Time-Dependent Climate Impact of Production and Use of Wood Pellets from Short Rotation Forestry and Logging Residues

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Abstract

Anthropogenic greenhouse gas (GHG) emissions are the main cause of climate change, with combustion of fossil fuels and land use changes being the main source of emissions. Wood pellets are considered a viable replacement for fossil fuels. Therefore this thesis sought to increase the knowledge base for planning new wood pellet systems. This was done by investigating the energy efficiency and time-dependent climate impact of production and use of wood pellets supplied to the Swedish heat and power sector from short rotation forestry grown in central Sweden (willow and poplar) and in central Mozambique (eucalyptus), and from residual forest biomass extracted from final felling in Sweden. In conventional life cycle assessment (LCA), all emissions from the system under study are usually summed up into a single pulse, irrespective of when in time they occur, but this approach overlooks temporal CO_2 fluxes between the soil, biomass and atmosphere connected to bioenergy systems. This motivated the development of a new time-dependent approach for conducting LCA in which both the timing and magnitude of GHG fluxes are considered in climate impact assessment.

The main findings were that all three wood pellet systems investigated were a better alternative than fossil coal for heat and power production from a climate impact perspective, both in terms of global warming potential (GWP) and global mean surface temperature change (ΔT_S). Establishing short rotation forest plantations on former agricultural land provided carbon sequestration potential in both live biomass and soil, which resulted in an initial negative ΔT_S, *i.e.* a cooling effect on the temperature. However, wood pellets produced from logging residues extracted from final felling of a boreal coniferous forest stand (Norway spruce) in northern Sweden resulted in a positive ΔT_S, *i.e.* warming temperature effect. Net emissions of biogenic CO_2 accounted for by far the largest part of this temperature effect, while GHG emissions from harvesting, upgrading and transport were of less importance. The energy output of the wood pellet systems studied was 7 to 11 times the primary energy input.

Keywords: Global warming, life cycle assessment, LCA, temperature change, biogenic carbon, torrefied wood pellets, bioenergy, willow, poplar, eucalyptus

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Dedication

To Karin and Einar

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 Ericsson, N., Porsö, C., Ahlgren, S., Nordberg, Å., Sundberg, C. and Hansson P.-A. (2013). Time-dependent climate impact of a bioenergy system – methodology development and application to Swedish conditions. *GCB Bioenergy* 5(5), 580-590.

II Porsö, C. and Hansson P.-A. (2014). Time-dependent climate impact of heat production from Swedish willow and poplar pellets – In a life cycle perspective. *Biomass and Bioenergy* 70, 287-301.

III Porsö, C., Mate, R., Vinterbäck, J. and Hansson P.-A (2016). Time-Dependent Climate Effects of Eucalyptus Pellets Produced in Mozambique Used Locally or for Export. *Bioenergy Research* 9(3), 942-954.

IV Porsö, C., Hammar, T., Nilsson, D. and Hansson P.-A (2016). Time-dependent climate impact and energy efficiency of non-torrefied and torrefied wood pellets from logging residues. *Submitted*

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

The contribution of Charlotta Porsö to the papers included in this thesis was as follows:

I Performed the model building, data collection and analysis of the results together with the first author. Wrote the paper together with the co-authors.

II Planned the study together with the co-author. Performed the data collection, calculations and analysis of the results. Wrote the paper with input from the co-author.

III Planned the study together with the co-authors. Performed the data collection, calculations and analysis of the results together with the second author. Wrote the paper with input from the co-authors.

IV Planned the study together with the co-authors. Performed the data collection, calculations and analysis of the results and wrote the paper with input from the co-authors.

Abbreviations

ΔCO_{2Bio}	Biogenic CO_2 fluxes
ΔT_S	Global mean surface temperature change
AGTP	Absolute global temperature potential
AGWP	Absolute global warming potential
CH_4	Methane
CHP	Combined heat and power plant
CO_2	Carbon dioxide
CO_2-eq.	CO_2-equivalents
CRF	Cumulative radiative forcing
DM	Dry matter
EI	Emission impulse
FU	Functional unit
GHG	Greenhouse gas
GTP	Global temperature potential
GWP	Global warming potential
ha	Hectare
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LCI	Life cycle inventory
LHV	Lower heating value
LUC	Land use change
N_2O	Nitrous oxide
RF	Radiative forcing
SRC	Short rotation coppice

1 Introduction

Anthropogenic greenhouse gas (GHG) emissions are the main cause of climate change, with combustion of fossil fuels and land use changes being the main source of emissions (Ciais *et al.*, 2013). Fossil fuels account for over 80% of the world's total primary energy supply (IEA, 2016) and this proportion needs to be reduced in order to mitigate climate change. In addition, fossil resources are finite and not evenly distributed globally. Diversifying the energy system and reducing the dependency on fossil fuels are therefore also motivated from an energy security point of view. Biomass is considered a viable approach to replace fossil fuels and this has increased the demand for biomass for energy conversion (Chum *et al.*, 2011).

Unrefined biomass is often bulky, with low energy density and high moisture content, which makes *e.g.* storage and transport challenging and expensive. Upgrading woody biomass to a dry and uniform fuel, such as pellets, briquettes or powder, makes the product more suitable for transport and storage and improves the combustion properties (Paulrud, 2004). Global wood pellet production has increased rapidly in recent decades (FAO, 2015) and a further increase is expected (Lamers *et al.*, 2015). Wood pellets are used for heat and power production in both dedicated bioenergy plants and for co-firing. Furthermore, wood pellets are considered a relatively economical and technically straightforward way to mitigate GHG emissions by replacing fossil fuels (Ehrig & Behrendt, 2013; Chum *et al.*, 2011; Zhang *et al.*, 2010).

Europe is currently the main market for wood pellets, partly as a consequence of the European Union's targets to reduce GHG emissions and to increase the share of renewables. Large-scale wood pellet production plants have emerged, especially in North America and Russia, with the main aim of exporting wood pellets to heat and power plants in Europe (Lamers *et al.*, 2012). With increased demand for wood pellets, it is likely that wood pellet plants will also be established in other parts of the world where feedstock is abundantly available (Sikkema *et al.*, 2011b).

Traditionally, sawdust and shavings have been the main raw materials used for wood pellet production. However, in many Western and Central European countries these residues from the sawmilling industry are already utilised to a large extent. Availability is also dependent on the shifting demand for timber products. This has increased the interest in alternative raw materials such as bark, short rotation forest, wood from thinnings, forest residues and even prime log wood (Obernberger & Thek, 2010).

With its great forest resources, Sweden has a large bioenergy sector which provided *e.g*. 23% of total domestic energy input in 2015 (Swedish Energy Agency, 2015). By using non-traditional woody raw materials such as forest residues or short rotation forest established on agricultural land for pellet production, Sweden has the potential to increase production of wood pellets for the domestic market, but also to meet the increasing demand from the European market.

Life cycle assessment (LCA) is a frequently used method to evaluate the climate impact of bioenergy systems (Matthews *et al.*, 2014; Agostini *et al.*, 2013) and other environmental aspects. Most LCAs of bioenergy systems include GHG emissions released from the production chain (*e.g.* harvest, upgrading and transport) in the climate impact assessment. However, these systems may also be connected to land use changes causing altered biogenic carbon stocks in soil and living biomass. Furthermore, the general assumption that bioenergy is carbon-neutral, *i.e.* assuming that the same amount of carbon dioxide (CO_2) released during combustion is sequestered during regrowth of new plants, has been questioned for disregarding the time lag between emission and uptake of biogenic CO_2 (Brandao *et al.*, 2013; Cherubini *et al.*, 2011).

The most commonly used metric in climate impact assessments is global warming potential (GWP) (Matthews *et al.*, 2014; Agostini *et al.*, 2013). When calculating the GWP, characterisation factors are used to convert the emissions to CO_2-equivalents (CO_2-eq.) (Myhre *et al.*, 2013a). In LCA, all emissions from the system are usually summed up into a single pulse, irrespective of when in time they occur. With this approach, net changes in biogenic carbon stocks during the study period can be captured in the climate impact assessment, but not the temporary fluxes. In order to include these temporary carbon fluxes connected to bioenergy systems, both the timing and magnitude of the GHG fluxes need to be considered in climate impact assessment.

Overall, the increasing demand for wood pellets is likely to result in new wood pellet systems, both with regard to raw materials and location of the pellet plant. Replacing fossil fuels with wood pellets, or bioenergy in general, is one approach to counteract global warming. However, it is important to evaluate the climate impact of these complex systems. It is also essential to increase knowledge of biogenic CO_2 fluxes between soil, biomass and atmosphere and their climate impact connected to bioenergy systems. Such knowledge is vital in the search for future bioenergy systems and determination of their climate effects.

2 Aim and structure

2.1 Aim and objectives

The overall aim of this thesis was to increase the knowledge base for planning new wood pellet systems. The focus was on non-traditional raw materials and time-dependent climate impact, including effects of temporal dynamics of carbon stock changes in biomass and soil. Specific objectives were to investigate the energy efficiency and time-dependent climate impact of production and use of wood pellets supplied to the Swedish heat and power sector from short rotation forestry grown in Sweden and in Mozambique, and from residual forest biomass extracted from final felling in Sweden.

2.2 Structure of the thesis

A time-dependent approach for conducting LCA was developed in order to include temporal aspects of CO_2 fluxes between atmosphere, biomass and soil, in addition to the GHG emissions from the production chain connected to the wood pellet system. This methodology, which was developed and evaluated in Paper I, was then used to assess the climate impact over time of different wood pellet production systems in Papers II-IV (*Figure 1*).

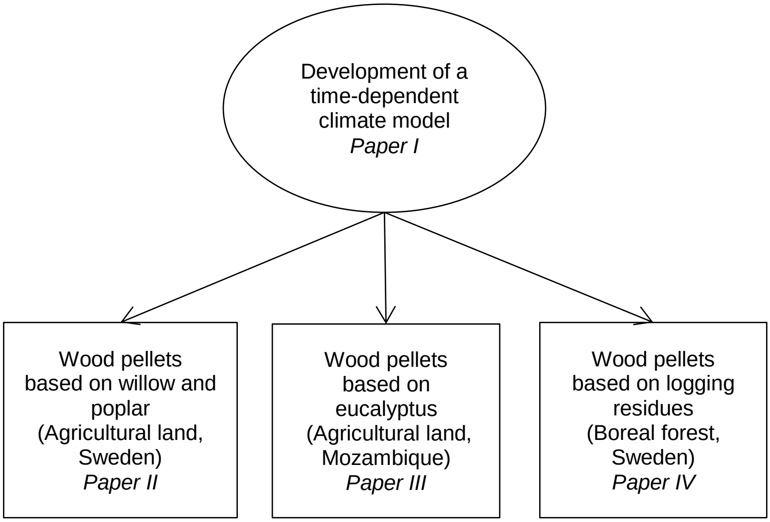

Figure 1. Structure of the thesis: A time-dependent climate model was developed in Paper I and then used in different case studies to examine the time-dependent climate impact of production and use of pellets from different non-traditional raw materials (Papers II-IV).

The case studies focused on different non-traditional raw materials grown directly for wood pellet production on agricultural land or by using residual forest biomass extracted from final felling. Short rotation forests established on former agricultural land were studied in Papers II and III. Willow and poplar grown in central Sweden were investigated in Paper II and eucalyptus grown in Mozambique in Paper III. Logging residues (branches and tree tops) extracted from final felling in northern Sweden were studied in Paper IV. In all case studies, the wood pellets were assumed to be delivered to and used in Swedish heat and/or power plants.

3 Background

3.1 Climate change and the role of bioenergy

Climate change is one of the greatest challenges of our time. It has consequences such as rising temperatures and sea levels, as well as changing precipitation and weather patterns (IPCC, 2013). The main cause of climate change is the increasing levels of GHG emissions, with atmospheric concentrations of the three major GHGs (CO_2, methane (CH_4) and nitrous oxide (N_2O)) having increased significantly since pre-industrial times. This is mainly due to fossil fuel combustion and land use changes (Ciais *et al.*, 2013).

In order to prevent serious impacts on human life, research indicates that global warming needs to be limited to less than 2 °C and global efforts are being made in order to stay below this level. For example, an agreement was signed in Paris 2015 by member countries of the United Nations Framework Convention on Climate Change (UNFCCC). That agreement recognises the urgent need to reduce GHG emissions to keep the global temperature increase below 2 °C and also that efforts should be made to keep the temperature increase below 1.5 °C compared with pre-industrial times (UNFCCC, 2015). Furthermore, the European Union has long-term goals to reduce its climate impact and energy consumption, *e.g.* a 80% reduction in GHG emissions by 2050 (compared with 1990 levels). Near-term targets for 2020 have also been defined, such as a 20% reduction in GHG emissions (compared with 1990 levels) and 20% renewable energy (EC, 2016). With the global energy supply dominated by fossil fuels (IEA, 2016), a transition to renewable energy sources is necessary to fulfil these agreements and targets.

Bioenergy is currently the largest renewable energy source, accounting for about 10% of the global primary energy supply in 2014 (IEA, 2016). Bioenergy is defined as energy derived from biomass fuels (CEN, 2004) and it exists in solid, liquid and gaseous forms. This enables usage in a large variety of both small-scale and large-scale applications, *e.g.* transport, heating, cooking and electricity production (Creutzig *et al.*, 2015). Biomass fuels are a viable approach to replace fossil fuels and are expected to play an important role in future energy systems in order to fulfil climate and energy targets (Creutzig *et al.*, 2015; Chum *et al.*, 2011).

In Europe, bioenergy accounts for about 15% of primary energy production (Eurostat, 2016), but the share of biomass for energy conversion varies widely between countries (Proskurina *et al.*, 2016). For example, in Sweden, Latvia and Finland, biomass fuels contribute over 20% of total energy use, whereas in *e.g.* the UK and the Netherlands less than 5% of total energy use comes from biomass fuels (Eurostat, 2016). In Europe, more than 80% of the biomass used for energy comes from wood-based biomass (woody biomass) (Proskurina *et al.*, 2016) and includes *e.g.* wood logs used for residential heating and wood pellets used in large-scale power production.

In Sweden, bioenergy accounts for 23% of the energy supply (Swedish Energy Agency, 2015). This is mainly based on forest biomass fuels, while agriculture-based biomass fuels are only used to a small extent (Ericsson & Werner, 2016). The main users of biomass for energy in Sweden are industry (mainly pulp and paper mills and sawmills) and the energy sector (district heat and power production) (Ericsson & Werner, 2016; Swedish Energy Agency, 2015).

Unrefined biomass is often bulky, has low energy density and a high moisture content. This makes storage, transport and use of the biomass challenging and expensive. Upgrading the biomass to a dry and uniform fuel, such as wood powder, pellets or briquettes, results in decreased transportation and storage costs and improved combustion properties (Paulrud, 2004).

3.2 Wood pellets

Wood pellets are a standardised fuel with low moisture content, high energy density and homogeneous shape. Production of wood pellets is a mature industrial process whereby the raw material is densified into a cylindrical shape with a diameter of about 6-8 mm (Obernberger & Thek, 2010). Before densification, pre-treatment of the raw material is required and this includes size reduction and drying. Depending on the shape of the incoming raw material, several grinding units may be necessary. To maintain the low moisture content and to increase the durability, the pellets are cooled after densification. Finally, dust from the process is separated out by sieves and returned back to the pelleting process. An overview of a typical pellet production chain is shown in *Figure 2*, where log wood, wood chips and sawdust are considered as raw materials.

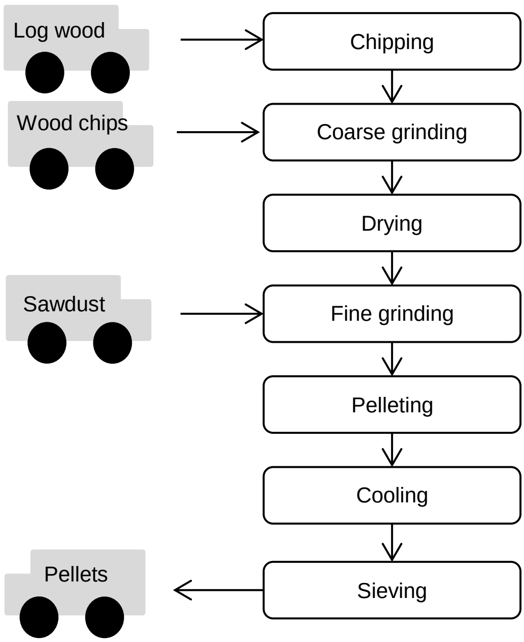

Figure 2. A typical wood pellet production chain based on the raw materials log wood, wood chips and sawdust.

