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Influence of Salix variety on climate impact of different biomass conversion routes

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Abstract

One key strategy to combat global warming is to reduce greenhouse gas (GHG) emissions by substitution of conventional fossil fuels and products with biomass based alternatives. Salix is a perennial crop providing fast growing biomass with low resource use, and have potential benefits for soil and climate mitigation. Several varieties of Salix have been developed, with differences in characteristics, including yield, morphology, chemical composition and physiology.

The aim of this thesis was to enhance understanding of the effect of Salix varieties on climate impact of various biomass conversion routes from a life cycle perspective. Six commercial Salix varieties and three conversion routes were analysed: combustion for heat, anaerobic digestion for compressed biomethane gas (CBG), and fermentation for yeast oil. The assessment included a time dynamic life cycle assessment method using variety specific field and laboratory data, and modelling of soil organic carbon (SOC) changes.

The results demonstrated that converting Salix biomass to heat and CBG across all varieties resulted in lower climate impact compared to fossil energy sources. Yeast oil from the Salix varieties exhibited a similar or lower net climate impact compared to Swedish rapeseed oil. Salix cultivation under the site conditions increased SOC stocks, contributing notably to climate mitigation. The yield and SOC sequestration potential of Salix varieties had the strongest influence on the climate impact of the analysed conversion routes. The SOC increase was not dependent on yield, but was instead influenced by variety and fertilisation. Varieties with high yields had a larger substitution effect, resulting in greatest climate mitigation per unit of land. While the SOC sequestration potential was more critical in determining climate impact per unit of product. The temporary carbon stored in the live biomass had a strong but short lived cooling effect on the time dependent climate impact.

Keywords: willow, soil carbon modelling, life cycle assessment, LCA, bioenergy, biomethane, biolipid, time dependent climate impact

Effekt av Salix-sort på klimatpåverkan för olika omvandlingsvägar för biomassa

Sammanfattning

En central strategi för att bekämpa global uppvärmning är att minska växthusgasutsläpp genom att ersätta konventionella fossila bränslen och produkter med alternativ baserade på biomassa. Salix är en flerårig snabbväxande energigröda som kan leverera biomassa med låg resursanvändning och kan bidra till förbättrad jordhälsa och lägre klimatpåverkan. Flera sorter av Salix har utvecklats med skillnader i skördenivåer, morfologi, kemisk sammansättning och fysiologi.

Syftet med denna avhandling var att öka förståelsen för effekten av valet av Salix-sort på klimatpåverkan av olika omvandlingsvägar för biomassan ur ett livscykelperspektiv. Sex kommersiella Salix-sorter och tre omvandlingsvägar analyserades: förbränning, anaerob nedbrytning för komprimerad biometan, och fermentering för jästolja. Bedömningen inkluderade en tidsdynamisk livscykelanalysmetod med specifik fält- och laboratoriedata för varje Salix-sort, samt markkolsmodellering.

Resultaten visade att omvandling av Salix-biomassa till värme och komprimerad biometan resulterade i lägre klimatpåverkan jämfört med fossila energikällor för alla sorter. Framställning av jästolja uppvisade en liknande eller lägre klimatpåverkan jämfört med svensk rapsolja. Salix-odling ökade mängden markkol, vilket bidrog till minskad klimatpåverkan. Avkastningen och markkolinlagringspotentialen hos Salix-sorterna hade störst inverkan på klimatpåverkan av de analyserade omvandlingsvägarna. Ökningen av markkol var dock inte korrelerad med skördenivån utan var istället mera beroende av sort och gödsling. Sorter med hög avkastning gav den största minskningen av klimatpåverkan per enhet mark, medan sorternas markkolbindningspotential hade stor inverkan på klimatpåverkan per produktenhet. Kolinlagringen i levande biomassa hade en betydande men relativt kortvarig kylande effekt på klimatet.

Nyckelord: klimatpåverkan, markkol modellering, livcykelanalys, LCA, bioenergi, biometan, biolipid, tidsberoende klimateffekt

Dedication

To everyone and everything that makes life worth living

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I. Kalita, S., Karlsson Potter, H., Weih, M., Baum, C., Nordberg, Å., Hansson, P-A. (2021). Soil Carbon Modelling in Salix Biomass Plantations: Variety Determines Carbon Sequestration and Climate Impacts. *Forests*, 12(11):1529.

II. Kalita, S., Ohlsson, J.A., Karlsson Potter, H., Nordberg, Å., Sandgren, M., Hansson, P-A. (2023). Energy performance of compressed biomethane gas production from co-digestion of Salix and dairy manure: factoring differences between Salix varieties. *Biotechnology for Biofuels and Bioproducts*, 16, (165)

III. Kalita, S., Karlsson Potter, H., Nordberg, Å., Sandgren, M., Hansson, P-A. (2024) Climate impact of compressed biomethane production from co-digestion of Salix and dairy manure – what role does Salix variety play? (manuscript)

IV. Sigtryggsson, C., Kalita, S., Karlsson Potter, H., Passoth, V. Hansson, P-A. (2024) Climate impact of microbial oil from fast-growing perennial biomass (willow). *Journal of Cleaner Production* (submitted - under review)

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

The contribution of Saurav Kalita to the papers included in this thesis was as follows:

I. Conceptualization, study design, methodology, modelling and analysis, writing – original, writing – review and editing

II. Conceptualization, methodology, process simulation and analysis, writing – original, writing – review and editing

III. Conceptualization, study design, methodology, modelling and analysis, writing – original, writing – review and editing

IV. Methodology, analysis, writing – review and editing

The following research paper was contributed to, but is not included in the thesis:

I. Rönnberg-Wästljung, A. C., Dufour, L., Gao, J., Hansson, P.-A., Herrmann, A., Jebrane, M., Johansson, A.-C., Kalita, S., Molinder, R., Nordh, N.-E., Ohlsson, J. A., Passoth, V., Sandgren, M., Schnürer, A., Shi, A., Terziev, N., Daniel, G., Weih, M. (2022). Optimized utilization of Salix—Perspectives for the genetic improvement toward sustainable biofuel value chains. *GCB Bioenergy: Bioproducts for a Sustainable Bioeconomy*, 14, 1128–1144.

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1. Introduction

Scientific evidence confirms that anthropogenic influences are the dominant drivers of contemporary climate change, underscoring the urgent need for mitigation and adaptation strategies to address their profound environmental, social, health and economic impacts (Calvin et al. 2023). According to the latest assessments from the Intergovernmental Panel on Climate Change (IPCC), in order to limit global warming to 1.5°C, it is imperative that global greenhouse gas (GHG) emissions peak before 2025, undergo a reduction of 43% by 2030, and achieve net-zero emissions by the early 2050s (Shukla et al. 2022). State and non-state entities representing 92% of the global gross domestic product (based on purchasing power parity) and 89% of the global population have either set a net zero target or have pledges in place to limit global warming (New Climate Institute et al. 2023). There is intense debate around the different strategies to curb GHG emissions.

Bio-based alternatives have received much interest as methods of reducing GHG emissions by replacing conventional fossil-based energy and products with a higher climate impact (Gomez San Juan et al. 2022; Perišić et al. 2022; Zuiderveen et al. 2023). Biomass use is often claimed to be carbon neutral as the carbon dioxide (CO_2) released during its utilisation is equivalent to the uptake during growth (Johnson 2009). However, production and processing activities leads to emissions as conventional machinery is typically powered by fossil fuels. Land use changes, leading to change in soil carbon stocks and soil emissions from fertilisers, also effects the GHG balance. While biomass can offer potential carbon mitigation benefits when sourced and utilised sustainably, its climate impact is reliant upon various factors (Daioglou et al. 2019). Careful assessment and quantification through a systems perspective that accounts for these aspects is necessary.

Life cycle assessment (LCA) has emerged as a popular tool for estimating the impacts arising from the emission and resource use during defined stages of the life cycle of products and services (e.g., cradle-to-gate, cradle-to-site). LCA methodology can be used to assess the climate impact of biomass systems and compare it to conventional or fossil-based systems. However, the complexity of biological systems present some challenges when applying LCA, such as in the handling of land use change, the definition of system boundaries, and quantifying soil organic carbon (SOC) changes. The LCA methodology is constantly evolving with the development of Knowledge around climate and the environment.

The most common climate impact metric used in LCA is global warming potential over a 100-year time horizon (GWP_{100}), with which the climate effect on the timing of GHG fluxes cannot be accounted for. Utilising a time-dependent climate methodology can provide greater temporal resolution on climate impact from GHG emissions and biogenic carbon changes (Ericsson et al. 2013).

Salix (commonly known as willow) is a promising candidate for biomass production, particularly in temperate regions, due to its fast growth rate and high biomass yield (Karp & Shield 2008; Weih et al. 2020). Salix is cultivated in a short rotation coppice (SRC) system, where the plant regrows from the stumps after harvest, which reduces energy and material requirement compared to annual energy crops (Dimitriou & Rutz 2015). Its adaptability to marginal lands, potential for SOC sequestration, and ecosystem services make it a valuable resource for renewable energy and biofuel production in the region (Volk et al. 2014). Climate strategies in Sweden propose expanding the cultivation of energy crops such as Salix to 40,000 hectares by 2030 (Klimatpolitika vägvals utredningen et al. 2020).

Salix biomass has conventionally been utilised and researched as a fuel for thermochemical conversion (e.g combustion, pyrolysis) (Djomo et al. 2011; Volk et al. 2014; Dimitriou & Rutz 2015). There have been efforts to investigate the use of Salix for biological and chemical conversion processes (Estevez et al. 2012; Kakuk et al. 2021; Baker et al. 2022). The recalcitrant nature of lignocellulosic biomass like Salix provides some obstacles to their conversion (Ohlsson et al. 2020a). Advancements in pretreatment and breeding are focussed on facilitating their use. Studies on biogas production from pretreated Salix exhibit a potential for use in anaerobic digestion (Horn et al. 2011; Estevez et al. 2012) and is an area of current research. With the advancement of efficient conversion processes, Salix biomass has the potential to be transformed into high-value chemicals and materials (Sassner et al. 2008; Serapiglia et al. 2013; Baker et al. 2022), contributing to the development of a bio-based economy. These novel conversion processes need to be analysed from a systems perspective to gain insight into the possible climate impacts and areas of improvement.

Salix breeding programs have led to the development of several newer varieties showing improvement in yields, pest and disease resistance, improved adaptability, and optimized suitability for specific end-uses. The varieties often exhibit major differences in traits such as yield (Stolarski et al. 2020b), SOC sequestration potential, biomass quality (Ohlsson et al. 2020a; Stolarski et al. 2020a), and response to fertilisation (Baum et al. 2020). These varietal differences can have a significant influence on the climate impact assessments of Salix biomass applications from a LCA perspective. However, there is a lack of studies addressing these implications from a systems perspective.

