of stumps was higher than for tops and branches during the first decades, due to the slower decomposition of stumps. After one forest rotation period this difference was very small. The temperature response of a single use of hard coal was much higher for the whole time frame, while natural gas gave a slightly lower impact during the first decade.

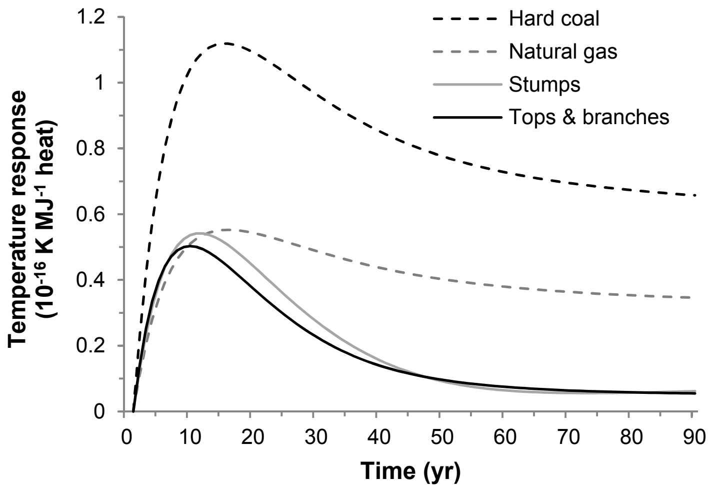

Figure 29. Temperature response of a single harvest (year one) of tops and branches or stumps for bioenergy, compared with the use of hard coal and natural gas (Central scenario in Papers II and III).

Forest stands located in the northern climate region gave lower temperature responses than in the south, due to slower decomposition. The carbon would then be stored in the biomass for a longer time if no harvesting takes place, *i.e.* the biomass would work as a carbon sink (Figure 30).

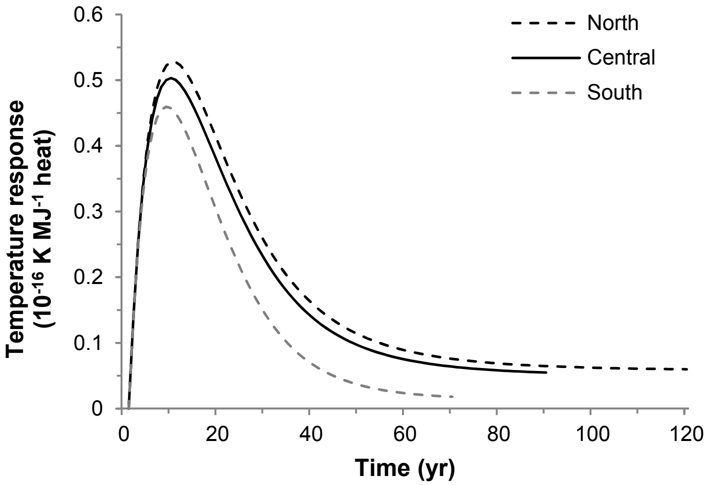

Figure 30. Temperature response of a single harvest (year one) of tops and branches in south, central and north Sweden for bioenergy (Paper II).

The temperature response of continuous harvesting (theoretical landscape) displayed a more even impact over time, where the temperature response levelled out at around $20 \cdot 10^{-16}$ K MJ^{-1} heat produced from stumps (Central Sweden scenario in Paper III) (Figure 31). The temperature response of the fossil fuel alternatives, natural gas and hard coal, was a continuous increase. The climate impact of forest residues was thus lower than for coal and natural gas over time, both when studying a single harvest and continuous harvesting. However, the interval before stump bioenergy gave a lower climate impact than natural gas was slightly longer when considering continuous harvesting, around 20-30 years.