With their consistent fuel quality, wood pellets are also suitable in a wide variety of applications, from small-scale use in stoves for residential heating to large-scale use in heat and power plants (Obernberger & Thek, 2010). Depending on the end-user of the wood pellets, different qualities are required. High quality wood pellets (also referred to as white pellets) are mainly used in the residential heating sector, while low quality wood pellets (industrial pellets or brown pellets) are also suitable for large-scale use due to more advanced combustion and control systems (Goh *et al.*, 2013; Obernberger & Thek, 2010). Standards have been developed (*e.g.* the European standard EN*plus*) in order to ensure the quality regarding *e.g.* ash content, ash melting point and mechanical durability for different wood pellet classes (European Pellet Council, 2015).

In order to further improve the characteristics of the wood pellets, a torrefaction step can be added before densification of the biomass. In this process, the biomass is exposed to temperatures between 220 and 300 °C in a low-oxygen atmosphere (Agar & Wihersaari, 2012). Typically, the torrefied biomass contains about 90% of the initial energy content but only 70% of the initial mass (Tumuluru *et al.*, 2011; van der Stelt *et al.*, 2011; Bergman, 2005). Pellets from torrefied woody biomass (referred to as torrefied wood pellets) are more similar to coal in terms of handling, transport and milling (Batidzirai *et al.*, 2013a; Koppejan *et al.*, 2012) than to non-torrefied wood pellets. Furthermore, torrefied wood pellets have higher energy density, are less moisture-sensitive and require less energy for grinding than non-torrefied wood pellets (Batidzirai *et al.*, 2013a; Agar & Wihersaari, 2012).

The interest in torrefied wood pellets has increased in recent years (Batidzirai *et al.*, 2013a; Koppejan *et al.*, 2012). In existing coal-fired power plants, co-firing rates of up 10-15% of non-torrefied wood pellets are possible without major modifications. Use of torrefied wood pellets could considerably increase the co-firing rate. Rates up to 50% (Agbor *et al.*, 2014; Nunes *et al.*, 2014; Batidzirai *et al.*, 2013a; Koppejan *et al.*, 2012; Tumuluru *et al.*, 2011) or even 100% are mentioned (Cocchi *et al.*, 2011). Great improvements have been made in the torrefaction technology during the past decade and the main challenge today is to move from demonstration to industrial scale (Thrän et al., 2016). However, with an extra process included as well as an increased raw material demand, the production costs will most likely increase.

3.3 The wood pellet market

Global wood pellet production has increased rapidly in recent decades, from 1.7 million tonnes in 2000 to 26 million tonnes in 2014 (FAO, 2015; Lamers *et al.*, 2012) (*Figure 3*) and a further increase is expected (Lamers *et al.*, 2015). The main market for wood pellets is located in Europe, with about 80% of global consumption in 2014 (FAO, 2015). However, wood pellet users differ within Europe. In *e.g.* Germany, Austria and Italy, small-scale use of wood pellets for residential heating accounts for a main part of the consumption, while in *e.g.* the Netherlands, Belgium and UK large-scale use in power plants for co-firing dominates. The increased use of wood pellets for co-firing is partly a consequence of the EU’s climate and energy targets for 2020 (Lamers *et al.*, 2012). However, with limited amounts of available raw materials, many of these countries rely on imports (Goh *et al.*, 2013).

In Sweden, densified wood fuels account for about 8% of the biomass used for energy (Swedish Energy Agency, 2015). Wood pellets are used in all market segments and a large part of the consumption is covered by domestic production, although Sweden is a net importer of wood pellets (21% of consumption in 2015) (Swedish Association of Pellet Producers, 2016).

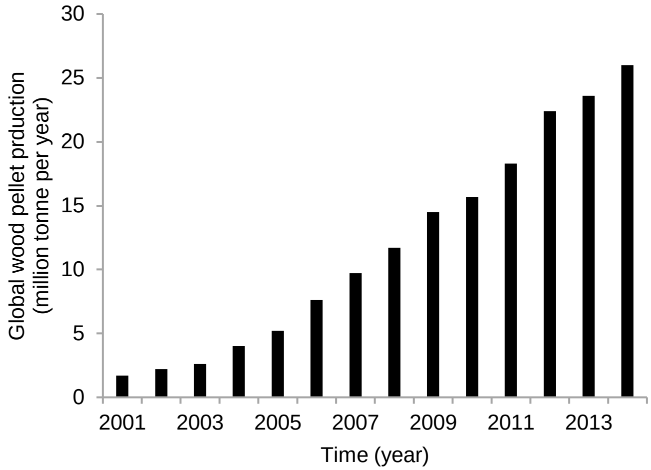

Figure 3. Global wood pellet production, 2000-2014 (FAO, 2015).

Wood pellets are the largest internationally traded solid biomass fuel (Sikkema *et al.*, 2011a), with about half of all wood pellets produced being traded internationally in 2014 (FAO, 2015). There is a large trade flow of wood pellets to Europe, mainly from North America. In recent years, wood pellet plants have been established, especially in southeastern USA, primarily exporting to the European market (Lamers *et al.*, 2015; Goh *et al.*, 2013). This development can be explained by a combination of large quantities of available raw material, competitive prices, relatively simple logistics and low-cost transport (Goh *et al.*, 2013; Cocchi *et al.*, 2011). Although the market is currently focused on Europe, there is also a growing pellet market in Asia, where production and consumption more than doubled in 2014 (FAO, 2015; Goh *et al.*, 2013).

3.4 Potential new wood pellet systems

The most common raw materials for wood pellet production are by-products from the sawmilling industry, such as sawdust and shavings (Obernberger & Thek, 2010). However, with growing demand for wood pellets, new raw materials are being considered, *e.g.* short rotation forestry, log wood, forest residues and bark (Goh *et al.*, 2013; Cocchi *et al.*, 2011; Fantozzi & Buratti, 2010; Obernberger & Thek, 2010).

Sweden has one of the largest wood pellets markets in Europe (FAO, 2015; Sikkema *et al.*, 2011a). With large forest and land resources, Sweden has the potential to increase its raw material assortment for wood pellet production.

For example, a possibility to increase the use of forest residues has been reported (de Jong *et al.*, 2014), with the potential for increased extraction of logging residues estimated to be 33 TWh (Pöyry, 2016). This can be compared with extraction of about 11 TWh of logging residues in 2014 (Pöyry, 2016). Within Sweden, there are also around 300 000 hectares (ha) of former agricultural land which have been removed from crop production since the 1980s (Statistics Sweden, 2014). Using a part of this land for cultivation of short rotation forestry plantations such as willow and poplar has been pointed out as a potential biomass supply option (Rytter, 2012). Other positive effects of short rotation forestry on *e.g.* farm diversification and biodiversity, and its possible use as a vegetation filter for contaminated water, have also been mentioned (Mola-Yudego, 2010). To date, there are few commercial poplar plantations in Sweden (Hjelm & Johansson, 2012), but commercial willow plantations expanded in the 1990s, partly as a consequence of subsidies for establishing willow (Mola-Yudego & Gonzalez-Olabarria, 2010). Currently, forest residues and short rotation forests in Sweden are used for heat and power production, but these raw materials could also be suitable for industrial wood pellet production (Hollsten *et al.*, 2011; Nilsson *et al.*, 2011; Lehtikangas, 2001).

In an international perspective, there are several countries that have the potential to establish and expand their pellet production. Along with countries such as Ukraine, the Baltic States, Brazil and Australia, Mozambique is reported to have potential for future wood pellet production (Lamers *et al.*, 2015; Goh *et al.*, 2013; Cocchi *et al.*, 2011). In this thesis, wood pellet production in Mozambique was chosen as a model system. Mozambique is located in south-east Africa and has favourable growing conditions and access to land, water and labour, as well as great bioenergy potential (Schut *et al.*, 2010). Its coastal position gives the country a geographical advantage over its inland neighbours. The area of available land for bioenergy production in the form of surplus agricultural and marginal land is estimated to range between 9 and 85 million ha (Batidzirai *et al.*, 2012). While there is no wood pellet industry in Mozambique today, good theoretical potential for establishing energy plantations, *e.g.* eucalyptus, for pellet production in Mozambique has been demonstrated (van der Hilst & Faaij, 2012; Batidzirai *et al.*, 2006).

3.5 Life cycle assessment of bioenergy systems

Life cycle assessment (LCA) is one of many methodologies available for environmental assessments (Finnveden *et al.*, 2009; Baumann & Tillman, 2004). Life cycle assessment is frequently used to evaluate climate effects of bioenergy systems (Matthews *et al.*, 2014; Agostini *et al.*, 2013). It is a standardised method (ISO 14040, 2006; ISO 14044, 2006) for assessing the potential environmental impact throughout the whole life cycle of a product or process. With a life cycle perspective, LCA can be a useful tool to find hotspots in the system under study, compare environmental burdens of different systems and avoid burden shifting from one part of the life cycle to another.

The LCA process is an iterative process divided into four steps (ISO 14040, 2006), as illustrated in *Figure 4*. The goal and scope of the study should be clearly defined, as well as a functional unit (FU) describing the primary function of the product or system to which all input and output data collected in the life cycle inventory (LCI) are related. The data collected in the LCI are then classified into different environmental impact categories such as climate impact, eutrophication or acidification. Finally, the results should be interpreted.

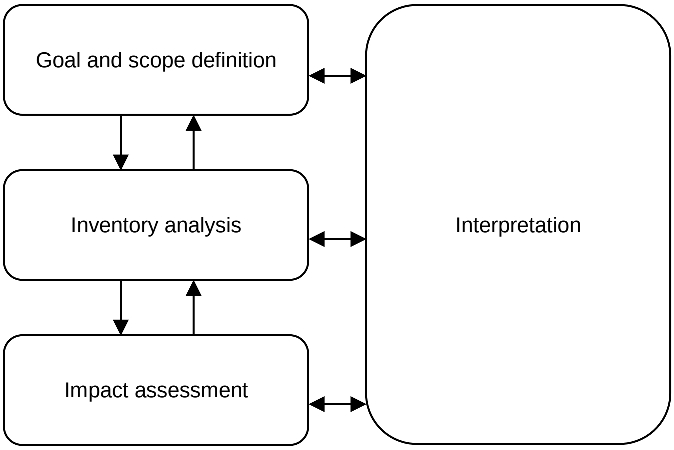

Figure 4. The different phases of a life cycle assessment (LCA) (ISO 14044, 2006).

A key issue connected to the climate impact of biomass-based systems is land use changes (LUC), *e.g.* by converting forest land to agricultural land to meet the growing demand for food, feed, fuel and raw material production (UNEP, 2014), which in turn may causes climate change. However, land use changes can have positive effects, such as carbon sequestration when establishing forest plantations on former agricultural land (Zanchi *et al.*, 2012). Direct LUC are immediately associated with the bioenergy system, *e.g.* when land is converted to produce bioenergy crops and previous crops, grass or forest are replaced. There are also indirect LUC, *e.g.* when a crop is displaced even though the demand remains, resulting in a new cultivation of the crop elsewhere in the world. However, large uncertainties have been reported when estimating emissions related to these land use changes (Ahlgren & Di Lucia, 2014).

Another key issue discussed in climate impact assessments of bioenergy is its carbon neutrality. Combustion of biomass releases CO_2 emissions in the same way as combustion of fossil alternatives. However, the difference between bioenergy and fossil systems is the CO_2 uptake during regrowth of new biomass in the bioenergy system. In LCA, all emissions from the system are usually summed up into a single pulse, irrespective of when in time they occur. With this approach, net changes in biogenic carbon stocks during the study period can be captured in the climate impact assessment, but not the temporary fluxes. Bioenergy is therefore generally assumed to be carbon-neutral within LCA. However, this assumption has been questioned for disregarding the time lag between release and uptake of CO_2 in new plants (Agostini *et al.*, 2013). For bioenergy systems with long rotations, this becomes especially important (Lamers & Junginger, 2013).

The importance of including temporary and more long-term carbon stock changes in biomass and soil in climate impact assessments of bioenergy systems has been repeatedly emphasised, *e.g.* by Brandao *et al.* (2013), Lamers and Junginger (2013), Zanchi *et al.* (2012), Cherubini *et al.* (2011) and Searchinger *et al.* (2009). In order to include these temporary fluxes, both the timing and the magnitude of the GHG fluxes need to be considered in the climate impact assessment.

3.6 Climate impact assessment

The climate impact of a GHG emission can be described by a cause-effect-chain (illustrated in *Figure 5*), where each step further down in the cause-effect-chain is a consequence of the previous step. Greenhouse gas emissions result in altered atmospheric concentrations, where the effect over time depends on the residence time of the GHG in the atmosphere. The altered atmospheric concentrations result in radiative forcing (RF), described in watts per square metre at the top of the troposphere. Radiative forcing is a concept for evaluating and comparing the energy imbalance on Earth, where a positive RF results in a warming temperature response and a negative RF in a cooling temperature response (Myhre *et al.*, 2013a). Finally, temperature changes have impacts on *e.g.* sea levels, precipitation and weather (Levasseur *et al.*, 2016), which may have severe consequences for ecosystems and human life.

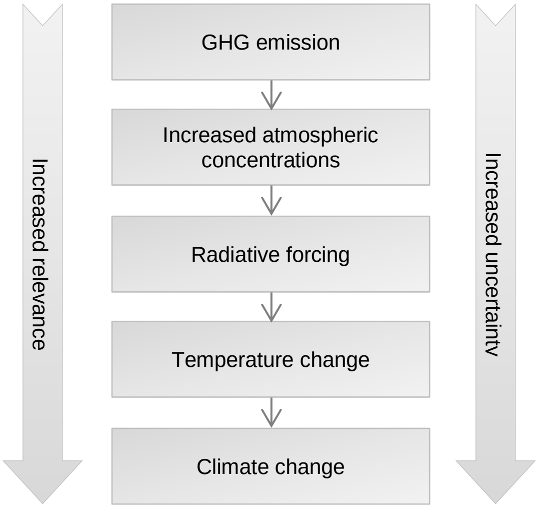

Figure 5. Cause-effect-chain of climate change from emission of a greenhouse gas (GHG) to climate change (modified from Myhre *et al.* (2013a)).

Different metrics have been developed in order to quantify and compare climate impacts. The climate impact metric can be anywhere along the cause effect-chain (Levasseur *et al.*, 2016). For every step downwards in the cause-effect-chain additional assumptions and uncertainties are introduced, but the result may be easier to interpret and more relevant to *e.g.* policymakers. The choice of climate impact metric is therefore often a trade-off between increased relevance and increased uncertainty for each step down the cause-effect-chain.

The most commonly used metric in climate impact assessments is global warming potential (GWP) (Matthews *et al.*, 2014; Agostini *et al.*, 2013). This method was developed in the 1980s and is widely used among policy makers and in the LCA community. Global warming potential is defined as the integrated RF due to a pulse emission relative to the integrated RF for a reference gas over a defined time horizon. The reference gas is generally CO_2 and the GWP is thereby expressed in CO_2-eq. (Myhre *et al.*, 2013b). Characterisation factors for different time horizons (often 100 years) are used to convert the emissions directly to CO_2-eq. in the GWP calculations (Myhre *et al.*, 2013a).

Advantages and disadvantages of using GWP have been discussed thoroughly by *e.g.* Cherubini *et al.* (2016), Levasseur *et al.* (2016), Fuglestvedt *et al.* (2010) and Fuglestvedt *et al.* (2003). Global warming potential is a cumulative metric where the RF is integrated over a defined time horizon. This makes the choice of time horizon important, as it determines the relative importance of long-term and short-term climate forces, with the importance of the latter decreasing with longer time horizons (Shine *et al.*, 2007). Moreover, a consequence of using a relative metric such as GWP is that the uncertainty is related to both the GHG emission and to the reference gas.

