Time-dependent climate impact of short rotation coppice willow–based systems for electricity and heat production

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Abstract

Fossil fuel use and man-made land use change has increased carbon dioxide (CO_2) levels in the atmosphere, contributing to climate impacts such as global warming. Perennial crops such as short rotation coppice (SRC) willow have received attention because of their potential to sequester carbon (C) from the atmosphere and build up soil organic carbon stocks while producing biomass which can be used to generate energy services.

The aim of this thesis was to assess the climate impact of bioenergy systems and develop the methodology used to evaluate these systems. The biomass from a SRC willow plantation can be used in a number of different ways to produce energy services. Specific objectives of this thesis were to investigate the energy efficiency and time-dependent climate impact of SRC willow–based bioenergy systems using different ways of converting the biomass into electricity and heat.

Life cycle assessment (LCA) methodology was used to enable the assessment of time-dependent climate impacts using a time-distributed inventory and a time-dependent indicator, i.e. the global mean surface temperature change (ΔT_S). Several different ways of generating electricity and/or heat from the biomass produced at a SRC willow plantation were compared, taking biogenic C stock changes into account.

The main conclusions were that SRC willow–based bioenergy systems can be truly C negative and help contribute to counteract the current trend in global warming while delivering renewable energy at the same time. The choice of energy conversion technology affects both the energy efficiency and the potential climate impact mitigation potential of the system. Biogenic C pools can have a very large influence on the climate impact in bioenergy systems. It is therefore important to take these pools into account whenever land use or management changes take place, in order to counteract global warming more effectively.

Keywords: Life cycle assessment, LCA, climate impact, time-dependency, system dynamics, Salix, bioenergy, biochar, pyrolysis, biogas, anaerobic digestion

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Dedication

Till Tindra och Heydy för att ni finns!

The environment isn't over here
The environment isn't over there
You are the environment

Oren Lyons – Faithkeeper of the turtle clan

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

III Ericsson, N., Nordberg, Å., Sundberg, C., Ahlgren, S. and Hansson, P.-A. (2014). Climate impact and energy efficiency from electricity generation through anaerobic digestion or direct combustion of short rotation coppice willow. *Applied Energy* 132, 86–98

IV Ericsson, N., Sundberg, C., Nordberg, Å., Ahlgren, S. and Hansson, P.-A. (2014) Time-dependent climate impact and energy efficiency of combined heat and power production from short rotation coppice willow using pyrolysis or direct combustion (manuscript).

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The contribution of Niclas Ericsson to the papers included in this thesis was as follows:

- I Developed the methodology. Carried out model building and analysis of results together with the second author. Wrote the paper together with the co-authors.
- II Planned the study together with the co-authors, assisted in scenario development and methodology applications, assisted in writing the paper together with the co-authors.
- III Planned the paper together the with co-authors. Performed the modelling and scenario analysis. Wrote the paper with assistance from the co-authors.
- IV Planned the paper together with the co-authors. Performed the modelling and scenario analysis. Wrote the paper with assistance from the co-authors.

Abbreviations

Cd	Cadmium
CH_4	Methane
CO_2	Carbon dioxide
CO	Carbon monoxide
C	Carbon
H_2	Hydrogen
N_2O	Nitrous oxide
N	Nitrogen
P	Phosphorus
ΔT_S	Global mean surface temperature change
AGTP	Absolute GTP
AGWP	Absolute GWP
AR	Assessment report
AR5	The Fifth IPCC Assessment Report (2013-2014)
CCS	Carbon capture and storage
CF	Carbon footprint
CHP	Combined heat and power
CN	Carbon neutrality factor
CRF	Cumulative radiative forcing
DH	District heating
DM	Dry matter
ER	External energy ratio (as defined in this thesis)
FAR	The First IPCC Assessment Report (1991)
FU	Functional unit
GHG	Greenhouse gas
GHGV	Greenhouse gas value
GTP	Global temperature potential
GWP	Global warming potential

GWP_{bio}	Biogenic GWP
ICBM	Introductory carbon balance model
IPCC	Intergovernmental Panel on Climate Change
IRF	Impulse response function
K	Potassium
LCA	Life cycle assessment
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
PE	Primary energy
RF	Radiative forcing
SOC	Soil organic carbon
SRC	Short rotation coppice
TAWP	Time-adjusted warming potential
TE	Time of evaluation
TH	Time horizon
UNEP	United Nations Environment Program
WMO	World Meteorological Organization
WW	Wet weight

1 Introduction

Climate change is a naturally occurring phenomenon. However, human activities have led to increases in the greenhouse gas (GHG) concentrations in the atmosphere, which have been causing global warming at a very high rate since the mid-20th Century. The major source of this trend is the increasing concentration of carbon dioxide (CO_2) in the atmosphere.

Historically, the two greatest sources of CO_2 emissions from anthropogenic activities have been the combustion of fossil energy sources and carbon losses to the atmosphere due to land use changes (Denman *et al.*, 2007). Both continue to be important contributors to the increasing concentration of CO_2 in the atmosphere.

More than 80% of the world's primary energy in 2012 came from fossil resources (IEA, 2014). Breaking this fossil dependence is a major, but it is necessary for a number of reasons, one of which is energy security. Resources are not evenly distributed between countries and regions, creating economic and political dependencies that may pose security risks.

Another concern is that fossil resources are finite, in the sense that we are consuming them at a rate which vastly exceeds the rate at which they are being formed. A pertinent question is how long our fossil resource base will last at the current rate of exploitation. It is nonetheless clear that it is large enough to have serious impacts on the climate system if its carbon content is emitted to the atmosphere.

The consequences of climate change due to fossil resource use can be expected to be felt sooner than those due to fossil resource scarcity. Nevertheless, these are two interconnected issues. Breaking our dependence on fossil resources is an important part of the solution to global warming. Converting our energy supply system to renewable and fossil-free sources is one of the major challenges we are facing.

Bioenergy, wind and solar power are three renewable energy sources whose contribution to the Swedish energy system has increased over time. Bioenergy has traditionally supplied a large share of the primary energy used in Sweden. Its main resource base has been Swedish forests. Wind and solar power have experienced very strong growth in their market share in recent years. But they are intermittent sources, whose availability is not controlled by demand, but by the availability of wind and sun.

Swedish agriculture may supply the Swedish energy system with additional renewable energy resources in the future. Over 10% of the productive land has been removed from crop production in Sweden since the 1980s. This represents more than 300 000 hectares of arable land (Statistics Sweden, 2014). Using part of this land for energy crop production could create an additional source of income for farmers and increase the availability of locally produced fossil-free energy feedstocks in the Swedish energy system.

In the 1980s, energy crops such as short rotation coppice (SRC) willow were established in many places in southern Sweden. This fast-growing woody crop can be readily used for co-firing with other woody feedstock in existing combined heat and power (CHP) plants.

Willow can also be converted into intermediate energy carriers, such as gas, bio-oil and char, which are then used to generate electricity and heat. This can be done through techniques such as anaerobic digestion and pyrolysis which are not yet commercially viable for lignocellulosic crops, but both conversion technologies have been actively researched over the last couple of decades.

Conversion to intermediate energy carriers could improve storage and handling properties, reduce transport and enable the recycling of nutrients back to agricultural fields together with carbon in the form of digestate or biochar.

Bioenergy has been questioned with regard to its carbon neutrality and thus its climate neutrality (Sedjo, 2011). Life cycle assessment (LCA) is a tool that is commonly used to compare the climate impact of both fossil and bioenergy systems. Fossil inputs are used within agriculture today, mainly for the production of fertilisers and for the energy required to operate machinery. These aspects are normally included in traditional LCAs when evaluating the climate impact.

Another aspect of bioenergy that has been under debate is the climate neutrality of biogenic carbon, *i.e.* the carbon that is cycled between living and dead biomass and the atmosphere (Cherubini *et al.*, 2011). When biomass is used for bioenergy, there is a time lag between emission of the carbon stored in the plant and uptake of this carbon in the growing crop. This time lag affects the CO_2 concentration of the atmosphere over time, but is normally not considered in traditional LCAs, due to the nature of the methodology being used.

Traditional LCAs can be used to assess permanent carbon stock changes, but they do not provide information about the timing of resource use, emissions and impacts. Additional understanding of the climate impacts of bioenergy systems could be achieved by considering the timing and magnitude of GHG emissions, both from the system components traditionally included in LCAs and from carbon stock changes taking place over time.

Cultivation of SRC willow also creates opportunities for storing carbon in the soil. This could potentially contribute to counteract global warming. Carbon storage in soils may come at the expense of energy efficiency, if the carbon returned to the soil could have been used to generate energy services. An important question is therefore what the main purpose of a willow plantation really is: to counteract global warming or to generate energy services such as electricity and heat.

2 Aim, objectives and structure of this thesis

2.1 Aim and objectives

The general aim of this thesis was to assess the climate impact of bioenergy systems and develop the methodology used to evaluate these systems.

Specific objectives were to investigate the energy efficiency and time-dependent climate impact of bioenergy systems based on SRC willow plantations and to compare different ways of converting the biomass generated into electricity and heat.

2.2 Structure of the work

The dynamics inherent in bioenergy systems and the climate system, together with their coupling to the carbon cycle, motivated the development of a new approach for conducting an LCA. This methodology, which was developed in Paper I and used in all papers in this thesis (Figure 1), facilitates better insights into the dynamics of the potential climate impacts from different parts of a system under study. In Paper I, it was applied to a district heat generating, SRC willow–based-bioenergy system to demonstrate its use and interpretation.

The energy efficiency and time-dependent climate impact of heat produced through direct combustion of biomass from a SRC willow plantation were further investigated in Paper II. Different management and crop yield scenarios were compared and the sensitivity of the results to changes in some of the model parameters and variables used in the methodology developed in Paper I were calculated in Paper II.

Different pathways for converting the energy stored in the biomass to energy have a large impact on total system performance of any bioenergy system. Four different energy conversion pathways were investigated in this thesis and compared with regard to their energy efficiency and time-dependent climate-impact. These were: biomass to heat through direct combustion (Papers I & II);

biomass to electricity and heat through either direct combustion or prior generation of biogas using anaerobic digestion (Paper III); and generation of electricity and heat through direct combustion or prior generation of bio-oil and char through pyrolysis (Paper IV). Using the char as biochar for soil application or for energy service generation was also compared.

2.3 Structure of the thesis

The structure of the thesis is as follows. Background information is provided in chapter 3, where the problem and prior research on the subject matter are introduced. Chapter 4 describes the methodological approach used in the Papers I–IV. It starts with a presentation of the system and scenarios and of the LCA-related methodological choices. It ends with a description of the time-dependent climate impact methodology that was developed and used in this thesis. Chapter 5 presents the energy efficiency of the different scenarios included in this thesis, while in chapter 6 the climate impact of the scenarios studied is presented, starting with the impact of the cultivation system, feedstock handling and energy conversion step. This corresponds to what is generally included in most bioenergy LCAs. It is followed by a description of the impact of biogenic carbon stock changes. Both aspects are then analysed together. Chapter 6 concludes by describing how energy efficiency, previous land use and yield may influence the climate impact of the system. A general discussion the time-dependent impact methodology in LCA, choosing less energy efficient conversion technologies, alternative bioenergy crops and land use, energy and climate mitigation potential is given in chapter 7. Finally, some conclusions are presented in chapter 8.

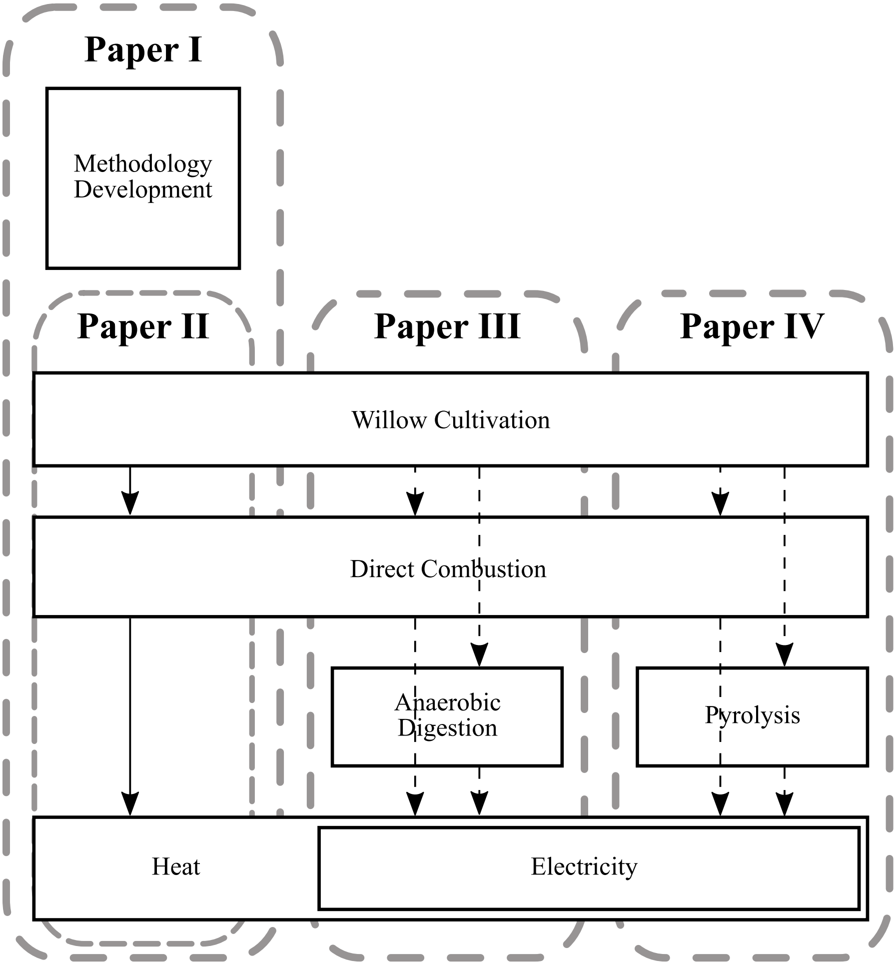

Figure 1. Structure of the work performed in this thesis. Time-dependent climate impact methodology was developed in Paper I and applied to different case studies in Papers I–IV. In these case studies electricity and/or heat was generated from the biomass produced at a SRC willow plantation. Different intermediate feedstock conversion technologies were used in different cases.

3 Background

3.1 Short rotation coppice willow–based bioenergy systems

3.1.1 Short rotation coppice willow

Short rotation energy forestry is a special form of forestry where fast growing tree species are cultivated and harvested at short intervals for energy purposes. These intervals are commonly referred to as coppicing cycles. Short rotation coppice willow is an energy forest crop that has been grown in Sweden for energy purposes well over 30 years. In Sweden, SRC willow is commonly used as fuel in local district heating (DH) or CHP plants. The dominant practice is to co-fire willow with other biofuels.

Well-managed commercial plantations can yield around 10 metric tonnes (t) of dry matter (DM) per (ha yr) (Verwijst *et al.*, 2013). Many of the willow plantations established in the 1980s and 1990s yielded considerably less than more recent plantations (Mola-Yudego & Aronsson, 2008). Some of the reasons for the low yield were poor management practices and the use of inadequate soils for the willow. Willow plants generally grow well when they have good access to water, light and nutrients (Hollsten *et al.*, 2013).

Newer clones outperform older clones due to continuous breeding efforts. An annual yield increase of over 300 kg per (ha yr) have been observed over a 15-year period (Mola-Yudego, 2011). Another important result from breeding is increased pest and disease resistance (Karp *et al.*, 2011). The amounts of fungicides and pesticides used in a SRC willow plantation are usually lower than in conventional agricultural crop plantations.

3.1.2 Upgrading of willow feedstock

In Sweden, willow is harvested in winter, when the plant has shed its leaves and the frozen soil has good carrying capacity. Moisture content at harvest is normally around 50%, on a wet weight (WW) basis. The bulkiness and high moisture content of the chipped willow makes decentralised upgrading of the material (Wright *et al.*, 2008), and electricity and heat generation (Kimming *et al.*, 2011) an interesting option .

There are two fundamentally different pathways that can be pursued to upgrade biomass. One is biochemical processing, where enzymes and microorganisms are responsible for converting the biomass into intermediate energy carriers. The other is thermochemical processing, where heat and catalysts are used to transform the biomass into intermediate energy carriers (Brown, 2011).

Anaerobic digestion is a form of biochemical processing where microorganisms convert biomass into biogas, which can be used to generate energy services. An important by-product from anaerobic digestion is digestate, which is the liquid residue from the biogas process. It contains most of the nutrients found in the feedstock in a form that is accessible to plants. It can be applied to new crops to increase the cycling of nutrients within agricultural units.

Anaerobic digestion of lignocellulosic crops could enable small-scale decentralised generation of electricity and heat from the biogas produced (Kimming *et al.*, 2011). Biogas production from lignocellulosic crops is not common, but is being researched (Dererie *et al.*, 2011; Horn *et al.*, 2011; Estevez *et al.*, 2012; Sun, 2015).

While anaerobic digestion represents a well-known pathway of converting biomass feedstock to biogas, it is a slow process compared with thermochemical conversion processes (Brown, 2011). Thermochemical processes such as torrefaction, pyrolysis and gasification can all be used to upgrade biomass. The choice of technology depends on the end use of the intermediate energy carrier.

Torrefaction is used to increase the energy density and stability of the feedstock before transportation and storage. It can also improve the combustion properties of the material (Huang *et al.*, 2013).