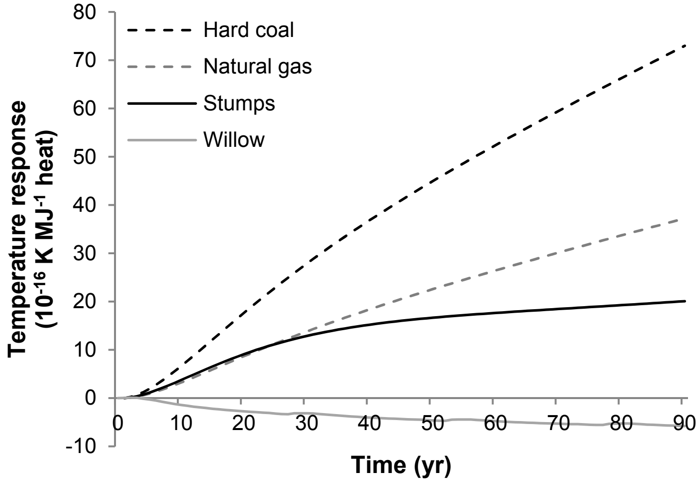

Figure 31. Temperature response of continuous harvesting of stumps for energy (theoretical landscape in central Sweden) compared with continuous use of hard coal and natural gas for producing district heating (Paper III). The diagram also shows the temperature response of willow energy from a landscape perspective (net land use effect, *i.e.* difference compared with the reference land use green fallow).

6 Discussion

6.1 General discussion

The findings in this thesis correspond well to those of previous life cycle assessments of willow systems (see section *3.3.3. Previous LCA of solid bioenergy*), which report cooling effects due to carbon sequestration. However, this thesis also displayed the importance of yield levels (Paper I), initial soil organic carbon content and reference land use (Paper IV). The average global warming potential found in this thesis was 6.9 g CO_2-eq MJ^{-1} heat (Paper IV) for the willow supply chain, while for the whole system (including biogenic carbon fluxes), the average was about -8 g CO_2-eq MJ^{-1} heat (net land use effect) or -2 g CO_2-eq MJ^{-1} heat (willow land use) (Paper IV). For the willow supply chain, the production and use of fertilisers required most primary energy and contributed most to the global warming potential.

The global warming potential of the supply chain for forest residues was lower than for willow, since less fossil energy was required. The supply chain for tops and branches (around 3.5 g CO_2-eq MJ^{-1} heat) also gave lower warming potential than the supply chain of stumps (around 4.2 g CO_2-eq MJ^{-1} heat), since harvesting stumps is more energy intense. Including biogenic carbon fluxes in GWP for forest biomass is problematic since the chosen time frame has a high impact on the results, which makes it difficult to compare forests with different rotation times. In a 50-year time frame, the total global warming potential (including biogenic carbon) was around 20 g CO_2-eq MJ^{-1} heat for tops and branches and 30 g CO_2-eq MJ^{-1} heat for stumps.

Using the temperature response metric is a better option for assessing the climate impact of bioenergy systems, since it better displays the impact over time. The final temperature response after one forest rotation period in central Sweden (90 years) was around $20 \cdot 10^{-16}$ K MJ^{-1} heat for stumps (continuous harvesting every year), which is of the same magnitude as that reported by *e.g.* Zetterberg and Chen (2015). The corresponding value for willow was

$-6\cdot10^{-16}$ K MJ^{-1} heat (landscape, net land use), and willow is thus a natural way to capture and store carbon. Assuming that the same temperature response could be achieved for all unused agricultural land globally if planted with willow (~440 million ha, 70 EJ), a cooling effect in the order of -0.03 degrees K could be reached in a 50-year time perspective. The corresponding value for all cropland globally (~1500 million ha, 250 EJ) would be -0.1 degrees K. Short-rotation coppice like willow could thus play an important role in climate change mitigation strategies.

Producing heat and power from tops, branches and stumps from existing forests does not capture and store carbon, but rather moves the timing of the CO_2 emissions. However, the climate impact of forest residues was still lower than for the reference fossil fuels. The temperature response of continuous consumption of hard coal and natural gas for the next 90 years was in the order of 35 and $70\cdot10^{-16}$ K MJ^{-1} heat, respectively, with a continual increase over time. Replacing fossil energy with alternatives like woody biomass, as well as decreasing total energy consumption, is thus very important for mitigating climate change.