Another used climate impact metric is the global mean surface temperature change, ΔT, (Peters *et al.*, 2011), also referred to as the absolute global temperature potential (AGTP) (Myhre *et al.*, 2013b). The temperature change can also be expressed as the relative metric global temperature potential (GTP) (Shine *et al.*, 2005). It is defined as the AGTP of a GHG at a specific point in time relative to the AGTP of the reference gas (most commonly CO_2) at the same point in time. In contrast to the cumulative (integrated) metric GWP, GTP is an instantaneous metric that expresses the climate impact at a specific point in time (*i.e.* not including the impact between the emission and the time of evaluation). GTP (and AGTP) is found one step further down in the cause-effect chain (*Figure 5*) than GWP, which is based on RF. By including the temperature response the inertia of the Earth is also considered, resulting in delayed temperature response after a RF.

When calculating the climate impact in LCA, a fixed time horizon is generally used, irrespective of when in the life cycle the emissions occur (Levasseur *et al.*, 2016). This approach makes it impossible to capture the effect of timing of emissions and the temporal GHG fluxes connected to biomass-based systems (Brandao *et al.*, 2013; Cherubini *et al.*, 2011). However, other methods have been proposed in order to include the timing of GHG fluxes. For example, Levasseur *et al.* (2010) and Kendall (2012) propose the use of time-dynamic characterisation factors in which the timing of the GHG emission is taken into account. Furthermore, for biomass-based systems, Cherubini *et al.* (2011) propose the use of GWP_{bio}, which includes the carbon cycle. The climate impact over time of bioenergy systems has also been expressed as RF, or as a cumulative radiative forcing (CRF) (also referred to as absolute global warming potential, AGWP) (Gustavsson *et al.*, 2015; Repo *et al.*, 2012) or as a temperature change (Zetterberg & Chen, 2015).

3.7 Previous LCAs of wood pellets

A lower climate impact of wood pellets, and torrefied wood pellets, instead of fossil fuel alternatives has been reported in several LCA studies, *e.g.* by Agar *et al.* (2015), Hansson *et al.* (2015), Roder *et al.* (2015), Batidzirai *et al.* (2013b) and Ehrig and Behrendt (2013). The GWP value for wood pellets used in Sweden is reported to range between 2 and 25 kg CO_2-eq. per GJ pellets, including both nationally produced and imported wood pellets (Hansson *et al.*, 2015). In comparison, a coal-based scenario would result in a GWP value of about 100 kg CO_2-eq. per GJ fuel. Roder *et al.* (2015) reported a GWP value of approximately 15 kg CO_2-eq. per GJ for pellets produced in the southeastern USA (from forest residues) and exported for end-use in the UK. Agar *et al.* (2015) found small differences in GWP between non-torrefied and torrefied wood pellets produced from logging residues in Finland for co-firing in Spain (recalculated to 12-13 CO_2-eq. per GJ fuel for non-torrefied and torrefied wood pellets). The climate impact of wood pellets from short rotation coppice (SRC) eucalyptus produced in Mozambique and delivered to Europe was studied by Batidzirai *et al.* (2013b), who found a climate impact of 13 kg CO_2-eq. per GJ pellets. Factors identified as having a large influence on the climate impact of wood pellet systems in that study were: fuel used for drying the raw material (often biomass or natural gas), moisture content of the incoming raw material, share of fossil in the electricity mix used, international transport and N_2O soil emissions for nitrogen-fertilised systems (Batidzirai *et al.*, 2013b). However, these studies did not include biogenic carbon stock fluxes.

Including carbon stock changes in litter and biomass, Jonker *et al.* (2014) calculated a carbon payback time of 5-11 years for wood pellet production from softwood plantations in southeastern USA. The carbon payback time is defined as the time after harvest required to reach an overall carbon balance of a bioenergy system, including carbon in the harvested biomass and in regrowth of new biomass, as well as avoided fossil emissions.

Biogenic carbon stock fluxes have been included in several LCAs of short rotation plantations and in LCAs of forest residue extraction. For example, SRC eucalyptus (Gabrielle *et al.*, 2013) and SRC willow (Zetterberg & Chen, 2015; Brandao *et al.*, 2011) established on abandoned agricultural land were shown to have climate benefits due to carbon sequestration in live biomass and/or soil. Furthermore, long-term climate benefits were shown for the extraction and use of forest residues compared with a fossil reference by *e.g.* Hammar *et al.* (2015), Zetterberg and Chen (2015) and Lindholm *et al.* (2011).

4 Methodological approach

4.1 Time-dependent climate impact assessment (Paper I)

One of the main objectives of this thesis was to develop a methodology to assess the time-dependent climate impact of bioenergy systems. The methodology was then used to assess the climate impact of different wood pellet systems (Papers II-IV).

In the methodology devised, which is described and evaluated in Paper I, use of the time-dependent metric global mean surface temperature change, ΔT_S, is proposed. As a time-dependent, absolute and instantaneous indicator, ΔT_S can give additional values besides the more commonly used climate metric GWP. Furthermore, when presenting the climate impact as a function of time, the need to choose a defined time horizon can be avoided and the dynamic behaviour of the atmospheric residence time of the GHG is captured. The methodology also enables the evaluation of GHG fluxes of both fossil and biogenic origin inherent to bioenergy systems. In this thesis work, the climate impact assessment was limited to include the three major GHG (CO_2, CH_4 and N_2O).

The temperature response, $\Delta T_S(n)$, is defined as the time-dependent global mean surface temperature change due to a specific emissions scenario, where n is the year relative to the first year of the time frame of the study. The calculation of $\Delta T_S(n)$ can be divided into three steps:

- Step 1: Recording annual net fluxes of the GHG in a time-dependent life cycle inventory.
- Step 2: Calculating the temperature response for all individual emission impulses (*EI*) recorded in step 1.
- Step 3: Calculating the total temperature response, $\Delta T_S(n)$, by adding together all individual temperature responses calculated in step 2.

Step 1: To calculate ΔT_S, a time-dependent life cycle inventory is required in which annual net GHG fluxes are recorded. This time-dependent life cycle inventory makes it possible to include annual net biogenic CO_2 fluxes between atmosphere, biomass and soil, as well as GHG emissions from the production system connected to the bioenergy system.

Step 2: In order to calculate the temperature response for all individual emission impulses, the change in atmospheric concentrations due to each *EI* of GHG *x* first needs to be modelled. For CH_4 and N_2O, the mean residence time is 12.4 and 121 years, respectively (Myhre *et al.*, 2013a), while the atmospheric residence time of CO_2 is more complicated as it is not chemically decomposed in the atmosphere. About half of all anthropogenic CO_2 emissions are taken up by the oceans and the terrestrial biosphere, while the rest of the CO_2 remains in the atmosphere (Joos *et al.*, 2001). Simple exponential decay functions can be used to model the decay for CH_4 and N_2O, while the decay of CO_2 can be modelled using the Bern carbon cycle model (Joos *et al.*, 2013; Myhre *et al.*, 2013b; Joos *et al.*, 2001). The relative atmospheric concentration of a pulse emission of CO_2, CH_4 and N_2O is shown in *Figure 6*.

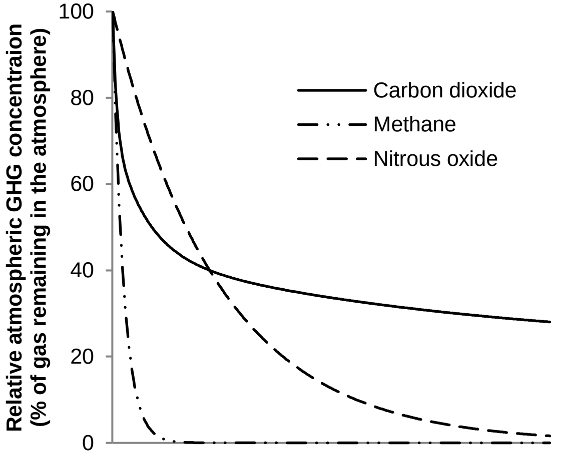

Figure 6. Fraction remaining in the atmosphere (%) over a time span of 500 years after a pulse emission of the greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) in year 0. Calculations based on Myhre *et al.* (2013b).

Changes in atmospheric concentrations result in radiative forcing. The RF of GHG *x* is described by:

$$RF_x(t) = RE_x \cdot f_x(t) \qquad \text{[W m}^{-2}\text{]} \qquad (1)$$

where RE_x is the radiative efficiency of the gas (Ramaswamy *et al.*, 2001) describing the impact on the energy balance of a one unit change in the atmospheric concentration of GHG x and $f_x(t)$ is the fraction of the gas remaining in the atmosphere after a unit emission in year t after a pulse emission at year 0.

The climate systems temperature response to a perturbation of the RF is represented by a temperature response function $\delta T_S(t)$, which describes the temperature response due to a unit increase in the RF. To calculate the temperature response a convolution between RF and the temperature response function, $\delta T_S(t)$, was used in Paper I and II based on the equation:

$$\Delta T_S^{X_i}(t) = \int_{t-\tau}^{t} RF_{X_i}(\tau)\delta T_S(t-\tau)d \qquad \text{[K]} \qquad (2)$$

In Papers III and IV the algebraic solution to equation 2 (equations 3-5) for ΔT_S (also referred to as AGTP) was used instead, as presented in the Fifth Annual Report of the IPCC (Myhre *et al.*, 2013b). These equations give the same result as equation 2, but are more convenient to use. In this thesis, all results presented were recalculated with updated parameter values from Myhre *et al.* (2013b). *Figure 7* shows the temperature response of a single *EI* of CO_2, CH_4 and N_2O, in year 0, which corresponds to an instantaneous RF of 1 W m^{-2}.

$$\Delta T_S^{CO_2}(t) = \mathrm{EI}_{CO_2} \cdot \mathrm{RE}_{CO_2} \sum_{j=1}^{2} \left\{ a_0 c_j \left(1 - \exp\left(-\frac{t}{d_j}\right)\right) + \sum_{i=1}^{3} \frac{a_i \tau_i^{CO_2} c_j}{\tau_i^{CO_2} - d_j} \left(\exp\left(-\frac{t}{\tau_i^{CO_2}}\right) - \exp\left(-\frac{t}{d_j}\right)\right)\right\} \qquad (3)$$

$$\Delta T_S^{CH_4}(t) = \mathrm{EI}_{CH_4} \cdot \mathrm{RE}_{CH_4} \sum_{j=1}^{2} \frac{\tau^{CH_4} c_j}{\tau^{CH_4} - d_j} \left(\exp\left(-\frac{t}{\tau^{CH_4}}\right) - \exp\left(-\frac{t}{d_j}\right)\right) \qquad (4)$$

$$\Delta T_S^{N_2O}(t) = \mathrm{EI}_{N_2O} \cdot \mathrm{RE}_{N_2O} \sum_{j=1}^{2} \frac{\tau^{N_2O} c_j}{\tau^{N_2O} - d_j} \left(\exp\left(-\frac{t}{\tau^{N_2O}}\right) - \exp\left(-\frac{t}{d_j}\right)\right) \qquad (5)$$

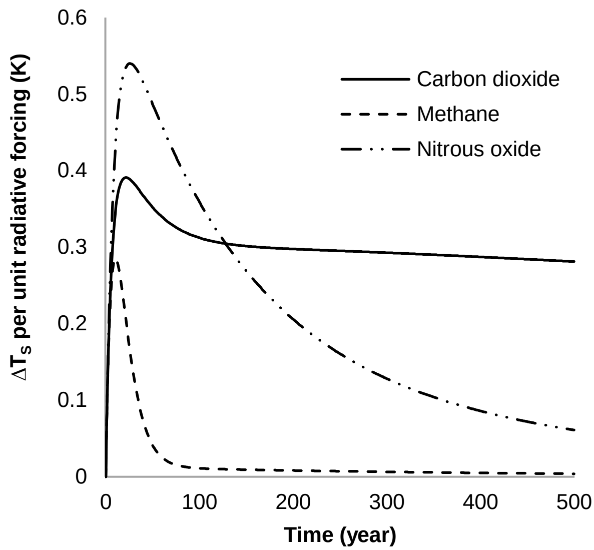

Figure 7. Temperature response (ΔT_S) after a pulse emission of carbon dioxide (570 Pg), methane (5 Pg) and nitrous oxide (3 Pg) in year 0. This corresponds to an instantaneous radiative forcing of 1 W per m^2, calculated based on Myhre *et al.* (2013b) and Joos *et al.* (2013).

Step 3: To calculate the total temperature response $\Delta T_S(n)$ of a system, all individual temperature responses for the GHG included (here CO_2, CH_4 and N_2O) are added up for every year during the study period *n*:

$$\Delta T_S(n) = \sum_{x=1}^{3} \sum_{i=1}^{n} \Delta T_S^{x_i}(t) \qquad \text{[K]} \qquad (6)$$

4.2 Global warming potential

Besides the time-dependent metric ΔT_S, the more commonly used metric GWP was used in all papers in this thesis. It is a relative metric, expressing the climate impact of a GHG in relation to the climate impact of a reference gas, most commonly CO_2. It is defined as the integrated RF (AGWP) due to a pulse emission of GHG *x* relative to the integrated RF of CO_2 over time horizon *TH* (Myhre *et al.*, 2013b):

$$\mathrm{GWP}_{TH}^{x} = \frac{AGWP_{TH}^{x}}{AGWP_{TH}^{CO_2}} \qquad (7)$$

To calculate GWP, in Papers I and II characterisation factors from IPCC (2007) were used. In this thesis, updated characterisation factors of 28 and 265 were used for CH_4 and N_2O, respectively, based on a 100-year time frame (Myhre *et al.*, 2013b). Emissions from combustion of wood pellets and soil carbon stock changes were not included in the GWP calculations.

4.3 Energy efficiency

There are many different approaches available to assess the energy efficiency of a bioenergy system (Djomo *et al.*, 2011; Murphy *et al.*, 2011). One commonly used indicator is the energy ratio, which describes the energy in the output biomass relative to the energy input required to produce the biomass (Djomo *et al.*, 2011).

In this thesis, the energy ratio (E_r) was calculated by dividing the energy in the pellets produced (E_{out}), based on lower heating value (LHV) of dry biomass adjusted for the specific moisture content, by the energy input to the system (E_{in}):

$$\mathrm{E}_r = \frac{E_{out}}{E_{in}} \qquad (8)$$

where E_{in} included primary energy input to the wood pellet system, but not the energy in the biomass feedstock. However, the part of biomass feedstock used within the system (*e.g.* for drying) and dry matter losses were captured in E_{out} in the energy ratio calculations.

4.4 Wood pellet scenarios studied (Papers II-IV)

The climate impact and energy efficiency of production and use of wood pellets from different non-traditional raw materials supplied to the Swedish heat and power sector were assessed in Papers II-IV. A time-dependent life cycle inventory of each wood pellet system was constructed in which annual GHG emissions connected to the production system and annual CO_2 fluxes (ΔCO_{2Bio}) due to biogenic carbon stock changes were recorded (including CO_2 emissions from combustion) (described further in section 4.5). Direct land use changes in the form of biogenic carbon stock changes in soil and biomass were included, but no indirect land use changes were assumed.

The production system included raw material supply, upgrading, transport to the end-user and final use (including non-CO_2 emissions from combustion). All upstream emissions from production of energy carriers, fertilisers and pesticides were accounted for in the year in which the input was used. All wood pellet systems studied were also compared with a coal-based reference scenario. An overview of these wood pellet systems is presented in *Figure 8*.

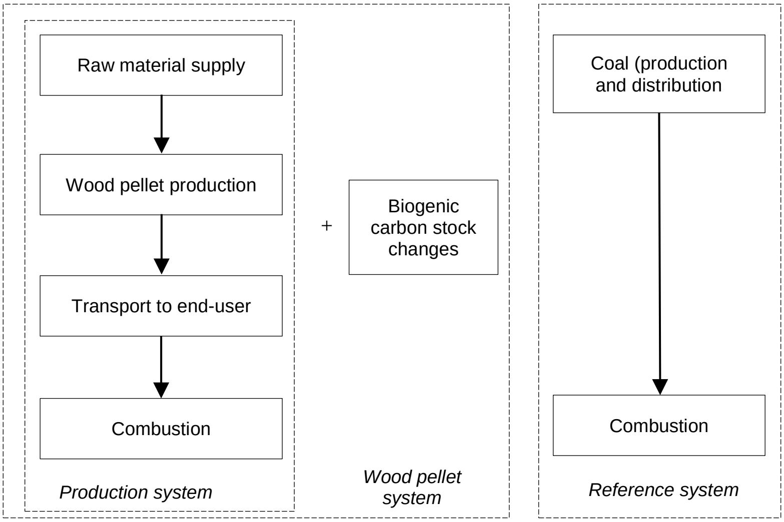

Figure 8. Overview of the wood pellet systems investigated, including the production system and CO_2 fluxes due to biogenic carbon stock change, compared with a coal-based reference scenario.