Pyrolysis can be used to generate a number of different energy carriers: bio-oil, pyrolysis gases and char. The composition of the products depends to a great extent on feedstock properties and process parameters (Garcia-Perez *et al.*, 2008). All products from a pyrolysis process can be further upgraded, or used directly to generate energy services.

The char that is produced in the pyrolysis process can also be applied to soils where it can remain for a long time due to the high stability of the char. This creates a carbon (C) sink which can counteract global warming (Woolf *et al.*, 2010). When applied to soils, the char is commonly referred to as biochar. It has been attributed numerous beneficial properties in addition to keeping CO_2 away from the atmosphere (Sohi *et al.*, 2010). It may act as a soil enhancer, improving crop yields through its capacity to retain water and nutrients. It can also be used to decontaminate soils due to its capacity to absorb heavy metals and other pollutants (Qian *et al.*, 2015).

Gasification is a third thermochemical option where the majority of the feedstock is converted into syngas. The syngas contains mainly carbon monoxide (CO) and hydrogen (H_2) gas. This can be used directly to generate energy services, or as raw material for other products in the chemical industry (Brown, 2011). Gasification is better suited for large-scale processes than torrefaction and pyrolysis (Wright *et al.*, 2008).

3.2 Life cycle assessment

3.2.1 Life cycle assessment methodology

Life cycle assessment (LCA) is one of many environmental impact assessment methodologies (Finnveden *et al.*, 2003). It is a standardised methodology (ISO 14040, 2006; ISO 14044, 2006) that can be used to assess the potential environmental impact of a system or a product[1].

One application of LCA is to avoid sub-optimising the environmental performance of a system by burden shifting from one part of a life cycle to another. Another application is to find hot-spots in the production chain, or life cycle, where potential resource use and emissions can be reduced. A common application is to compare the environmental impacts of different systems or products. To ensure that all products fulfil the same function, resource use and emissions are related to a functional unit (FU). The FU describes the actual function that all systems or products have to fulfil to be considered equivalent.

As suggested by the name, all processes taking place during the entire life cycle of the product are ideally included in the assessment. This means that every resource used and all emissions connected to every process in the life cycle should be included, from raw material extraction until waste finally leaves the technosphere.

Actual product systems are often intertwined and may produce multiple products, or be open or closed to varying degrees with regard to reuse and recycling of products (Baumann & Tillman, 2004). Waste from one product system may also be raw material in another product system. For these reasons, several allocation techniques and procedures have been developed (Luo *et al.*, 2009).

The ISO standards recommend avoiding allocation by dividing a process into sub-processes for which data can be collected, or including additional functions in the FU. If this is not possible, use of physical allocation is recommended or, as a last resort, economic allocation. It might not be possible, or desirable, to follow these recommendations in all cases. System boundaries, the FU and type of allocation should be guided by the aim and purpose of the study, while the guidelines should be regarded as recommendations (Ahlgren *et al.*, 2015).

An LCA consists of four stages (ISO 14040, 2006). The goal and scope definition, which should be clearly defined and consistent with the intended

[1]The word product in this context includes services.

application of the study; the life cycle inventory analysis (LCI), where input and output data are collected, validated and related to the FU; the life cycle impact assessment (LCIA), where the LCI results are classified into different impact categories and category indicator results are calculated, and the final stage which is the life cycle interpretation. The interpretation includes completeness checks, sensitivity analysis, identification of significant issues, conclusions and recommendations based on previous stages.

Climate impact is one of many impact categories that can be used in an LCA. Other impact categories that are often included in bioenergy LCAs are eutrophication and acidification (Cherubini *et al.*, 2009). Many more impact categories exist, *e.g.* impacts on biodiversity, toxicity and depletion of finite resources.

3.2.2 Life cycle assessment of SRC willow systems

The environmental impacts of willow cultivation have been investigated using LCA methodology (e.g. Heller *et al.*, 2003; Brandão *et al.*, 2011; González-García *et al.*, 2012a). Several authors have focused on the energy efficiency and climate impact of electricity from willow-based CHP systems (e.g. Heller *et al.*, 2004; Styles & Jones, 2007; Goglio & Owende, 2009; Froese *et al.*, 2010; Kimming *et al.*, 2011). Other end uses of the willow feedstock, such as different biofuels, have also been studied (Börjesson & Tufvesson, 2011) and compared with electricity (González-García *et al.*, 2012b) and heat (González-García *et al.*, 2013).

The majority of the published LCA studies conducted on SRC willow have characterised the climate impact and included some kind of indicator for the energy efficiency, or the net energy yield of the system.

Almost all studies have identified SRC willow as having a higher energy yield per hectare if the harvest residues are left on the field. It generates less emissions and requires less energy input in the cultivation system than first-generation bioenergy crops, *e.g.* wheat and oilseed rape (Hillier *et al.*, 2009).

The use of mineral fertilisers and diesel in farm operations has been identified as having a large impact on the energy efficiency of the system, as well as contributing to a large share of the impacts in several impact categories (Keoleian & Volk, 2005; Goglio & Owende, 2009; González-García *et al.*, 2012b).

Short rotation coppice willow has also been compared to other second generation bioenergy crops, such as miscanthus (e.g. Styles & Jones, 2007; Hillier *et al.*, 2009; Brandão *et al.*, 2011). The outcome of these studies depend to a great extent on how the potential soil organic carbon (SOC) stock changes are calculated for each of the crops investigated (Harris *et al.*, 2015).

A number of LCAs have investigated different aspects of SOC in SRC willow bioenergy systems. Hillier *et al.* (2009) illustrated the importance of previous land use for the outcome of an LCA by using a dynamic soil C model to calculate the SOC stock changes when establishing willow on sites with differing land use history.

Styles & Jones (2007) and Börjesson & Tufvesson (2011) both illustrated the importance of considering C stocks that could have taken place under an alternative land use, if the SRC willow plantation had not been established.

The effect of alternative land use was also illustrated by Brandão *et al.* (2011), using a methodology where the benefit of C uptake from the soil by an SRC willow plantation and a number of other bioenergy crops was compared with the C uptake in a scenario where the land was assumed to return to a state of natural vegetation.

3.3 Climate and climate impact

3.3.1 An introduction to climate research

The climate has been thoroughly researched and discussed over the last 25 years, both in the media and within the scientific community. The climate can be thought of as 'the meteorological conditions, including temperature, precipitation, and wind, that characteristically prevail in a particular region' (Climate, n.d.). The climate exhibits a regularity and pattern that can be observed, in contrast to the weather, which exhibits a high degree of randomness.

The climate of the Earth has been researched in depth over the last two centuries. Our understanding of the mechanisms governing the climate have advanced substantially since Fourier (1878) presented his analytical theory of heat[2] in 1822. He is often recognised as the discoverer of the greenhouse effect.

The importance of the greenhouse effect in governing the climate was first made clear by Arrhenius (1896), who calculated the effect of increased levels of carbonic acid[3] on the temperature of the Earth, and pointed to the fact that human interference may actually alter the global mean temperature. He was inspired by, among others, the works of Fourier and Tyndall (1861)[4].

Temperature records start in the mid-19th century, and atmospheric CO_2 evolution has been monitored continuously since the late 1950s. Concerns about the climate consequences of human activities have increased with a growing understanding of how the climate and CO_2 concentrations have evolved over geological time-scales. There are indications of mass extinctions in periods of rapid environmental changes (Barnosky *et al.*, 2011).

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[2]In his work Fourier tried to develop an all-embracing theory for the phenomena governing the temperature of the earth. From analytical calculations, he managed to explain a number of climate phenomena, such as the driving forces behind the sea and atmospheric currents, the trade winds,the temperature distribution of the seas and the behaviour of sunlight.

[3]Carbon dioxide (CO_2) was commonly referred to as carbonic acid at the time.

[4]Tyndall was among the first to experimentally show the radiative properties of different gases and vapours, most importantly water vapour, CO_2 and N_2O.

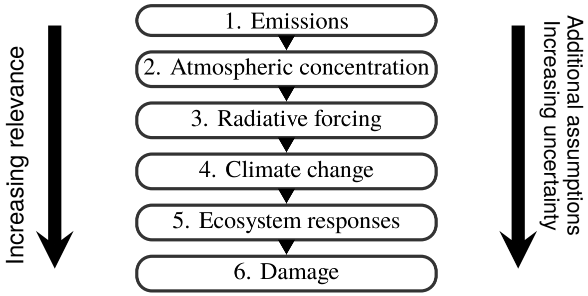

Figure 2. Cause-effect chain from emission of a greenhouse gas (GHG) to damage to human society.

In 1988, the Intergovernmental Panel on Climate Change (IPCC) was established and set up by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) to prepare assessments on all aspects of climate change, based on available scientific information.

The aim of establishing the IPCC was to facilitate the formulation of realistic response strategies to possible future climate change. The IPCC has since published five assessment reports (AR), which cover a wide range of topics.

The latest AR include the physical science basis (IPCC, 2013), impacts, adaptations and vulnerability (IPCC, 2014a; IPCC, 2014b) and the mitigation of climate change (IPCC, 2014c).

Today there is consensus among most scientists that human activities have had and will continue to have a significant effect on the Earth's climate system. The question is what we can do to counteract the negative impacts that we have already caused and how to reach a new state of equilibrium.

3.3.2 Climate impact of GHG emissions

One of the main reasons for paying attention to climate change is the impact that it might have on human society. Impacts may appear in the form of economic damages, health impacts, effects on the security of food and energy supply, and many more (IPCC, 2014a).

To better understand the concept of climate impact it can be conceptualised as a cause-effect chain (Fuglestvedt *et al.*, 2003), where each step down the chain represents an impact that is further away from the original source (Figure 2). This cause-effect chain can also be used when developing models to evaluate different climate impacts. A dynamic relationship can often be found between two successive steps.

Each step down the chain is a consequence of the previous step, and a direct cause of the following step. In every step, multiple responses can appear. For example a change in radiative forcing (RF), which describes the energy balance of the earth, causes a climate change which can be seen in responses such as temperature change, sea level change and change weather patterns, amongst others. These will eventually propagate down the cause-effect chain and impact on human society.

An important aspect of the cause-effect chain is that for each step down the chain additional assumptions and uncertainties have to be introduced when modelling the relationships between cause and effect (Figure 2). However, at the same time the relevance to human society increases, as the impacts are evaluated closer to actual damages to human society.

3.3.3 Assessment of climate impacts

Assessments of climate impacts can focus on any impact along the cause-effect chain in Figure 2 on page 24. The choice of metric, or indicator, used to assess the impact therefore depends on the purpose of the assessment (Fuglestvedt *et al.*, 2010).

A number of choices have to be made with regard to what to measure, how to measure it, type of model used to arrive at the metric and the experimental set-up used to calculate the metric values, amongst other things (Tanaka *et al.*, 2010).

Global warming potential The most commonly used metric in climate impact assessments is the global warming potential (GWP). It was developed in the late 1980s, and was introduced in the first IPCC AR (FAR, 1991, p.58) as 'a simple approach ... to illustrate the difficulties inherent in the concept [of comparing GHG][5], to illustrate the importance of some of the current gaps in understanding and to demonstrate the current range of uncertainties.'

The GWP is calculated by dividing the cumulative RF of any GHG (x) over a specified time horizon (TH[6]) by the cumulative radiative forcing of a reference gas, which is normally CO_2, over the same TH (equation 1). The results from a GWP calculation are therefore commonly referred to as CO_2-equivalents.

$$\mathrm{GWP}_{\mathrm{TH}}^{x} = \frac{\mathrm{AGWP}_{\mathrm{TH}}^{x}}{\mathrm{AGWP}_{\mathrm{TH}}^{\mathrm{CO_2}}} = \frac{\int_0^{\mathrm{TH}} \mathrm{RF}_x dt}{\int_0^{\mathrm{TH}} \mathrm{RF}_{\mathrm{CO_2}} dt} \tag{1}$$

The GWP represents a relative metric, meaning that the impact of a GHG is assessed relative to that of another GHG (CO_2). It can also be expressed as an absolute metric. It is then known as the absolute GWP (AGWP). The AGWP is also known as cumulative radiative forcing (CRF). The AGWP of a

[5]The text in square brackets has been added for clarification purposes. It was not included in the source text, but part of the context.

[6]The TH refers to the time over which impacts from a GHG emission are evaluated. All impacts occurring within this time frame are given equal weight, while those taking place after the end of the TH are ignored.

GHG is calculated by removing the denominator in equation 1, and the results are normally expressed in W per square metre[7].

A consequence of using a relative metric is that the uncertainty of the reference gas is automatically included in the values of all other GHGs. The values of all other GHGs also change whenever the CRF of the reference gas changes. One of the reasons for the updates to the GWP values of N_2O and CH_4 every time a new IPCC AR is published is that the atmospheric concentration of CO_2 keeps changing, which only affects the AGWP of CO_2.

The GWP has gained strong support among policy makers and the LCA community. A great contributing factor has been its inclusion in the Kyoto protocol (Shine, 2009) and its ease of use in LCAs. However, it is not obvious that GWP is an optimal metric in all situations. Its pros and cons have been thoroughly investigated and discussed in the scientific literature since its inclusion in the first IPCC AR (e.g. IPCC, 1991; Wigley, 1998; O'Neill, 2000; Manne & Richels, 2001; Fuglestvedt *et al.*, 2003; Shine *et al.*, 2005; Shine, 2009; Daniel *et al.*, 2012).

The GWP uses the RF as a basis for comparing the climate impact of different GHGs. This can be found just below changes in atmospheric concentration in Figure 2, and above climate impacts, such as temperature change or sea level change. It is quite far from the impacts on ecosystems and human society that concern many other disciplines of science, such as biologists and economists (Godal, 2003).

Global temperature potential An alternative approach to assess the climate impact is the global temperature potential (GTP) (Shine *et al.*, 2005). The approach used to calculate the GTP is similar to that used for GWP. However, it takes account of the change in global mean surface temperature (ΔT_S) induced by emission of a GHG (x) at a specific time of evaluation (TE[8]), and divides this by the corresponding ΔT_S for a reference gas (CO_2) (equation 2).

$$\mathrm{GTP_x\,(TE)} = \frac{\mathrm{AGTP}_x\,\mathrm{(TE)}}{\mathrm{AGTP_{CO_2}\,(TE)}} = \frac{\Delta T_S^x\,\mathrm{(TE)}}{\Delta T_S^{\mathrm{CO_2}}\,\mathrm{(TE)}} \tag{2}$$

When used as a relative metric, the results of the GTP are referred to as CO_2-equivalents, just as for the GWP. It can also be expressed as an absolute metric by removing the denominator in equation 2. Similarly to the AGWP, it is then known as the absolute GTP (AGTP), but the results are expressed in °C.

[7]The units of the AGWP refer to the change in energy flux between the atmosphere and outer space, expressed per m^2 of the Earth.

[8]The TE refers to a specific point in time after a GHG emission has taken place at which the climate impact is being evaluated.

A major difference between the GTP and GWP is that the GTP uses an indicator located one step further down the cause-effect chain. This inevitably increases the uncertainty in the results, but also approaches the actual damage that emissions of GHGs may cause.

Another important difference is that the GTP uses a TE and only evaluates the impact at that specific point in time after an emission has taken place. The GWP, on the other hand, uses a TH and integrates the impacts between the time of emission and the end of the TH. This means that the GTP says nothing about impacts between the time of emission and the chosen point in time of the TE, while the GWP "remembers" all impacts from the time of emission up to the end of the TH. Metrics formulated like the GTP, in this sense, are commonly referred to as *instantaneous*, while metrics formulated like the GWP are commonly referred to as *cumulative*.

Other approaches When the GWP and the GTP are used with a fixed[9] TH or TE, they also give the same weight to emissions, regardless of when they occur. Neither of the two metrics give any information about the rate of change. Although the GTP is conceptually different from the GWP, it is still based on physical phenomena, which may not provide sufficient information for developing cost-effective mitigation strategies or evaluating damage costs and actual ecosystem impacts.

For these reasons a number of other approaches have been proposed to evaluate climate impacts. Some methods give different weight to emissions depending on the proximity of the emission to a specific target year (Manne & Richels, 2001; Kendall *et al.*, 2009; Levasseur *et al.*, 2010).

The method proposed by Manne & Richels (2001) is specifically aimed at finding an optimal mitigation strategy from a cost-effectiveness perspective in a multi-gas emission reduction scenario. The contributions from Kendall *et al.* (2009) and Levasseur *et al.* (2010) are directly aimed at LCA applications and offer a way of including the timing of emissions in the characterisation factor.

Other approaches include different parts of the C cycle in calculation of the metric values, such as the GWP_{bio} (Cherubini *et al.*, 2011) and the greenhouse gas value (GHGV) (Anderson-Teixeira & Delucia, 2011).

Both of these include time-dependent C fluxes of a system in the assessment. Both also express the results in CO_2-equivalents. However, they are not comparable to each other.

The GWP_{bio} includes the regrowth of the specific plant used for energy in a bioenergy scenario, and was developed to take the time-dependent fluxes of the biogenic carbon into account when performing LCAs on bioenergy systems. It

[9]A fixed TH, or TE refers to the same TH or TE being used for all emissions, regardless of when they take place.

evaluates the impacts on the RF in step 3 of the cause-effect chain (Figure 2), just like the GWP.

The GHGV tries to include impacts on ecosystems and their responses by giving them a value. This is located two steps further down the cause-effect chain. However, it uses the RF as the indicator by which impacts are compared, and bases the ecosystem values primarily on C fluxes. Effects due to climate responses are thereby not taken into account. This illustrates some of the difficulties involved in developing a metric that can easily be quantified and at the same time is close enough to the impacts of primary concern.