6.2 Uncertainties

Some degree of uncertainty is unavoidable when conducting a life cycle assessment, which should be considered when interpreting the results. There are many sources of uncertainties and variabilities: *e.g.* data inaccuracy, missing or unrepresentative data, model uncertainty, uncertainty due to choices, spatial and temporal variability, variability between objects and sources, epistemological uncertainty and uncertainty due to mistakes (Björklund, 2002). In the following section, the main uncertainties in this thesis are discussed.

Biogenic carbon fluxes were shown to have a high impact on the final climate impact for both willow and forest residues (Papers I-IV). Modelling future soil carbon stocks is associated with relatively large uncertainties, however. For willow, a problem is the lack of long-term empirical data for validating the results. To test the parameter uncertainty of the soil carbon model, the humification factor (describing the decomposability of the biomass) and the external factor (accounting for *e.g.* weather and soil texture) were varied in a sensitivity analysis (Paper I). A high humification factor gave a larger carbon build-up, while a high external factor gave a smaller build-up (*i.e.* more carbon released as CO_2 due to faster decomposition). Furthermore, the willow productivity had a strong influence on the results. Therefore the net primary production of leaves and fine roots was varied (Paper I). The productivity of fine roots was found to have a larger influence on the carbon stock development than the productivity of leaf litter (due to slower decomposition and lower decomposability of belowground biomass).

To account for differences in soil properties in the landscape analysis, the external factor was varied with soil texture to give more representative values of the spatial variability (Paper IV). A constant willow yield level was assumed, owing to lack of a suitable biomass production model. Instead, the yield was randomly varied in a scenario analysis, which gave an effect on a stand level perspective, while the overall climate impact over the whole landscape was affected to a small degree (Paper IV). The total climate impact was also dependent on the net land use effect, *i.e.* difference compared with the alternative land use (continued fallow). A lower willow yield would most likely also mean lower fallow productivity, and the overall effect would then be small.

For the forest carbon model, according to Ortiz *et al.* (2013) the largest uncertainty is that in annual litter production. However, the most important factor in this thesis was the decomposition rate of the biomass, since annual litter production was assumed to be unaffected by harvesting of forest residues. An uncertainty analysis was performed to assess the effect of parameter uncertainty in the Q model (Paper III). The results showed a relatively small variation in the final global temperature response of stump harvesting. Furthermore, stump harvesting leads to soil disturbances, which may increase the decomposition of old organic matter by altering the physical environment for decomposer microbes. To assess the possible outcome of soil mixing on the overall climate impact of stump harvesting, a sensitivity analysis was performed where the mean annual soil temperature was increased in the Q model (Paper III). This gave a small warming effect on the temperature response after a single harvest of stumps due to the added emissions of old humus.

How future climate change will affect carbon stocks is debated. Both productivity and decomposition rates are dependent on climate factors (*e.g.* temperature, precipitation and length of growing season) that vary over the globe. Forest carbon stocks (biomass and soil) have increased in Europe during recent decades (Köhl *et al.*, 2015), but globally they have decreased, with the largest decrease occurring in South America and Africa. There are projections that global warming may increase decomposition rates in the future, but it is still uncertain how sensitive the decomposition of soil organic matter is to temperature change (Smith *et al.*, 2008). The productivity in high-latitude countries like Sweden will also be limited by the growing season (due to limited sunlight) even if temperatures rise, which could have negative effects on the total carbon stock in boreal forests (biomass and soil).

The uncertainties of the climate model has been assessed in previous studies, as reviewed by Myhre *et al.* (2013b). The atmospheric lifetime and radiative efficiency of greenhouse gases determines the uncertainty of the cumulative radiative forcing, which affects the uncertainty of both climate metrics used in this thesis. Since the temperature response metric goes one step further down the cause-effect chain, the associated uncertainties are higher than for the global warming potential metric. On the other hand, the relevance is higher, since the result is displayed as temperature change, as are many climate targets (*e.g.* the Paris agreement (UNFCCC, 2015)). The temperature metric also considers the timing of greenhouse gas fluxes, and can thus account for temporal variability.