A stand perspective was adopted in all papers, which means that 1 ha of agricultural or forest land was studied. The functional unit (FU) of 1 GJ pellets delivered to the end-user was used for the GWP calculations. However, the global mean surface temperature change (ΔT_S) was related to more than one FU. For wood pellets produced from short rotation forest (Papers II & III) 1 ha was used as the FU, while 1 GJ fuel and 1 GJ electricity produced in year 1 were used as FUs for wood pellets produced from logging residues (Paper IV).

4.4.1 Production system

In Papers II and III, short rotation forestry established on former agricultural land was assumed to be used for wood pellet production. The wood pellet plants were assumed to be located close to the plantation. The studies included primary energy input and GHG emissions for all activities connected to soil preparation, planting, production and application of herbicides and fertilisers (N-P-K), harvest, chipping and transport to the pelleting plant. In Paper II, a SRC willow (*Salix* ssp.) and poplar (*Populus* ssp.) plantation established in the Mälardalen region (59°N, 16°W) of central Sweden were studied, while a SRC eucalyptus (*Eucalyptus grandis* W. Hill ex. Maiden) plantation established in

Manica province (19°S, 33°W) in central Mozambique was studied in Paper III.

In Paper IV, logging residues were assumed to be used for wood pellet production. These logging residues were assumed to be extracted from a boreal coniferous forest stand (Norway spruce (*Picea abies* (L.) H. Karst)) in Västerbotten in northern Sweden (64°N). The rotation interval was assumed to 120 years and extraction of logging residues (70% of available biomass) was assumed to take place during year 1 of a 120-year time frame. In this case, the raw material supply included extraction, chipping and transport to a wood pellet plant, while emissions occurring prior to final felling were not included. The average distance between the forest site and the pelleting plant was assumed to be the same as the average transport distance of forest fuels in northern Sweden.

A similar pellet production chain was assumed in all papers. The main steps included were comminution, drying, fine milling and pelleting of the raw material and finally cooling of the wood pellets in order to retain the low moisture content and to increase the durability. Heat required in drying the raw materials (to 10% moisture content) was considered to be produced from part of the ingoing raw material. The fuel demand was approximated to 3.6 GJ per Mg of evaporated water (Thek & Obernberger, 2004).

Wood pellet production was assumed to take place in Sweden in Papers II and IV. For the results from Paper II cited in this thesis, the electricity mix was updated to a Nordic electricity mix (originally a Swedish electricity mix was assumed) in order to make the results more comparable with those from Paper IV. In Paper III, the national electricity mix in Mozambique was used. Input data and assumptions made in Papers II-IV are presented in *Table 1*.

Table 1. *Description of the wood pellet systems investigated in Papers II-IV.*

	Paper II: Willow/poplar	Paper III: Eucalyptus	Paper IV: Logging residues
Location	Central Sweden (59 °N, 16 °W)	Mozambique (19 °S, 33 °W)	North Sweden (64 °N)
Land type	Agricultural land	Agricultural land	Boreal forest
Average yield ($Mg\ ha^{-1}yr^{-1}$)	9.2/12.6	15.4	33.5[a]
Rotation period/harvest cycle[a]) (yr)	Willow: 25/3[b] Poplar: 10	20/4[b]	120
Moisture content (at transport to pellet plant)	50%	30%	45%
Average transport to pellet plant (km)	5/6	9	73
Transport to end-user (km)	Truck: 150	Truck: 10 Rail: 240 Ship: 17 500	Rail: 1200
End-user (efficiency)	District heat plant (91%)	Combined heat and power plant (89%)	Power plant (35%)

[a]Single harvest from one forest stand in year 1 ($Mg\ ha^{-1}$); [b]Short rotation coppice.

4.4.2 Torrefied wood pellets

In Paper IV, in addition to the climate impact of non-torrefied wood pellets, the climate impact of production and use of torrefied wood pellets was also assessed. To produce the torrefied wood pellets, a torrefaction step was added in the pellet production process. The heat demand for pre-drying the raw material and for the torrefaction process was assumed to be covered by combustion of the torrefaction gases released and by direct combustion of a part of the incoming raw material. The systems studied for non-torrefied wood pellets and torrefied wood pellets from logging residues are depicted in *Figure 9*.

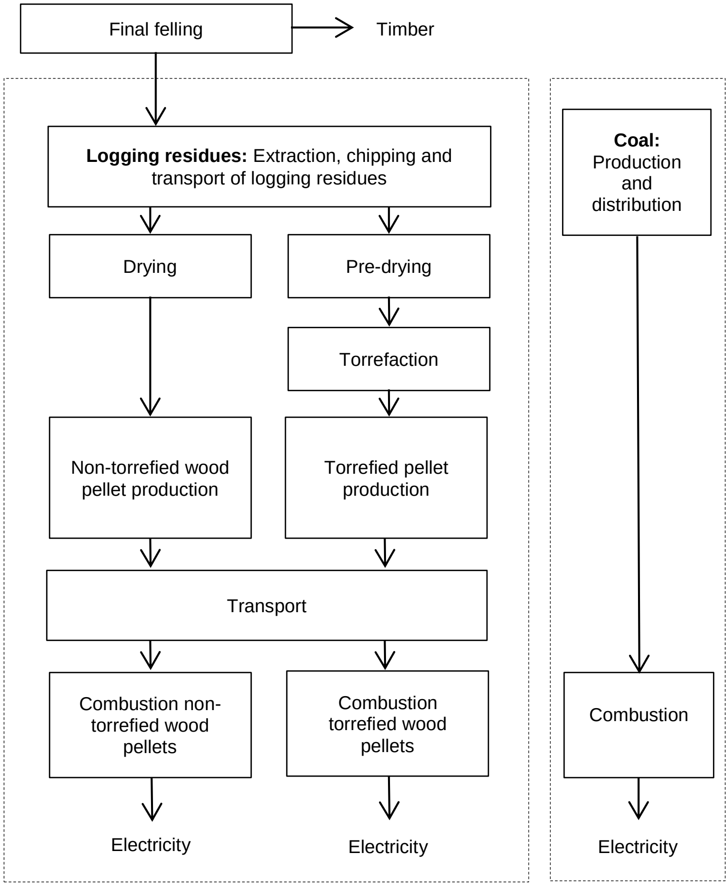

Figure 9. Overview of the production system for non-torrefied and torrefied wood pellet systems based on logging residues, compared with its coal-based reference scenario.

The electrical efficiency of using conventional wood pellets in a dedicated biomass power plant was assumed to be 35% for conventional wood pellets, while for coal it was set to 45% based on Giuntoli *et al.* (2014). With the properties of torrefied wood pellets being more similar to those of coal, the efficiency of torrefied wood pellets was assumed to lie between that of coal and non-torrefied wood pellets (40%).

Higher electrical efficiency and a higher co-firing rate can be expected for torrefied wood pellets than for non-torrefied wood pellets. The total climate impact per GJ electricity of co-firing non-torrefied and torrefied wood pellets with coal was therefore studied for different co-firing rates for non-torrefied wood pellets (5, 10 and 15% co-firing rate) and torrefied wood pellets (40, 50 and 60% co-firing rate), including emissions originating from both the wood pellets and the coal.

Furthermore, with the high energy density of torrefied wood pellets, more efficient transport is possible compared with non-torrefied wood pellets. In the base scenario, transport within Sweden or nearby countries was assumed (1200 km by rail) but different transport alternatives and distances were also analysed in three scenarios (S1 (base case), S2 and S3), to assess the effect of transport on the total climate impact (*Table 2*). Transport scenario S2 represented export to *e.g.* the UK or the Benelux countries (600 km rail, 3000 km ship) and scenario S3 (600 km rail, 25 000 km ship) represented export to *e.g.* Asia, where wood pellet consumption more than doubled in 2014 (FAO, 2015).

Table 2. *Transport distance (km) by different modes for the different transport scenarios S1-S3*

Scenario	Train	Ship
S1 (base scenario)	1200	0
S2	600	3 000
S3	600	25 000

4.5 Biogenic carbon stock modelling

In Paper II, willow and poplar were assumed to be established on fallow land in Sweden. The growing site used for cultivation was assumed to have fallow for the past 20 years and the soil organic carbon pool was assumed not to have reached steady state since the transition to fallow. In Paper III, eucalyptus plantation was considered to be established on surplus land with a soil organic carbon pool in steady state.

The annual net biogenic CO_2 flux (ΔCO_{2Bio}) in year *t* was calculated as the difference in total biogenic carbon stocks in biomass and soil organic carbon stocks (referred to as soil carbon in this thesis), recalculated to CO_2 (by multiplying by 44/12), between year *t* and the previous year (*t* - 1):

$$\Delta CO_{2Bio}(t) = (C_{Bio}(t-1) - C_{Bio}(t)) \times \frac{44}{12} \quad (9)$$

The annual net biogenic CO_2 fluxes between atmosphere and carbon stocks in biomass and soil were modelled based on estimations, allocation patterns and carbon balance models. The carbon stocks were divided into live biomass and soil. Dead biomass was not included as a separate pool, but the biomass was instead assumed to be directly transferred from the live biomass carbon pool to the soil carbon pool.

To estimate annual changes in the soil organic carbon pool, the ICBM model (Andren & Katterer, 1997) was used for the SRC willow and poplar plantation in Sweden (Paper II). The ICBM model has two carbon pools, one for ‘young’ (*Y*) and one for ‘old’ (*O*) carbon. The carbon input (*i*) from plant litter first enters the young pool. From the young pool, a fraction of the carbon, determined by the humification coefficient (*h*), is assumed to be transferred to the old pool. The different pools have different decay rates (*k*), with a slower decomposition rate of the old pool than the young pool being assumed. External factors such as soil moisture and temperature are compensated for by the parameter r_e. The model was adapted to account for the input biomass (*i*) to two separate pools, above-ground (i_{AG}) and below-ground (i_{BG}) residues. The below-ground residues were assumed to contribute more to refractory soil organic carbon than the above-ground residues by assuming a higher humification coefficient value (h_{BG}=2.3h_{AG}) (Kätterer *et al.*, 2011)).

A dynamic soil carbon model, Yasso07, was used to estimate yearly changes in the soil organic carbon stock for the SRC eucalyptus plantation in Mozambique (Paper III), employing the graphical user interface software developed for the Yasso07 model (Tuomi *et al.*, 2011). The model describes litter decomposition and the soil carbon cycle based on the chemical composition of the litter, size of woody litter components and climate conditions. The Yasso model requires data on litter input and its chemical composition, as well as climate data.

In Paper IV, pellet production from logging residues extracted after final felling was assumed. Yearly differences in biogenic CO_2 emissions from combustion or decomposition of the biomass were included by comparing combustion in year 1 with leaving the residues in the forest to decompose over time. Data for a stand in northern Sweden (Paper IV) were taken from a previous study that estimated biogenic carbon stock changes for different Swedish climate zones, comparing extraction and use of logging residues with no extraction of the residues (Hammar *et al.*, 2015). Biomass stock changes were simulated using the Heureka forestry decision support system and the Q model. The Heureka system is a software developed for forest planning analysis (Wikström *et al.*, 2011) and can be used *e.g.* for projection of forest growth modelling of live biomass stocks. The Q model can be used to simulate carbon stock changes in Heureka (Rolff & Agren, 1999). The Q model describes the decomposition over time of different litter fractions of a certain litter quality and requires data on annual input of litter and annual climate data.

5 Results and discussion

5.1 Energy use and efficiency

The primary energy input to the wood pellet systems studied in Papers II-IV ranged between 90 and 150 MJ per GJ pellets and the energy ratio, *i.e.* energy output relative to primary energy input to the system, was approximately 7-11. The wood pellet systems based on logging residues and eucalyptus had a lower energy ratio than the wood pellet systems based on willow and poplar (*Figure 10*).

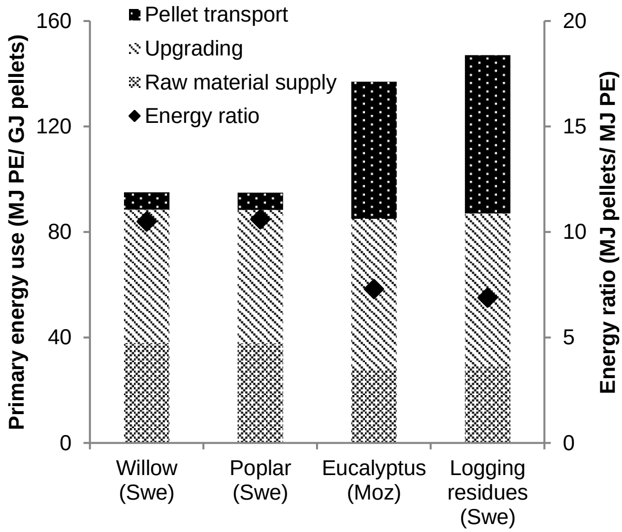

Figure 10. Primary energy (PE) input in MJ per GJ wood pellets (columns) and energy ratio (dots) for the different wood pellet systems, divided into raw material supply, upgrading and wood pellet transport to a Swedish end-user, from willow, poplar and logging residues in Sweden (Swe) and from eucalyptus in Mozambique (Moz).

In Papers II and III, in which short rotation forestry grown directly for pellet production was investigated, raw material supply included site preparation, establishment and management of the plantation, as well as harvest and transport of the raw material to the pelleting plant. For the eucalyptus plantation in Mozambique, a more manual management system compared with the willow and poplar plantations in Sweden was assumed. In Paper IV, the raw material supply included only extraction of logging residues (and not primary energy input occurring prior to final felling) and transport of the raw material to the pellet plant. Furthermore, a considerably longer transport distance between the forest site and the pelleting plant was assumed for logging residues compared with short rotation forest.

Regarding transport of the wood pellets to the end-user, a longer transport distance was assumed for wood pellets from logging residues extracted in northern Sweden (1200 km rail) than for wood pellets from willow and poplar, which were assumed to be grown in plantations on agricultural land close to the end-user in central Sweden (150 km truck). A significantly longer transport distance was associated with import of wood pellets to Sweden from Mozambique (10 km truck, 240 km rail and 17 500 km ship). However, there was a relatively small difference in primary energy input for the considerably longer transport distance in Paper IV compared with Papers II-III, which is explained by the more energy-efficient transport by ship than by truck and rail (*Figure 10*).

5.2 Time-dependent life cycle inventory

Annual GHG emissions from the production system and annual CO_2 fluxes (ΔCO_2) due to biogenic carbon stock changes were estimated for the wood pellet systems investigated in Papers II-IV.

5.2.1 Biogenic carbon stock changes - short rotation forestry

For the wood pellet systems based on short rotation forestry, biogenic CO_2 fluxes due to biogenic carbon stock changes in live biomass and soil were included. The CO_2 fluxes due to live biomass carbon stock changes varied in a repeating pattern following harvest and rotation cycles for all short rotation plantations. A maximum live biomass carbon pool was reached within the first rotation (for poplar) or second harvest cycle (for SRC willow and eucalyptus). The higher yield assumed for poplar and eucalyptus and the assumed longer time between harvests of poplar resulted in a larger maximum amount of carbon sequestered in the live biomass pool for the eucalyptus and poplar plantation than for the willow plantation. Overall, the soil organic carbon pool increased during the study period (50-100 years) for all short rotation plantations investigated, striving towards a new steady state. Annual biogenic CO_2 fluxes for the short rotation plantations are presented in *Figure 11*.