Research on the climate impact of different Salix varieties has become increasingly important as the demand for renewable biomass sources continues to grow. Understanding the specific environmental benefits and drawbacks of each variety is crucial in determining the most sustainable and effective application of Salix biomass. The thesis at hand investigates how differences between six commercial varieties of Salix influence climate impact when these varieties are used as feedstock for different conversion routes, including combustion, anaerobic digestion, and the production of bio-lipids. The conversion routes also signify technological advancements in the utilization of Salix, transitioning from traditional combustion methods to the production of bio-lipids for future applications. The results provide novel and valuable knowledge as a basis for the selection of climate optimal conversion routes for Salix biomass utilisation.

2. Aim, objectives and structure.

2.1 Aim and objectives

The overall aim of this thesis was to increase the knowledge on the influence of Salix variety on the climate impact of different conversion routes from a life cycle perspective.

Specific objectives were:

- Improve assessments of soil carbon stock changes using a soil carbon model based on variety specific data of measured harvest and soil carbon (Paper I).
- Assess the energy performance and climate impact (including GWP and time dynamic climate impact) from a life cycle perspective of different Salix conversion systems:
  - Direct combustion (Paper I).
  - Anaerobic digestion to produce compressed biomethane gas (Paper III).
  - Yeast fermentation to produce bio lipids (Paper IV)
- Analyse the mass and energy flows of compressed biomethane production from Salix biomass co-digestion with dairy manure (Paper II) based on experimental biochemical methane potential (BMP) values.
- Identify Salix characteristics with most influence on the climate impact of the conversion routes (Paper I–IV)

2.2 Research structure

The research presented in this thesis is a culmination of the analyses carried out in Papers I-IV. The common theme across the papers was the inclusion of six varieties of Salix (Björn, Gudrun, Loden, Jorr, Tora, Tordis) to capture the effect of the varietal differences on the results. The groundwork related to the setting up of the soil carbon modelling and cultivation operations was done in Paper I and used in the subsequent studies with relevant modifications. Time-dependent LCA methodology was used across the studies. The data for the specific Salix varieties and treatments were from a field trial in Pustnäs, Uppsala. An overview of the papers is given in Table 1.

The focus of Paper I was on establishing the emissions related to cultivation processes and the soil carbon dynamics for the different varieties. A conventional conversion route of biomass combustion was defined. The soil carbon model ICBMr was utilised to model and estimate changes in SOC stock under Salix cultivation. The net primary production of different parts of the plant (stems, leaves, fine and coarse roots) between the varieties with and without fertilisation was estimated based on the harvest data and soil carbon values obtained from the field study.

The next conversion route analysed was anaerobic digestion to produce compressed biomethane gas (CBG) which would be a replacement to fossil natural gas. A cradle-to-grave approach was adopted, from Salix cultivation to the production of CBG and digestate application. The analysis was divided between papers II & III. Paper II dealt with a process modelling approach to determine the mass and energy flows of a proposed co-digestion plant with Salix and dairy manure feedstock. Experimental data on composition and bio-chemical methane potential (BMP) values for the Salix samples was used in combination with process model simulation (using Aspen Plus software). Paper III investigated the climate impacts of CBG produced from the Salix biomass by expanding the data from Paper II to include biogenic carbon and land use changes.

The third conversion route was yeast-based fermentation of the Salix biomass to produce bio-lipids (also called as yeast oil), which has similar properties to plant oils. The yeast oil production and climate impacts of using the different Salix feedstocks were analysed and presented in paper IV.

The analysis in papers III & IV did not include the unfertilised varieties. The reasoning for this was that harvests might diminish without fertilisation, as the removal of nutrients due to harvest would lead to decreased fertility over time. This would result in reduced productivity of the varieties in the long term.

The selection of conversion routes in the papers encompassed a broad spectrum of applications of the Salix biomass—from conventional combustion to advanced biological conversion. The selection was enabled by the availability of relevant data for the systems analysis of the conversion routes from complementary research activities within SLU.

Table 1. A brief overview of the key characteristics of the papers in the thesis

	Paper I	**Paper II**	**Paper III**	**Paper IV**
Salix varieties	Björn, Gudrun, Loden, Jorr, Tora, Tordis			
Salix treatment	Fertilised & Unfertilised		Fertilised	
Conversion Route	Combustion	Anaerobic Digestion	Anaerobic Digestion	Yeast Fermentation
End product	Heat	CBG (primary) Digestate (secondary)	CBG (primary) Digestate (secondary)	Yeast oil
Reference product	Heat from natural gas		Natural Gas Mineral (primary) Mineral fertiliser (secondary)	Rapeseed oil
Reference Land Use	Fallow		Fallow	Fallow
Results in terms of	Energy performance GWP_{100} ΔT[1]	Energy performance	GWP_{100} ΔT[1]	GWP_{100} ΔT[1]

[1] ΔT is the time dependent climate metric. It represents the effect on global mean surface temperature as a result of GHG fluxes over time

3. Background

3.1 Climate change and mitigation

The balance between incoming solar radiation and outgoing infrared radiation drives the climate system on Earth. Global climate has been changing over time due to its internal dynamics and the effect of external factors, known as ‘forcings’ (Le Treut et al. 2007).

Certain gases in the Earth’s atmosphere have infrared active properties, allowing them to absorb and emit infrared radiation from the Earth. This contributes to an insulating effect called the greenhouse effect that helps maintain the average surface temperature of the Earth at about 15°C, which otherwise would have been a freezing −19°C (Le Treut et al. 2007). These infrared active gases contributing to the greenhouse effect are known as greenhouse gases (GHGs) and account for less than 0.1% of the atmosphere (Archer 2012). There has been a significant rate of increase in atmospheric concentrations of three major GHGs (CO_2, CH_4, and N_2O) from human activities such as fossil fuel use and land use change since the dawn of the Industrial age (Gulev et al. 2021). Evidence points to this leading to positive radiative forcing through the strengthening of the greenhouse effect, leading to the observed global warming in recent decades (Eyring et al. 2021). Anthropogenic climate change is different from natural climate variation in the Earth’s recent history (centuries to millennia) due to its unprecedented rate of global warming. The global mean surface temperature in 2011–2020 was 1.1°C higher than the average in 1850–1900 (Calvin et al. 2023).

According to the latest IPCC climate models, global temperatures are projected to rise by approximately 1.5°C to 2.0°C by the mid-century (2050) under moderate emission scenarios. By the end of the 21st century (2100), temperatures could increase by 2.5°C to 4.5°C or more, depending on the level of greenhouse gas emissions, with the higher end reflecting a business-as-usual scenario without significant mitigation efforts (Shukla et al. 2022).

The warming climate is leading to far reaching consequences on the biogeochemical systems on our planet that affects all life on the planet (Eyring et al. 2021). Climate change exacerbates extreme weather events, disrupts ecosystems, and threatens food and water security, leading to increased risks to human health and biodiversity. Mitigation efforts are being implemented on local to global levels to deal with the associated risks from the warming climate. The most significant global treaty is the Paris Agreement which has set targets of limiting global warming to well below 2°C, with efforts to keep it below 1.5°C above pre-industrial levels. The European Union has a target of reaching climate-neutrality by 2050 (European Commission, 2016), while Sweden aims to reach the neutrality target by 2045 (Swedish Environmental Protection Agency 2024). However, concerns have been raised across different sectors about slow progress towards meeting these targets and worsening of the climate crisis.

3.1.1 Biomass for climate change mitigation

The global economy at present is fuelled by fossil fuels, responsible for significant GHG emissions (Calvin et al. 2023). The reduction of dependency on fossil fuels has been highlighted as a major step for climate change mitigation. Biomass can play a crucial role in climate mitigation by serving as replacement for fossil based products and lower GHG emissions (Biilgen et al. 2007). As biomass is derived from organic materials such as plants, agricultural residues, and wood, its utilisation for energy can result in a closed carbon cycle. When biomass is burned or converted into biofuels, the CO_2 released is offset by the CO_2 absorbed by the plants during their growth phase. This cycle potentially results in lower net emissions compared to fossil fuels, which release carbon that has been sequestered for millions of years (Cherubini et al., 2011). Furthermore, advancements in conversion technologies, such as second-generation biofuels and biogas production, enable the replacement of conventional products with more sustainable biomass which can contribute to reductions in greenhouse gas emissions.

Sustainable bioenergy is especially significant in sectors where replacing fossil fuels is challenging, such as heavy industry, aviation, and heavy transportation. In scenarios aimed at achieving net-zero emissions by 2050, the contribution of bioenergy is projected to increase substantially, with its supply expected to expand from 65 EJ in 2020 to 100–248 EJ by 2050 (IEA 2021; Shukla et al. 2022). Furthermore, crises in global geopolitics have also affected policies that aim to reduce dependency on imported food and fuels. For example, the REPowerEU action plan envisions boosting EU biomethane production to 35 bcm by 2030 to reduce dependency on Russian natural gas (European Comission 2022).

To address the increasing demand for bioenergy and fully harness its potential, various feedstocks are under investigation. Energy crops have significantly contributed to biogas production in countries like Germany (Jain 2019). Consequently, there is a pressing need to explore alternative feedstocks that do not complete with food production and supply. These alternatives include waste streams, short-rotation lignocellulosic crops, and other biomass sources that can be cultivated on unused and lower value lands.

3.2 Short rotation coppice Salix biomass and its conversion

Plants in the genus Salix (commonly known as willows, osiers and sallows) comprise about 400 species in a wide range of sizes — from large trees to dwarf shrubs (Newsholme 1992). They are prevalent in the temperate and cold regions of the Northern Hemisphere.

The history of Salix use dates back to ancient civilizations, where it was primarily valued for its medicinal properties and cultural uses (Karp et al. 2011). Beyond medicine, varieties of Salix have been used historically for basket making, furniture, and construction. The active ingredient, salicin, was identified in the 19th century, leading to the development of acetylsalicylic acid, commonly known as aspirin (Karp 2014).

3.2.1 Short rotation coppice Salix

The oil crisis of the 1970s led to an increased pressure on several countries to explore alternatives to fossil fuels. This period marked the initial interest in exploring fast growing woody crops which could provide a sustainable supply of biomass for energy production, such as shrub varieties of Salix (Karp et al. 2011). Shrub varieties of Salix attain a height of about 4–7 meters, have multiple shoots and regrow from the stump after cutting

(Willowpedia, Cornell University 2024). Pioneering trials of Salix as a biomass source were carried out in Sweden in the mid−1970s, with expansion to the UK, the United States and other European countries over the following decades (Volk et al. 2006; Willowpedia, Cornell University 2024).