Due to the many aspects of climate impacts no single indicator can cover all needs. Many more methods of assessing the climate impact than those mentioned above have been proposed (e.g. Kandlikar, 1996; Wigley, 1998; Tanaka *et al.*, 2009; Gillett & Matthews, 2010; Johansson, 2012). The pros and cons of these have been thoroughly discussed in several review articles (e.g. Fuglestvedt *et al.*, 2003; Fuglestvedt *et al.*, 2010; Aamaas *et al.*, 2013).

3.3.4 Climate impact assessment in bioenergy LCAs

Bioenergy LCAs face particular challenges when assessing the climate impact due to interactions with the C cycle (Searchinger *et al.*, 2009; Cherubini *et al.*, 2009), as well as the time-dependent nature of the dynamics in these interactions (Levasseur *et al.*, 2012).

Faced with these challenges, attempts have been made to take temporary C sequestration and storage in living biomass and SOC pools into account when performing LCAs (Brandão *et al.*, 2013). The time-adjusted warming potential (TAWP) (Kendall *et al.*, 2009) and the dynamic LCA approaches (Levasseur *et al.*, 2010), mentioned in section 3.3.3, both weight GHG emissions depending on the timing of the emissions. These address the effect of using a fixed TH in the GWP, which has led to the convention of counting biogenic carbon used for energy as climate-neutral in LCA. Both methods effectively assign a metric value to postponing an emission. They can also be used for other GHGs than CO_2.

Others have addressed the issue of using bioenergy specifically for bioenergy purposes (Cherubini *et al.*, 2009; O'Hare *et al.*, 2009). These methods address the time-dependence of the CO_2 fluxes in the system specifically, by giving biogenic CO_2 emissions a metric value expressed as CO_2-equivalents. The ambition is to make them comparable with other GHGs by using the CRF as a common indicator for comparison.

The close relationship between LCA and carbon footprinting (CF) has also contributed concepts such as the carbon neutrality factor (CN) (Zanchi *et al.*, 2012), the aim of which is direct assessment of the climate impact of bioenergy systems. However, it assesses the change in C stocks, which is encountered in the first step of the cause-effect chain (Figure 2). It therefore serves as a proxy, indicating possible impacts, but does not represent any climate impact *per se*.

All of the above methods have in common the fact that they attempt to formulate characterisation factors that can be used directly with standardised LCA methodology (ISO 14040, 2006). This makes it necessary to choose a TH or TE, depending on the metric used. In doing so, information about rates of change and their time dependence is lost. Peters *et al.* (2011) addressed this issue in an LCA about different transportation options by using an absolute and time-dependent indicator, $\Delta T_S(n)$. This methodology is not commonly used in bioenergy LCAs, however.

4 Methodological approach

This chapter begins with the scope and the methodological choices related to LCA. It is followed by a presentation of the scenarios included in this thesis. The scenarios and the methodologies used to calculate the GHG fluxes and energy inputs are then described in detail. The chapter is concluded with a description of the energy efficiency and time-dependent climate impact assessment methods.

4.1 Scope and methodological choices related to LCA

Life cycle assessment methodology was used to assess the climate impact of electricity and/or heat generated from the feedstock of a Swedish SRC willow plantation. All stages of the production chain were included, beginning with the cultivation of the feedstock and ending with the generation of energy services. The climate impact was assessed using time-dependent climate impact methodology. The methodology, which was developed in Paper I, is introduced in section 4.5.

The assessment was limited to the impact of the three major greenhouse gases contributing to global warming: CO_2, nitrous oxide (N_2O) and methane (CH_4). Emissions were recorded for the fossil inputs used in the technical production system and for sources of other origin, such as N_2O emissions from biomass decomposition and nutrients applied to the crops, as well as carbon stock changes in the soil over time.

In Papers III and IV, generation of both electricity and heat was studied. Since these two products do not perform equivalent energy services it was necessary to allocate the climate impact and primary energy use between them.

The allocation in Papers III and IV was performed using the separate production reference method (Swedenergy, 2012; Beretta *et al.*, 2012). This approach takes into account both the actual amount of electricity and heat generated at the co-generation facility and the amount that could have been generated using the same fuel if these two products had been generated in separate facilities, such as a conventional power plant and a hot water boiler.

The formulation of the separate production reference method includes the conversion efficiency both at the co-generation plant and at the separate production facilities (Figure 3). As a consequence, a higher share of the burden is assigned to the product with the largest relative loss in efficiency when comparing co-generation with separate production.

$$\alpha_{el} = \frac{\left(\dfrac{\text{Amount of co-generated electricity}}{\text{Conversion efficiency at a power plant using separate production}}\right)}{\left(\dfrac{\text{Amount of co-generated electricity}}{\text{Conversion efficiency at a power plant using separate production}}\right) + \left(\dfrac{\text{Amount of co-generated heat}}{\text{Conversion efficiency at a heating plant using separate production}}\right)}$$

Figure 3. Allocation using the separate production reference method. The allocation factor for heat (α_{heat}) is calculated by replacing the nominator with the amount of heat generated at the co-generation plant and the conversion efficiency at a heating plant using separate production.

Several FUs were used in this thesis, namely the area used for cultivation and the energy services generated. One hectare of willow cultivation represents a resource, and was chosen because many functions of land use are directly related to the land use efficiency. Using area as the FU might be important in cases where land is a restricted resource and it is desirable to optimise the impact of the chosen land use, or management.

The energy services are output-based FUs. These functions normally drive the development of bioenergy systems. By using energy services as FUs, it is possible to compare the impacts that their use generates, regardless of the land use efficiency. The FUs chosen to represent the energy services were 1 kWh of electricity (Papers III and IV) and 1 MJ of heat (Papers I-IV).

Different intermediate feedstock conversion technologies were compared in Papers III and IV, resulting in different overall energy efficiencies from feedstock to electricity and heat. System expansion was applied to the less energy efficient scenarios to make different technologies comparable between scenarios within the same paper. Electricity and heat generated using other sources than the willow were added to the less energy efficient scenarios of each paper. The reference flows in each scenario were thereby made equal. Emissions and primary energy (PE) generated from the external energy sources were assigned to these scenarios (Figure 4). A direct combustion scenario was included in all four papers. This was the most energy efficient use of the feedstock included in this thesis.

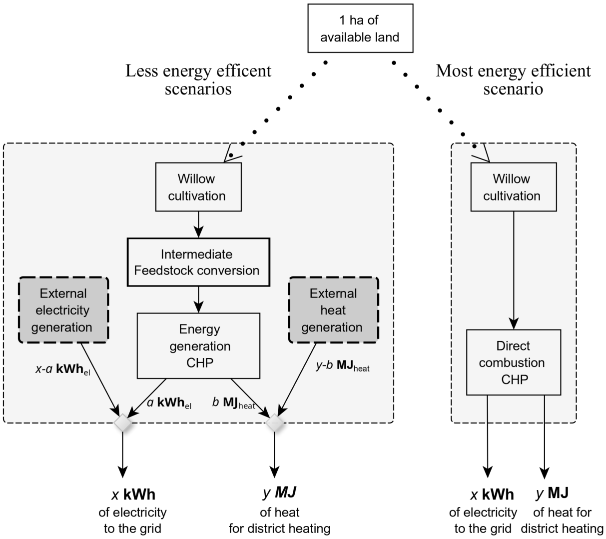

Figure 4. System expansion was performed to make scenarios of different energy conversion efficiency comparable. Within each paper, the reference flows were made equal for all scenarios by including electricity and heat generated using other sources to the less energy efficient scenarios (dashed grey boxes). The emissions and primary energy inputs generated by this production were assigned to these scenarios.

4.2 Scenarios included in the thesis

Different scenarios were compared, where electricity and/or heat were generated using SRC willow feedstock. There were four main scenarios (Table 1). Some of the scenarios were divided into different cases in which the previous land use, length of the cultivation period, yield and handling of the products from the intermediate feedstock conversion steps were varied (Table 2).

The basic scenario in Papers I and II was to generate heat through direct combustion (DC-DH). Paper I included two different cases in which the previous land use was either 20 years of fallow crop or annual crops. Paper II had seven

Table 1. *Distribution of scenarios in Papers I–IV of this thesis*

Scenario	Paper I	Paper II	Paper III	Paper IV
DC-DH	x	x		
DC-CHP			x	x
BG-CHP			x	
Pyr-CHP				x

Table 2. *The cases studied in Papers I–IV, where previous land use, management, yield and use of products from the intermediate conversion step were varied*

Case	DC-DH	DC-CHP	BG-CHP	Pyr-CHP
Previous land use				
Fallow (base case)[1,2]	I,II	III,IV	III	IV
Annual crops[1]	I,II			
Ley	II			
Management				
Single rotation	II			
Yield				
Improved clone	II			
Low yield	II			
High yield	II			
Product use				
Char-for-energy				IV
Biochar-to-soil				IV

[1] The previous land use of the base case (20-year-old fallow) was used in the cases in Paper II with a different yield or management.
[2] The fallow and annual crops cases were identical in Papers I and II.

different cases. The first two were the same as in Paper I. In a third case the previous land use was ley. Paper II also had three cases with different yield levels and one case where the willow cultivation was ended after 25 years (single rotation), whereupon previous land use was resumed. The yield was either decreased by 44% (low yield) or increased by 41%(high yield) throughout the entire study period. In one case the yield was assumed to increase by 10% at each subsequent rotation due to new and improved clones (improved clone).

There were two main scenarios in each of Papers III and IV. Electricity and heat were generated in either a large-scale CHP through direct combustion of the raw feedstock (DC-CHP; Papers III and IV) or in a small-scale biogas engine, following conversion to biogas through anaerobic digestion (BG-CHP; Paper III) or in a large-scale CHP, following conversion to bio-oil and char using pyrolysis (Pyr-CHP; Paper IV). Paper IV included two cases, where the char produced in the pyrolysis process was used either to generate energy services (char-for-energy) or to sequester C through soil application (biochar-to-soil). In this thesis, the term biochar is used instead of char in the context of soil application.

4.3 Scenario description and emission modelling

4.3.1 SRC willow base system

A complete SRC willow cultivation was modelled. The willow plantation was managed in three-year coppicing cycles. After each harvest, the willow was allowed to grow back. Eight coppicing cycles constituted one rotation. Each rotation started with the preparation of the soil one year before establishing the plantation and ended with the killing and breaking up of the remaining willow stools to prepare the soil for a new rotation.

The life of the plantation was 100 years in Papers I and II, including four full rotations of 25 years each. At the end of each rotation, annual crops were assumed to be cultivated for one year to reduce pressure from perennial weeds before re-establishing the willow. In Papers III and IV, two rotations were modelled, with a total length of 50 years.

The plantation was assumed to be located in eastern Sweden, with mean annual temperature of 5.5 °C and an mean annual precipitation of around 600 mm. The size of the plantation varied between the papers depending on the conditions for the intermediate feedstock conversion process. The yield was set to the same value in all four papers. The yield at full production was 10 t of DM per (ha yr). The first coppicing cycle yielded two-thirds of the yield at full production.

All operations related to the management of the plantation were included: soil preparation, weed control, planting, application of herbicides, fertiliser production and application, harvest, chipping and transportation of the biomass to the energy conversion facility, as well as the return transport and application of residues in the form of ash, digestate and biochar. Seedling production was also included in the SRC willow base system.

The operations taking place in the willow cultivation were identical in all four papers, with the exception of application of nutrients and the harvesting method, which were influenced by the requirements of the intermediate feedstock conversion systems and the residues generated by these.

Nutrients were supplied in the form of mineral fertiliser and the residues of the energy conversion process. In the direct combustion scenarios ash was returned to the field. In the biogas scenario digestate was returned to annual crop cultivations and in the pyrolysis scenario the biochar or the ash was returned to the willow field.

Phosphorus (P) and potassium (K) was applied in the second year of every coppicing cycle. In Papers II–IV, nitrogen (N) was applied in the second year of the coppicing cycle, starting in the second cycle. In Paper I, N was applied every year, starting in the second cycle. No N was applied during the first coppicing cycle.

The total amount of P and K applied to the plantation was 0.73 and 2.43 kg per t of expected DM at harvest, respectively. This included the nutrients in mineral fertiliser, ash (Papers I–IV), digestate (Paper III) and biochar (Paper IV). A total of 5.3 kg of N per t of expected DM was applied in Papers II–IV. In Paper I, 7.3 kg of N per t of expected DM was applied.

Two harvest chains were modelled, depending on the conversion technology used.

- Direct chipping followed by immediate transportation to the energy conversion plant was used together with direct combustion. The willow was assumed to be combusted within four months of delivery in the direct combustion scenario.

- Whole stem harvest with storage of the stems at the field edge was used in the biogas and pyrolysis scenarios, since the intermediate feedstock conversion was a continuous process, taking place throughout the entire year.

An advantage of storing the harvested willow as whole stems is that it can be allowed to dry at the field edge over the summer, which reduces the energy requirement in any subsequent drying process. In the scenarios with an intermediate feedstock conversion step, the stems were chipped using a mobile wood chipper before the willow was transported back to the biogas or pyrolysis facility.

4.3.2 Intermediate feedstock conversion systems

In the context of this thesis, intermediate feedstock conversion systems are technical systems that convert the raw feedstock into an intermediate energy carrier before the final conversion into electricity and/or heat.

Anaerobic digestion In the biogas scenario (Paper III), the willow was co-digested with cow manure on the farm in a biogas reactor (Figure 5). Before entering the biogas reactor the particle size of the willow was reduced through comminution to make it more accessible to microorganisms and improve the biogas yield. The main product from the anaerobic digestion process was the biogas, which was used to generate electricity and heat.

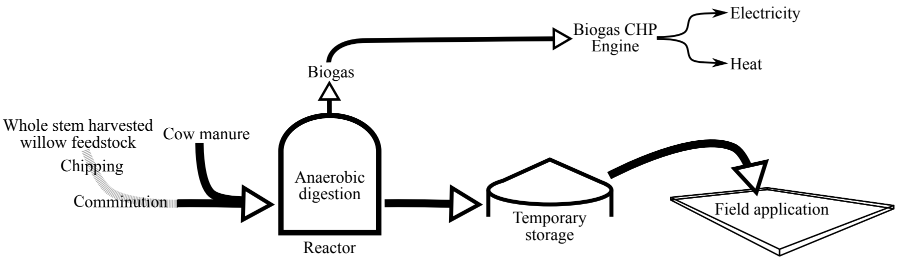

Figure 5. The intermediate conversion step in anaerobic digestion started with chipping of the willow stems before comminuting the willow chips and mixing them with cow manure. The mixture was then co-digested, generating biogas for the CHP and digestate which was returned to crops on the farm.

An important by-product from the biogas process is digestate, which takes the form of a liquid slurry that can be pumped and used as fertiliser on the farm.

It has a high fertiliser value, since it contains all of the P and K and a significant part of the N entering the digester, in a form that is more accessible to plants than before entering the biogas process.

In Paper III, the digestate was assumed to be spread on other crops than the willow. The fertiliser value of the digestate was credited to the willow, since the reduced need for mineral fertiliser in crop production was a direct consequence of the recycled nutrients from the willow.

Pyrolysis In the pyrolysis scenario (Paper IV), the willow was pyrolysed at the farm in an auger reactor to generate bio-oil and char (Figure 6). Before entering the reactor unit, the chipped willow was further reduced in size by comminution and dried to a moisture content of 10 % (dry weight basis) in order to reduce the reaction time. This reduced the required size of the reactor and made the pyrolysis process more energy efficient by also reducing the inert gas requirement.

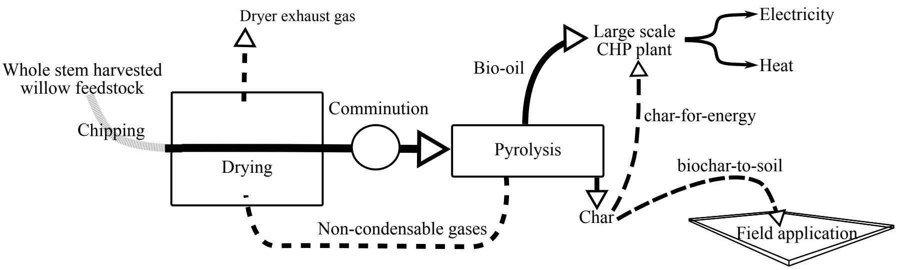

Figure 6. The intermediate conversion step in pyrolysis started with chipping of the willow stems that were dried and comminuted before being fed to the pyrolysis reactor. The bio-oil was used to generate electricity and heat in a large-scale CHP while the char was either used for energy or soil application in the char-for-energy and biochar-to-soil case, respectively. The non-condensable (NC) gases were used to dry the biomass before entering the pyrolysis reactor.

The main products from the pyrolysis process were bio-oil, char and uncondensable gases.

The bio-oil was condensed, collected and shipped off to a large-scale CHP. It was assumed to be produced continuously throughout the year and used without storage due to its unstable nature.

The char was used in one of two different ways:

- To generate electricity in a large-scale CHP, co-fired with biomass (char-for-energy).
- Applied as biochar to the soil to act as a carbon sequestration agent and potential soil improver (biochar-to-soil).

On leaving the hot reactor the char has to be quenched by adding water. This prevents the char from reacting with the air and spontaneously igniting. The water content of the quenched char was assumed to be 60% (WW). The char was then transported to the CHP plant in the char-for-energy case, and applied to the willow plantation using a lime spreader in the biochar-to-soil case.