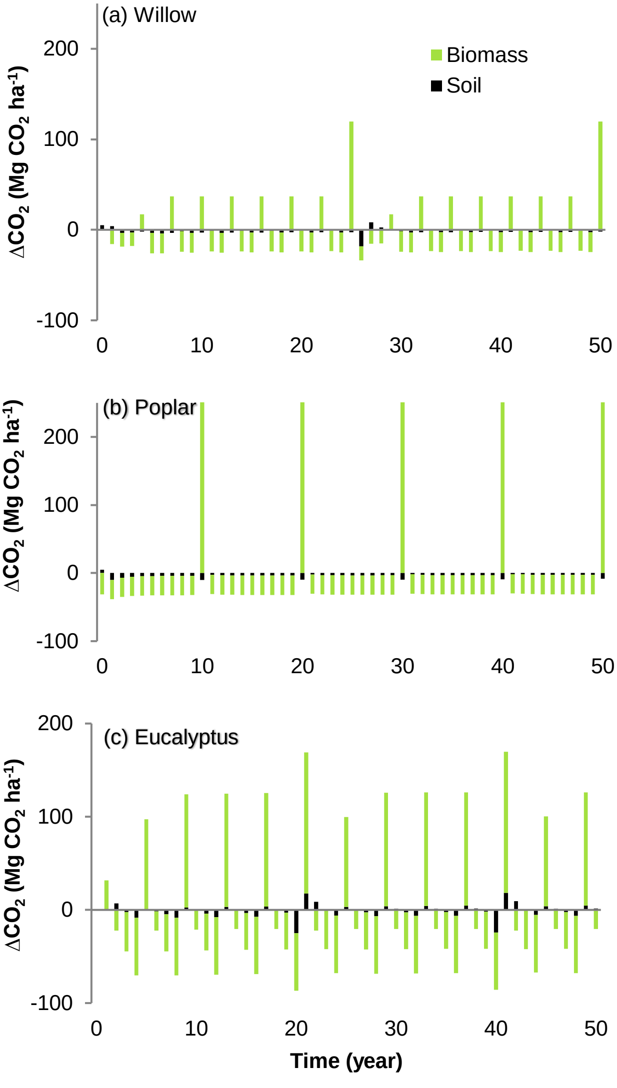

Figure 11. Yearly biogenic CO_2 fluxes (Mg CO_2 ha^{-1}), referred to as ΔCO_2, due to variations in carbon stock in live biomass and soil for (a) short rotation coppice willow and (b) poplar established on former agricultural land in Sweden, and (c) short rotation coppice eucalyptus established on former agricultural land in Mozambique. A positive ΔCO_2 value represents uptake of carbon by soil and biomass and a negative value represents release of CO_2 due to decreased carbon stocks.

Carbon sequestration potential for short rotation willow and poplar plantations established on agricultural land has also been reported by *e.g.* Djomo *et al.* (2011), Rytter (2012), Rytter *et al.* (2015) and Grogan and Matthews (2002). Furthermore, increased carbon stocks in live biomass and soil following establishment of eucalyptus plantations on degraded forest land in Mozambique has been recorded by Guedes (2016). For SRC eucalyptus established on former agricultural land in France, an average increase in carbon storage in live biomass has also been reported by Gabrielle *et al.* (2013), who concluded that an increase in soil organic carbon stocks is likely.

5.2.1 Biogenic carbon stock changes - logging residues

Extraction of logging residues from long rotation forestry (Paper IV) differed from the other raw material systems in that biomass was only harvested, pelleted and combusted once during the study period (in year 1). All emissions associated with this production system were therefore assumed to be emitted in year 1, while net CO_2 emissions were taken as the difference in CO_2 emissions between combustion of the pelleted logging residues in year 1 and leaving the residues in the forest to decompose over time (*Figure 12*). The carbon in biomass ends up in the atmosphere regardless of whether the biomass is combusted or left in the forest. The positive ΔCO_2 in year 1 for the logging residues system mainly represented CO_2 emissions from combustion, while the negative ΔCO_2 during the rest of the time frame represented the decomposition of the logging residues over time (*Figure 12*).

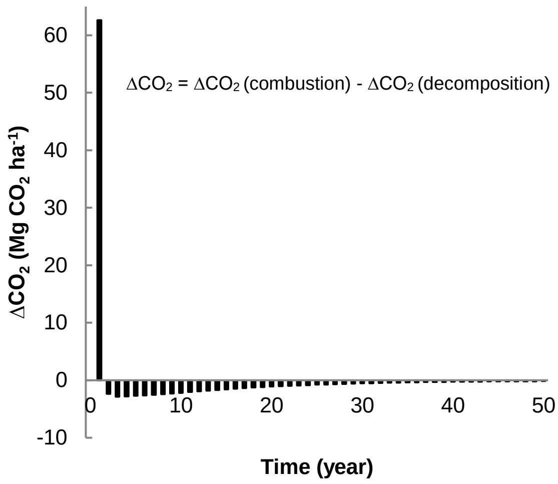

Figure 12. Yearly differences in biogenic carbon dioxide (CO_2) emissions (Mg CO_2 ha^{-1}), referred to as ΔCO_2, between direct combustion of logging residues in year 1 and leaving the residues in the forest to decompose over time.

5.3 Global warming potential

The global warming potential (GWP) ranged between 5 and 13 kg CO_2-eq. per GJ wood pellets (not including GHG emissions from end-use) for the wood pellet systems investigated in Papers II-IV (*Figure 13*). Biogenic CO_2 fluxes due to carbon stock changes in soil and biomass were not included in these calculations. In comparison, the fossil fuel reference scenario using coal resulted in a much higher GWP of 114 kg CO_2-eq. per GJ fuel.

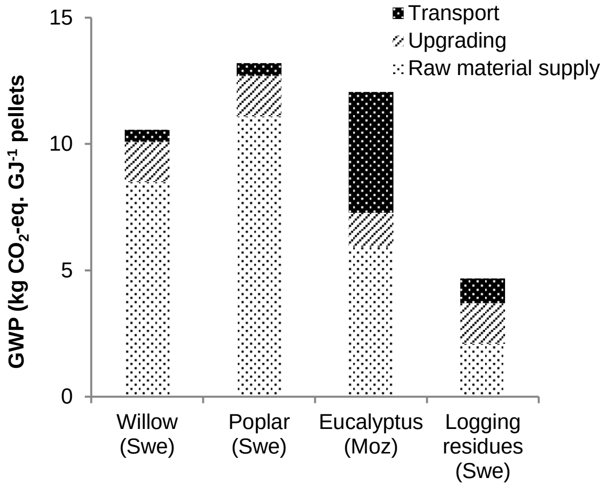

Figure 13. Global warming potential (GWP) for wood pellet production and transport to end-user in Sweden (not including emissions from end-use of the pellets), divided into raw material supply, upgrading and transport to end-user. The wood pellets were made from willow, poplar and logging residues produced in Sweden (Swe) and from eucalyptus produced in Mozambique (Moz).

Raw material supply contributed the largest share of GWP for all wood pellet systems investigated. Hotspots in the wood pellet production based on short rotation forestry plantations (Papers II and III) were emissions from production of fertiliser and N_2O emissions from soil. In Paper II, these emissions accounted for about 65% of the total CO_2-eq. per GJ willow pellets, which is consistent with findings in similar studies of willow, *e.g.* by Hammar *et al.* (2016).

Electricity use in the upgrading process accounted for a large part of the total primary energy input to the wood pellet systems. Despite this, upgrading had a relatively low impact on the total GWP of the systems. This was due to the relativity high share of renewables with low GHG emissions in both the electricity mix used for the wood pellet production assumed in Papers II and III (Nordic electricity mix) and in Paper III (Mozambique's national electricity mix). Assuming an electricity mix with a higher share of fossil fuels resulted in considerable higher GWP values. For example, assuming 100% coal-based electricity production in Paper II resulted in about 70-100% higher GWP values for willow and poplar pellets. The importance of choice of electricity mix used was also pointed out by Hansson *et al.* (2015), who compared national and regional electricity mixes and found that a Nordic electricity mix, which was used in the Swedish wood pellet systems in this thesis, generates *e.g.* higher emissions than the Swedish national mix. In Paper III, the national electricity mix in Mozambique was assumed. However, a regional mix would also be interesting to study, as the electricity grid in Mozambique is connected with nearby countries.

In Paper IV, the climate impact of torrefied wood pellets from logging residues was also estimated. The results showed a small difference in GWP between non-torrefied and torrefied wood pellets for all transport scenarios investigated. In contrast to the shorter transport scenarios (S1 and S2), a slightly lower GWP value was obtained for torrefied wood pellets for the longest transport scenario (S3) compared with non-torrefied wood pellets (*Table 3*). However, a long transport distance resulted in significantly higher GWP values for both non-torrefied and torrefied wood pellets.

Table 3. *Global warming potential (GWP) for production and use (including non-CO_2 emissions from large-scale combustion, but not biogenic CO_2 emissions) of 1 GJ non-torrefied and torrefied wood pellets delivered to a power plant for no transport and for transport scenarios S1-S3*

	GWP (kg CO_2-eq. GJ^{-1})	
Transport scenario:	Non-torrefied wood pellets	Torrefied wood pellets
No transport	5.6	6.2
S1 (1200 km truck)	6.5	6.9
S2 (600 km rail, 3000 ship)	8.5	8.8
S3 (600 km rail, 25 000 ship)	26.5	24.6

The most common approach for assessing the climate impact of both non-torrefied and torrefied wood pellet production chains in earlier studies has been to use GWP and not include biogenic CO_2 fluxes (*e.g.* (Hansson *et al.*, 2015; Roder *et al.*, 2015; Batidzirai *et al.*, 2013b). The findings in this thesis were in line with the results of those previous LCA studies (presented in section 3.7). However, as also pointed out by *e.g.* Hansson *et al.* (2015) and Ehrig and Behrendt (2013), the design of the supply chain determines the climate impact and energy efficiency of a system. Different assumptions regarding *e.g.* raw material used, transport alternatives and electricity origin mean that the results of different studies of wood pellet production chains are not directly comparable.

5.4 Temperature response

5.4.1 Willow and poplar

In terms of total global mean surface temperature change, ΔT_S, the willow and poplar pellet system contributed to a negative ΔT_S (*i.e.* cooling temperature effect). A greater negative ΔT_S per hectare was obtained for the pellet system based on poplar than for the pellet system based on willow. This was mainly due to more carbon sequestration in live biomass and soil due to assumed higher poplar yield per hectare, as well as longer growth periods between harvests in the poplar scenario compared with the willow scenario (*Figure 14*). Using coal for heat production instead of wood pellets from willow and poplar had a considerably higher climate impact, contributing to a positive ΔT_S (*i.e.* warming temperature effect). The higher yield per hectare of poplar was also reflected in the higher positive ΔT_S for the corresponding reference scenario for poplar compared with the reference scenario for willow (*Figure 14*).

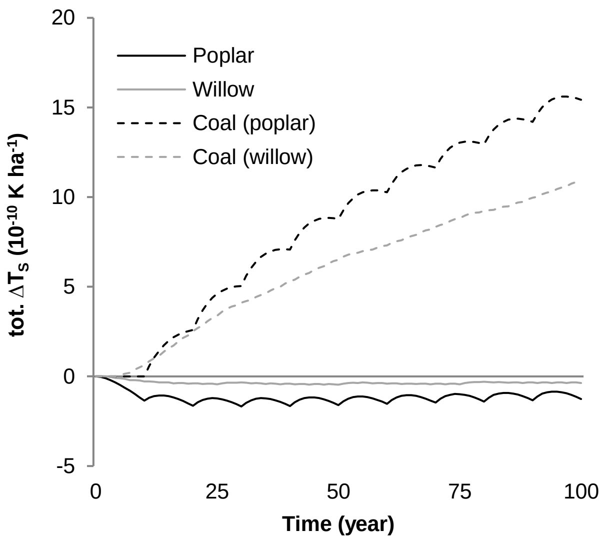

Figure 14. Change in global mean surface temperature, ΔT_S, over time for wood pellet systems based on willow and poplar from 1 ha of plantation used in a Swedish district heating plant, and their corresponding reference scenarios where coal was used to produce an equivalent amount of heat to that obtained from the wood pellet systems.

Establishing willow and poplar plantations on former agricultural land in Sweden was shown to result in continued sequestration of carbon in the soil during the whole study period, striving towards a new steady state. This resulted in a continuous increasing cooling effect on ΔT_S, which is shown for willow in *Figure 15*. However, the soil is not an infinite carbon sink (Lal, 2004). If the land were to be converted back to the previous land use, most of the sequestered carbon would be emitted back to the atmosphere over time. In contrast to the long-term carbon sequestration in soil, a maximum carbon stock in live biomass is reached relatively fast, as is its corresponding maximum negative ΔT_S (*Figure 15*).

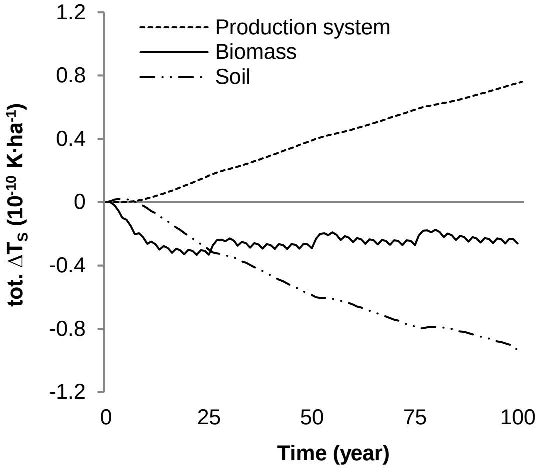

Figure 15. Change in global mean surface temperature, ΔT_S, over time for willow pellets from 1 ha of plantation used in a Swedish district heating plant, divided into effect on carbon stock changes in biomass and soil and greenhouse emissions from the production system.

5.4.2 Eucalyptus in Mozambique

Production and use of wood pellets from short SRC eucalyptus contributed to an initial negative ΔT_S (*Figure 16*). The increased biogenic carbon stocks in both soil and biomass resulted in an overall negative ΔT_S. In contrast, the production system in which there were only GHG emissions and no carbon sinks caused a positive ΔT_S that increased over time (*Figure 17*). In total, this resulted in the initial cooling effect declining over time, resulting in a positive ΔT_S after about 27 years (*Figure 16*). The corresponding coal-based reference scenarios, in which equivalent amounts of heat and power were produced as in the wood pellet scenario, all had a positive ΔT_S during the whole study period (*Figure 16*).

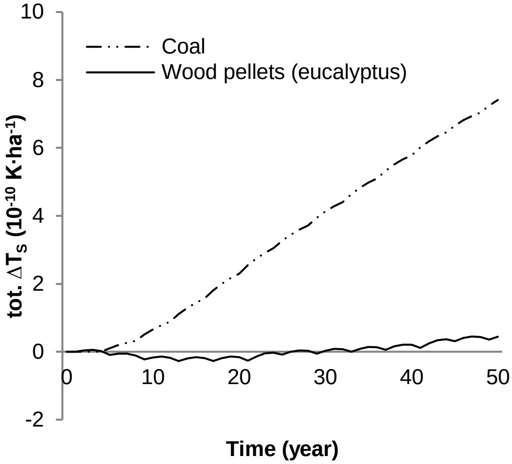

Figure 16. Change in global mean surface temperature, ΔT_S, over time for eucalyptus pellets from 1 ha of plantation used in a combined heat and power plant in Sweden and its corresponding reference scenario where coal was used to produce an equivalent amount of heat and power to that obtained from the wood pellet system.

Year 0 was defined as the initial carbon stock before establishment of the plantation. The harvesting cycle gave regular peaks in the ΔT_S curve for biomass due to pulse emissions of CO_2 when the pellets were combusted, followed by carbon sequestration in growing biomass until the next harvest (*Figure 17*). The initial positive ΔT_S for the biomass curve was due to the removal and combustion of the initial vegetation.