Salix is cultivated for its biomass potential due to its fast growth, high biomass yield, and adaptability to various soil types. The cultivation process involves planting cuttings, which root easily and grow rapidly under a wide range of conditions (Dimitriou & Rutz 2015; Weih et al. 2020). The plants are cultivated in a short rotation coppice (SRC) systems with harvests every 2–4 years over a 20–25-year period, before replanting is needed. Once established, Salix plantations can yield significant amounts of biomass with relatively low maintenance. Salix requires lower inputs compared to traditional agricultural crops, reducing the need for fertilizers and pesticides (Karp et al. 2011). Commercial plantations of Salix have historically been shown to yield 10–15 tDM hectare^{-1} yr^{-1} (Verwijst et al. 2013), with the potential of producing up to 20 tDM hectare^{-1} yr^{-1} on productive sites (Biomass Connect 2024). SRC Salix prefers moist conditions for efficient growth, with dry conditions hampering growth. Properly planned and efficiently managed Salix cultivations can contribute to rural development by diversification of the economy and the creation of job opportunities in biomass production and processing (Volk et al. 2004; Baker et al. 2022).

SRC Salix cultivation in Sweden expanded in the 1990s due to government incentives and policies, resulting in a peak cultivation area of 18,000 hectares (Lindegaard et al., 2016; Nicolescu, 2017). However, yields were poorer than expected due to a combination of poor land selection, inadequate management, and lack of experience among farmers (Dimitriou, Rosenqvist and Berndes, 2011). This in combination with changing policy and market forces led to a lack of interest in the following decades. The Salix cultivation area in Sweden is around 3900 hectares in 2023, making up about 0.1% of the total agricultural area in Sweden (Jordbruksverket, 2024).

3.2.2 Ecosystem services of Salix cultivation

Salix plants have been shown to provide several other ecosystem services besides providing biomass feedstock. In fact, 12% of the total planted Salix area was defined as for environmental protection within the member countries of IPC in 2015 (FAO 2016). Salix plantations can act as windbreaks and snow fences, and provide protection against soil erosion (Isebrands et al. 2014). The low inputs and soil disturbance in Salix plantations provide favourable conditions for higher biodiversity. Salix plantations have been used for phytoremediation, due to their large capacity for water and nutrient uptake, and have been association with beneficial microbes and mycorrhizae (Isebrands et al. 2014). The previous land use, management practices, plantation size and layout are the factors that determine the positive and negative effects of Salix plantations (Langeveld et al. 2012; Weih & Dimitriou 2012; Bacenetti et al. 2016).

3.2.3 Development of Salix varieties and its implications

Breeding efforts to enhance Salix as a biomass crop began in Sweden in 1987, initiated by Svalöf Weibull AB (now known as Lantmännen Seed) (Karp et al. 2011). In the following years, international breeding programs were initiated in the UK and USA (Karp et al. 2011; Baker et al. 2022). Efforts were made to improve desirable characteristics such as yield, resistance to disease, and ease of mechanical harvesting (Lindegaard et al. 2001; Baker et al. 2022). Despite limited genetic knowledge, yields nearly doubled in the early years of improvement (Karp et al. 2011). These programs employ both traditional breeding techniques and modern genetic approaches to create hybrids that combine the best characteristics of different willow species. For example, hybridization between Salix viminalis and Salix schwerinii has led to varieties that exhibit vigorous growth and high yield potential under diverse environmental conditions. Varieties such as 'Tora,' 'Inger,' and 'Tordis' are notable for their high biomass yield and robustness, making them well-suited for bioenergy farming.

Numerous studies have reported differences between Salix varieties, such as yield (Stolarski et al. 2011, 2020b; Hoeber et al. 2018), response to fertilisation (Heinsoo et al. 2009; Baum et al. 2020), biomass composition (Stolarski et al. 2011, 2020a; Gao et al. 2021), methane potential (Ohlsson et al. 2020b; a), and soil carbon sequestration(Gregory et al. 2018; Baum et al. 2020).

Systems-scale studies (such as Life Cycle Assessments) that accounts for these varietal variations and their effect on the environmental impacts are rare. Consequently, it is essential to investigate how different Salix varieties affect soil carbon sequestration and climate impact within the context of biomass-based systems.

3.3 Life cycle assessment

It is essential to evaluate the GHG flows associated with a product, service or process to assess whether they are beneficial or detrimental for the climate. This assessment identifies associated risks and opportunities related to climate change. Life cycle assessment (LCA) is one of the most prevalent methods for the quantification of environmental impact. It is a comprehensive approach that ideally aims to account for every resource used and emission generated at all process stages in the life cycle. LCA can be used in an attributional sense to account for the impacts of the processes within the life cycle, or in a consequential sense to determine how environmental flows are impacted due to decisions or changes in the system (Ekvall 2020).

LCA is standardised by the International Organization for Standardization (ISO) under standards 14040:2006 (outlining principles and framework) (ISO 2006a) and 14044:2006 (establishing requirements and guidelines) (ISO 2006b). An LCA consists of four iterative phases, enabling amendments and refinements along the chain:

- Goal & scope definition – The goal states the purpose and intended audience for the analysis. The scope describes the system and its boundaries, the functional unit (FU), methodological details and assumptions. The FU is the reference to which the inputs and outputs are related and is crucial to ensuring consistency and comparability of the results.
- Life cycle inventory (LCI) analysis – An inventory is created of the flows of inputs (e.g. energy, raw materials) and outputs (e.g. by-products, emissions) throughout the system processes in relation to the FU.
- Life cycle impact assessment (LCIA) – The LCI data is classified, characterised and quantified across different impact categories to calculate potential environmental impacts. Climate impact is one of the impact categories in LCA, while several other impact categories exist (e.g., eutrophication, resource depletion, water use).
- Interpretation – The LCI and LCIA results are analysed and checked, and can include sensitivity and uncertainty analyses, for the identification of key issues. Results are used to draw

conclusions and make recommendations relative to the goal and scope of the study.

Many systems are complex, with multiple degrees of circularity and interconnectedness between processes, with multiple products and by-products which fulfill different functions. This complicates issues like the selection of a FU to best represent the system purpose and the allocation of flows. Multiple FUs could be selected based on inputs (e.g., hectare of land) or outputs (e.g., kg of product) to compare different aspects of the system (Klöpffer & Grahl 2014). ISO standards advise avoiding allocation by dividing the system or expanding to include additional functions. If unavoidable, physical allocation or economic allocation can be used while ensuring consistency and transparency (ISO 2006b).

The application of LCAs has extended far from its origins as an energy and resource use analysis tool in companies, becoming a decision-making tool used in policy and standard setting (McManus et al. 2015). LCA studies are increasingly widening in scope (from attributional and retrospective to a consequential and prospective), complexity, and detail – for both systems and indicators (Guinée et al. 2011; McManus & Taylor 2015). While its versatility and comprehensive approach make LCA a valuable tool in systems analysis, the increase in complexity and detail raises issues for methodology, completeness, data availability, resource demand and standardisation.

3.3.1 LCA of biomass systems

LCA methodology has become common for quantifying environmental impacts and resource use of both existing and prospective biomass conversion systems. Biomass based systems are complex, dynamic, and have a high degree of interaction with local systems. These systems have a higher degree of temporal and spatial variability depending on factors such as climate, soil, and environment and management practices. This presents challenges when implementing LCA methodology and standardisation, which in turn is drive its evolution and improvement (McManus & Taylor 2015). Despite challenges and criticisms, LCA has become a well-recognised and effective tool for the assessment of biomass based system (Fan et al. 2022).

3.3.2 Soil organic carbon in LCA

Soils are estimated to contain between 1500-2400 gigatons of organic carbon within the first meter of mineral soils – which is more than the combined carbon in the atmosphere and vegetation (Jobbágy & Jackson 2000; Stockmann et al. 2013). Soil organic carbon (SOC) is the balance between biological inputs and decomposition. The large size of the SOC pool compared to anthropogenic CO_2 emissions means that small changes can have a profound impact on atmospheric CO_2 concentrations (Ciais et al. 2014; Crowther et al. 2016). The carbon flux in soils is dependent on land use, management practices, soil characteristics and climatic conditions, which can make soils a source or sink for GHGs. The flux in SOC stocks influences the net GHG emissions from the system, which can have a significant effect on the climate and environmental impacts in an LCA study. The need to consider changes in soil carbon stocks in biomass LCAs has been discussed and highlighted in literature (Guinée et al. 2009; Bird et al. 2011; Brandão et al. 2011, 2013; Goglio et al. 2015; Bessou et al. 2020; De Feudis et al. 2022).

Goglio et al. (2015) have highlighted four main methods with different levels of data requirement and certainty to account for SOC in LCAs: measurements, emission factors, simple carbon models, and dynamic crop-climate-soil models. Due to the high resource demand for measurements and the lack of long-term data, modelling approaches are widely applied to assess SOC changes (Joensuu et al. 2021). Currently, there is no standardized approach for quantifying changes in SOC stocks within the LCA framework, making comparisons difficult. However, as more biomass LCAs begin to incorporate soil carbon, it will underscore its importance and methodology development.

3.3.3 Climate impact assessment metrics and time

The Global Warming Potential (GWP) metric in is commonly used in LCA studies for assessing climate impact. This metric normalizes the warming potential of various greenhouse gases by relating them to carbon dioxide (CO_2) over a specific time horizon (TH), typically 100 years (Shine et al. 1990). The metric expresses climate impact as CO_2-equivalents. As a result, GHGs with different atmospheric lifetimes—ranging from a few years to centuries—are aggregated into a common scale. Despite its widespread use, GWP's limitation lies in its temporal focus; it does not account for the actual timing of emissions and their corresponding temperature impacts, which can affect the interpretation of long-term climate consequences (O'Neill 2000). This limitation is particularly pronounced when assessing biogenic carbon, which can exhibit significant temporal variability in its net impact on climate (Neubauer & Megonigal 2015).

Biogenic carbon, derived from biomass and bioenergy sources, can lead to fluctuations in CO_2 concentrations, depending on the timing of carbon uptake and release. For example, a bioenergy plantation may temporarily sequester CO_2 during its growth phase and release it upon harvest or decomposition. The conventional GWP metric, which aggregates emissions and removals over a fixed time horizon, fails to capture these temporal variations (O'Neill, 2000). However, there is a temporary carbon storage in the live biomass which is eventually emitted as CO_2 at a later time causing a delay in radiative forcing. There have been efforts to develop alternate accounting methods and metrics such as tonne-year accounting (Fearnside et al. 2000; Moura Costa & Wilson 2000) and GWP_{bio} (Cherubini et al. 2011) to credit the temporary carbon storage in biomass. However, equating the short-lived carbon storage to CO_2 removals and its accounting methodology has been a matter of scientific debate (Holtsmark 2015; Chay et al. 2022).