The uncondensable gases have a calorific value, since they contain CO, CH_4, H_2 and larger hydrocarbons. However, they are costly to store and transport, since their main constituent is CO_2. In Paper IV the uncondensable gases were used to provide the necessary heat to maintain the pyrolysis process and dry the feedstock prior to entering the reactor.

4.3.3 Energy service generation

In the direct combustion scenarios in Papers I and II, heat was generated in a boiler at a local district heating plant and delivered to a local DH distribution network.

In the direct combustion scenarios in Papers III and IV, the biomass was fired in a grate furnace at a large-scale CHP plant to generate electricity in a back pressure steam turbine and subsequently recover heat from the hot steam. These were fed into the national electric grid and local DH distribution system. In Paper IV, flue gas condensation was also assumed to be applied, increasing the overall heat efficiency of the system.

The amount of energy services generated was calculated at the point of delivery to the electric grid and district heating distribution system. Losses taking place in the distribution of the electricity and heat were not included in the assessments of energy efficiency.

4.3.4 Biogenic carbon stock modelling

In all scenarios the CO_2 fluxes between the atmosphere and the biosphere were modelled and included in the assessment of the climate impact. The biosphere was divided into three different pools for which the carbon stocks were tracked through the use of different models. These pools were soil organic carbon (SOC), live biomass and biochar (Figure 7). Dead biomass was not included, since the live biomass was either returned to the atmosphere immediately upon energy service generation or used as input to the SOC or biochar pools.

The size of the annual CO_2 flux was calculated from the difference in the C stock of each pool (x) between two subsequent years. A positive result obtained on using equation 3 would indicate net emission of CO_2 to the atmosphere as a result of C being lost from one of the pools.

$$\mathrm{CO}_{2\,net}^{\,x}(t) = \frac{44}{12}\left(\mathrm{C}_{t-1}^{x} - \mathrm{C}_{t}^{x}\right) \tag{3}$$

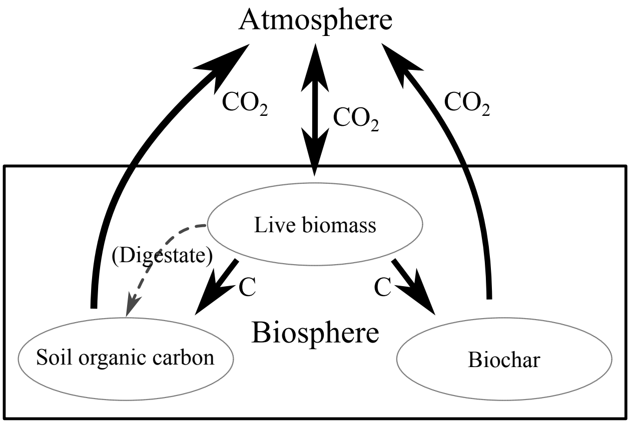

Figure 7. The carbon dioxide (CO_2) fluxes between the atmosphere and the biosphere and the carbon (C) flows between different pools within the biosphere that were modelled in this thesis.

Soil organic carbon The model used to calculate the annual SOC stock changes was a version of the introductory carbon balance model (ICBM) (Andrén *et al.*, 2004), modified to account for the aboveground (*ag*) and belowground (*bg*) ground input separately (Figure 8 and equations 4 and 5).

In this model the C is separated into pools with different decay rates, determined by the *k* parameters. All C input enters the young (Y) pools. A part of the C that leaves the Y pools every year enters the old (O) pool. The humification coefficient (h) determines the size of the fraction leaving a Y pool that will enter the O pool. The remaining fraction of the C leaving a Y pool is returned to the atmosphere. The decomposition rate of the O pool is slower than that of the Y pools due to a lower k value. All of the C leaving the O pool is returned to the atmosphere. In this thesis it was assumed that all C leaving the SOC was converted into CO_2.

$$Y_{[ag,bg]}(t) = \left(Y_{[ag,bg]_{t-1}} + i_{[ag,bg]_{t-1}}\right) \cdot \exp^{-k_y r_e} \tag{4}$$

$$\begin{aligned} O(t) = {} & \left(O_{t-1} - \left(f(Y,i) + g(Y,i)\right)\right) \cdot \exp^{-k_o r_e} \\ & + \left(f(Y,i) + g(Y,i)\right) \cdot \exp^{-k_y r_e} \end{aligned} \tag{5}$$

where:

$$f(Y,i) = \frac{h \cdot k_y}{k_o - k_y} \cdot \left(Y_{ag_{t-1}} + i_{ag_{t-1}}\right)$$
$$g(Y,i) = \frac{2.3 \cdot h \cdot k_y}{k_o - k_y} \cdot \left(Y_{bg_{t-1}} + i_{bg_{t-1}}\right)$$

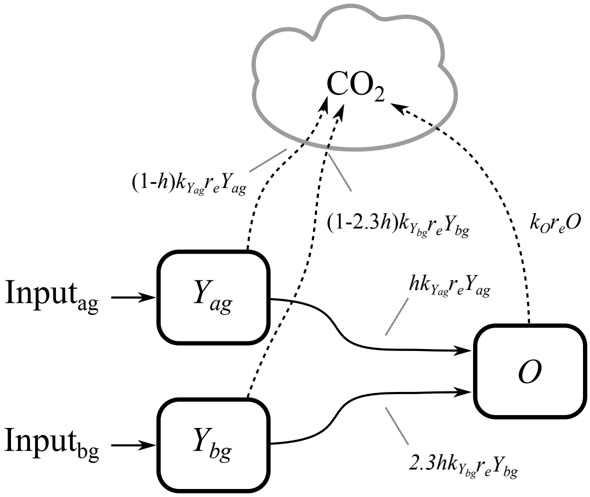

Figure 8. Schematic illustration of the Introductory Carbon Balance Model (ICBM) used in this thesis to calculate changes in soil organic carbon (SOC) stocks. The arrow labels indicate the parameters governing each carbon (C) flow.

ICBM also has a parameter (r_e) that can compensate for the decomposition rate owing to external influences such as soil moisture and temperature. The r_e parameter was set to 1 and kept constant in all scenarios.

Live biomass Carbon stock changes in the live biomass were modelled based on the annual growth rate and carbon allocation patterns of the willow. These were derived from calculations in Rytter (2001).

The C allocated to the leaves was multiplied by 0.58 when calculating the C stock to account for the fact that the plants only have leaves for approximately seven months of the year. The entire mass of the C was treated as input to the above-ground SOC pool in the following year.

Since no estimates of coarse root turnover could be found in the literature, the coarse roots and stumps were assumed to accumulate the entire mass found at the end of the rotation during the first coppicing cycle and to show no net change for the remainder of the rotation. At the end of each rotation, the coarse roots and stumps were treated as C input to the belowground SOC pool.

The C allocated to the fine roots were not accounted for in the live biomass pool, since the fine root turnover rate can be up to 5 yr^{-1}(Rytter & Rytter, 1998). This C was instead treated directly as input to the below ground SOC pool.

Biochar The total biochar C stock in the soil (C_{tot}) in a given year (t) was calculated as the sum of the remaining C from all the individual applications that took place prior to this year ($C_i(t)$), calculated as.

$$C_{tot}(t) = \sum_{i=0}^{t} C_i(t) \tag{6}$$

The C fraction remaining in the soil of the C amount initially applied (C_0), was calculated for each annual application using the following exponential decay function (Zimmerman, 2010):

$$C_i(t) = C_0 - \left(\frac{C_0 \exp^b}{m+1} (t-i)^{m+1} \right) \tag{7}$$

The b and m parameters in equation 7 describe the degradation rate as a function of biochar properties and time. Their relation to the logarithmically transformed first order degradation rate constant (k) can be described by $\ln(-k) = m \ln(t) + b$. Since willow was not used in the calibration of this model, the setting for coarse pine wood pyrolysed for four hours at 525 °C was used to model the biochar evolution of the willow in Paper IV.

Calculation of SOC for different previous land uses The land use prior to the establishment of the willow plantation affects SOC evolution, since the amount of C lost in a year depends on the amount of C available in the soil. The effect of previous land use on the climate impact was investigated in Papers I and II.

In the base case the previous land use was assumed to be a fallow established 20 years earlier. Before establishing the fallow, the land use was assumed to have been annual crops and the SOC was assumed to have been in steady state. The SOC level at the time of willow establishment was calculated by modelling the SOC changes over the 20 years of fallow.

In a second case the willow replaced annual crops. The SOC was assumed to be in steady state before establishing the willow. This case was included in both Paper I and Paper II.

A third case, where willow replaced ley crops, was also included in Paper II. As for the annual crops, the SOC was assumed to be in steady state when switching to willow.

The steady state SOC levels were calculated by performing spin-up simulations over 1000 years, using ICBM. The initial SOC levels were lowest in the green fallow, followed by the ley and the annual cropping. The initial SOC levels in Paper II were 96, 98 and 100 t of C per ha, respectively.

4.4 Energy efficiency calculations

Life cycle assessment has its origins in energy analysis (Hunt & Franklin, 1996). When performing an LCA of energy systems, it is natural to also perform an energy analysis.

There are a number of ways to determine the energy efficiency of a bioenergy system. The external energy ratio (ER) (Murphy *et al.*, 2011) was used as indicator of the energy efficiency in Papers I–IV in this thesis. The ER definition used was the ratio between the delivered energy service and all the external energy input used in the process of generating this service (equation 8).

$$\mathrm{ER} = \frac{\text{delivered energy}}{\text{external energy input}} \tag{8}$$

The external energy input includes all primary energy used upstream and the direct energy used in the operation of the system. The external energy input does not include the energy contained in the feedstock. Feedstock energy used in the energy conversion process is therefore ignored. However, the efficiency of the energy conversion process is reflected in the ER by the use of the delivered energy in the formulation.

4.5 Time-dependent climate impact methodology development

Assessing the time-dependent climate impact of bioenergy systems was a specific objective of this thesis. Time-dependent impacts may occur due to the interaction of bioenergy systems with the carbon cycle, as well as the inherent differences in the dynamic behaviour of different GHGs when emitted to or taken up from the atmosphere. A methodology to assess these effects was developed in Paper I.

This methodology built mainly upon standardised LCA methodology (ISO 14040, 2006; ISO 14044, 2006), with the exception of the use of a time-distributed inventory and a time-dependent indicator for the climate impact.

4.5.1 Time-distributed inventory

A time-distributed inventory is a prerequisite to calculate time-dependent effects from emission scenarios (Yuan *et al.*, 2015). A basic requirement for a time-distributed inventory is that both the magnitude and the timing of all emissions are recorded for all activities taking place in the system. This is frequently done in economics to perform temporal discounting (Ludwig *et al.*, 2005). It is also an integral part of the TAWP and dynamic LCA methods (Kendall *et al.*, 2009; Levasseur *et al.*, 2010).

Time-distributed inventories were developed for all scenarios in this thesis. In these, the size of each annual net emission was recorded for each activity taking place in the system, in the year that it took place.

The modelling of the technical system was rather straightforward, and did not give rise to more complicated questions than the year to which upstream emissions should be assigned. In Papers I–IV they were assigned to the same year as the activity giving rise to them took place. This was a compromise. Upstream emissions have clearly occurred prior to the use of a resource, but the use of a resource does not send a signal to generate more resources until the actual decision to consume it has been taken. The emissions from this production will just as clearly take place in the future.

The modelling of biogenic carbon stock changes required the use of different carbon stock models. The models used in this thesis were presented in section 4.3.4.

4.5.2 Time-dependent indicator

The nature of formulation of a metric influences the results and the conclusions that can be drawn from these. Time-dependent indicators and traditional characterisation factors are complementary. The former give information about, and insights into, how impacts might develop over time, while the later are useful in traditional greenhouse gas accounting schemes and their applications.

Global mean surface temperature change, ΔT_S For the purposes of this thesis the contribution to the global mean surface temperature change over time, $\Delta T_S(n)$, was chosen as an indicator of the climate impact. It is an instantaneous metric which can give information about the impacts at varying points in time without including past impacts.

Another reason for choosing ΔT_S was that it is an absolute metric. The impacts are given directly in temperature change caused by the GHG investigated, which is more convenient than the impact relative to a reference gas when trying to understand the climate response.

The global mean surface temperature change is also the climate variable with the strongest response signal to a change in the energy balance of the earth on relevant time scales. It might not be the most important variable, however. Sea level or weather pattern changes might eventually prove more important and costly to human society. However, global mean surface temperature change responds faster to an imbalance in the energy balance of the earth, and it is normally a precursor to other responses. It therefore serves as a proxy, indicating the direction in which changes are taking place.

Finally, the temperature was chosen as an indicator that is easily interpreted in physical terms. One of the main reasons for basing the climate impact assessment in this thesis on the temperature rather than RF was that the stratospherically adjusted RF[10] does not take the increased rate of loss of energy back to space into account as the amount of energy increases in the climate system. Calculation of the temperature does on the other hand take this into account: The rate of change

[10]The stratospherically adjusted RF is the definition of the RF used in the formulation of the GWP. There are several other definitions of the RF that behave differently.

in the temperature will be zero when the outgoing energy once again equals the incoming energy, while the RF[11] of the initial impulse still remains. It is therefore not possible to interpret the cumulative RF as the amount of energy accumulated in the system. This applies to all metrics based on cumulative RF.

The time-dependent climate impact was calculated for each of the scenarios in Papers I–IV from the annual emission impulses recorded in the inventory. The results were presented as plotted curves representing the contribution to ΔT_S over time, since the aim was to increase insights into system behaviour over time rather than produce an absolute value of the impact (chapter 6). The plots were the most important tool in the interpretation phase.

4.5.3 Calculation steps

The time-dependent climate impact methodology can be summarised in the following steps:

1. Creation of the time-distributed inventory
2. Calculation of the temperature response from individual emission impulses ($\Delta T_S^{x_i}(t)$).
3. Calculation of the total system response ($\Delta T_S(n)$) as the sum of all individual temperature responses.
4. Plotting and interpreting the results.

Step 1 The creation of the inventory is described in sections 4.3.4 and 4.5.1. It is thus not described further here, except for adding that it is the most time-consuming part of the LCA. The requirement to have the timing of emissions from processes that span several years makes this methodology more time consuming than constructing a conventional inventory. However, it also gives the modeller a better understanding of the system, which is helpful when searching for errors that may have been inadvertently introduced into the inventory during the modelling, as well as when interpreting the results.

Step 2 The temperature response ($\Delta T_S(t)$) due to an emission impulse (EI) of a single GHG (x) in a specific year of the study period (i) was modelled using impulse response functions (IRF) for the first four steps of the cause-effect chain shown in Figure 2. The GHG concentration changes ($f_{x_i}(t)$, equation 9) due to point emissions taking place at $t = 0$ were calculated with the same IRFs ($f_x(t)$) used in the calculation of the global warming potential (Forster *et al.*, 2007).

[11]This is valid for the stratospherically adjusted RF.

Parameter values for $f_x(t)$ were taken from Ciais *et al.* (2013) in Papers I–III and Myhre *et al.* (2013) in Paper IV.

$$f_{x_i}(t) = EI_{x_i} \cdot f_x(t) \qquad [\mathrm{kg}] \tag{9}$$

The change in the radiative forcing (*RF*) was then calculated by multiplying $f_{x_i}(t)$ by the radiative efficiency[12] of each GHG (RE_x) (Ramaswamy *et al.*, 2001)) as:

$$RF_{x_i}(t) = RE_x \cdot f_{x_i}(t) \qquad \left[\mathrm{W{\cdot}m^{-2}}\right] \tag{10}$$

To move from the change in *RF* to $\Delta T_S(t)$, a convolution between $RF(t)$ and the temperature response function ($\delta T_S(t)$) due to a perturbation in the *RF* was used in Papers I–III based on the equation:

$$\Delta T_S^{x_i}(t) = \int_{t-\tau}^{t} RF_{x_i}(\tau)\, \delta T_S(t-\tau)\, d\tau \qquad [\mathrm{K}] \tag{11}$$

In Paper IV the algebraic solution for the absolute global temperature potential (AGTP) was used directly to calculate $\Delta T_S(t)$ (equation 12, Fuglestvedt *et al.*, 2010), using updated parameter values from the Fifth IPCC AR (Myhre *et al.*, 2013, AR5). This formulation yields the same results, but is more convenient than equation 11 when testing or updating parameter values. A convolution has to be resolved each time any parameter value is altered.

$$\begin{cases} \Delta T_S^{\mathrm{CO_2}}(t) = EI_{\mathrm{CO_2}} \cdot RE_{\mathrm{CO_2}} \sum_{j=1}^{2} \{ a_0 c_j \left(1 - \exp\left(-\frac{t}{d_j}\right)\right) \\ \qquad + \sum_{i=1}^{3} \frac{a_i \tau_i^{\mathrm{CO_2}} c_j}{\tau_i^{\mathrm{CO_2}} - d_j} \left(\exp\left(-\frac{t}{\tau_i^{\mathrm{CO_2}}}\right) - \exp\left(-\frac{t}{d_j}\right)\right) \} \\ \Delta T_S^{\mathrm{CH_4}}(t) = EI_{\mathrm{CH_4}} \cdot RE_{\mathrm{CH_4}} \left(F_{\mathrm{CH_4}}^{\mathrm{O_2}} + F_{\mathrm{CH_4}}^{\mathrm{H_2O}}\right) \cdot \sum_{j=1}^{2} \frac{\tau^{\mathrm{CH_4}} c_j}{\tau^{\mathrm{CH_4}} - d_j} \\ \qquad \cdot \left(\exp\left(-\frac{t}{\tau^{\mathrm{CH_4}}}\right) - \exp\left(-\frac{t}{d_j}\right)\right) \\ \Delta T_S^{\mathrm{N_2O}}(t) = EI_{\mathrm{N_2O}} \cdot RE_{\mathrm{N_2O}} \cdot \sum_{j=1}^{2} \frac{\tau^{\mathrm{N_2O}} c_j}{\tau^{\mathrm{N_2O}} - d_j} \left(\exp\left(-\frac{t}{\tau^{\mathrm{N_2O}}}\right) - \exp\left(-\frac{t}{d_j}\right)\right) \end{cases} \tag{12}$$

[12] The RE is the ability of a GHG to interact with long-wave radiation, measured in (W per m^2). The RE is a fixed value for each GHG, unlike the RF, which depends on time after emission.