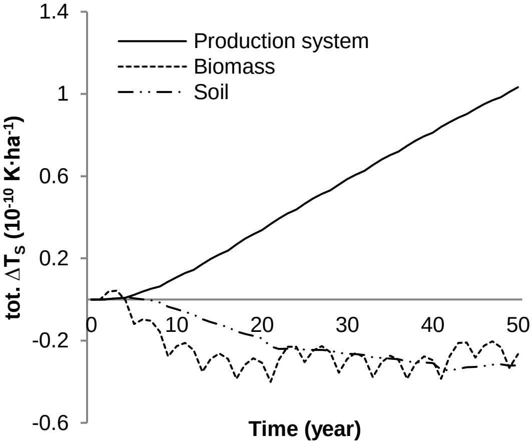

Figure 17. Change in global mean surface temperature, ΔT_S, over time for eucalyptus pellets from 1 ha of plantation used in a combined heat and power plant in Sweden, divided into effect on carbon stock changes in biomass and soil and greenhouse emissions from the production system.

5.4.3 Logging residues

In contrast to pellets from short rotation plantations (Papers II and III), wood pellets from logging residues (Paper IV) had a positive ΔT_S, *i.e.* warming temperature effect, during the whole period investigated for the system. However, both non-torrefied and torrefied wood pellets still contributed to a lower global mean surface temperature change (ΔT_S) during the whole study period compared with coal (*Figure 18*).

Non-torrefied wood pellets had a slightly lower ΔT_S value than torrefied wood pellets per GJ fuel. The difference in ΔT_S between non-torrefied and torrefied wood pellets peaked after about 10 years (0.4×10^{-14} K) and then decreased over time. The highest positive ΔT_S for all fuels was obtained about 10-15 years after the emissions impulse due to combustion in year 1. This delay in temperature response after an emissions impulse is due to the inertia of the Earth's climate processes. For both torrefied and non-torrefied wood pellets, the ΔT_S curves declined faster over time compared with coal (*Figure 18*). This was because of the resulting negative CO_2 fluxes after year 1 when comparing combustion with leaving the residues to decompose over time, as illustrated in *Figure 12*.

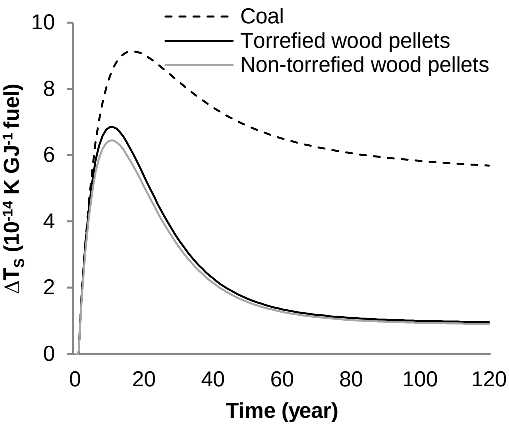

Figure 18. Change in global mean surface temperature, ΔT_S, for 1 GJ non-torrefied and torrefied wood pellets produced from logging residues combusted at a power plant in Sweden compared with 1 GJ coal (produced and combusted in year 1) for one rotation period of 120 years.

Net emissions of biogenic CO_2 accounted for by far the largest part of the global temperature effect for both non-torrefied and torrefied wood pellets (*Figure 19*). These emissions were also found to be the main cause of the higher ΔT_S for torrefied wood pellets compared with non-torrefied wood pellets. The higher raw material demand for production of torrefied wood pellets resulted in greater net emissions of biogenic CO_2, as these are fixed per hectare. Factors such as thermal efficiency and the degree of torrefaction affect the raw material demand within the torrefaction process. Thermal efficiency is an important indicator of the technical performance of the process and is determined by thermal losses, moisture content and heating value of the raw material used. In a long-term perspective, Batidzirai *et al.* (2013a) point out that the thermal efficiency is likely to increase due to expected technical improvements in the torrefaction process, as well as more optimised use of torrefaction gas. This would result in a smaller difference in ΔT_S between non-torrefied and torrefied wood pellets.

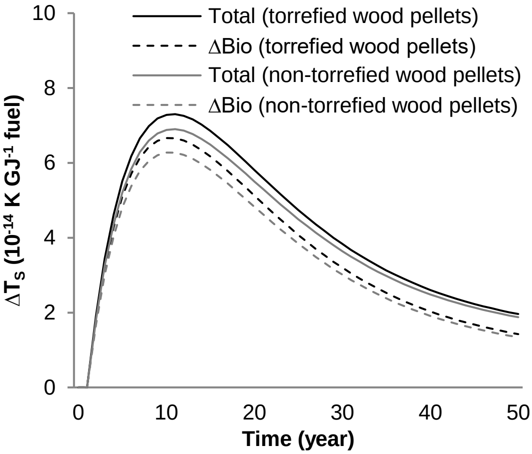

Figure 19. Change in global mean surface temperature, ΔT_S, over time for 1 GJ non-torrefied and torrefied wood pellets produced from logging residues and used in a power plant in Sweden, and temperature change for only biogenic carbon stock changes (ΔBio).

Despite a more energy efficient transport for torrefied wood pellets, the total ΔT_S was found to be lower for non-torrefied than for torrefied wood pellets for all transport scenarios (described in *Table 2*). This is explained by the dominating effect of biogenic CO_2 emissions on the results (which is not included in the GWP values presented in *Figure 13*). Nevertheless, the long transport distance in scenario S3 resulted in higher ΔT_S and significantly higher GWP values for both non-torrefied and torrefied wood pellets compared with scenarios S1 and S2.

Higher electrical efficiency was assumed for torrefied compared with non-torrefied wood pellets, which can be expected since the characteristics of the torrefied product are more similar to coal. Thus, when also including the energy conversion efficiency, a lower ΔT_S was obtained per GJ electricity produced for the torrefied wood pellets (*Figure 20*).

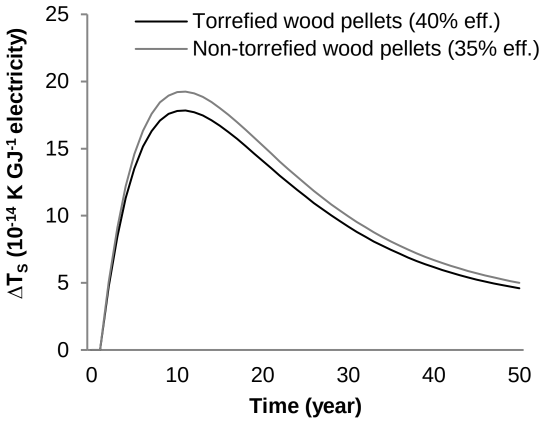

Figure 20. Change in global mean surface temperature, ΔT_S, over time for 1 GJ electricity generated in year 1 from non-torrefied and torrefied wood pellets produced from logging residues and used in a power plant in Sweden.

Furthermore, ΔT_S from co-firing non-torrefied or torrefied wood pellets with coal (including GHG fluxes from both pellets and coal) was also substantially lower for torrefied wood pellets than for non-torrefied. This was due to the expected higher co-firing rates for torrefied wood pellets (rates tested: 40, 50 and 60 %) than for non-torrefied wood pellets (rates tested: 5, 10 and 15 %), and thus more coal being replaced in the former alternative (*Figure 21*).

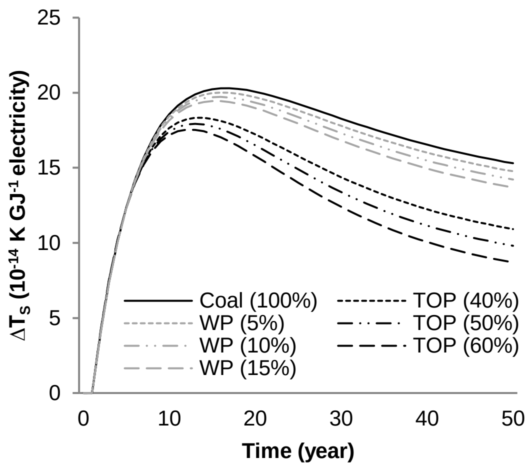

Figure 21. Change in global mean surface temperature, ΔT_S, over time for 1 GJ electricity generated in year 1 from non-torrefied (WP) and torrefied wood pellets (TOP) produced from logging residues and used in a power plant in Sweden in different scenarios for co-firing WP (5, 10 or 15 %) and TOP (40, 50 or 60 %) with coal, compared with using 100% coal.

6 General discussion

6.1 Time-dependent climate impact assessment and GWP

The time-dependent approach for LCA developed in this thesis gives additional insights into the complexity of bioenergy systems compared with using GWP with a fixed time horizon. With the time-dependent approach, temporal CO_2 fluxes between the soil, biomass and atmosphere connected to bioenergy systems are included. This information is not available by assuming a fixed time horizon, where essentially only net changes in biogenic carbon stocks can be obtained. In turn, this means that the time lag between emission and uptake of CO_2 is disregarded and this has a major effect on the temporal climate impact, especially for long rotation bioenergy systems. For the wood pellet systems investigated in this thesis, the temporal fluxes had a major effect on the climate impact.

Furthermore, expressing the climate impact as annual global mean surface temperature change (ΔT_S), as proposed in this thesis, can help to increase understanding of the role of bioenergy systems in climate mitigation strategies. This is beneficial since the aim of these strategies is often expressed as a limited temperature change, *e.g.* the maximum temperature increase target of 2 °C set by the UNFCC. However, calculating ΔT_S is not as straightforward as determining the GWP and presenting the climate impact as a temperature change over time is more complicated than presenting it as a single value given in CO_2-eq. It is therefore likely that the well-recognised climate metric GWP will continue to be important in the future.

6.2 Temperature response of wood pellet systems

For the short rotation forest plantations established on agricultural land, overall carbon sequestration in living biomass and soil was demonstrated. This resulted in a negative ΔT_S (*i.e.* cooling temperature effect). In contrast, extraction of logging residues resulted in a positive ΔT_S (*i.e.* warming temperature effect). The carbon in biomass eventually ends up in the atmosphere as CO_2 regardless of whether it is combusted or left to decompose over time. This is also true for other by-products such as the traditionally used raw materials, sawdust and shavings. However, it should be pointed that fossil coal was shown to have a considerably higher positive ΔT_S than logging residues (see *Figure 18*).

Furthermore, the increasing negative ΔT_S due to carbon sequestration in soil and biomass for the short rotation plantations will eventually reach a new steady state (assuming continuous cultivation). On the other hand, ΔT_S will increase due to continuous GHG emissions from the production system. To reduce the climate effects of a bioenergy system in a longer-term perspective, it is therefore important to strive for more energy-efficient and fossil-free solutions for bioenergy production systems.

The carbon sequestration potential is to a large extent dependent on the initial carbon stocks. In the production systems investigated in this thesis, former agricultural land where the carbon stocks were generally low was used for plantation. Using land with higher initial carbon stocks would result in an earlier or an immediately positive ΔT_S. It is also worth noting that if the land were to be converted back to its previous land use, the carbon stock level would return to its previous value and would result in a reversed temperature response. The cooling effect obtained by the systems is thus dependent on continuous cultivation and retaining the sequestered carbon in the soil and biomass, as also concluded by Hammar *et al.* (2014).

Yield is also an important factor for the total temperature response, as it determines the carbon stock in the live biomass and the input to the soil carbon pool. Variations in yield can be explained by the management of the plantation, soil type and climate conditions. A relatively high yield was assumed for the short rotation forest plantations investigated in this study, assuming optimal management of the plantations. However, large variations in yield have been reported, for example a considerably lower yield, 7-8 Mg ha^{-1} yr^{-1}, was reported for willow and poplar established on agricultural land in Sweden by Dimitriou and Mola-Yudego (2017). Yields for willow and poplar ranging from 4 to 17 Mg ha^{-1} yr^{-1} have also been reported in a review by Djomo *et al.* (2011). Furthermore, yields ranging from 13 to 20 Mg ha^{-1} yr^{-1} have been reported for eucalyptus in moist tropical regions with a dry season reported by IPCC (2006a).

The calculated temperature responses in this thesis were in the same range as reported for willow and logging residues by Zetterberg and Chen (2015), Hammar *et al.* (2015) and Hammar *et al.* (2014). However, those studies assumed direct combustion of the biomass for energy conversion, and consequently did not include pellet production. The temperature response, on the other hand, was shown to be mainly due to biogenic carbon stock changes, which makes extra GHG emissions from pellet production less important for the total temperature response.

6.3 Other methodological choices

Different functional units can be used when assessing the climate impact of bioenergy systems. In order to capture the varying energy output between years a functional unit of 1 hectare was used for wood pellets from short rotation forestry in Papers II and III. A consequence of using this functional unit is that the difference in energy output (GJ pellets or heat/electricity produced) per hectare is not captured, which makes comparisons between different systems not completely straightforward. However, by including a fossil reference (corresponding to the same amount of heat and power produced as in the wood pellet system), the total climate benefits of the system can be demonstrated.

Paper IV analysed the advantages of using torrefied wood pellets compared with non-torrefied wood pellets in dedicated power plants for biomass fuels and for co-firing with coal. However, biomass fuels are mainly used in heat and combined heat and power (CHP) plants in Sweden. It should also be pointed out that coal contributed only about 5% of the total fuels used in Swedish CHP plants in 2015 (SCB, 2016). Nonetheless, the assessment in Paper IV is relevant in a global perspective, where coal accounts for 40% of the total global electricity generation (IEA, 2016) and co-firing is a viable approach to reduce the use of fossil coal.

All studies included in this thesis adopted a stand perspective, *i.e.* one hectare of agricultural or forest land was studied. However, a landscape perspective including a continuous supply of biomass has been recommended elsewhere, *e.g.* by Cintas *et al.* (2015). By using a landscape perspective, other factors can be captured in the climate impact assessment, such as spatial differences in the landscape regarding *e.g.* soil type and water availability (Hammar *et al.*, 2016). This in turn affects productivity and could be useful information when drawing general conclusions on a regional or national level. However, an advantage of using a stand-level approach is its simplicity, as also pointed out by Lamers and Junginger (2013). This could facilitate a better understanding of *e.g.* the effect on biogenic carbon stock of establishing short rotation forestry on agricultural land or of increasing extraction of logging residues after final felling of timber.

6.4 Uncertainty

Biogenic carbon changes represented a large part of the total temperature response for the wood pellet systems studied in this thesis. Biogenic carbon dynamics are complex, however, and there are often few empirical data available (Lamers & Junginger, 2013). Large uncertainties are therefore associated with their estimation, both regarding the carbon balance models and the accuracy of the input data and assumptions.

Another large uncertainty factor was estimation of N_2O soil emissions in climate impact assessments of the wood pellet systems based on short rotation forestry. The IPCC default values were used when estimating these emissions (IPCC, 2006b), but these values are general and do not consider site- and crop-specific conditions. The actual emissions can thus vary widely between different locations.

Moreover, Myhre *et al.* (2013b) and Joos *et al.* (2013) mention large uncertainties associated with the climate models used. However, although the total temperature response of any individual wood pellet system investigated has uncertainties, the same uncertainties applies to all systems investigated.

Overall, uncertainties are inevitable in LCA and the wood pellet systems studied in this thesis suffer from uncertainties associated with the models used, as well as the parameters, choices and data quality. Despite this high degree of uncertainty, it is still important to evaluate complex bioenergy systems, but the result should not be regarded as an exact number, but more as an indication of the potential climate impact.

6.5 Available raw materials

A prerequisite for increasing global wood pellet production is the availability of biomass feedstock. Estimation of global bioenergy potential is complex and a large range has been reported (50-1000 EJ yr^{-1} by 2050) (Creutzig *et al.*, 2015). This can be compared with the global primary energy supply of 574 EJ in 2014 (IEA, 2016). However, only a part of the potentially available biomass would be used for pellet production.

This thesis focused partly on agricultural-based feedstock for wood pellet production. A key question for these systems is the availability of agricultural land. Campbell *et al.* (2008) estimated the global potential of abandoned agricultural land to be 385-472 million ha, excluding land converted to urban areas or forest. According to their study, about 7-8% of global primary energy demand could be covered by using this land for energy crop production. Estimating the global potential of available land is difficult, however, as it involves the demand for other land use activities, such as food and feed production. The availability of agricultural land reported to be abandoned has also been questioned (Creutzig *et al.*, 2015).

In this thesis, short rotation forest plantations were assumed to be established in Sweden and Mozambique and available former agricultural land has been reported in both these countries (van der Hilst & Faaij, 2012; SJV, 2009). However, it should be stressed that grasslands play an important role in securing the livelihood of around 80% of the Mozambican population, by providing feed, food, fibre and ecosystem services. Today there is marked interest among foreign investors in large-scale agriculture and forest projects in Mozambique. Land conflicts involving forest plantations have been reported (Overbeek, 2010; Schut *et al.*, 2010), mainly concerning land access processes and weak community consultation processes, combined with weak negotiating ability by local people due to their low education level (Ministério de Agricultura, 2010).