Alternative metrics, such as Absolute Global Temperature Change Potential (AGTP) and Global Temperature Potential (GTP), have been introduced to address the temporal shortcomings of GWP (Levasseur et al. 2016). AGTP, or ΔTs, measures the impact of greenhouse gases at a specific point in time rather than over a defined period, considering the direct effect of emissions on temperature (Ericsson et al. 2013; Myhre et al. 2013). GTP, which is derived from AGTP, compares the temperature impact of one gas relative to another at a particular time. These metrics provide a more detailed view of climate impact by incorporating the timing of emissions and their influence on temperature, though they introduce higher uncertainty compared to GWP due to their location further down the cause-effect path. Climate impacts can be expressed as a function of time using absolute metrics like ΔT which can provide valuable insights and improve transparency in LCAs (Peters et al. 2011; Ericsson et al. 2013). Levasseur et al. (2016) highlight how employing multiple metrics in LCA can more effectively reveal uncertainties and the impacts associated with different metrics, thereby providing multiple perspectives and improving understanding.

4. Methodological approach

4.1 Salix data and scenario description

4.1.1 Salix varieties and field trial data

Six commercial varieties of Salix were a part of the analysis presented in this thesis: 'Björn' (Salix *schwerinii E. Wolf.* × *S. viminalis L.*), 'Gudrun' (*S. burjatica Nasarow* × *S. dasyclados Wimm.*), 'Jorr' (*S. viminalis*), 'Loden' (*S. dasyclados*), 'Tora' (*S. schwerinii* × *S. viminalis*) and 'Tordis' ((*S. schwerinii* × *S. viminalis)* × *S. viminalis*). The data for these varieties came from a field trial conducted in Pustnäs, located near Uppsala in central Sweden (Weih & Nordh 2005) between 2001–2017. The experimental design featured two treatments – fertilized (approximately 100 kg N, 14 kg P, 47 kg K ha^{-1} yr^{-1}) and unfertilized. From here on, the suffix F+ and F0 are used to refer to the fertilised and unfertilised treatments, respectively.

The plot dimensions measured 6.75 m × 7.00 m with 84 plants per plot, yielding a planting density of approximately 18,000 plants per hectare. Each variety and treatment combination was replicated across four plots. The prevailing soil type was identified as a vertic cambisol, characterized by a sandy loam topsoil layer (0–20 cm soil depth) comprising 66% sand, 16% silt, and 18% clay.

The plantation was established in 2001, followed by triennial cutting cycles with harvests in winter of 2004, 2007, 2010, 2013 and 2016. The mean air temperature of the growing period (April–October) was 12.5°C and annual precipitation was 841mm during the relevant years (Baum et al.

2020). The flatness of the field site contributed to uniform soil characteristics among the plots.

The average yield for each variety under fertilised and unfertilised conditions was calculated from the harvest data collected during the field study (Table 2). Average yields for first and subsequent harvests were calculated separated, as the first yield is typically lower due to the early stages of root establishment. For projections beyond the study period, it was assumed that future yields of the varieties would follow the calculated average yield values.

The soil in each plot was sampled to a depth of 10 cm before ploughing in 2001, followed by an additional sampling in 2002, and was sampled to a depth of 20 cm in 2018. The SOC stock measured in the 0–10 cm soil profiles for the time points are reported in Baum et al. (2020). Ploughing did not have any significant effect on the SOC and bulk density measured between the first and second year. The topsoil (0–20 cm) was assumed to have homogeneous characteristics because of the ploughing depth of about 25 cm. Hence, the starting SOC content in the 10–20 cm was considered to be similar to the measured value in the 0–10 cm layer. There was no significant difference from the initial bulk density values in 2018, which can be attributed to a lack of tillage disturbance and improved aeration by increased SOC content. Additionally, SOC stock in the 10–20 cm soil layer in 2018 was assessed using the same methodology as described by Baum et al. (2020). The resulting SOC stocks for the Salix varieties and treatments in 0–20 cm topsoil in 2001 and 2018 are summarized in Table 2.

Table 2. The average harvested biomass yield (dry weight, DW) and soil organic carbon stock (Mg ha^{-1}) in the 0–20 cm soil layer of the six Salix varieties under two fertilization regimes at Pustnäs, Sweden between 2001–2018. F0 and F+ refer to the unfertilized and fertilized treatment respectively.

Variety and Treatment	Average Yield of 1st Harvest (DW Mg ha^{-1})	Average Yield of subsequent Harvest (DW Mg ha^{-1})	Soil Carbon Stock 2001 (Mg ha^{-1})	Soil Carbon Stock 2018 (Mg ha^{-1})	Increase in SOC Stock (Mg ha^{-1})
Björn F0	7.4	31.9	28.9	39.7	10.8
Björn F+	15.5	42.7	28.9	33.0	4.2
Gudrun F0	8.8	20.8	28.9	43.6	14.7
Gudrun F+	11.6	20.6	28.9	34.8	5.9
Jorr F0	4.5	14.4	28.9	50.3	21.5
Jorr F+	16.9	36.9	28.9	41.8	12.9
Loden F0	3.9	14.4	28.9	44.2	15.3
Loden F+	10.4	18.3	28.9	33.2	4.4
Tora F0	6.7	18.2	28.9	41.6	12.7
Tora F+	16.6	38.3	28.9	40.0	11.2
Tordis F0	10.8	28.5	28.9	43.9	15.0
Tordis F+	19.8	48.5	28.9	38.5	9.6

4.1.2 Salix cultivation system

Field operations

The Salix cultivation system is represented by the steps shown in Figure 1. The SRC Salix cultivation system followed a three-year harvest cycle with regrowth from the stumps left in the field. Each rotation period lasted 25 years following practical guidelines (Caslin et al. 2015). The rotations started with site preparation one year prior to establishment and terminated with the breaking up of the stumps; replanting was done with new cuttings after this. The lifetime for each individual plantation included in Papers I–IV was 50 years, comprised of two rotations. The same yield values were used in all four papers based on the values for the variety and treatment from the field study for the first and subsequent harvests (as mentioned in Table 1).

The field preparation was done by mechanical harrowing and the application of chemical agents followed by establishment with prepared seedlings. Fertiliser application for the fertilised treatments took place every the year except year of planting (Weih & Nordh 2005)

Harvests were done during the winter as the biomass is drier and hard frozen ground has a higher machinery carrying capacity (Caslin et al. 2015; Dimitriou & Rutz 2015). Field operations were identical in all papers (I–IV) except for harvest method. Two harvest methods were considered based on the conversion process:

- In paper I, Salix was harvested using the conventional method of direct harvest and chipping, producing chipped biomass on the field. This was followed by transport of chips to the combustion plant.
- In papers II–IV, whole stem harvesting of Salix was assumed. The harvested stems would be transported to the conversion facility, where they would be stored and chipped on demand to ensure a year-long supply of biomass.

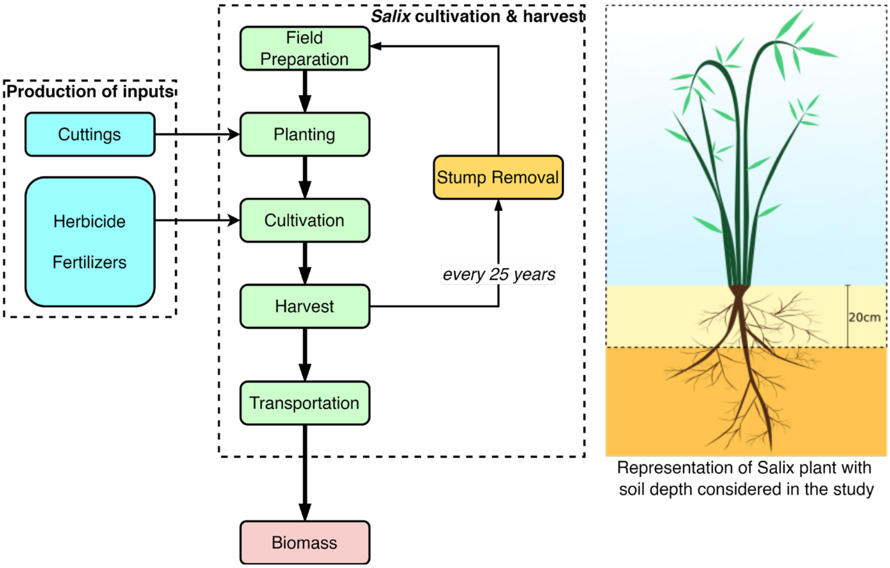

Figure 1. The processes involved within Salix cultivation. The greenhouse gas and energy fluxes associated with the processes represented within the system boundaries (dotted lines) were included in the study.

Transport

All transport operations were assumed to be carried out by diesel vehicles. In Paper I, the Salix chips were transported an average distance of 40 km by vehicles with a load capacity of 34.6 tons, a fuel economy of 0.58 l/km, and a load rate of 54% (Baky et al. 2009; Andersson & Frisk 2012).

In the case of whole stem harvest of Salix, the transport distance was 35 km from field to facility, and the energy consumption was calculated based on the reported values for whole stem harvest and transport (Baky et al. 2009).

4.1.3 Salix composition and biomethane potential

Compositional analysis and biomethane potential (BMP) tests of the Salix samples were used in the analysis for anaerobic digestion (Papers II & III). The composition and BMP values were used in the process modelling of CBG production from Salix varieties.

The monomeric carbohydrate and lignin composition of the acid-hydrolysed samples were analysed based on three replicates. The BMP tests were performed on chipped and steam-pretreated samples, with inoculum from a wastewater plant in Uppsala (Paper II). Samples were steam pre-treated at relatively mild conditions of 185°C for 4 minutes with 2% (mass/mass) SO_2. The same conditions were used for the steam explosion stage in the process modelling of CBG production.

4.1.4 Biomass conversion routes

Three different conversion routes for Salix biomass were explored within the context of the thesis work: direct combustion for heat, anaerobic digestion to produce compressed biomethane gas (CBG), and yeast fermentation to produce yeast oil.

Direct Combustion

In paper I, the chipped Salix biomass was assumed to be transported to a heating plant to be incinerated in the boiler of a heating plant. The moisture adjusted lower heating value (LHV) for the Salix chips was calculated based on a higher heating value (HHV) of 19.9 GJ/Mg DM (dry and ash-free) (Börjesson et al. 2010; TNO Biobased and Circular Technologies 2020). The combustion plant was equipped with flue gas condensation, with an overall efficiency of 94% on a LHV basis. The ash content of the Salix biomass was set at 3% dry matter (Nilsson & Bernesson 2008). The ash was assumed to be transported an average distance of 100 km for its downstream processing.

The activities related to the end-use of ash were considered to be beyond the scope of the system under investigation.

Anaerobic Digestion

The co-digestion of Salix biomass with dairy manure was explored in Papers II & III. The reported monomeric carbohydrate composition was used to estimate the cellulose and hemicellulose content of untreated biomass (Table 3), which was used to build a process model for a CBG conversion plant. The model was built and simulated in the software Aspen Plus V11 to calculate mass and energy flows.