Step 3 The contribution from each scenario to the global mean surface temperature change ($\Delta T_S(n)$) was calculated by summing the temperature responses from the individual emission impulses for every year of the evaluation period (n) using equation 13. The contribution from different parts of the system was also calculated using the same formula, including only relevant emissions.

$$\Delta T_S\,(n) = \sum_{x=1}^{3}\sum_{i=1}^{n} \Delta T_S^{x_i}\,(t) \qquad \text{[K]} \qquad (13)$$

In Papers III and IV the terms ‘study period’ and ‘evaluation period’ had different interpretations. Study period was used to refer to the time frame during which activities were modelled and emissions recorded. No emissions were recorded in the inventory after the end of the study period. Evaluation period was used to refer to the time frame during which the effects of the emissions in a scenario were evaluated.

The length of the evaluation period and of the study period were not equal in Papers III and IV. Because of the inertia of the climate system and the behaviour of GHGs in the atmosphere, the full temperature response to an emission was not fully realised for up to 20 years after the time of emission (Figure 9). By setting the evaluation period to 100 years, the effects of emissions taking place close to the end of the 53-year long study period could also be studied.

Step 4 Plotting and interpreting the results was the last step in the methodology. Data from previous steps were used for plotting and interpreting the systems studied. The level of detail in the modelling of the scenarios and the amount of information returned by the use of a time-dependent indicator created a huge amount of data. Some of the results from each step were selected for description in chapter 6

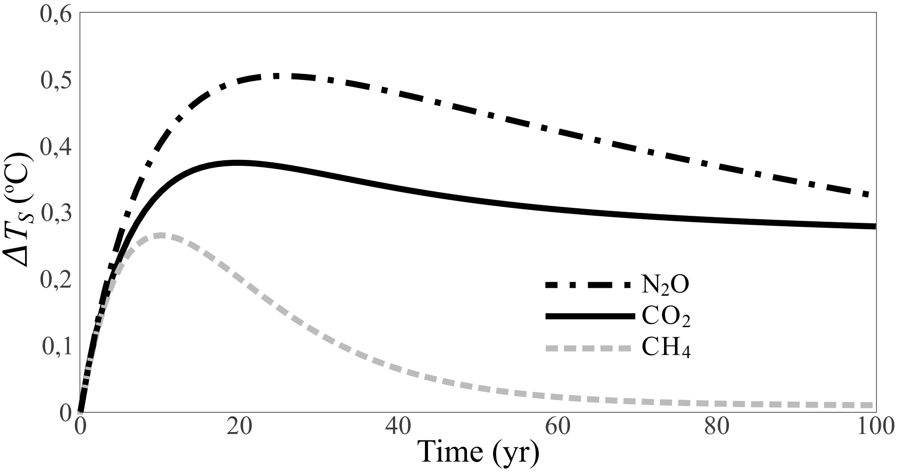

Figure 9. The temperature response from single large emission impulses of carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) taking place at year 0. The initial emission of each of these three greenhouse gases (GHG) corresponded to an instantaneous radiative forcing (RF) of 1 W per m^2.

5 Energy efficiency of SRC willow systems for energy and heat

The ER of the heat in the cases studied in Paper II was all around 25 (Table 3).

The heat had a higher ER when produced in a CHP due to the heat efficiency, which was increased by the use of flue gas condensation, and due to the allocation of some of the energy inputs to the electricity (Table 4).

The ER of the electricity in the CHP scenarios was lower than the heat due to the lower electric efficiency and the allocation of energy inputs. It was further reduced in the biogas and pyrolysis scenarios by the low amounts of electricity delivered in these scenarios, due to the intermediate conversion steps.

Table 3. *Amount of energy used in, and delivered from, the different direct combustion district heating scenario (DC-DH) case in Paper II and their external energy ratio (ER)*

Scenario	Case	Energy in $\frac{MJ}{(ha \cdot yr)}$	Energy out $\frac{MJ}{(ha \cdot yr)}$	ER
II (DC-DH)	Base case	5.9	149	25
	Single rotation	5.8	145	25
	Improved clones	6.6	173	26
	Low yield	3.0	61	20
	High yield	7.8	211	27

The amount of energy input required was around 6 MJ per (ha yr) in most scenarios. A noticeable exception was the biogas scenario in Paper III, where less transports and a lower use of fertiliser led to a 24% reduction in energy use compared with the direct combustion scenario in the same paper.

The total amount of energy generated varied between the scenario cases investigated (Tables 3 and 4). When direct combustion was applied, around

Table 4. *Energy input to, and delivered from, the combined heat and power (CHP) scenario cases in Papers III and IV and the external energy ratio (ER) of the delivered electricity and heat. There was only one case for each of the biogas (BG) and direct combustion scenarios, while the pyrolysis (Pyr) scenario included two cases: char-for-energy (CfE) and biochar-to-soil (BtS)*

Scenario	Case	Energy in $\frac{MJ}{(ha \cdot yr)}$	Energy out $\frac{MJ}{(ha \cdot yr)}$	ER_{el}	ER_{heat}
III (DC-CHP)		6.4	141	13	33
III (BG-CHP)		4.9	16	3	4
IV (DC-CHP)		6.1	137	10	36
IV (Pyr-CHP)	CfE	5.8	105	7	29
	BtS	5.7	65	5	17

150 MJ of heat per (ha yr) were delivered in the DH scenario. Combined heat and power production was slightly less efficient in converting the feedstock into energy services.

6 Climate impact from SRC bioenergy

When modelling the inventory, GHGs were conceptually separated into those arising from operations and upstream resource use in the cultivation system, feedstock handling and energy service generation step of the system, and those arising from biogenic carbon stock changes. Nitrous oxide emissions from soils, originating from applied fertilisers and nutrients, as well as biomass decomposition, are also partly due to biological activity but were, however, grouped with the emissions from the cultivation system. One reason for doing so was that the first group corresponded roughly to emissions that are commonly included in most bioenergy LCAs, while the biogenic carbon stock changes are less frequently included.

6.1 Cultivation system, feedstock handling and energy service generation

6.1.1 Emissions from the cultivation system, feedstock handling and energy service generation

The amount and composition of emissions from the cultivation system, feedstock handling and energy service generation steps mainly differed in the harvest and transport steps between different scenarios. The intermediate feedstock conversion technologies used required storage of the willow for different periods of time and also generated different amounts of energy carriers that had to be transported to the DH or CHP plant.

Total emissions from the cultivation system, feedstock handling and energy conversion steps were dominated by CO_2 and N_2O in all scenarios, except for the biogas scenario, which had high CH_4 emissions due to a 2% leakage at the site of the digester and digestate storage (Figure 10).

The main sources of CO_2 were found to be production of fertiliser and application of nutrients, followed by harvesting operations and transport (Figure 11).

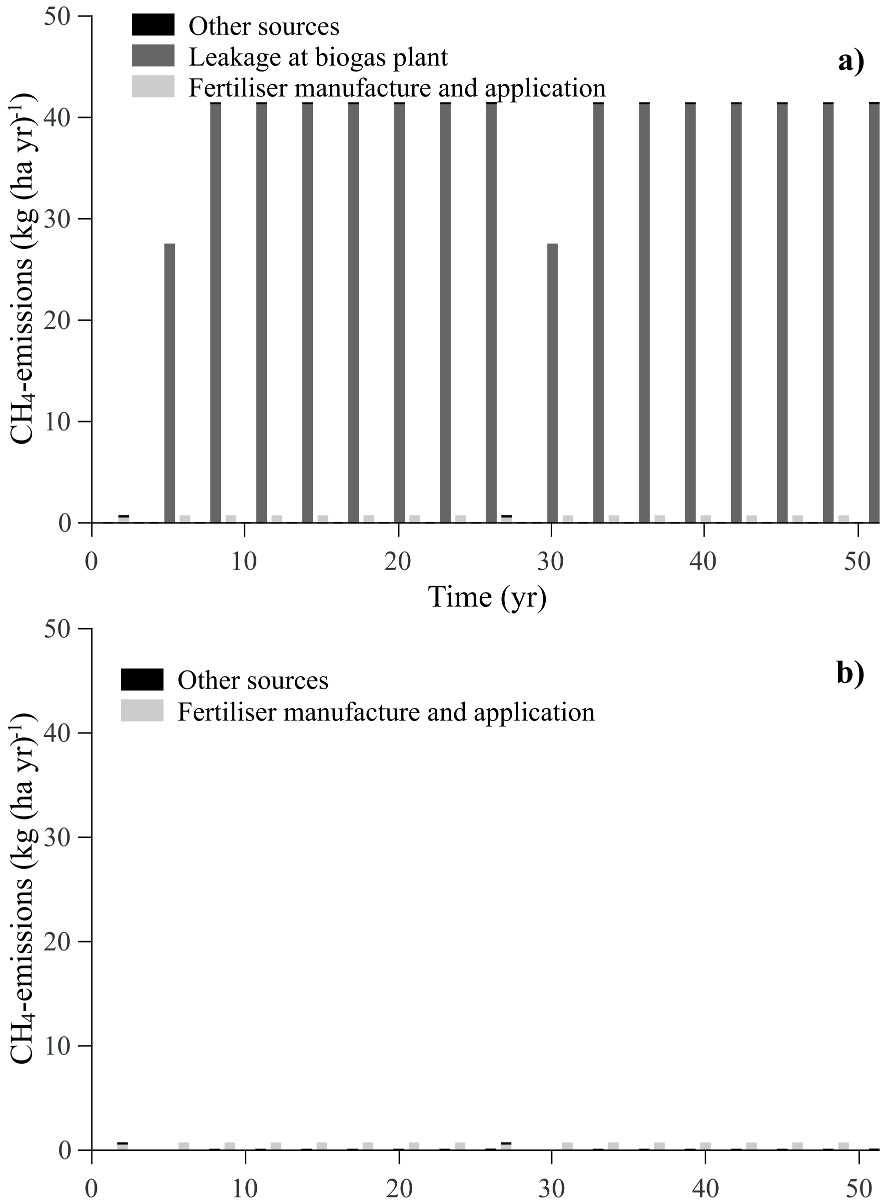

Figure 10. Methane (CH_4) emissions in (a) the biogas scenario and (b) the direct combustion scenario in Paper III. The CH_4 emissions in all other scenarios in Papers I–IV were similar to those in the direct combustion scenario in Paper III.

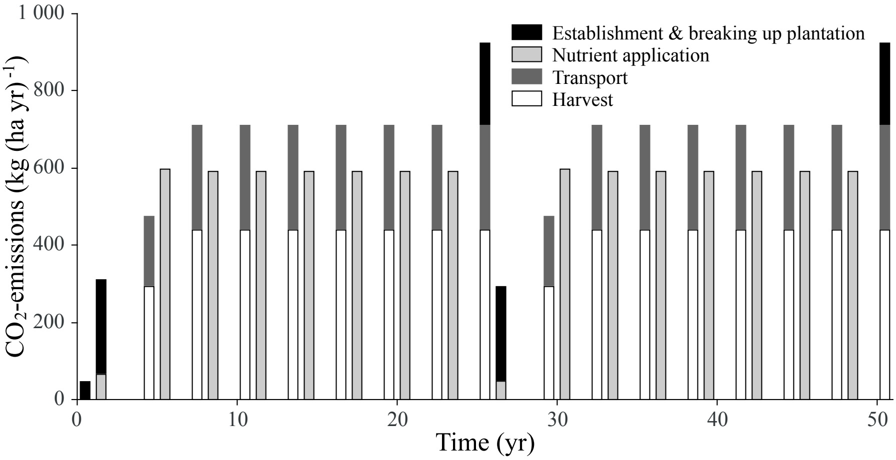

Figure 11. Carbon dioxide (CO_2) emissions from the cultivation system, feedstock handling and energy service generation step in the direct combustion scenario in Paper IV.

Single large emission impulses of CO_2 were caused by operations related to the establishment and breaking up of the willow plantation, but they did not contribute significantly to the total amount of CO_2 emissions, since these events only occurred once every rotation. The CO_2 emission profiles were similar for all scenarios, except for the biogas and pyrolysis scenarios in Papers III and IV, which had lower harvest and transport emissions.

Nitrous oxide emissions were mainly induced by biomass decomposition and applied nutrients (Figure 12). Manufacture and application of mineral fertilisers was also a significant source of N_2O emissions. Nitrous oxide emission sources were similar in all scenarios. The only source for which the magnitude varied between scenarios was manufacture and application of mineral fertiliser due to different degrees of nutrient recycling of within the farm.

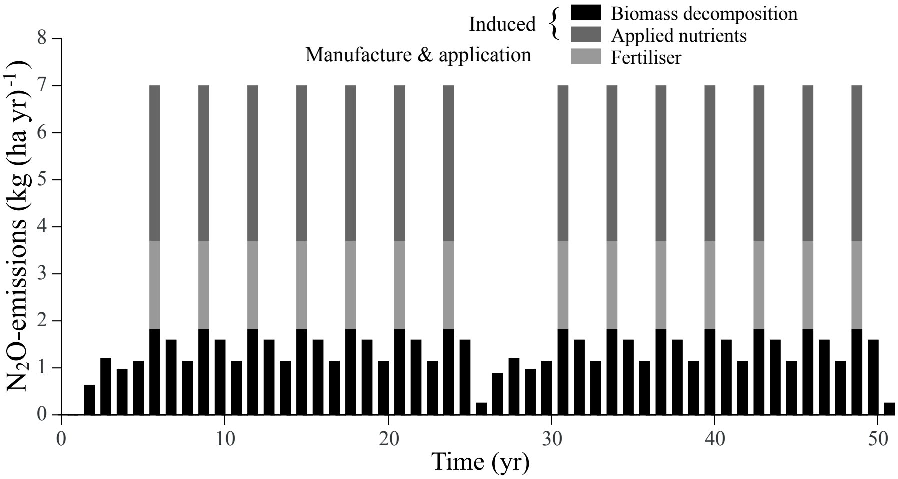

Figure 12. Nitrous oxide (N_2O) emissions from the cultivation system, feedstock handling and energy service generation step in the direct combustion scenario of Paper IV.

6.1.2 Climate impact of the cultivation system, feedstock handling and energy service generation

The contribution to ΔT_S from the cultivation system, feedstock handling and energy conversion steps were dominated by the N_2O emissions in all scenarios, except for the biogas scenario in Paper III (Figure 13).

The CH_4 leakage in the biogas scenario had a stronger influence on ΔT_S during the first rotation than the N_2O and CO_2 sources in the system, even though only 2% of the biogas produced was lost to the atmosphere (Figure 13 a). This shows the importance of actively working to reduce leaks in CH_4 producing systems.

Over time, the relative influence of the CH_4 emissions diminished, as a result of their shorter atmospheric lifetime compared with N_2O and CO_2 (see Figure 9). However, emissions of CH_4 continued throughout the entire study period, as can be seen *e.g.* in Figure 10.

The high proportion of CH_4 in total GHG emissions in the biogas scenario could also be seen when comparing the progress of its total contribution to ΔT_S with that of the other scenarios (Figure 14). The biogas scenario had a higher rate of change, contributing more to an increase in ΔT_S during the study period than the other scenarios, and also contributed more to a decrease in ΔT_S after the end of the study period.

The temperature response curves due to the emissions taking place in the cultivation system, feedstock handling and energy conversion steps were similar in the direct combustion and pyrolysis scenarios in Papers III and IV (Figure 14). The difference in magnitude between these was partly due to inherent differences

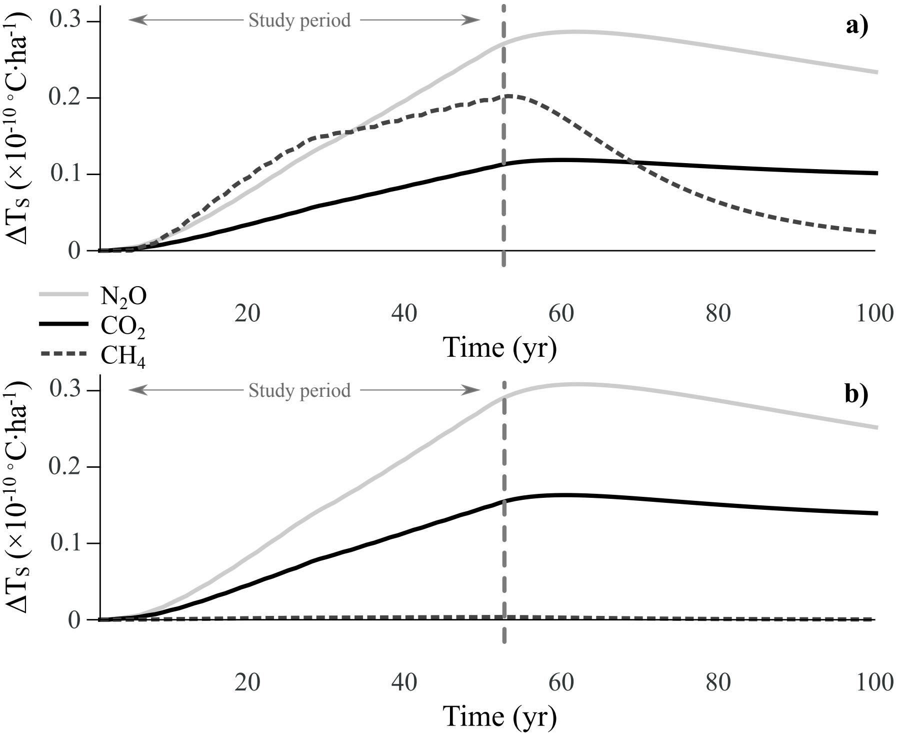

Figure 13. Contribution to the global mean surface temperature change (ΔT_S) from each of the greenhouse gases (GHGs) emitted from the cultivation system, feedstock handling and energy service generation step in (a) the biogas scenario and (b) the direct combustion scenario in Paper III.

in emission levels of each scenario and partly due to the effect of using different parameter values for the temperature response models used in Papers III and IV.