An advantage of using forest plantations dedicated to wood pellet production is that the raw material is geographically concentrated. This improves the logistics and decreases transport distances compared with *e.g.* logging residues, which can be scattered over larger areas. Another advantage of forest plantations dedicated to wood pellet production is that they are not directly connected to the sawmilling industry and thereby the shifting demand for other wood products, as pointed out by Goh *et al.* (2013).

The development of new large-scale pelleting plants in the southeastern USA, where chipped log wood is used directly for pellet production, is partly a result of the declining paper and pulp industry (Goh *et al.*, 2013). With a paper and pulp industry in transition, this development can also be possible in other parts of the world. In Europe, only 60-70% of the annual growth in forests is harvested (Proskurina *et al.*, 2016), which could give opportunities for a raw material supply directly from these forests to wood pelleting plants.

Theoretically, all woody raw materials can be used for pellet production (Obernberger & Thek, 2010). However, many of the suggested raw materials would result in wood pellets with lower quality than those produced from traditional raw materials. Large-scale use is therefore more suitable for these pellets. Non-woody raw materials, such as reed canary grass, hemp and agricultural waste and waste products have also been suggested as feedstock for pellet production (Nilsson *et al.*, 2011).

6.6 Why wood pellets?

From a climate impact point of view, wood pellets are not necessarily better than using unrefined biomass for direct combustion for heat and power production. On the other hand, wood pellets provide opportunities to use biomass in other applications than unrefined biomass. For example, wood pellets have been identified as a relatively fast and straightforward way to start phasing out coal in large-scale power production and as an alternative to fossil oil for residential heating (Goh *et al.*, 2013).

In order to fulfil energy and climate targets by partly increasing the use of biomass fuels, many European countries need to rely on import of biomass. Wood pellets are a homogeneous, dense and dry fuel, which makes storage and transport easier than with unrefined biomass. Long transport distances enable new markets to be accessed, creating more export possibilities for regions with available biomass.

Besides being easier to store and transport, less modifications are needed when wood pellets are used in existing heat and power plants compared with unrefined biomass. The properties of wood pellets can be improved further by including a torrefaction process. Torrefied wood pellets have advantages such as higher electrical conversion efficiency and higher co-firing rates when used for power production compared with non-torrefied wood pellets. However, in the long term, new power plants dedicated to using biomass, or high co-firing rates, may reduce the benefits of using torrefied wood pellets compared with non-torrefied wood pellets, as discussed by Koppejan *et al.* (2012).

Furthermore, the properties of wood pellets enable more flexible use of the biomass. This is an advantage as flexible power production is likely to become more important in order to balance demand and supply, with an increasing share of intermittent electricity production.

If limited access to biomass is assumed, comparisons are needed not only between biomass- and fossil-based systems, but also between different biomass-based applications in order to find *e.g.* the most economic, energy-efficient solution or the least GHG-emitting. This is also discussed by Cherubini and Stromman (2011). However, assuming that there is available biomass, all potential ways to reduce the use of fossil fuels, and thereby GHG emissions, are relevant.

7 Conclusions

In this thesis, a time-dependent approach for conducting LCA was developed and both the timing and the magnitude of GHG fluxes were considered in climate impact assessments. With this approach, temporal CO_2 fluxes between the soil, biomass and atmosphere connected to bioenergy systems are included. This methodology was used to investigate the time-dependent climate impact of different wood pellet systems.

The analysis focused on wood pellet systems based on short rotation forestry in Sweden and in Mozambique and residual forest biomass extracted from final felling in Sweden. The main conclusions were:

- From a climate impact perspective, all wood pellet systems studied were a better alternative than fossil coal for heat and power production.
- Establishing poplar and SRC willow on former agricultural land in central Sweden provided potential for carbon sequestration in both live biomass and soil, which resulted in a cooling global temperature effect.
- Carbon sequestration potential was also shown for SRC eucalyptus established on former agricultural land in Mozambique.
- Over time, the cooling effect due to carbon sequestration in soil and biomass will decline as a new steady state is reached, whereas the warming effect due to GHG emissions from the production system will continue to increase, resulting in a net warming temperature effect of the wood pellet systems over time.
- Wood pellets produced from logging residues extracted from final felling had a warming temperature effect. Net emissions of biogenic CO_2 accounted for by far the largest part of this temperature effect.

- Torrefied wood pellets were better from a climate perspective due to assumed higher electrical efficiency and a higher co-firing rate (with coal) compared with non-torrefied wood pellets.
- The electricity used in the upgrading process accounted for a large part of the total primary energy input to the wood pellet systems. Despite this, upgrading had a relatively low climate impact due to the relativity high share of renewables with low GHG emissions in the electricity mixes used.
- The energy output of the wood pellet systems studied was 7 to 11 times the primary energy input.

The time-dependent climate impact methodology developed in this thesis provided a better understanding of the wood pellet systems studied and their climate effects and also captured the time-dynamic behaviour of the atmospheric residence times of GHG emissions from the systems, as well as the biogenic CO_2 fluxes between soil, biomass and atmosphere. This methodology could be used for other bioenergy systems to complement climate impact assessments and to increase knowledge of these complex systems.

8 Future research

Extensive use of fossil fuels is the main cause of the climate changes the world is now experiencing. In order to reduce the dependency on fossil fuels diversification of the energy system is necessary, and bioenergy could play a central part in such diversification. However, bioenergy has been questioned with regard to its climate or carbon neutrality. It is therefore important to increase knowledge of the climate impact of different bioenergy systems and to identify hotspots within the systems. Factors that could be addressed in future studies in order to increase understanding of the environmental effects of these systems are as follows:

- Further empirical studies could help achieve better reliability of biogenic carbon stock models. Improved access to input data could also increase the accuracy of model estimates.
- In addition to the site-specific approach used in this thesis, a landscape perspective could provide more general conclusions on regional and national scale.
- This thesis focused on the major GHG (CO_2, CH_4 and N_2O) but there are other GHG and other climate processes, such as impact on albedo due to changes in land cover that need further study.
- This thesis focused on climate change, but there are other relevant features of a sustainable bioenergy system, such as biodiversity, nutrient loss and social and economic aspects, that should also be addressed.

References

Agar, D., Gil, J., Sanchez, D., Echeverria, I. & Wihersaari, M. (2015). Torrefied versus conventional pellet production - A comparative study on energy and emission balance based on pilot-plant data and EU sustainability criteria. *Applied Energy,* 138, pp. 621-630.

Agar, D. & Wihersaari, M. (2012). Bio-coal, torrefied lignocellulosic resources – Key properties for its use in co-firing with fossil coal – Their status. *Biomass and bioenergy,* 44, pp. 107-111.

Agbor, E., Zhang, X.L. & Kumar, A. (2014). A review of biomass co-firing in North America. *Renewable & Sustainable Energy Reviews,* 40, pp. 930-943.

Agostini, A., Giuntoli, J. & Boulamanti, A. (2013). *Carbon accounting of forest bioenergy. Conclusions and recommendations from a criticial literature review*. Report EUR 25354 EN. Publications Office of the European Union, Luxembourg.

Ahlgren, S. & Di Lucia, L. (2014). Indirect land use changes of biofuel production - a review of modelling efforts and policy developments in the European Union. *Biotechnology for Biofuels,* 7(35).

Andren, O. & Katterer, T. (1997). ICBM: The introductory carbon balance model for exploration of soil carbon balances. *Ecological Applications,* 7(4), pp. 1226-1236.

Batidzirai, B., Faaij, A. & Smeets, E. (2006). Biomass and bioenergy supply from Mozambique. *Energy for Sustainable Development,* 10(1), pp. 54-81.

Batidzirai, B., Mignot, A.P.R., Schakel, W.B., Junginger, H.M. & Faaij, A.P.C. (2013a). Biomass torrefaction technology: Techno-economic status and future prospects. *Energy,* 62, pp. 196-214.

Batidzirai, B., Smeets, E.M.W. & Faaij, A.P.C. (2012). Harmonising bioenergy resource potentials-Methodological lessons from review of state of the art bioenergy potential assessments. *Renewable & Sustainable Energy Reviews,* 16(9), pp. 6598-6630.

Batidzirai, B., van der Hilst, F., Meerman, H., Junginger, H.M., André, P.C. & Faaij, A.P.C. (2013b). Optimization potential of biomass supply chains with torrefaction technology. *Biofuels, Bioproducts and Biorefining,* 8(2), pp. 253-282.

Baumann, H. & Tillman, A.-M. (2004). *The Hitch Hiker's Guide to LCA – An orientation in life cycle assessment methodology and application*. Lund, Sweden: Studentlitteratur.

Bergman, P.C.A. (2005). *Combined torrefaction and pelletisation - The TOP process*. Energy research Centre of the Netherlands (ECN), Petten, The Netherlands.

Brandao, M., i Canals, L.M. & Clift, R. (2011). Soil organic carbon changes in the cultivation of energy crops: Implications for GHG balances and soil quality for use in LCA. *Biomass and bioenergy,* 35(6), pp. 2323-2336.

Brandao, M., Levasseur, A., Kirschbaum, M.U.F., Weidema, B.P., Cowie, A.L., Jorgensen, S.V., Hauschild, M.Z., Pennington, D.W. & Chomkhamsri, K. (2013). Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. *International Journal of Life Cycle Assessment,* 18(1), pp. 230-240.

Campbell, J.E., Lobell, D.B., Genova, R.C. & Field, C.B. (2008). The global potential of bioenergy on abandoned agriculture lands. *Environmental science & technology,* 42(15), pp. 5791-5794.

Cherubini, F., Fuglestvedt, J., Gasser, T., Reisinger, A., Cavalett, O., Huijbregts, M.A., Johansson, D.J., Jørgensen, S.V., Raugei, M. & Schivley, G. (2016). Bridging the gap between impact assessment methods and climate science. *Environmental Science & Policy,* 64, pp. 129-140.

Cherubini, F., Peters, G.P., Berntsen, T., Stromman, A.H. & Hertwich, E. (2011). CO2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. *Global Change Biology Bioenergy,* 3(5), pp. 413-426.

Cherubini, F. & Stromman, A.H. (2011). Life cycle assessment of bioenergy systems: State of the art and future challenges. *Bioresource Technology,* 102(2), pp. 437-451.

Chum, H., Faaij, A., Moreira, J., Berndes, G., Dhamija, P., Dong, H., Gabrielle, B., Goss Eng, A., Lucht, W., Mapako, M., Masera Cerutti, O., McIntyre, T., Minowa, T. & Pingoud, K. (2011). *Bioenergy. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J. & Heimann, M. (2013). Carbon and other biogeochemical cycles. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* Cambridge University Press, pp. 465-570.

Cintas, O., Berndes, G., Cowie, A.L., Egnell, G., Holmström, H. & Ågren, G.I. (2015). The climate effect of increased forest bioenergy use in Sweden: evaluation at different spatial and temporal scales. *Wiley Interdisciplinary Reviews: Energy and Environment,* 5(3), pp. 351-369.

Cocchi, M., Nikolaisen, L., Junginger, H.M., Goh, C.S., Heinimö, J., Bradley, D., Hess, R., Jacobson, J., Ovard, L.P., Thrän, D., Hennig, C., Deutmeyer, M., Schouwenberg, P.P. & Marchal, D. (2011). *Global Wood Pellet*

Industry Market and Trade Study. Task 40: Sustainable International Bioenergy trade. IEA Bioenergy, Paris, France.
Creutzig, F., Ravindranath, N.H., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., Chum, H., Corbera, E., Delucchi, M., Faaij, A., Fargione, J., Haberl, H., Heath, G., Lucon, O., Plevin, R., Popp, A., Robledo-Abad, C., Rose, S., Smith, P., Stromman, A., Suh, S. & Masera, O. (2015). Bioenergy and climate change mitigation: an assessment. *Global Change Biology Bioenergy*, 7(5), pp. 916-944.
de Jong, J., Akselsson, C., Berglund, H., Egnell, G., Gerhardt, K., Lönnberg, L., Olsson B & von Steding H (2014). *Consequences of an increased extraction of forest biofuel in Sweden - a synthesis from the biofuel research programme 2007- 2011. Summary of synthesis report*. IEA Bioenergy Task 43. Report 2014:01.
Dimitriou, I. & Mola-Yudego, B. (2017). Poplar and willow plantations on agricultural land in Sweden: Area, yield, groundwater quality and soil organic carbon. *Forest Ecology and Management*, 383, pp. 99-107.
Djomo, S.N., El Kasmioui, O. & Ceulemans, R. (2011). Energy and greenhouse gas balance of bioenergy production from poplar and willow: a review. *Global Change Biology Bioenergy*, 3(3), pp. 181-197.
EC (2016). *European Commission, Climate Action*. Avaliable from: http://ec.europa.eu/clima/policies/strategies/2030/index_en.htm [2016-11-20].
Ehrig, R. & Behrendt, F. (2013). Co-firing of imported wood pellets - An option to efficiently save CO2 emissions in Europe? *Energy Policy*, 59, pp. 283-300.
Ericsson, K. & Werner, S. (2016). The introduction and expansion of biomass use in Swedish district heating systems. *Biomass and bioenergy*, 94, pp. 57-65.
European Pellet Council (2015). *ENplus Handbook. Part 3: Pellet Quality Requirement. Version 3.0*. AEBIOM - European Biomass Association. Brussels, Belgium.
Eurostat (2016). *Share of renewables in gross inland energy consumption, 2014 (%)*. Avaliable from http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Share_of_renewables_in_gross_inland_energy_consumption,_2014_(%25)_YB16.png [2016-12-01].
Fantozzi, F. & Buratti, C. (2010). Life cycle assessment of biomass chains: Wood pellet from short rotation coppice using data measured on a real plant. *Biomass & Bioenergy*, 34(12), pp. 1796-1804.
FAO (2015). *2014 Global Forest Products Facts and Figures*. Food and Agriculture Organization of the United Nation, Rome, Italy.
Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinee, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D. & Suh, S. (2009). Recent developments in Life Cycle Assessment. *Journal of Environmental Management*, 91(1), pp. 1-21.
Fuglestvedt, J.S., Berntsen, T.K., Godal, O., Sausen, R., Shine, K.P. & Skodvin, T. (2003). Metrics of climate change: assessing radiative forcing and emission indices. *Climatic Change*, 58(3), pp. 267-331.

Fuglestvedt, J.S., Shine, K.P., Berntsen, T., Cook, J., Lee, D.S., Stenke, A., Skeie, R.B., Velders, G.J.M. & Waitz, I.A. (2010). Transport impacts on atmosphere and climate: Metrics. *Atmospheric Environment,* 44(37), pp. 4648-4677.

Gabrielle, B., The, N.N., Maupu, P. & Vial, E. (2013). Life cycle assessment of eucalyptus short rotation coppices for bioenergy production in southern France. *Global Change Biology Bioenergy,* 5(1), pp. 30-42.

Giuntoli, J., Agostini, A., Edwards, R. & Marelli, L. (2014). *Solid and gaseous bioenergy pathways: input values and GHG emissions*. JRC Science and policy reports, European Commission.

Goh, C.S., Junginger, M., Cocchi, M., Marchal, D., Thrän, D., Hennig, C., Heinimö, J., Nikolaisen, L., Schouwenberg, P.P. & Bradley, D. (2013). Wood pellet market and trade: a global perspective. *Biofuels, Bioproducts and Biorefining,* 7(1), pp. 24-42.

Grogan, P. & Matthews, R. (2002). A modelling analysis of the potential for soil carbon sequestration under short rotation coppice willow bioenergy plantations. *Soil Use and Management,* 18(3), pp. 175-183.

Guedes, B. (2016). *Impacts of pine and eucalyptus plantations on carbon and nutrients stocks and fluxes in miombo forests ecosystems.* Diss.: Swedish University of Agricultural Sciences.

Gustavsson, L., Haus, S., Ortiz, C.A., Sathre, R. & Le Truong, N. (2015). Climate effects of bioenergy from forest residues in comparison to fossil energy. *Applied Energy,* 138, pp. 36-50.