Soil N_2O emissions from application of mineral fertilisers and biomass residues accounted for a relatively large share of the greenhouse gas emissions in the willow supply chain (Papers I and IV). The emission factors used for calculating the emissions are uncertain, however, and therefore a sensitivity analysis was performed which showed that the direct N_2O emissions from nitrogen application and the indirect N_2O emissions from nitrogen leaching had a relatively small impact on the overall climate impact (Paper I). No soil N_2O fluxes were included for the forest system (Papers II and III), since the effect of harvesting forest residues is unclear.

6.3 Stand and landscape perspective

The issue of stand compared with landscape perspective has two dimensions: (1) single harvest compared with continuous harvesting; and (2) spatial variability. The first point has more relevance the longer the rotation period of the forest system, since the time between harvests (*i.e.* energy output) is longer. Evaluating the climate impact of an energy system based on forest residues requires a landscape perspective for a yearly energy output. However, a stand perspective is helpful for better understanding the biogenic carbon dynamics. In this thesis, both perspectives showed lower climate impacts than for the fossil fuels coal and natural gas over time (Papers II and III).

Willow is often harvested with a three-year cutting cycle, which means that the energy output has a much shorter interval than for conventional forest. The temperature response of a willow stand has similar dynamics as for a willow landscape. The importance of a landscape perspective for willow is therefore more to capture spatial variations within a landscape in order to give more realistic values. From a decision-making perspective, in terms of policy making a landscape perspective is more relevant if the overall effect of an altered energy system is of interest. An additional value of a real landscape perspective is the possibility to evaluate future biomass potential in a region.

6.4 The role of biogenic carbon

Papers I-IV all showed that biogenic carbon dynamics are of major importance for the overall climate impact of bioenergy systems. Biogenic carbon had a larger impact for forest residues than for fossil greenhouse gases, but the effect decreased over time at single harvest (Papers II and III), or started levelling out after some decades of continuous harvesting (Paper III).

For the willow system, the impact of biogenic carbon even gave a negative climate impact (*i.e.* cooling effect). The carbon sequestration for willow cultivation was shown to be temporary, and if the plantation was broken up and returned to fallow land, the captured carbon was shown to return to the atmosphere over time (scenario 4 in Paper I). The carbon sequestration still showed beneficial effects during the soil storage, but growing willow should not be considered as a counteracting measure that allows more fossil fuel to be used. It should instead be considered as a complement in efforts to decrease greenhouse gas emissions, because although biogenic carbon fluxes had the largest climate effect, emissions from fossil fuel use will add additional gases to the atmosphere-biosphere pool. Developing efficient bioenergy supply chains with low fossil fuel use is important from both an environmental and an economic perspective.

The choice of starting and ending point of the study also plays an important role for the biogenic carbon balance. In this thesis a forward looking perspective was applied, since it was considered to be most relevant for assessing future climate change mitigation potential. However, if an existing willow plantation were studied, or if land were afforested with conventional forest for producing heat and power, the biogenic carbon fluxes would be different.

6.5 Conventional and short-rotation forestry

The question of whether to grow willow on agricultural land or establish conventional forest may arise when deciding the best measure to produce solid bioenergy from unused agricultural land. Short-rotation coppice has advantages compared with conventional forest, since the harvesting interval is shorter, which gives faster energy return and thereby economic return for the land owner. Under Swedish regulations, agricultural land is still considered cropland when willow is established and farmers can thereby apply for different subsidies for their land, as long as the willow is harvested at an interval of at least 10 years (Swedish Board of Agriculture, 2016). Willow cultivation also gives greater freedom for the land owner to terminate the plantation after one rotation period and go back to traditional farming.