The temperature response curves for the DH scenario in Papers I–II were similar to the direct combustion scenario in Paper III.

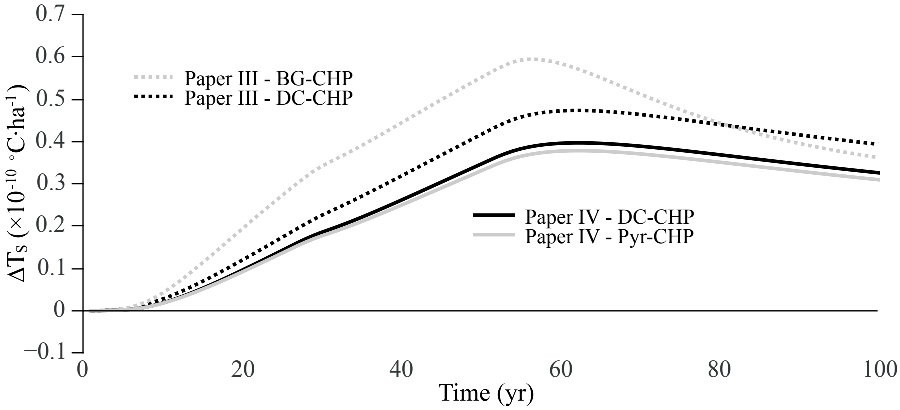

Figure 14. Total temperature response due to emissions from the cultivation system, feedstock handling and energy service generation in the main scenarios in Papers III and IV.

6.2 Biogenic carbon stock changes

Biogenic C fluxes went in several directions: between different pools within the biosphere and between these pools and the atmosphere. The main flux of relevance for the climate impact was the net flux of CO_2 between the biosphere and the atmosphere. The C stock changes were calculated and summed as CO_2 fluxes. In the following subsections C fluxes are presented and discussed as CO_2.

6.2.1 Carbon dioxide fluxes due to biogenic C stock changes

Live biomass The establishment of willow gave rise to a rapid C stock increase in the live biomass when replacing previous fallow land or annual crops. There was no net sequestration in the live biomass over a complete coppicing cycle, since the C stored in the live biomass was either returned to the atmosphere when generating electricity and heat, or transferred to other C pools. It was either transferred to the SOC pool as fresh input or digestate after having undergone anaerobic digestion, or to the biochar C pool after having undergone pyrolysis. The net CO_2 fluxes in the live biomass followed a cyclic pattern with two years of sequestration followed by one year of net emissions (Figure 15). This pattern was the same in all scenarios, and was due to growth of the willow biomass and its subsequent conversion to energy.

Soil organic carbon The change in land use and management practices caused a slow but steady increase in the SOC pool. Scenarios with the same previous land use also had the same SOC increase due to the input from the willow.

The net CO_2 fluxes due to the input and decay of willow biomass followed the same cyclic pattern as the live biomass in all scenarios (Figure 15). The net emissions to the atmosphere during the first few years of each rotation were larger than for the remainder of the rotation since the decay rate of SOC exceeded the input rate of fresh biomass from the young willow plantation in these years.

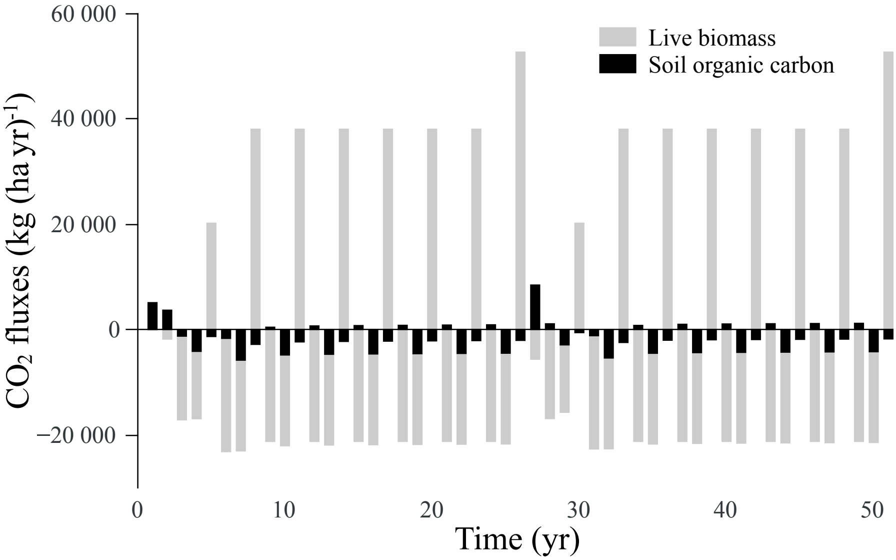

Figure 15. Net carbon dioxide (CO_2) fluxes due to live biomass and soil organic carbon (SOC) stock changes in the direct combustion scenario in Paper IV.

Digestate The C in the digestate applied to crops in the biogas scenario of Paper III (Figure 16) also contributed to an increase in the SOC pool. A large sequestration event was recorded every third year when the digestate generated from 1 ha of willow was applied to the soil (Figure 17). In the two years following digestate application, a significant part of the C in the applied digestate decayed, leading to large net emission impulses of CO_2.

Biochar The biochar applied to the soil in the pyrolysis scenario in Paper IV also created a large sink of C in the soil, similar to that of the digestate in the biogas scenario of Paper III. Less than half as much biochar was returned to the soil compared with the digestate, due to the higher efficiency of the intermediate feedstock conversion process in the pyrolysis scenario (Figure 16). However, the CO_2 fluxes to the soil in the year of application were only two-thirds of that for the digestate in the biogas scenario (Figure 17). The CO_2 fluxes to the atmosphere in the years between biochar applications were also small compared with the biogas scenario. Both of these effects were due to the much lower decay rate of biochar compared with digestate.

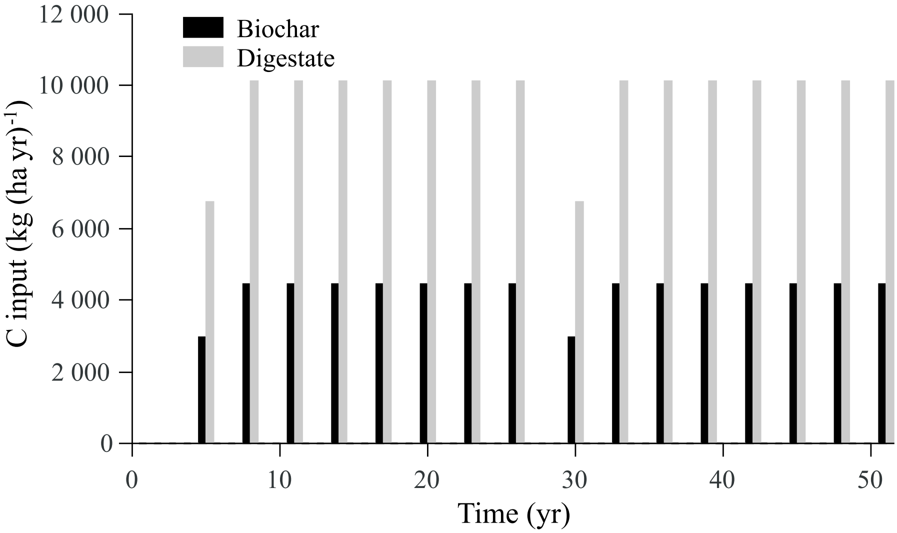

Figure 16. Amount of (C) returned to the field with the residues in the biogas scenario in Paper III and the biochar case in the pyrolysis scenario in Paper IV.

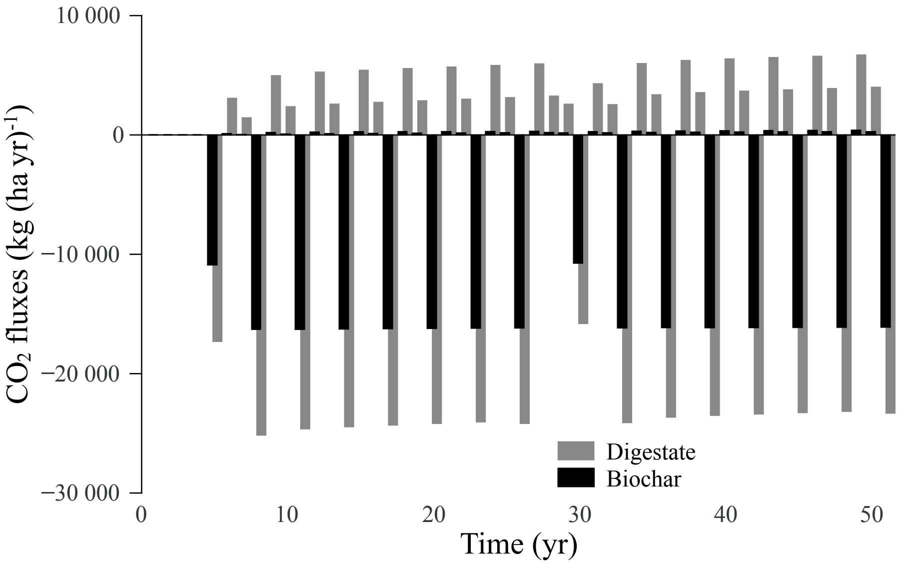

Figure 17. Net carbon dioxide (CO_2) fluxes due to soil application of digestate and biochar in Papers III and IV, respectively.

6.2.2 Climate impact of the biogenic C stock changes

The progress of the C stock changes in the the different biogenic C pools was clearly reflected in their contribution to ΔT_S.

Live biomass The initial contribution from the live biomass tended to lower ΔT_S rapidly in the direct combustion scenario in Paper IV, but soon reached a new level where the influence on ΔT_S was much less pronounced (Figure 18). This was due to the net C stock changes only taking place at the beginning of the study period. The same pattern was observed in Papers I and II, with a 100-year study period (not shown).

At the end of the study period, all of the C in the live biomass was removed from the live biomass pool. The temperature response therefore returned to slightly above its initial level within a few years after final harvest. The reason it did not return to its initial level was that there was no live biomass left in the system at the end of the study period, while there was a small amount of live biomass in the fallow preceding the willow establishment.

Soil organic carbon Soil organic carbon did not contribute much to ΔT_S initially, but its influence grew over time as the SOC levels increased. At the end of the study period, the contribution to ΔT_S was more than double that of the live biomass (Figure 18). During the short time frame of the study period in Papers III and IV (53 years), the rate of C sequestration did not decrease much. However, if the time frame of the study period had been longer, the rate of sequestration would eventually have ceased, since the SOC levels would have approached a new steady state.

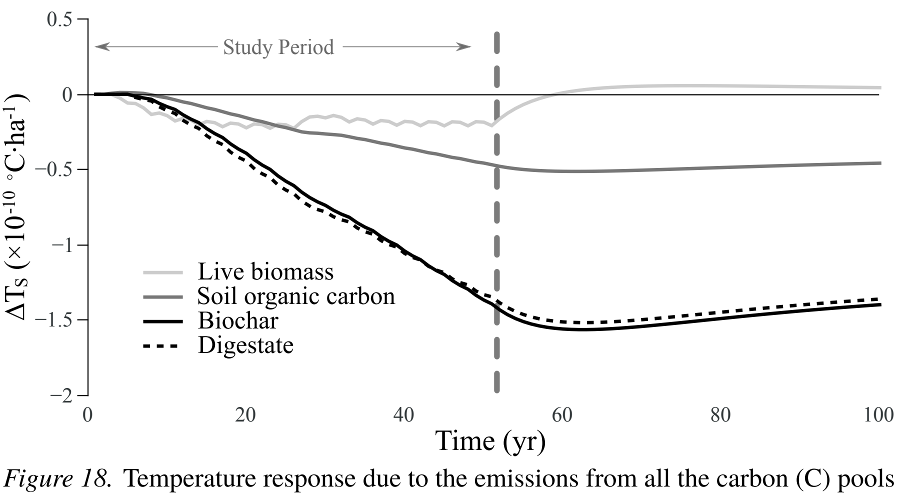

Figure 18. Temperature response due to the emissions from all the carbon (C) pools in Paper IV and the digestate in Paper III.

Digestate The SOC increase due to the digestate application (Paper III) contributed approximately 2.5 times more than the live biomass input to a decrease in ΔT_S. The evolution over time was identical, however, since the same model was used to calculate the SOC evolution. The difference arose from the estimated higher stability of the C source in the digestate compared with the live biomass.

Biochar The contribution to ΔT_S from the biochar in Paper IV was very similar to that from the digestate in Paper III, both in size and in timing (Figure 18). This happened because the net sequestration of C over the entire study period was of a similar magnitude in both scenarios. The temperature response curves from the biochar and the digestate crossed each other after approximately 40 years. This was due to the higher amount of C applied to the soil in the biogas scenario and the higher stability of the biochar. The higher amount of C applied to the soil in the biogas scenario led to a higher rate of change in ΔT_S at the beginning of the study period compared with the biochar. However, the rate of change in ΔT_S caused by the biochar decreased more slowly, since less CO_2 was released back to the atmosphere due to its higher stability. With time, the biochar C pool grew larger than the digestate SOC pool. This indicates that it will a take longer time before the C pool created by a steady supply of biochar reaches a steady state compared with the SOC created by digestate application.

6.3 Total system response

After having calculated the contributions from all the separate emission sources, the total contribution to ΔT_S was calculated for each scenario in Papers I–IV, and related to the chosen FUs. In Papers I and II one hectare of willow plantation was the only FU used. In Papers III and IV, 1 kWh of electricity delivered to the grid and 1 MJ heat delivered to the district heating distribution network were also used as FUs.

6.3.1 Temperature response per hectare

When calculating the temperature response per hectare of willow plantation, no consideration was given to the energy efficiency of the systems. Although the function of a bioenergy system is to generate energy services willow could theoretically also fulfil other functions, such as providing raw material for basket and furniture making or salicin for the pharmaceutical industry. By determining the climate impact per hectare, the land use can also be compared with that of other non-energy land uses.

In the case where the willow was used to generate electricity and heat in a large-scale CHP plant it did not make much difference whether the willow was incinerated directly or converted into bio-oil and char before generating electricity

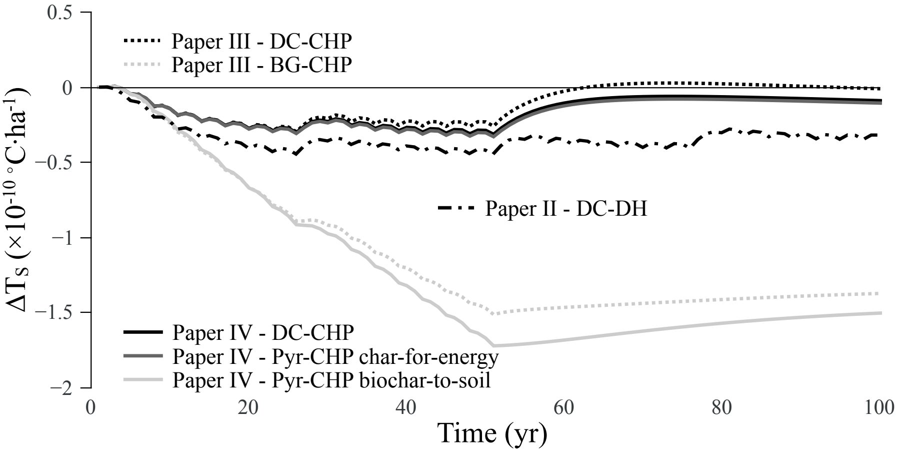

Figure 19. Total temperature responses from six different cases of the four major scenarios in Papers II–IV.

and heat (Paper IV, Figure 19). The direct combustion scenario in Paper III made a similar contribution to ΔT_S as the direct combustion and the char-for-energy cases in Paper IV.

Both the biogas scenario and the biochar-to-soil case of the pyrolysis scenario contributed strongly to a decrease in ΔT_S over the duration of the study period (Figure 19). The difference between these two scenarios and those where all the feedstock was converted into energy services was entirely attributable to the C sinks created by the digestate and biochar applied to the soil.

6.3.2 Temperature response per kWh of electricity

In Papers III and IV, the temperature response of the system was allocated between the electricity and heat delivered. The allocation methodology meant that the share of the total climate impact assigned to the electricity was not the same in all scenarios. However, the influence of the allocation on the relative importance of different scenarios to the contribution to ΔT_S was much smaller than that of the amount of electricity delivered in each scenario.