Hammar, T., Ericsson, N., Sundberg, C. & Hansson, P.-A. (2014). Climate impact of willow grown for bioenergy in Sweden. *BioEnergy Research,* 7(4), pp. 1529-1540.

Hammar, T., Hansson, P.A. & Sundberg, C. (2016). Climate impact assessment of willow energy from a landscape perspective: a Swedish case study. *GCB Bioenergy*.

Hammar, T., Ortiz, C., Stendahl, J., Ahlgren, S. & Hansson, P.-A. (2015). Time-Dynamic Effects on the Global Temperature When Harvesting Logging Residues for Bioenergy. *BioEnergy Research,* 8(4), pp. 1912-1924.

Hansson, J., Martinsson, F. & Gustavsson, M. (2015). Greenhouse gas performance of heat and electricity from wood pellet value chains - based on pellets for the Swedish market. *Biofuels Bioproducts & Biorefining-Biofpr*, 9(4), pp. 378-396.

Hjelm, B. & Johansson, T. (2012). Volume equations for poplars growing on farmland in Sweden. *Scandinavian Journal of Forest Research,* 27(6), pp. 561-566.

Hollsten, R., Arkelöv, O. & Ingelman, G. (2011). *Handbok för Salixodlare*. Swedish Board of Agriculture. Available from http://www2.jordbruksverket.se/webdav/files/SJV/trycksaker/Pdf_ovrigt/ovr250.pdf [2017-01-09].

IEA (2016). *Key world statistics*. International Energy Agency. Paris, France: IEA Publications.

IPCC (2006a). *Good Practice Guidance for Land Use, Land-Use change and Forestry*. IGES, Japan.

IPCC (2006b). *IPCC Guidelines for National Greenhouse Gas Inventories*. IGES, Japan.

IPCC (2007). *Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Chapter 2: changes in atmospheric constituents and in radiative forcing.* Cambridge, United Kingdom and New York, NY, USA.

IPCC (2013). *Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA.

ISO 14040 (2006). Environmental Management - Life Cycle Assessment - Requirements and Guidelines (ISO-standard, EN ISO 14040:2006 ISO/TC 207, CMC. Brussels: European Commission for Standardization.

ISO 14044 (2006). Environmental Management - Life Cycle Assessment - Requirements and Guidelines (ISO-standard, EN ISO 14044:2006 ISO/TC 207, CMC. Brussels.

Jonker, J.G.G., Junginger, M. & Faaij, A. (2014). Carbon payback period and carbon offset parity point of wood pellet production in the South-eastern United States. *Global Change Biology Bioenergy,* 6(4), pp. 371-389.

Joos, F., Prentice, I.C., Sitch, S., Meyer, R., Hooss, G., Plattner, G.K., Gerber, S. & Hasselmann, K. (2001). Global warming feedbacks on terrestrial carbon uptake under the Intergovernmental Panel on Climate Change (IPCC) emission scenarios. *Global Biogeochemical Cycles,* 15(4), pp. 891-907.

Joos, F., Roth, R., Fuglestvedt, J.S., Peters, G.P., Enting, I.G., von Bloh, W., Brovkin, V., Burke, E.J., Eby, M., Edwards, N.R., Friedrich, T., Frolicher, T.L., Halloran, P.R., Holden, P.B., Jones, C., Kleinen, T., Mackenzie, F.T., Matsumoto, K., Meinshausen, M., Plattner, G.K., Reisinger, A., Segschneider, J., Shaffer, G., Steinacher, M., Strassmann, K., Tanaka, K., Timmermann, A. & Weaver, A.J. (2013). Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. *Atmospheric Chemistry and Physics,* 13(5), pp. 2793-2825.

Kendall, A. (2012). Time-adjusted global warming potentials for LCA and carbon footprints. *International Journal of Life Cycle Assessment,* 17(8), pp. 1042-1049.

Koppejan, J., Sokhansanj, S., Melin, S. & Madrali, S. (2012). *IEA Bioenergy Task 32 report. Final report. Status overview of torrefaction technologies*. Enschede, The Netherlands

Kätterer, T., Bolinder, M.A., Andrén, O., Kirchmann, H. & Menichetti, L. (2011). Roots contribute more to refractory soil organic matter than above-ground crop residues, as revealed by a long-term field experiment. *Agriculture, Ecosystems & Environment,* 141(1), pp. 184-192.

Lal, R. (2004). Soil carbon sequestration to mitigate climate change. *Geoderma,* 123(1-22).

Lamers, P., Hoefnagels, R., Junginger, M., Hamelinck, C. & Faaij, A. (2015). Global solid biomass trade for energy by 2020: an assessment of potential import streams and supply costs to North-West Europe under different

sustainability constraints. *Global Change Biology Bioenergy,* 7(4), pp. 618-634.
Lamers, P. & Junginger, M. (2013). The 'debt' is in the detail: A synthesis of recent temporal forest carbon analyses on woody biomass for energy. *Biofuels Bioproducts & Biorefining-Biofpr,* 7(4), pp. 373-385.
Lamers, P., Junginger, M., Hamelinck, C. & Faaij, A. (2012). Developments in international solid biofuel trade-An analysis of volumes, policies, and market factors. *Renewable & Sustainable Energy Reviews,* 16(5), pp. 3176-3199.
Lehtikangas, P. (2001). Quality properties of pelletised sawdust, logging residues and bark. *Biomass and bioenergy,* 20(5), pp. 351-360.
Levasseur, A., Cavalett, O., Fuglestvedt, J.S., Gasser, T., Johansson, D.J., Jørgensen, S.V., Raugei, M., Reisinger, A., Schivley, G. & Strømman, A. (2016). Enhancing life cycle impact assessment from climate science: Review of recent findings and recommendations for application to LCA. *Ecological Indicators*, 71, pp. 163-174.
Levasseur, A., Lesage, P., Margni, M., Deschenes, L. & Samson, R. (2010). Considering Time in LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments. *Environmental science & technology,* 44(8), pp. 3169-3174.
Lindholm, E.-L., Stendahl, J., Berg, S. & Hansson, P.-A. (2011). Greenhouse gas balance of harvesting stumps and logging residues for energy in Sweden. *Scandinavian Journal of Forest Research,* 26(6), pp. 586-594.
Matthews, R., Sokka, L., Soimakallio, S., Mortimer, N., Rix, J., Schelhaas, M.-J., Jenkins, T., Hogan, G., Mackie, E., Morris, A. & Randle, T. (2014). *Review of literatur on biogenic carbon and lifecycle assessment of forest bioenergy. Final Task 1 report, DG ENER project, 'Carbon impacts of biomass consumed in the EU'*. Forest Research: Farnham.
Ministério de Agricultura (2010). *Relatório de trabalho de campo realizado no âmbito do cumprimento das decisões de S. Excia . o Senhor Primeiro Ministro na sua visita à Província do Niassa*. Lichinga, Mozambique.
Mola-Yudego, B. (2010). Regional Potential Yields of Short Rotation Willow Plantations on Agricultural Land in Northern Europe. *Silva Fennica,* 44(1), pp. 63-76.
Mola-Yudego, B. & Gonzalez-Olabarria, J.R. (2010). Mapping the expansion and distribution of willow plantations for bioenergy in Sweden: Lessons to be learned about the spread of energy crops. *Biomass & Bioenergy,* 34(4), pp. 442-448.
Murphy, D.J., Hall, C.A., Dale, M. & Cleveland, C. (2011). Order from chaos: A preliminary protocol for determining the EROI of fuels. *Sustainability,* 3(10), pp. 1888-1907.
Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T. & Zang, H. (2013a). *Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Chang*. [Stocker, T.F.,

D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J.S., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T. & Zhang, H. (2013b). *Anthropogenic and Natural Radiative Forcing Supplementary Material. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Nilsson, D., Bernesson, S. & Hansson, P.A. (2011). Pellet production from agricultural raw materials - A systems study. *Biomass & Bioenergy,* 35(1), pp. 679-689.

Nunes, L.J.R., Matias, J.C.O. & Catalao, J.P.S. (2014). A review on torrefied biomass pellets as a sustainable alternative to coal in power generation. *Renewable & Sustainable Energy Reviews,* 40, pp. 153-160.

Obernberger, I. & Thek, G. (2010). *The Pellet Handbook - The production and thermal utilisation of biomass pellets*. London, UK, Washington DC, USA: Earthscan.

Overbeek, W. (2010). *The Expansion of Tree Monocultures in Mozambique. Impacts on Local Peasant Communities in the Province of Niassa*. World Rainforest Movement, CIFOR Occasional Paper.

Paulrud, S. (2004). *Upgraded biofuels-effects of quality on processing, handling characteristics, combustion and ash melting.* Diss. Umeå, Sweden: Swedish University of Agricultural Sciences

Peters, G.P., Aamaas, B., Lund, M.T., Solli, C. & Fuglestvedt, J.S. (2011). Alternative "Global Warming" Metrics in Life Cycle Assessment: A Case Study with Existing Transportation Data. *Environmental science & technology,* 45(20), pp. 8633-8641.

Proskurina, S., Sikkema, R., Heinimö, J. & Vakkilainen, E. (2016). Five years left– How are the EU member states contributing to the 20% target for EU's renewable energy consumption; the role of woody biomass. *Biomass and bioenergy,* 95, pp. 64-77.

Pöyry (2016). *Bioenergi från skog och skogsindustry (Bioenergy from forest and forest industry)*. Pöyry Management Consulting (Sweden) AB made for The Swedish Forest Industries Federation. Stockholm, Sweden.

Ramaswamy , V., Boucher, O., Haigh, J., Hauglustaine, D., Haywood, J., Myhre, G., Nakajima, T., Shi, G. & Solomons, S. (2001). *Radiative forcing of climate change. In: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (eds Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA).* Cambridge University Press, Cambridge, UK and New York, NY. 881 p.

Repo, A., Känkänen, R., Tuovinen, J.P., Antikainen, R., Tuomi, M., Vanhala, P. & Liski, J. (2012). Forest bioenergy climate impact can be improved by allocating forest residue removal. *GCB Bioenergy*, 4(2), pp. 202-212.

Roder, M., Whittaker, C. & Thornley, P. (2015). How certain are greenhouse gas reductions from bioenergy? Life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues. *Biomass & Bioenergy*, 79, pp. 50-63.

Rolff, C. & Agren, G.I. (1999). Predicting effects of different harvesting intensities with a model of nitrogen limited forest growth. *Ecological Modelling*, 118(2-3), pp. 193-211.

Rytter, R.-M. (2012). The potential of willow and poplar plantations as carbon sinks in Sweden. *Biomass and bioenergy*, 36, pp. 86-95.

Rytter, R.-M., Rytter, L. & Högbom, L. (2015). Carbon sequestration in willow (Salix spp.) plantations on former arable land estimated by repeated field sampling and C budget calculation. *Biomass and bioenergy*, 83, pp. 483-492.

SCB (2016). *Electricity supply, district heating and supply of natural and gasworks gas 2015*. Statistic Sweden, Örebro, Sweden.

Schut, M., Slingerland, M. & Locke, A. (2010). Biofuel developments in Mozambique. Update and analysis of policy, potential and reality. *Energy Policy*, 38(9), pp. 5151-5165.

Searchinger, T.D., Hamburg, S.P., Melillo, J., Chameides, W., Havlik, P., Kammen, D.M., Likens, G.E., Lubowski, R.N., Obersteiner, M. & Oppenheimer, M. (2009). Fixing a critical climate accounting error. *Science*, 326(5952), pp. 527-528.

Shine, K.P., Berntsen, T.K., Fuglestvedt, J.S., Skeie, R.B. & Stuber, N. (2007). Comparing the climate effect of emissions of short- and long-lived climate agents. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*, 365(1856), pp. 1903-1914.

Shine, K.P., Fuglestvedt, J.S., Hailemariam, K. & Stuber, N. (2005). Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. *Climatic Change*, 68(3), pp. 281-302.

Sikkema, R., Junginger, M., Pichler, W., Hayes, S. & Faaij, A.P.C. (2011a). The international logistics of wood pellets for heating and power production in Europe: Costs, energy-input and greenhouse gas balances of pellet consumption in Italy, Sweden and the Netherlands (vol 5, pg 226, 2011). *Biofuels Bioproducts & Biorefining-Biofpr*, 5(2), pp. 226-226.

Sikkema, R., Steiner, M., Junginger, M., Hiegl, W., Hansen, M.T. & Faaij, A. (2011b). The European wood pellet markets: current status and prospects for 2020. *Biofuels Bioproducts & Biorefining-Biofpr*, 5(3), pp. 250-278.

SJV (2009). *Agriculture, bioenergy and the environment. Report 2009:22*. Swedish Board of Agriculture, Available from: http://www2.jordbruksverket.se/webdav/files/SJV/trycksaker/Pdf_rapporter/ra09_22.pdf [2017-01-09].

Statistics Sweden (2014). *Statistical Yearbook of Sweden 2014*. Örebro, Sweden, Statistics in Sweden, communication department.

Swedish Association of Pellet Producers (2016). Delivery statistics Swedish market 1997-2015. Avalible from: http://pelletsforbundet.se/statistik/ [2016-06-08].
Swedish Energy Agency (2015). *Energy in Sweden 2015*. Eskilstuna, Sweden.
Thek, G. & Obernberger, I. (2004). Wood pellet production costs under Austrian and in comparison to Swedish framework conditions. *Biomass & Bioenergy*, 27(6), pp. 671-693.
Thrän, D., Witt, J., Schaubach, K., Kiel, J., Carbo, M., Maier, J., Ndibe, C., Koppejan, J., Alakangas, E. & Majer, S. (2016). Moving torrefaction towards market introduction–Technical improvements and economic-environmental assessment along the overall torrefaction supply chain through the SECTOR project. *Biomass and bioenergy,* 89, pp. 184-200.
Tumuluru, J.S., Sokhansanj, S., Hess, A.R., Wright, C.T. & Boardman, R.D. (2011). A review on biomass torrefaction process and product properties for energy applications. *Industrial Biotechnology,* 7(5), pp. 384-401.
Tuomi, M., Rasinmaki, J., Repo, A., Vanhala, P. & Liski, J. (2011). Soil carbon model Yasso07 graphical user interface. *Environmental Modelling & Software,* 26(11), pp. 1358-1362.
UNEP (2014). *Assessing Global Land Use: Balancing Consumption with Sustainable Supply*. A Report of the Working Group on Land and Soils of the International Resource Panel. In: Bringezu S., Schütz H., Pengue W., O´Brien M., Garcia F., Sims R., Howarth R., Kauppi L., Swilling M., and Herrick J (ed).
UNFCCC (2015). *ADOPTION OF THE PARIS AGREEMENT* United Nations Framework Convention on Climate Change, Paris.
van der Hilst, F. & Faaij, A.P.C. (2012). Spatiotemporal cost-supply curves for bioenergy production in Mozambique. *Biofuels Bioproducts & Biorefining-Biofpr,* 6(4), pp. 405-430.
van der Stelt, M.J.C., Gerhauser, H., Kiel, J.H.A. & Ptasinski, K.J. (2011). Biomass upgrading by torrefaction for the production of biofuels: A review. *Biomass & Bioenergy,* 35(9), pp. 3748-3762.
Wikström, P., Edenius, L., Elfving, B., Eriksson, O.L., Lämås, T., Sonesson, J., Öhman, K., Wallerman, J., Waller, C. & Klintebäck, F. (2011). The Heureka Forestry Decision Support System: An Overview. *Mathematical and Computational Forestry & Natural-Resource Sciences,* 3(2), pp. 87-94.
Zanchi, G., Pena, N. & Bird, N. (2012). Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *Global Change Biology Bioenergy,* 4(6), pp. 761-772.
Zetterberg, L. & Chen, D.L. (2015). The time aspect of bioenergy - climate impacts of solid biofuels due to carbon dynamics. *Global Change Biology Bioenergy,* 7(4), pp. 785-796.
Zhang, Y.M., Mckechnie, J., Cormier, D., Lyng, R., Mabee, W., Ogino, A. & Maclean, H.L. (2010). Life Cycle Emissions and Cost of Producing Electricity from Coal, Natural Gas, and Wood Pellets in Ontario, Canada. *Environmental science & technology,* 44(1), pp. 538-544.

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