Salix biomass underwent pre-treatment by acid-catalysed steam explosion at 185°C for 4 minutes, with 2% SO_2 as a catalyst to reduce its recalcitrance to anaerobic digestion. Mild pre-treatment primarily breaks down the hemicelluloses into simpler carbohydrates, while lignin and cellulose remain largely unchanged. The Salix was co-digested with dairy manure in a 1:1 VS ratio. The manure underwent hygienisation at 70°C for 1 hour to reduce the infection and contamination risk when the digestate would eventually be applied to soils.

Table 3. The estimated polysaccharide content, volatile solid (VS) content, and biomethane potential (BMP) of the Salix varieties under fertilised (F+) and unfertilised (F0) conditions.

Variety	Lignin (%VS)	Cellulose (%VS)	Hemi-cellulose				VS (%TS)	BMP (mL/gm VS)
			Xylan (%VS)	Galactan (%VS)	Arabinan (%VS)	Mannan (%VS)		
Björn F0	24.5	54.0	9.4	1.9	0.4	1.8	97.9	194
Björn F+	24.7	51.3	8.9	1.6	0.4	1.6	98.1	232
Gudrun F0	28.0	50.0	9.2	1.6	0.6	1.6	97.7	246
Gudrun F+	28.7	48.8	8.3	1.7	0.6	1.5	97.3	235
Jorr F0	28.1	49.3	8.6	2.4	0.8	2.3	97.7	216
Jorr F+	27.8	46.9	7.8	2.0	0.9	2.2	98.1	190
Loden F0	29.0	47.3	8.4	1.7	0.7	1.8	96.9	236
Loden F+	29.6	47.3	8.5	1.8	0.8	2.0	97.3	251
Tora F0	29.1	48.0	9.4	2.1	0.7	1.9	97.3	246
Tora F+	26.7	46.1	9.0	1.6	0.6	2.1	97.8	248
Tordis F0	26.0	52.3	9.0	1.9	0.5	2.1	98.1	271
Tordis F+	26.2	50.4	8.9	1.6	0.4	1.8	98.2	268

The pretreated Salix biomass and hygienised manure underwent co-digestion in a reactor under mesophilic conditions (37 °C) with a retention time of 45 days. The digestate from the reactor was stored in covered tanks, where a secondary biogas flow was collected. The raw biogas was upgraded to biomethane (>95% CH_4) using a water scrubber followed by compression to 200 bar at 21°C to produce CBG.

The digestate was assumed to be transported an average distance of 30km to agricultural fields for application. The digestate was not dewatered and was assumed to be treated like liquid fertilisers. Nitrogen, phosphorus and potassium in the feedstocks were assumed to pass into the digestate, leading to reduced mineral fertiliser use. The allocation of inputs and outputs between the two feedstocks of Salix and dairy manure was done based on the composition of the two feedstocks.

Yeast oil production

In paper IV, the conversion of Salix feedstock to yeast oil using oleaginous yeast was explored. The resulting yeast oil was assumed to be comparable to rapeseed oil in its technical and nutritional properties (Sigtryggsson et al. 2023). The biomass underwent size reduction (chipping) to below 45 mm, followed by pretreatment via dilute SO_2 catalysed steam explosion. The pretreated biomass underwent enzymatic hydrolysis followed by solid-liquid separation. The solid fraction consisting mainly of lignin was used as fuel in a combined heat and power plant to meet the overall process energy demand. The liquid fraction was fermented using the yeast *Rhodotorula babjevae* for 72 hours. Lipid accumulation in the yeast was promoted by maintaining N-limited conditions in the fermenter. The assumed lipid yield was 0.2 g/g sugar and 50 % lipids per dry cell biomass. The lipids were separated from the yeast biomass by mechanical disruption of the cells and solvent extraction using hexane. Further details on the fermentation process are found in Sigtryggsson et al. (2023). The remaining yeast biomass post lipid extraction was used in biogas plant to produce biogas, and the digestate was utilised as bio-fertiliser. Economic allocation was used to allocate the climate impact between the two system outputs of yeast oil and biogas.

4.2 Biogenic carbon

The biogenic carbon fluxes from the CO_2 fluxes between the atmosphere and biosphere caused by biomass growth and changes in soil organic carbon (Figure 2) were calculated and included when estimating the climate impact for papers I, III and IV. The biogenic carbon is represented by two parts: live biomass and SOC. The dead biomass was assumed to return to the atmosphere during the use phase or becomes input for the SOC pool.

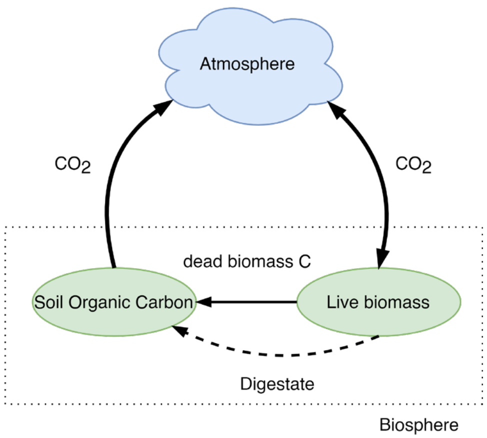

Figure 2. Representation of the C flows that take place between the biosphere and atmosphere.

4.2.1 Soil carbon modelling

The SOC change was modelled using the regional Introductory Carbon Balance Model (ICBMr), which calculates SOC change based on the decomposition of biomass C inputs to soil following first-order kinetics with an annual time step (Andrén & Kätterer 1997; Andrén et al. 2004). The model (Figure 3) compartmentalises the C into two pools: a young (Y) pool and an old (O) pool, governed by decay rates (*k*). All biomass C input (*i*) first enters the Y pool. The humification factor (*h*) determines the fraction of Y pool carbon that enters the more stable O pool. The decay rate of the O pool is lower than the Y pool, leading to slower decomposition of the C. Decomposed C from the two pools is assumed to be released into the atmosphere as CO_2. The parameter r_e describes the effect of external factors such as climate and soil conditions. It was assigned a value of 1, as it was the normalized value for central Swedish conditions (Andrén et al. 2012). The net SOC content at any point in time is the sum of the carbon in Y and O pools. The young pool was further divided into two sub pools to consider the differences between above and belowground biomass as studies have shown that roots can provide relatively higher contribution to SOC than aboveground residues (Rytter & Rytter 1998; Kätterer et al. 2011).

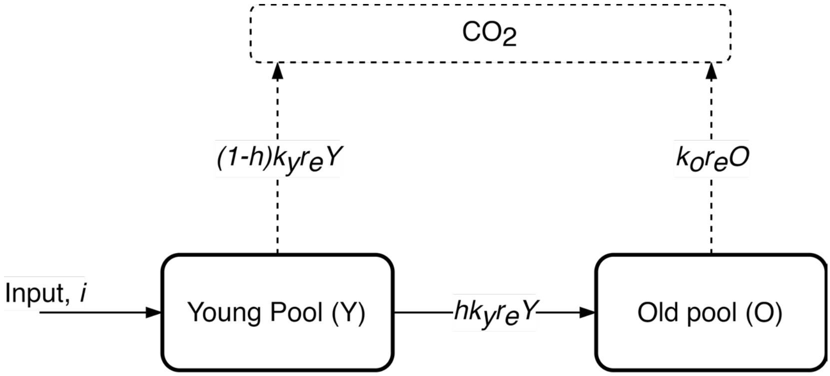

Figure 3. A schematic of the Introductory Carbon Balance Model (ICBM) and its parameters, used to calculate the soil organic carbon fluxes.

The parameters for the model were based on previous studies on Salix using the same model and assumptions (Ericsson et al. 2013, 2014; Hammar et al. 2014). The humification coefficient for the digestate in paper III was calculated analytically based on the C fraction remaining in the digestate from each substrate based on Ericsson et al. (2014).

4.2.2 Salix biomass accumulation

The biomass accumulation in Salix plants was divided into an aboveground and belowground fraction. A ratio (η) was defined to denote the net primary production (NPP) of aboveground biomass to belowground biomass after 3 years:

$$\eta = \frac{S + L}{F + C} = \frac{(1 + a)S}{(1 + b)F}$$

S, L, F and C represent the net production of stems, leaves, fine roots, and coarse roots (including stumps) over the 3-year Salix cutting cycle. Additionally, a stands for the ratio of leaves to stems, while b represents the ratio of coarse roots to fine roots and was assumed to be identical between varieties. The η ratio can be expected to vary between the Salix varieties and treatments, which in turn would lead to variation above and belowground biomass inputs culminating in variation in SOC accumulation. The factor η was introduced to account for genetic variations among the Salix types in biomass growth and allocation.

The values of a and b were derived from studies on Salix growth (Rytter 2001) to be 0.244 and 0.238 respectively, while the value of S was available from the harvest data from the field trial. In paper I, the η value was adjusted so that the SOC values measured from the ICBMr model matched the field trial values for each Salix variety (table 3). The root biomass in the 0–20 cm topsoil was set to 70% of the total root NPP based on studies on depth distribution of Salix roots (Rytter & Hansson 1996). The ratio of aboveground NPP to belowground NPP in the analysis was estimated to be 1.9 – 8.0 and 0.4–1.8 for fertilised and unfertilised varieties.

Table 4. The ratio of net primary production between aboveground and belowground biomass over a 3-year growth cycle calculated using field measurements in combination with the ICBMr model. F0 and F+ denote fertilised and unfertilised treatments.

Parameter	Treatment	Björn	Gudrun	Jorr	Loden	Tora	Tordis
η	F0	1.80	0.85	0.40	0.55	0.80	1.20
	F+	8.00	1.85	1.85	2.00	2.30	3.75

4.3 Scope and methodological choices related to LCA

The climate impact of using Salix biomass for the different conversion routes was evaluated using life cycle assessment (LCA) methodology. The contribution of the three major GHGs of carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) was included in the climate impact assessment. Emissions from operations in the technical systems, soil N_2O emissions from nutrients and biomass decomposition, and changes in biogenic carbon stocks over time were included.

4.3.1 Functional Units

The combustion (Paper I) and CBG production (Paper III) systems were evaluated on the basis of two functional units (FU) — one hectare of willow cultivation and MJ of energy delivered. The bio-lipid production had a functional unit of kg_{oil} produced.

The FU of a hectare of land represents the use of land as a resource and enables visualisation of impacts from a land use perspective. Land is generally a limited resource and this FU helps when considering optimal use of the available land.

The FU of MJ and kg_{oil} makes it possible to compare the impacts from the product (energy or oil in our case) perspective. It enables the evaluation of the output of the system and a comparison with the use of the product, irrespective of the land use efficiency.