A disadvantage with willow is the limited end use, since longer-rotation forestry can be used as timber or pulp wood, in addition to energy. This can provide greater security if the market turns in the future. In this regard, short-rotation poplar could be an alternative that gives greater freedom for the land owner, since it can be used for energy or for timber or pulp wood. Short-rotation poplar has also been shown to give climate benefits (Porsö & Hansson, 2014).

The pressure on land could also come to increase in the future, both as a result of climate changes and due to population growth, since urbanisation may lead to expansion into agricultural land. This, together with a national strategy for food security, could potentially lead to less interest in using arable land for energy crops. Willow is also sensitive to frost, which makes it unsuitable for northern regions of Sweden, but this energy crop could play a larger role in southern regions where more of the country's agricultural land is located.

Forest residues have the advantage that they are available unused biomass that requires no land use change (only management change). The greatest biomass potential is also in forest. However, the largest forest areas are located in northern Sweden, while the largest energy need is in the south. For long-distance transport, pellet systems could be an alternative (Porsö, 2017). The two types of biomass are complementary in that regard.

6.6 Bioenergy and sustainability

The assessment of the climate impact of willow and forest residues in this thesis showed lower climate impact than for the fossil fuels coal and natural gas, and even negative temperature responses for willow energy. However, there are more aspects than solely climate change to consider when determining whether bioenergy from willow and forest residues is sustainable. The concept of sustainability was defined by the United Nations (1987) as "a process in which changes are made consistent with future as well as present needs", and is usually built on three pillars: economic, environmental (or ecological) and social (Zamagni, 2012).

There are concerns regarding potential negative environmental aspects that are limiting the use of forest residues today. For instance, the Swedish Forest Stewardship Council (FSC) standard (which certifies around half of Swedish forests) has so far not approved stump harvesting and only a few exceptions have been made, primarily for research purposes, which may limit further expansion (FSC, 2016). A major concern for forest bioenergy, especially regarding stump harvesting, is potential negative effects on biodiversity and also nutrient loss, which may have negative consequences on future forest productivity. Dead wood forms a major habitat for organisms (*e.g.* fungi, mosses and insects) and removing forest residues may therefore have negative consequences for the biodiversity of the forest. Another concern is the risk of 'ecological traps' when forest residues are stored in piles that can attract insects for breeding substrate and are later combusted for energy.

Since stump harvesting is an untested method and due to concerns raised regarding potentially negative effects, a large research project studying different environmental aspects has been carried out recently (de Jong & Dahlberg, 2017; Persson, 2016). de Jong and Dahlberg (2017) concluded that the impact of harvesting forest residues (compared with clearcutting) has a small to negligible impact on species of conservation interest. They also concluded that there are reasons for limiting the amount of harvested residues at landscape level. However, it is difficult to estimate the importance of forest residues, and therefore the level to which outtake should be limited is also uncertain. The risk of biodiversity loss is higher when forest residues are harvested from deciduous tree species, since more red-listed species are dependent on the biomass of deciduous trees. According to de Jong *et al.* (2017), the risk of biodiversity loss and species extinction increases when more than 50% of the clear-cut area is harvested with tops and branches, while the limit for stumps is around 10-20%.

Besides biodiversity loss, soil mixing during stump harvesting could, in the same way as mechanical site preparation, eliminate competing vegetation, which could have a positive effect on nutrient availability for future tree growth (de Jong *et al.*, 2017).

Short-rotation coppice like willow has been shown to have positive values for biodiversity compared with conventional farming (Verheyen *et al.*, 2014; Augustson *et al.*, 2006). For willow energy, the main limiting factor to date has been the lack of economic return, even though analyses of willow have shown positive values compared with other energy crops in terms of cost and energy efficiency (Börjesson, 2006; Heller *et al.*, 2003). However, this has been 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, as was also shown in this thesis

(Paper I), and the results for willow plantations in practice have not lived up to the high yield expectations in the past (Dimitriou *et al.*, 2011).

Energy and climate targets worldwide are all pointing towards a fossil-free society. The demand for bioenergy will therefore most likely increase in the future. This thesis showed that replacing hard coal and natural gas with bioenergy from forest residues and willow is beneficial for climate change mitigation. However, in order to determine how much biomass can be extracted from Swedish forests and agricultural land, more transdisciplinary research that considers aspects in addition to climate impact is required.