The lower energy efficiency of the biogas and pyrolysis scenarios compared with direct combustion meant that the total climate impact had to be assigned to less electricity and heat. The biogas scenario in Paper III was the most prominent example. This scenario only delivered 17% of the electricity delivered in the direct combustion scenario. This made the contribution to a decrease in ΔT_S per kWh of electricity much larger than in the other scenarios (Figure 20). The same effect was seen in the pyrolysis scenario in Paper IV.

In all cases studied, the contribution to ΔT_S per kWh of electricity was lower than for the reference case where electricity was generated in a natural-gas fired

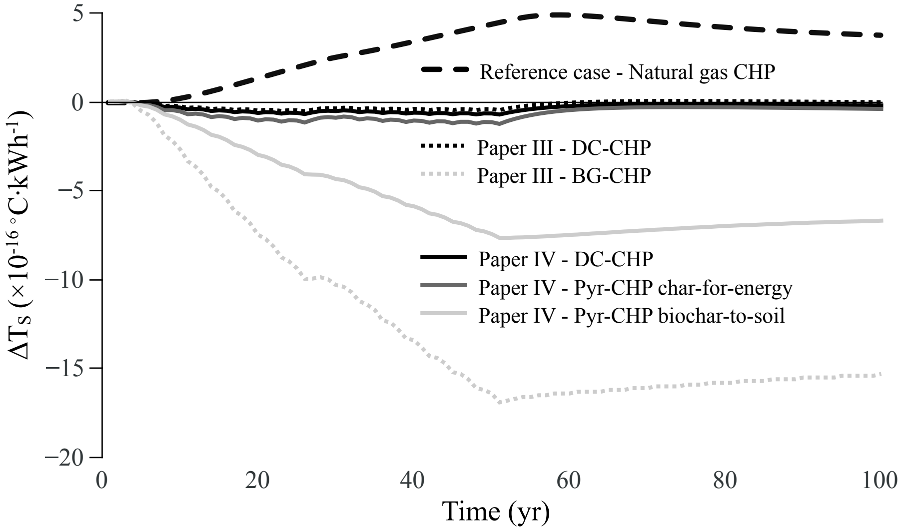

Figure 20. Temperature response per kWh of electricity delivered to the grid for each case of the scenarios in Papers III and IV compared to the temperature response of a natural-gas fired combined heat and power (CHP) plant.

CHP.

6.3.3 Temperature response per MJ of heat

The contribution to ΔT_S per MJ of heat was very similar to that of electricity (Figure 21). The result for the heat in the biogas scenario in Paper III was even more inflated than that of the electricity, since it only delivered 9% of the heat delivered in the direct combustion scenario.

The pyrolysis scenario in Paper IV was not inflated like the biogas scenario in Paper III. In that case, a lot of the energy content of the flue gases was recovered in the flue gas condensation step of the CHP. This was possible due to the high water content of the bio-oil and increased the heat efficiency of the pyrolysis scenario, both for the char-for-energy and the biochar-to-soil cases.

Just as for the electricity, all cases studied made a contribution to ΔT_S per MJ of heat that was lower than for the natural gas reference case.

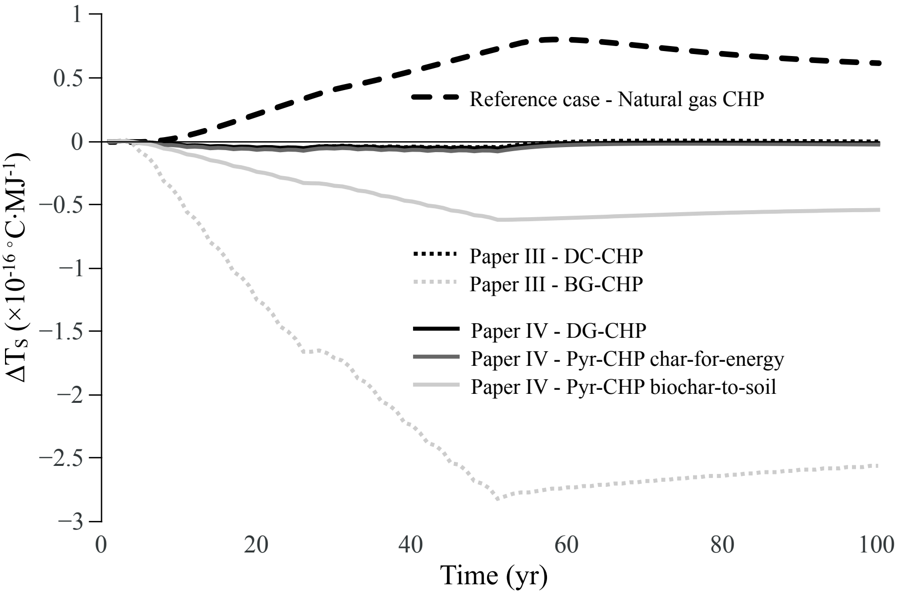

Figure 21. The temperature response per MJ of heat delivered to the district heating (DH) distribution network for each case of the scenarios in Papers III and IV compared with the temperature response of a natural-gas fired combined heat and power (CHP) plant.

6.4 Considering the energy efficiency of different feedstock conversion systems

As mentioned in section 4.1, the use of different intermediate feedstock conversion technologies resulted in different amounts of electricity and heat being delivered in each scenario. Although the impact per kWh and per MJ given in section 6.3 represents the impacts generated by the isolated systems, a fair comparison would require the reference flows of energy services to be equal for all scenarios.

To take the energy efficiency into account, system expansion was applied. Emissions from external energy service generation were added to the biogas and pyrolysis scenarios, making them deliver the same amount of electricity and heat as in the direct combustion scenarios.

No attempt was made to try to predict which source would be most likely to generate the external electricity and heat. The effect of choosing a specific intermediate conversion technology was instead investigated by using different electricity sources, with different GHG intensities, as well as by having different GHG compositions in their emissions. The same was done for heat.

In the biogas scenario in Paper III, the emissions from the Swedish electricity mix in 2008 were used, representing a source with relatively low GHG emissions per kWh of electricity. An electricity with 10% wind and an equal share of coal, natural gas and nuclear sources in its production mix was used to represent a more GHG-intensive source. The effect of the external heat source was not published in Paper III. In Figure 22, the external sources in the biogas scenario have been switched to the same sources as in Paper IV to make it comparable to the biochar case in the pyrolysis scenario.

In Paper IV, coal and natural gas were used as external sources for both electricity and heat. Wind power was chosen as a third alternative electricity source, since it generates very low GHG emissions and because the installed wind power capacity has grown steadily in the European power generation system over the last decade. Household waste was chosen as a third alternative heat source, since a lot of household waste is currently being used in the Swedish district heating system. The coal was assumed to be used in a conventional CHP, while the natural gas was assumed to be used in a combined cycle CHP and the household waste in a heat-only DH plant.

The most important observations from the expanded biogas and pyrolysis scenarios were as follows:

- Regardless of the GHG intensity of the external energy sources, the biochar-to-soil case in the pyrolysis scenario in Paper IV made a lower contribution to ΔT_S than the biogas scenario. This was mainly due to the much higher energy efficiency of the pyrolysis process, leading to less external electricity and heat generation.
- When coal was used as the fuel source for the external energy the biogas scenario contributed more to an increase in ΔT_S than the natural gas reference case.
- The pyrolysis scenario always made a lower contribution to ΔT_S than the reference case, regardless of the external energy source used (Figure 22).
- In all cases where the external energy source came from fossil fuels the contribution to ΔT_S was higher for the biogas and biochar-to-soil cases than if the willow had been used in a conventional direct combustion process (Figure 22).

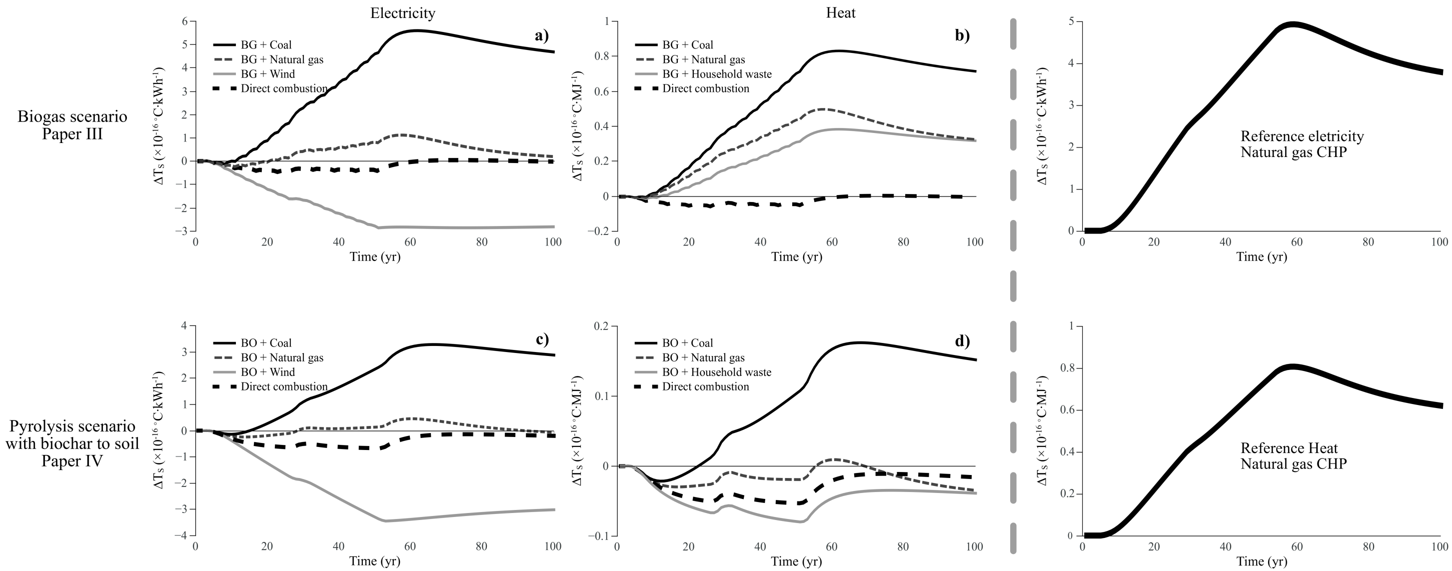

Figure 22. Temperature response from the electricity (a and c) and heat (b and d) of the expanded systems in the biogas scenario (Paper III) and the biochar-to-soil case in the pyrolysis scenario (Paper IV). Biogas (BG) and bio-oil (BO) were used together with external heat sources to make the reference flows of these cases equal to that of the direct combustion scenario in each paper.

When natural gas was assumed to be the external energy source, the timing of the impact became an influential variable in interpretation of which scenario made a lower contribution to ΔT_S. For the biochar-to-soil case in the pyrolysis scenario, direct combustion initially made a lower contribution to ΔT_S. When emissions ceased, the contribution from the pyrolysis scenario decreased quickly, to end up below the direct combustion scenario (Figure 22d). This was due to CH_4 emissions from the production chain of natural gas electricity and heat, corresponding to 1% of the gas used. Although the fraction lost was small, it had a visible effect on the short-term temperature impact, similar to the CH_4 leakage in the biogas scenario.

6.5 Effect of previous land use and yield level

In Papers I and II, the effect of previous land use on the contribution to ΔT_S was investigated for the direct combustion scenario. In Paper II, the effect of the yield level was also investigated.

The previous land use had a noticeable influence on the contribution to ΔT_S (Figure 23). Nevertheless, it was significantly smaller than the influence from different yield levels.

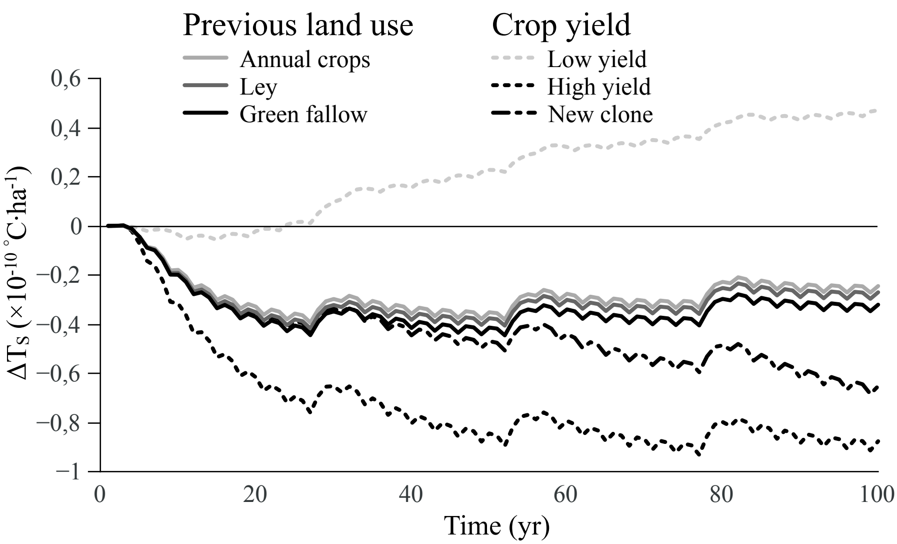

Figure 23. Temperature response per hectare of willow plantation in Paper II, which was more sensitive to willow yield than the previous land use in the direct combustion scenario. The response curves from Paper I are not shown, since the annual crops and green fallow cases were identical in Paper I and II.

A higher yield level may lead to more C input to SOC in the form of leaves and fine roots, giving the system a lower contribution to ΔT_S. Lower yield, on the other hand, may lead to less C input and even losses of SOC. This can eventually lead to the system contributing to an increase in ΔT_S, as in the low yield case in Paper II, which was no longer a C sequestering system after the first rotation (Figure 23).

The magnitude of the impacts from higher and lower yields in Paper II was comparable to that of the impacts from the biochar in the pyrolysis scenario in of Paper IV.

The impact from successively increased yield for each new clone was not very pronounced during the second rotation, but for each new rotation it grew in importance compared with the base case (Figure 23). This case was different from the others in that the rate of change in ΔT_S increased for each new rotation, due to the stepwise increase in C input to the soil. In all other scenarios the rate of change in ΔT_S decreased as the soil approached a new steady state.

7 General Discussion

This chapter provides a general discussion, beginning with the contribution of time-dependent methodology to LCA. Some perspectives on biogas and biochar systems are also given to illustrate why less energy efficient conversion pathways might make sense. This is followed by a perspective on some of the dedicated energy crops that could also be cultivated on the land used for the SRC willow plantations. A short discussion about the land used for the SRC willow plantation, and how it might affect the energy and climate mitigation potential is also given. The chapter ends by highlighting some future research needs related to SRC willow bioenergy systems to better assess their potential climate impact.

7.1 Time-dependent climate impact methodology in LCA

As mentioned in section 4.5.2, the use of time-dependent methodology, and a time-dependent indicator complements the traditional use of characterisation factors when assessing the climate impact in LCA. The overall conclusions do not necessarily change. The results from the scenarios investigated using time-dependent climate impact methodology in this thesis confirmed the results from other studies using GWP, indicating that SRC willow bioenergy systems may create carbon sinks and counteract global warming by accumulating C in biogenic C pools (Lemus & Lal, 2005; Caputo *et al.*, 2014; Djomo *et al.*, 2015).

However, time-dependent climate impact methodology in an LCA can contribute increased insights into the timing and rate of change, as illustrated in this thesis. Timing might be of great importance for mitigation strategies, since different GHGs have different atmospheric lifetimes, leading to differences in their long- and short-term impacts (Shine *et al.*, 2007).

Both the timing and rate of change have impacts on ecosystems. Ecosystems are stressed by high rates of change to their environment and exhibit a high degree of non-linear responses and sudden threshold effects, which are not known beforehand (Pederson *et al.*, 2010). This also affects human society. Mankind depends on ecosystem services for food supply. Our ability to adapt to a changing environment also depends on the rate of change. Incorporating methods to assess when, how much and how fast impacts may occur might therefore be of great value to LCAs.

The climate impact indicator used with time-dependent methodology does not have to be the ΔT_S. Many interesting climate impact indicators have been developed over the past 30 years (Tanaka *et al.*, 2010). It is possible to use indicators from earlier or later steps in the cause-effect chain between emissions and impacts. Climate researchers have studied other impacts, such as cloud cover, precipitation and sea level change (Hooss *et al.*, 2001; Joos *et al.*, 2013). These could also serve as useful indicators for many impacts further down the cause-effect chain, since they are closely related to potential economic damages.

7.2 Choosing less energy efficient conversion pathways

In this thesis the generation of electricity and/or heat using willow feedstock was investigated from a climate impact and energy efficiency perspective only. Due to the extra conversion steps included in the biogas and pyrolysis scenarios it is inevitable that these will generate less energy. However, energy service generation is not necessarily the main driver behind these systems.

From the point of view of the farmer, one of the most important incentives for choosing a biogas or pyrolysis system is the possibility to use more resources for income-generating purposes. Anaerobic digestion and pyrolysis can facilitate the production of energy carriers from residues such as manure and straw, for example.

Biogas systems can offer a means of making residues easier to manage. By converting them into digestate, nutrient cycling within the farm can be improved. Furthermore, co-digestion with willow biomass will increase the amount of organic material in the digestate, which can be beneficial for the soil. This may increase soil fertility and potential yield levels.