4.3.2 Energy performance

There are different methods of determining the energy performance of a conversion system. Three different energy performance indicators were used to show the energy balance of the systems analysed:

- Energy ratio (ER) was used in Paper I, which was defined as the ratio between the delivered thermal energy and the total primary energy input of the system.
- Input-output ratio (R) was used in Paper II, defined as the ratio of the energy content of CBG produced and the secondary energy demands (heating, cooling, and diesel use) of the different operations and processes in the system.
- Fossil primary energy demand (PED_{fossil}) in GJ per metric ton of oil output was utilised in Paper IV, which defined the primary energy input from fossil fuels throughout the process chain allocated to production of one ton of yeast oil.

4.3.3 N_2O soil emissions

The introduction of nitrogen into the soil from mineral fertilizers, biomass inputs, and digestate application results in the emission of N_2O through nitrification and denitrification processes. In this study, the assessment of both direct and indirect N_2O emissions relied on the methodology outlined in the IPCC Guidelines for National Greenhouse Gas Inventories (Buendia et al. 2019). The Tier 1 approach was used, along with default parameters. The direct (N_2O_{direct}) and indirect ($N_2O_{indirect}$) emissions were calculated as:

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

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

where $N_{applied}$ is the nitrogen from applied fertilizers, N_{litter} and N_{roots} are the nitrogen contained in aboveground litter and roots respectively, and $N_{leached}$ is the nitrogen lost through leaching. EF_N, EF_D, and EF_L are emission factors for direct emissions from applied nitrogen, indirect emissions from volatilization and re-deposition, and leaching, respectively. F_A represents the fraction of applied nitrogen emitted as ammonia.

The nitrogen (N) content in leaf litter was calculated according to the abscission leaf N content by variety and fertilization (Weih & Nordh 2002), while for stems it was set to 0.43% total solids (TS) for all varieties. The root N content was estimated from a dataset by Manzoni et al. (2021) to be 1.76% and 0.83% (TS) for plants with and without fertilisation respectively.

4.3.4 Climate impact assessment

Global warming potential

Global Warming Potential (GWP) is a metric used to compare the potency of various greenhouse gases in causing global warming, relative to that of carbon dioxide (CO_2). It quantifies the effectiveness of a greenhouse gas emission over a specific time horizon (usually 100 years) by measuring the amount of heat trapped in the atmosphere compared to the same mass of CO_2. It is widely used in LCA studies to determine climate impact (Cherubini & Strømman 2011). A GWP metric with a 100-year time horizon (GWP_{100}) was used to determine climate impact in Papers I, III and IV. The GHG emissions are multiplied by its respective characterization factors and summarized to obtain the net GWP_{100}.

Time-dependent climate impact

The GWP metric does not capture the timing of emissions and the effect on global mean surface temperature (Ericsson et al. 2013; Myhre et al. 2013). A time-dependent climate model developed by Ericsson et al. (2013), which is based on the absolute global temperature change potential (AGTP), was used. The metric considers the timing of an emission and shows the instantaneous impact on global mean surface temperature.

The time-dependent methodology for assessing climate impact needs the development of a yearly inventory of GHG fluxes distributed across the duration of the study period. Subsequently, a GHG flux causes a change in its atmospheric concentration, resulting in alteration of the radiative forcing. This change in the energy balance on Earth leads to an increase or decrease in temperature. The individual temperature responses attributable to each emission impulse are calculated based on the yearly GHG inventory. The total system response, denoted as ΔTs, is the aggregation of these individual responses plotted as change in temperature over time.

4.3.5 Allocation methods

The biomethane system in paper III handles two substrates - Salix and dairy manure. As we are interested in the Salix fraction, physical allocation was used to separate resource use, outputs and subsequent climate impacts between the two substrates. The CBG output and associated emissions from its production were allocated based on the non-lignin C content of the two substrates (as lignin is expected to remain relatively undigested by anaerobic digestion). The digestate amount arising from each substrate (and its C and NPK content) was calculated based on the initial composition and fraction converted to biogas by the AD process. Emissions from digestate transport and spreading were allocated based on the digestate amount originating from each substrate. The C and NPK content in the digestate fraction (of each substrate) was calculated to determine the SOC effect, fertilisation effect and soil N2O emissions.

In paper IV, the impacts were allocated between the primary (yeast oil) and the secondary (biomethane and excess power) outputs using economic allocation. Economic allocation was used because the outputs had different end uses and economic valuation. The economic valuation was based on ten-year (2010–2020) average prices. Yeast oil was valued as equivalent to rapeseed oil (972 USD/tonne), biomethane as European natural gas (7.32 USD/GJ) and electricity to the northern European grid price (1.51 USD/GJ) (1 USD = 0.81 €).

4.3.6 Sensitivity analysis

The inclusion of multiple Salix varieties in the analyses inherently captures some variability in properties, such as biomass productivity, soil carbon changes, composition, and influence on conversion processes. Uncertainties associated with methodological choices, assumptions, parameters and data availability are an unavoidable part of LCAs (Huijbregts 1998). Sensitivity analysis of the climate impact of the three conversion processes addressing different uncertainties were addressed in the papers:

- Paper I: Sensitivity analysis on the soil profile depth was done to assess the effect of a deeper soil profile on the results. The system boundaries were adjusted to increase the soil profile to 25 cm (motivated by the average plough depth of 20–25 cm), changing the related belowground biomass input and SOC values. All other parameters were unchanged.

- Paper III: The parameters used in soil carbon modelling (especially for the digestate) are a source of uncertainty. Sensitivity analysis was performed by varying the ICBM parameters of the digestate humification coefficient (h_{dig}) and external factor effect (r_e) by ±20% while keeping the other values constant.
- Paper IV: A sensitivity analysis was conducted on the average performing Salix variety, 'Tora', by varying four factors individually — yeast oil price, allocation method, acid-base use in fermentation, and transport distance. A 10% increase in yeast oil price was assumed, altering the economic allocation pattern. An alternative allocation method based on the energy content of outputs was also evaluated. The pH of the fermentation process is adjusted with acid and base, the quantities of which are based on laboratory data, which may be overestimated. To address this, a 20% reduction in acid-base use was tested. The sensitivity of the climate impact to transport distance was assessed by doubling the distance for Salix biomass transport from 35 km to 70 km.

5. Results and discussion

5.1 Biogenic carbon

5.1.1 Soil organic carbon modelling of Salix cultivation

In Paper I, All the Salix varieties led to an increase in SOC stocks in the topsoil (0–20 cm) compared to the initial levels and reference fallow, under both fertilised and unfertilised conditions over 50 years of cultivation under the site conditions (Figure 4). The changes in SOC modelled using ICBMr showed that the SOC sequestration by unfertilised treatments was about 1.6 to 3.3 times greater than with the equivalent fertilised treatment. The exception to this was the variety 'Tora', which had a similar increase in SOC stocks under both treatments.

It is typical practice in many studies to assume that higher yields lead to greater amounts of both above and belowground biomass, leading to higher SOC sequestration (Hammar et al. 2014; Keel et al. 2017; Smith et al. 2020). This was not observed in our analysis; instead, the potential for SOC sequestration was dependent on variety and its response to fertilisation. Fertilisation generally led to greater yields, but not greater increase in SOC stocks. Low yielding 'Jorr' had the highest SOC sequestration under the given soil conditions for both treatments. The fertilised treatments of 'Björn' and 'Loden' had only slightly greater SOC sequestration compared to the reference fallow.

The differences in SOC sequestration can be attributed to the allocation of the NPP between different plant parts. Studies have supported the idea that fertilisation can contribute to lower fine root biomass accumulation (Heinsoo et al. 2009; Rytter 2013) but does not change the turnover rates[2]. Salix roots have been observed to have high turnover rates (Rytter 1999), even during winter months (Rytter 2001) which suggests relatively higher biomass inputs to soil from root biomass in unfertilised Salix plants. The variety and growing conditions have been seen to have a significant influence on biomass growth and allocation, and even in root density (Sevel et al. 2012; Cunniff et al. 2015; Gregory et al. 2018). While the production of stems can be estimated from harvest data, the belowground biomass accumulation is particularly difficult to determine and remains an area of research interest, which can provide valuable insights into carbon sequestration.

[2] The turnover rate of roots refers to the rate at which roots in a plant system are replaced or regenerated. It is a measure of how quickly old roots die and are replaced by new ones.

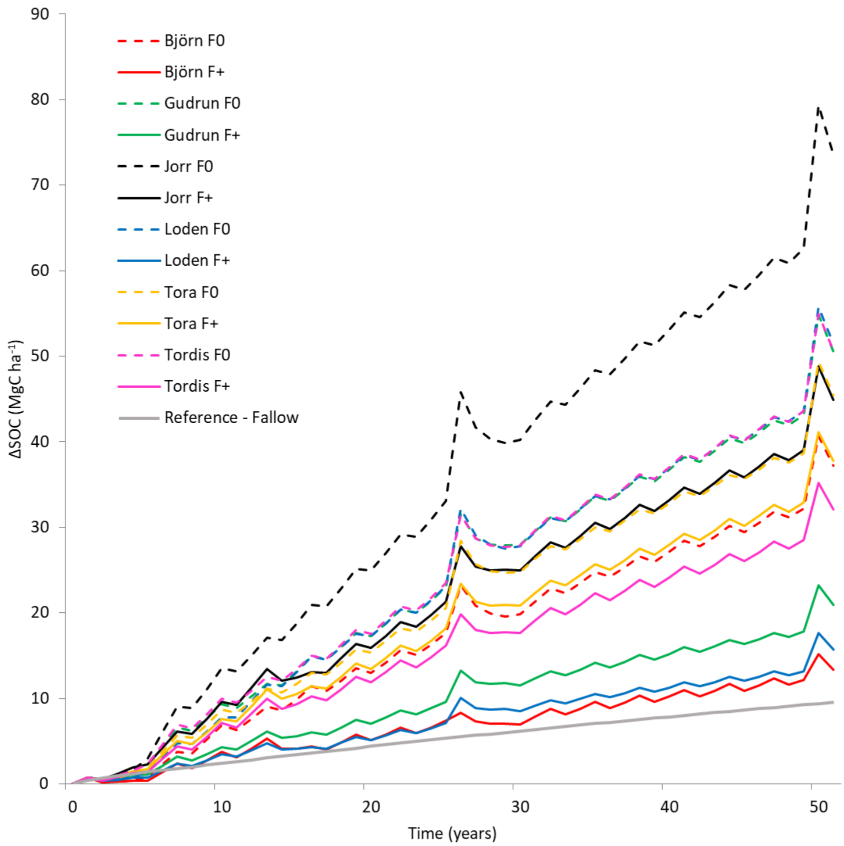

Figure 4. The change in Soil Organic Carbon (SOC) stock under 50 years of Salix cultivation modelled using ICBMr soil carbon model for the six Salix varieties and fertilised (F+) and unfertilised (F0) treatments with fallow as a reference.