7 Conclusions

The overall conclusions of this thesis were:

- Using woody biomass for bioenergy gave lower climate impacts than the fossil fuels hard coal and natural gas. However, the initial climate impact of using forest residues was slightly higher than for natural gas.
- Willow energy gave a lower climate impact than forest residues, but the energy return was higher for forest residues.
- The fossil greenhouse gas emissions from the bioenergy supply chains had relatively little impact on the overall climate impact compared with biogenic carbon fluxes, but it is still important to decrease the consumption of fossil fuels in order to achieve high energy ratios and a fossil-free society.
- Using a time-dependent LCA for evaluating woody biomass systems is helpful, since it considers the timing of biogenic carbon fluxes, which can vary greatly between short- and long-rotation forest systems.
- Both a stand and landscape perspective can be useful in LCA. Applying a stand perspective is valuable for displaying and better understanding the dynamics of biogenic carbon. Applying a landscape perspective is useful for: (1) giving more realistic values of climate impacts by including spatial variations; (2) modelling continuous harvesting to fulfil future energy demands; (3) evaluating the effect of increased bioenergy use from a landscape, which is more relevant for decision making; and (4) assessing future biomass potential in a region.

The conclusions on willow energy were:

- Growing willow on previous fallow land gave a negative climate impact, *i.e.* cooling temperature response, due to increased soil organic carbon content and carbon in standing biomass.

- Willow productivity was highly important for the magnitude of the climate impact, since higher yield increases carbon uptake in biomass and soil and, conversely, low productivity decreases uptake and thus gives a higher climate impact. Attaining high yield levels was also important for the overall energy performance of the willow energy system.
- The carbon sequestration under willow cultivation was temporary and, when terminated, the carbon would slowly return to the atmosphere. However, the temporary carbon uptake was still beneficial from a climate change mitigation perspective.
- The initial carbon content was important for soil organic carbon changes under both willow and fallow land use. High initial carbon content could give decreased carbon content under willow cultivation, but the carbon content would decrease even more under fallow. Thus the net effect of willow cultivation was beneficial from a climate change mitigation perspective.
- The climate impact could be improved by selecting the best-performing fields, but all fields should be used in order to maximise the energy output.

The conclusions on harvesting forest residues for energy were:

- A single harvest of forest residues for energy gave an initial warming impact, due to the release of biogenic CO_2 at combustion. This warming effect decreased over time, as the biogenic CO_2 would have been released by decomposition in any case.
- Due to the faster decomposition rates in southern Swedish climate zones, the climate impact was smaller than in the northern region. Northern forest stands worked as carbon sinks for a longer period when not harvested and, as a consequence, the climate impact of harvesting forest residues from northern sites was slightly higher than for southern sites.
- Stumps gave a slightly higher climate impact than tops and branches, since stumps decompose more slowly, *i.e.* act as a carbon sink for a longer period when not harvested. Stumps also required more energy in the supply chain, which gave a lower energy return.
- With continuous harvesting of stumps, the temperature response levelled off over time, while with continuous use of hard coal and natural gas it constantly increased over time.

8 Future research

To build on the work in this thesis, empirical data on willow cultivation are needed for validating soil carbon balances. Models for calculating net primary production of short-rotation coppice under different growing conditions (*e.g.* soil texture, water availability, climate region, clone *etc*.) would also improve the results. Furthermore, this thesis showed that the reference land use chosen plays an important role for the results, and therefore it would be very interesting to study other types of energy crops, as well as applying the landscape methodology developed here to a forest landscape.

The goal for the future is to devise sustainable energy systems that do not contribute to further climate change or affect other sustainability aspects in a negative way. There is therefore a need for integrated models that consider other relevant aspects, such as biodiversity, nutrient balances, productivity, economic return or social aspects, as well as combining bioenergy systems studies with *e.g.* food production systems.

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