Pyrolysis systems can be used to improve the storage and handling properties of the energy carriers. Pelleted and chipped biomass creates serious health and safety hazards when stored and handled (Sebastian *et al.*, 2006). Fungus and microbial activity produces spores and carbon monoxide (CO) and increases the temperature of biomass stored in piles to the point where it can self-ignite (Noll & Jirjis, 2012). Char is more stable than biomass, making it storable for longer periods of time, and it also has a higher energy density, which improves transport efficiency. Char normally does not have the problems associated with biological activity. It is therefore easier and safer to store and handle than raw biomass.

The char can be used directly as an energy carrier, but it can also be used for soil application, generally referred to as biochar. This has many potential, but also disputed, benefits (Lehmann, 2007). The results from the biochar-to-soil case in Paper IV confirmed the conclusions reached in other studies that biochar can create a substantial C sink, making it an alternative use of the feedstock with a high climate mitigation potential (e.g. Hammond *et al.*, 2011; Field *et al.*, 2013; Peters *et al.*, 2015).

The bio-oil generated in a pyrolysis process may also have many more potential applications than the raw feedstock. Today, bio-oil cannot compete with fossil fuels in applications other than direct combustion. Some of the greatest hurdles for the bio-oil are its chemical complexity, instability and great variability in composition. Much research has been conducted on recovering valuable chemicals from the bio-oil in cost-effective ways. This research is essential for the future viability of pyrolysis systems (Mettler *et al.*, 2012).

Economic incentives are important to encourage investment in less energy efficient conversion pathways. The benefits of SRC willow plantations might not translate directly into higher revenues. The future of bioenergy systems therefore depends on the feedstock prices of biomass and fossil fuels, as well as other economic incentives designed to shift the energy system from fossil to renewable fuels, such as CO_2 credits or certificates (Meerman *et al.*, 2012).

Carbon dioxide credits may play an even greater role if some of the available carbon is used for temporary C capture and storage in soils, as in the biogas scenario and biochar-to-soil case. An alternative to biochar and digestate application is maximising energy output in a biomass CHP and using carbon capture and storage (CCS) technology (Boot-Handford *et al.*, 2014). This may be a more competitive pathway by virtue of its higher energy efficiency. However, temporary C storage in soils benefits from not requiring advanced technology or new infrastructure to transport, store and ensure the permanence of the storage.

From a societal perspective, the points above translate into positive values. Jobs are generated in areas where employment and income-generating activities are often decreasing. This can have positive multiplier effects in the economy of these areas (Hillring, 2002). The potential effect of biochar and digestate when applied to soils might lead to reduced fertiliser usage which could translate into a reduction in other environmental impacts.

7.3 Alternative bioenergy crops

In this thesis the source of biomass was a SRC willow plantation. Other bioenergy crops could also have been chosen to generate the feedstock, using the same land. Some alternatives to SRC willow are woody crops, such as poplar or aspen, oleaginous crops such as rapeseed, conventional cereal crops and energy grasses such as reed canary grass, miscanthus and switchgrass.

The choice of crop always represents a risk to the farmer. Annual and perennial crops differ in that the opportunity cost is higher for perennial crops. Short rotation coppice willow needs particularly strong incentives, given that it locks in the land use for a number of years in the future. Annual crops have a clear advantage over perennial crops such as SRC willow in that perspective. However, SRC willow can be used for phytoremediation of contaminated soils due to its ability to take up heavy metals (Pulford & Watson, 2003). This is especially relevant to arable soils with an elevated level of cadmium (Cd) from phosphate fertilisers.

Regardless of which crop is chosen, the same general principles are applicable when determining the climate impact mitigation potential. The yield level is crucial for the amount of energy delivered by the system. The carbon allocation within the plant, together with the yield level, determines the amount of C input to the soil. The stability of the C input may vary between crops and has a large impact on SOC evolution, and thus the climate impact. The lignin fraction in woody crops is generally more difficult for microorganisms to access than the higher shares of cellulose and hemicellulose in annual crops. Carbon input from lignin-rich crops may therefore remain longer time in the soil for a longer time.

The potential contribution from root input to SOC is not the same for annual and perennial crops. The root system of perennial crops is not disturbed on a regular basis, giving them the opportunity to develop a deeper, coarser and more extensive root system. In contrast, the shallow root system of annual crops mainly consists of fine roots. This difference increases the climate impact mitigation potential of perennial crops such as SRC willow and energy grasses such as miscanthus and switchgrass.

Crop residues from annual crops are a low-cost resource that can also be used for energy service generation. A difference between cultivating dedicated energy crops and removing crop residues is that energy crops contribute extra input to build up SOC through roots, leaves and harvest residues, while removal of C with crop residues can lead to a net reduction in SOC and a deterioration in soil physical properties (Powlson *et al.*, 2011). This may counteract the climate mitigation potential achieved by the extra energy services generated from the residues.

7.4 Land use, energy and climate mitigation potential

The SRC willow plantations studied in this thesis were all assumed to be established on set-aside or abandoned agricultural land.

If primary agricultural land is used for bioenergy crop production, it may give rise to indirect land use change (iLUC) effects. Indirect land use change effects are market-mediated responses to the change in land use when new bioenergy cultivations are established. The land where the iLUC takes place is not necessarily close to, or in any other way related to, the land where the bioenergy crops are established. It is simply a response to the altered balance between supply and demand.

However, indirect land use change is not a phenomenon which is unique to bioenergy crops. These effects inevitably occur whenever land use or management is altered, regardless of whether the new land use is aimed at food, feed, fuel, timber, clothes or any other land use–related commodity.

The availability of abandoned or set-aside land that could be used for bioenergy crop production without competing with agricultural production varies between countries and can be difficult to assess. In Sweden alone, over 300 000 ha of agricultural land has been set aside or abandoned over the past 30 years (Statistics Sweden, 2014). In England, it has been estimated that there are 3.5 million ha of non-primary agricultural land which could potentially be used for bioenergy crop production (Lovett *et al.*, 2014).

Globally, an estimated 385–472 million ha of agricultural land have been abandoned over the past 300 years, not including land converted into forest or urban land use (Campbell *et al.*, 2008). According to those authors, bioenergy crops grown on this land could have supplied approximately 8% of the world's primary energy demand at that time. In that study, the area-weighted mean production of aboveground biomass was 4.3 t of DM per (ha yr).

By assuming that the average yield on 400 million ha would be the same as in the base case SRC willow plantation in this thesis, a theoretical estimate can be made of the potential contribution from SRC willow bioenergy systems, although not all of this land is suitable for SRC willow plantations. According to this estimate, the potential primary energy supply would be twice as reported by Campbell *et al.* (2008). This energy could be used to replace other fuel sources, and thereby mitigating climate impacts.

If the climate impact from the cultivations equalled that of the DH scenario in Paper II, the bioenergy systems could contribute with −0.02 °C to ΔT_S over the next 50 years, without considering any fossil fuel replacement. If the climate impact equalled that of the biochar-to-soil case in Paper IV, the contribution to ΔT_S would be −0.07 °C over the same time period. For reference, the global mean surface temperature (T_S) has increased by approximately 0.5 °C over the past 50 years (Hartmann *et al.*, 2013).

7.5 Future research

There is great uncertainty about how different biogenic carbon pools evolve over time. This is especially true for SOC pools due to the complexity of activities influencing the stability of the C sources in the soil, *e.g.* the local climate, type of soil, nutrient availability, the nature of the C source and the biological activity in the soil. Soil organic carbon pools can accumulate or release C over long periods of time. There are many models that can be used to estimate SOC development over time, *e.g.* ICBM, RothC, DayCent, Yasoo and DNDC. The accuracy and value of the results from these estimations depend on the availability of data from long-term field studies to calibrate the models to conditions similar to those of a particular study in which the models are being applied. Further field trials to calibrate dynamic carbon models and research to increase understanding of SOC dynamics are two essential tasks in improving the reliability and usefulness of LCAs on bioenergy systems, as well as other systems affecting SOC stock levels.

Biochar can be considered a very heterogeneous material group. The chemical properties and physical structure of a particular biochar depend on feedstock properties, process and post-process conditions (Spokas, 2010). Biochar stability in soils and its effects on soil biota, nutrient availability and crop yields are highly dependent on these factors, in addition to the factors governing SOC decay mentioned previously. Further research is required on different types of biochar, to understand how they affect and are affected by soil processes and to reduce uncertainty about their long-term stability.

Accurate predictions of effects on nutrient availability and crop yield and of biochar stability are important for the acceptance of biochar by farmers and the possibility to include biochar in voluntary C markets, or other GHG protocols and international treaties. The work carried out under the European Biochar Foundation and the International Biochar Initiative in creating uniform characterisation practices is essential for the acceptance and marketability of biochar (EBC, 2012; IBI, 2014). However, biochar is a very young field of research. Many of the long-term effects of biochar application and methods for effectively applying biochar to soils are still poorly quantified and understood for the wide range of different types of biochar in existence. Rectifying this will require substantial research efforts, both in practical applications and long-term field studies.

System studies looking at the climate impact–energy efficiency trade-off of pyrolysis have been conducted in the past (*e.g.* Hammond *et al.*, 2011; Ibarrola *et al.*, 2012; Woolf & Lehmann, 2012; Woolf *et al.*, 2014). This trade-off is also present in other systems that use part of the C to build up SOC pools instead of generating energy, such as the biogas system included in this thesis. In addition, there are numerous other applications for pyrolysis products, creating a multiple trade-off situation. Given the variability in both pyrolysis products and biochar properties, great research efforts are required to better understand the environmental impacts and economic effects of different system configurations and the end use of the products.

In the majority of LCAs conducted to date, there is no explicit consideration of time, making it difficult to understand assumptions made *e.g.* on rates of application and timing of impacts if they are not explicitly stated. As data from empirical studies on biogenic C pool dynamics continue to accumulate, it will be possible to model the impacts from bioenergy systems with more accuracy in LCAs and contribute insights into how these might change over time due to the choices made with regard to the trade-offs inherent in these systems.

8 Conclusions and perspective

This chapter starts with some general conclusions drawn from the work performed in this thesis. The following sections present specific conclusions based on the results reported in Papers I–IV and the work performed during the development and analysis of the scenarios studied, followed by concluding remarks.

Short rotation coppice willow–based bioenergy systems can be truly carbon negative. This thesis demonstrated that electricity and/or heat can be generated while counteracting global warming using SRC willow plantations that actively contribute to increasing the C stocks in soils.

Even SRC willow-based bioenergy systems using low energy conversion pathways, *i.e.* the biogas and biochar systems in this thesis, can have a high climate impact mitigation potential due to their high C sequestration potential. However, a trade-off exists between energy efficiency and climate impact mitigation potential whenever some of the potential energy is diverted to soil in the form of C inputs instead of being used for energy service generation. If the energy supply system to which the energy is being delivered is dominated by GHG-intensive fuel sources, it might be better to maximise energy production from the SRC willow-bioenergy system and avoid the use of fossil fuels rather than maximising the C sequestration of the system.

Biogenic C pools can have much greater impacts on the climate impact from a bioenergy system than the fossil contributions in the system. The dynamic nature of these pools makes the impacts highly time-dependent. The timing, magnitude and rate of change caused by GHG emissions and C stock changes in the system can all be better understood by using a time-dependent climate impact method together with a time-dependent indicator, as illustrated in this thesis.

8.1 Methodology considerations

- ➢ When including all emissions and uptakes of GHGs in a system in the modelling stage of a time-dependent methodology, it is not necessary to distinguish between fossil and biogenic sources.

- Time-dependent climate impact methodology requires additional work, compared with conventional climate impact assessments in LCA, but generates additional information on timing of impacts and rates of change. The use of time-dependent climate impact methodology improves understanding of the dynamic behaviour of the system under study.

- A time-dependent indicator, such as ΔT_S, can be used directly in the assessment of the contribution from different bioenergy systems to specific climate goals, *e.g.* the EU 2 °C climate target.

8.2 Energy efficiency of SRC willow–based bioenergy systems

- A DH system with a SRC willow–fuelled biomass boiler can deliver around 20–27 times more energy than what is used in the production chain of the feedstock. The lower and higher end of that range correspond to systems with low and high yielding plantations, respectively. The ER in the base case in this thesis was 25.

- A CHP system co-firing SRC willow feedstock with other biomass in a large-scale furnace–back-pressure steam turbine configuration can deliver around 18–22 times more energy than what is used in the production chain of the feedstock. The lower and higher end of that range correspond to the case when bio-oil and char from an intermediate pyrolysis step are used for energy service generation and when willow wood chips are combusted directly in the CHP, respectively.

- If only the bio-oil from the pyrolysis process is used for electricity and heat generation, the energy efficiency of the system is reduced by approximately 50% compared with direct combustion of willow chips in a large-scale CHP.

- If biogas is produced from the willow biomass in an anaerobic digestion process before generation of electricity and heat, the energy efficiency of the system is reduced by approximately 85% compared with direct combustion in a large-scale CHP.

8.3 Climate impact of SRC willow–based bioenergy systems

- All studied scenarios studied here contributed less to global warming than their fossil fuel reference cases, indicating that SRC willow bioenergy systems may help mitigate climate impacts if they are used instead of fossil fuel based energy systems.

- ➢ The climate impacts from the biogenic C stock changes in a SRC willow plantation may counteract the impact from the fossil inputs and induced N_2O emissions used in the SRC willow bioenergy system. Their potential magnitude can make the system counteract global warming.
- ➢ Carbon sequestered in biochar and digestate has the largest climate impact mitigation potential in a SRC willow bioenergy system, if applied to soils. Biochar has a higher potential than digestate due to its higher stability, which leads to the sequestered carbon being kept out of the atmosphere for a longer time.
- ➢ The long-term climate impact mitigation potential of SOC stock changes is larger than that from the C stock changes in the live biomass pool when establishing a new SRC willow plantation. However, the live biomass has great short-term climate impact mitigation potential due to its high initial rate of change.
- ➢ The climate impacts from a SRC willow bioenergy system are highly time-dependent. Any climate impacts due to C stock changes may be reversed if the previous land use is resumed and C stocks return to their previous levels.
- ➢ The climate impact mitigation potential of a biogas system can be much larger than that of a pyrolysis system per kWh of electricity and MJ of heat when digestate and biochar are applied to soils, as a direct consequence of the lower energy efficiency of the biogas system.
- ➢ When performing a system expansion to compensate for the lower energy efficiency of the biogas and pyrolysis systems compared with the direct combustion system, the climate impact mitigation potential of the biogas system was much more sensitive to the GHG intensities of the external energy sources used in the system expansion than that of the biochar-pyrolysis system.
- ➢ The climate mitigation potential of the direct combustion CHP system was higher than that of the biogas and the biochar-pyrolysis systems when natural gas and hard coal were used in the system expansion.
- ➢ Previous land use is an important factor when determining the climate impact of a new SRC willow plantation, since the impact is directly dependent on the SOC and the live biomass C stocks before establishing the willow.
- ➢ Willow yield has a high impact on the climate mitigation potential of a SRC willow bioenergy system, both through its influence on C stock changes

and their consequent climate impacts, and also through its connection to the amount of energy the system can deliver.

- ➢ Higher yielding clones and plantations could increase the climate mitigation potential of SRC willow bioenergy systems in the future.

8.4 Perspective

The focus in this thesis was entirely on climate impact, trying to shed some light on how SRC willow bioenergy systems could contribute to climate mitigation work. Before concluding this thesis, it is worth taking some time to think about why the work was carried out in the first place. There are certainly a handful of issues facing mankind in this contemporary world that seem far more important and urgent than climate change to us living here and now. However, this is a question of how we prioritise and how we value time. We might not see any impacts directly, or they might even benefit some of us. After all, with change comes opportunity. However, for the vast majority the consequences of changes in precipitation patterns, temperature increase and sea level rise will most likely not be beneficial in the long run. Many will lose their property and livelihood. Those worst affected might even have to abandon their homes, making them climate refugees, another problematic situation, together with others, that has to be dealt with.

Climate change is more than anything an inter-generational equity question. Right now we are enjoying very high standards of living in Northern Europe and many other parts of the world, thanks to readily accessible cheap labour in the form of fossil fuels. The rate at which we are consuming such fuels and returning their C to the atmosphere is extremely unsustainable when viewed in light of the rate at which they were/are being formed and the time it took to remove all that C from the atmosphere. It is becoming increasingly clear that this cannot continue for long without severe consequences for future generations. Not only will they have to carry the burden of the impacts caused by our over-consumption of fossil resources, they will also have to accept much lower standard of living if we do not spend some of our energy and effort on finding alternative and renewable sources of energy that can break our dependence on fossil fuels.

This is where bioenergy has an obvious role to play. There is no way in which bioenergy alone, or any other renewable energy source for that matter, can replace fossil fuels at the rate we are consuming them today. All efforts to develop new and more efficient energy systems are required, in concert with efforts to reduce energy use in all sectors and levels of society. Short rotation coppice willow is neither more, nor less, than a small piece of the puzzle. While no single person can solve the climate problem, every single one of us can contribute a part to the solution. Bioenergy systems that can capture and build up C pools in the soil may represent more than one piece of the puzzle. Not only can they offer energy, which is essential to our way of life, but they can also actively contribute to counteract the current trend in global warming. They can thereby contribute in more than one way to creating a sustainable future

Finally, it is important to remember that sustainable management of our resources is the ultimate goal in order to achieve a world without inter-generational equity conflicts. There are many more aspects to sustainability than climate impact, which is just one of a multitude of potential environmental impacts from human activities. However, climate impact is important since it affects all parts of society. Just as important are the social and economic aspects when striving towards finding the best energy supply systems. This thesis has shed some light on a small part of this complex issue and can hopefully be of some help in making judicious calls for the energy supply and climate of the future.

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