5.1.2 Live biomass

Salix is a highly productive crop compared to fallow and annual crops, which can give a rapid increase in the C stock of live biomass. Salix plants takes up CO_2 from the atmosphere in the live biomass during the growth, which is released in the year of harvest. Thus, the CO_2 flux from the biomass follows a cyclical pattern. This is visualised for the variety Tora in Figure 5. Live biomass does not lead to carbon sequestration over the complete coppice cycle unless the carbon becomes an input to the SOC pool (as dead biomass or digestate) as the carbon in the harvested biomass was assumed to be released after undergoing conversion. Fertilisation typically leads to greater aboveground biomass productivity, leading to a greater magnitude of CO_2 fluxes.

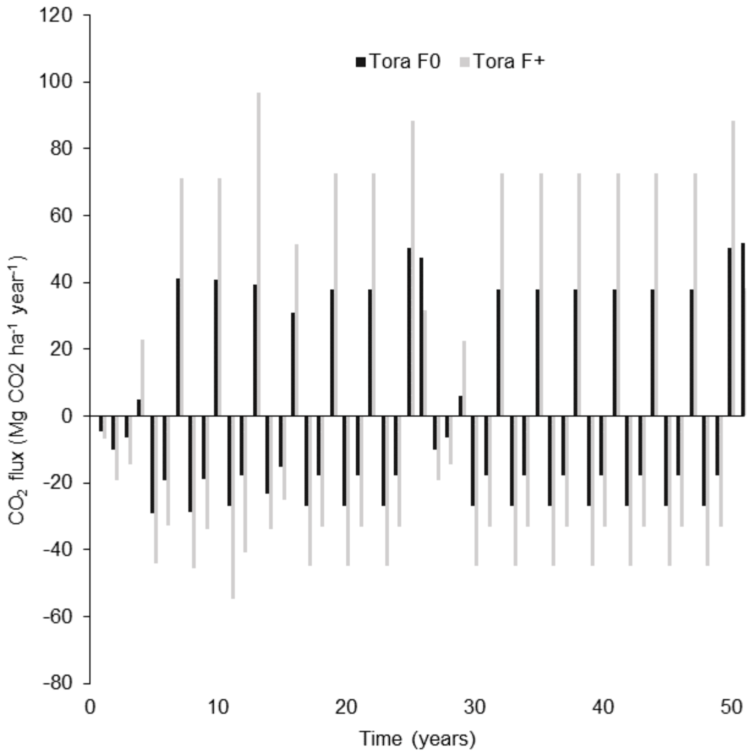

Figure 5. Carbon dioxide (CO_2) flux caused by the live biomass stock change during cultivation for fertilised (F+) and unfertilised (F0) Tora. Negative flux represents an uptake of CO_2 from the atmosphere.

Within the conventional GWP accounting, the live biomass is carbon neutral during the study period and has no net effect on the GWP. The effect of live biomass is seen in the temperature response (ΔT) from the time dependent climate impact as it considers the timing of GHG fluxes. Initially, the magnitude of CO_2 uptake is greater and its rate is faster for the live biomass compared to SOC sequestration. This is seen as a greater influence on ΔT during the first rotation (Figure 6). The SOC gradually accumulates over time and its contribution to ΔT increases, while the effect of live biomass stagnates as a steady level is reached. Ending the cultivation after two rotations leads to the release of all the carbon from the live biomass leading to a slight increase in temperature response after some years. The effect of SOC on the temperature response is longer lasting due to slower decomposition.

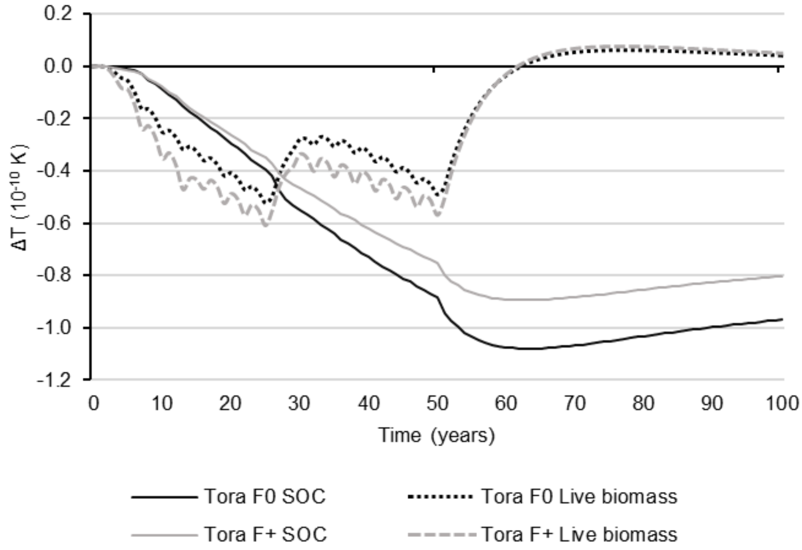

Figure 6. Temperature changes caused by CO_2 emissions and uptake from live biomass and soil organic carbon for fertilised (F+) and unfertilised (F0) Tora. The study period is 50 years. No CO_2 flux is assumed after year 51.

5.2 Energy performance

The energy performance of Salix conversion routes in terms of the different metrics used in the studies (Paper I, II and IV) are presented in Table 5. The ER of the unfertilised treatment was about two-fold greater than the fertilised treatment using Salix biomass for heat production (Paper I). This was because of the greater energy demand from production and the spreading of fertilisers during cultivation. Higher yielding varieties are more efficient in their energy use. ER values for the energy analysis of combustion reported in literature range from 16–79 (Gustavsson et al. 1995; Börjesson 1996; Matthews 2001; Lettens et al. 2003; Heller et al. 2004; Styles & Jones 2007; Boehmel et al. 2008; Goglio & Owende 2009) demonstrating wide variability due to the different assumptions and system processes considered.

The CBG production phase has higher energy demands arising from the processes involved in pretreatment, anaerobic digestion, upgrading and compression (Paper II). However, CBG is a more versatile form of energy and has a wider range of applications (e.g. vehicle fuel). There was minor variation in the range of R values between varieties. The base scenario without heat recovery had R values between 1.57–1.88. Implementing energy efficiency measures like heat exchange between the hot and cold streams improved energy performance by 46–61%. The R values in our analysis (1.57–2.94) were at the lower end of some of the reported values (7.3–12.3) for Salix biogas production (Uellendahl et al. 2008), but those systems did not include upgrading of biogas. The R values from the energy efficient scenario were comparable to biomethane (2.0–2.9) produced from other energy crops (Salter & Banks 2009; Prade et al. 2012).

The PED_{fossil} metric was used to show the total fossil energy input to produce one metric ton of the yeast oil from the different varieties of Salix biomass (Paper IV). The PED_{fossil} per ton of oil produced using the Salix biomass was in the range of 13.9–16.6 GJ ton_{oil}^{-1}. The varieties with higher yield had a lower fossil energy demand per unit mass harvested, leading to better energy performance.

Table 5. The energy performance of the three biomass conversion routes in terms of the three different metrics used for each pathway. F0 and F+ refer to unfertilised and fertilised treatments of Salix.

	Combustion	CBG production – no heat exchange	CBG production – with heat exchange	Yeast oil production
	ER	R	R	PED_{fossil} GJ ton_{oil}^{-1}
Björn F0	48.2	1.67	2.59	
Björn F+	26.5	1.73	2.66	14.6
Gudrun F0	46	1.81	2.83	
Gudrun F+	17.5	1.69	2.54	16.8
Jorr F0	43.3	1.71	2.63	
Jorr F+	24.7	1.57	2.36	14.9
Loden F0	43.2	1.77	2.75	
Loden F+	16.1	1.68	2.5	17.4
Tora F0	45.1	1.79	2.78	
Tora F+	25.1	1.72	2.62	14.9
Tordis F0	47.7	1.88	2.94	
Tordis F+	28.2	1.83	2.82	14.3

5.3 Climate impacts

5.3.1 Salix for heat production

The analysis of the climate impact of using Salix biomass for combustion (paper I) showed that the variety has a significant effect in determining climate impact. Furthermore, the performance of varieties was different on a land-use (per hectare) and energy delivered (per MJ) basis, indicating that the choice of functional unit can be important for the interpretation of the results. The effect of temporary carbon storage in the biomass is not seen in the conventional GWP climate metric, but plays a role in the time-dependent climate impact.

The GWP caused by emissions from the Salix production chain could be mitigated by the SOC sequestered during cultivation for all varieties for both functional units (Figure 7, Figure 8). The only exception to this was fertilised

Björn, where the climate impact of emissions was greater than the SOC sequestration effect. In general, fertilisation contributed to higher GHG emissions in the production phase, leading to a greater climate impact from the production chain. Unfertilised Jorr had the greatest climate mitigation effect in absolute terms (without including the substitution effect) for both hectare (−6.5 MgCO_2-eq ha^{-1} year^{-1}) and MJ (−97 gCO_2-eq MJ^{-1}) of heat. The substitution effect reflects the avoided emissions of producing heat from fossil fuel (natural gas in this case).

On a per hectare basis (Figure 7a, Figure 8a), high-yielding varieties were most effective in mitigating climate change due to their ability to substitute fossil fuels. High biomass yields led to greater climate mitigation effects due to higher substitution of fossil fuels. This substitution effect was particularly significant in high-yielding varieties such as fertilized 'Tordis', 'Björn', 'Jorr', and 'Tora', as seen in their climate mitigation effect across both climate metrics. Fertilized varieties generally had higher biomass yields, which enhanced their substitution effects, but had a greater impact from the production phase due to fertiliser related emissions. Fertilized 'Gudrun' and 'Loden' had the poorest climate performances compared to other fertilised varieties attributed to lower yield increases upon fertilisation.

The net climate impact from a land-use perspective involves assessing both the positive effects of biomass yield and SOC sequestration against the negative effects of increased GHG emissions from fertilizer use. The study (Paper I) suggests that for certain high-yielding varieties, the benefits of replacing fossil fuels can outweigh the negative impacts of fertilization, but unfertilized varieties can still play a crucial role in long-term carbon sequestration.

In terms of the energy delivered (Figure 7b, Figure 8b), the varieties with greater SOC sequestration relative to their energy output typically performed better. The higher SOC sequestration but lower yields for the unfertilised varieties resulted in greater SOC sequestration per unit harvested biomass. In terms of GWP_{100} (Figure 7b), fertilized 'Jorr' had the highest climate mitigation effect (−192 gCO_2-eq MJ_{heat}^{-1}) while fertilized 'Gudrun' (−74 gCO_2-eq MJ_{heat}^{-1}) was at the other end of the spectrum. A different perspective emerges from the time dependent climate impact (ΔT) results per MJ of heat (Figure 8b). The unfertilised varieties showed a greater reduction in global mean surface temperature during the study period due to the additional mitigation effect from the live biomass (in combination with the

SOC sequestration and substitution effect). The live biomass had a neutral effect on the GWP. Over a 50 year period, unfertilised 'Jorr' showed the greatest cooling effect per MJ (-5.11×10^{-15} K MJ^{-1}), while fertilized 'Björn' (-2.39×10^{-15} K MJ^{-1}) had the lowest. This is relevant when comparing energy generation systems in contexts where land availability is not a constraint. The unfertilized 'Jorr' and 'Loden' varieties performed best in terms of potential temperature reduction per unit of energy, despite having the lowest biomass yield.

Production of heat from the Salix varieties included here showed a 95–237% in GWP compared with a fossil reference. This was has higher compared to the 90–99% reduction reported by Djomo et al. (2011), but SOC sequestration effects were included by a single study in the review.

Sensitivity analysis showed that increasing the soil depth from 20 cm to 25 cm generally led to a higher annual SOC uptake per hectare, resulting in a reduced climate impact compared to the base scenario. However, the fertilized varieties 'Björn', 'Gudrun', and 'Loden' were exceptions. Greater soil profile depth meant a higher starting SOC level, which in combination with lower SOC sequestration for these varieties, contributed to a greater climate impact compared to the base scenario.

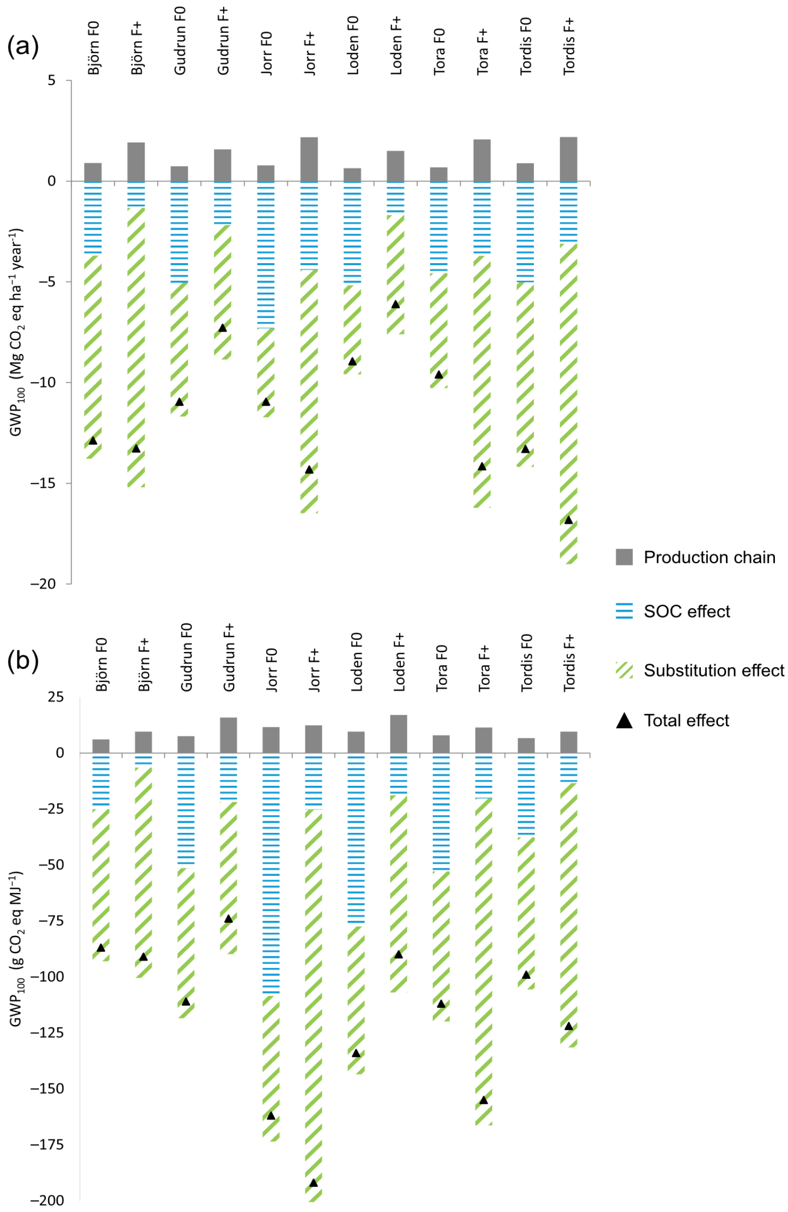

Figure 7. The global warming potential (GWP_{100}) for heat production from Salix biomass, including SOC effect and substitution effect from the reference scenario. The climate impact is calculated in terms of two functional units of (a) per hectare and (b) MJ energy.

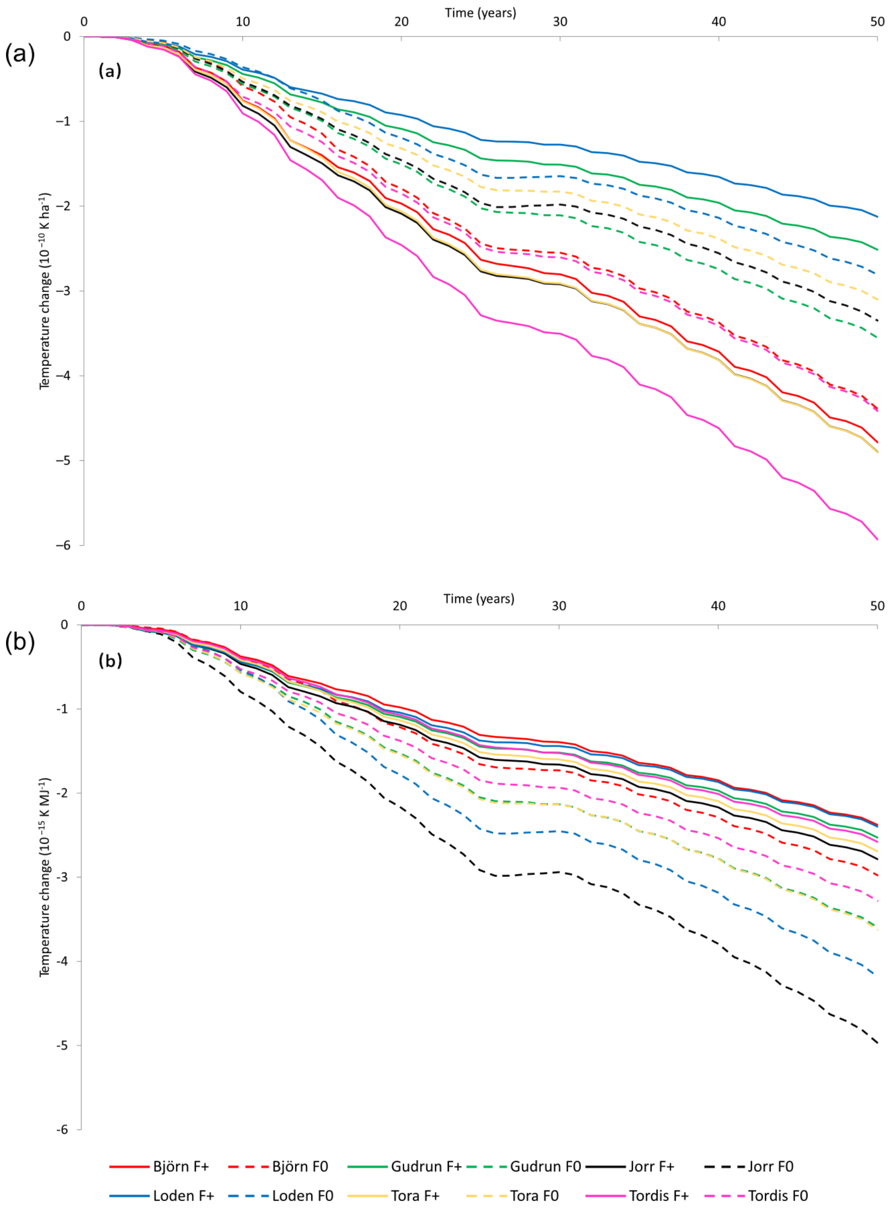

Figure 8. Time dependent climate impact in terms of temperature response (ΔT) for the total system including substitution effect of using Salix for heat production in terms of two functional units of (a) per hectare and (b) MJ energy.

5.3.2 Salix to compressed biomethane gas

The climate impacts of producing CBG from the fertilised varieties of Björn, Gudrun, Jorr, Loden, Tora and Tordis was investigated in Paper III. The digestate replaced mineral fertiliser on agricultural fields. The Salix scenarios were compared to a reference scenario with fallow as the land use, natural gas as alternate energy, and mineral fertiliser as an alternative to digestate application. The climate impact in terms of GWP_{100} for two functional units of hectare and MJ of energy delivered, including the reference scenarios are shown in Figure 9. The CBG production included the pretreatment of Salix biomass, anaerobic digestion and biogas upgrading and compression.

In the base Salix scenarios, the Salix cultivation had the greatest contribution to positive GWP due to the use of fossil diesel. Although the energy demand of the CBG production was higher, its net contribution to climate impact was lower due to use of the electricity and biomass to meet the energy demand. The Swedish electricity mix and biomass had low emission factors (European Environment Agency 2024). SOC sequestration, resulting from the application of digestate is the largest GHG sink and significantly contributes to the climate mitigation effect. The SOC sequestration potential offsets the emissions from Salix cultivation, leading to negative net GWP values for all Salix varieties. Almost half of the initial carbon (especially lignin) in Salix biomass remains in the digestate, leading to a high SOC sequestration potential from digestate application. Moreover, the humification coefficient of the digestate was higher compared to Salix biomass inputs, meaning that a larger portion of the carbon ends up in the more stable old pool in the soil carbon model. The mitigation effect of SOC sequestration could mitigate the positive contribution to GWP_{100} from the operations in the supply chain for both functional units.

The GWP values (excluding biogenic carbon) from a land use perspective (Figure 9a) range from 1.60 to 2.49 Mg CO_2-eq. ha^{-1} $year^{-1}$ for the different Salix varieties. The greatest substitution effect arises from the avoided emissions from natural gas. Including the substitution effect of the reference scenario, the net GWP ranges from −4.74 Mg CO_2-eq. ha^{-1} $year^{-1}$ for Loden to −14.68 Mg CO_2-eq. ha^{-1} $year^{-1}$ for Tordis. This is also seen as contributing to the mitigating effect on global temperature in terms of ΔT across all the varieties Figure 10a. Highly productive Tordis showed the greatest climate mitigation effect of -55.82×10^{-11} K ha^{-1} during the study period. While

Loden had the lowest performance with a net ΔT of -18.67×10^{-11} K ha^{-1}, about one-third of Tordis's impact.

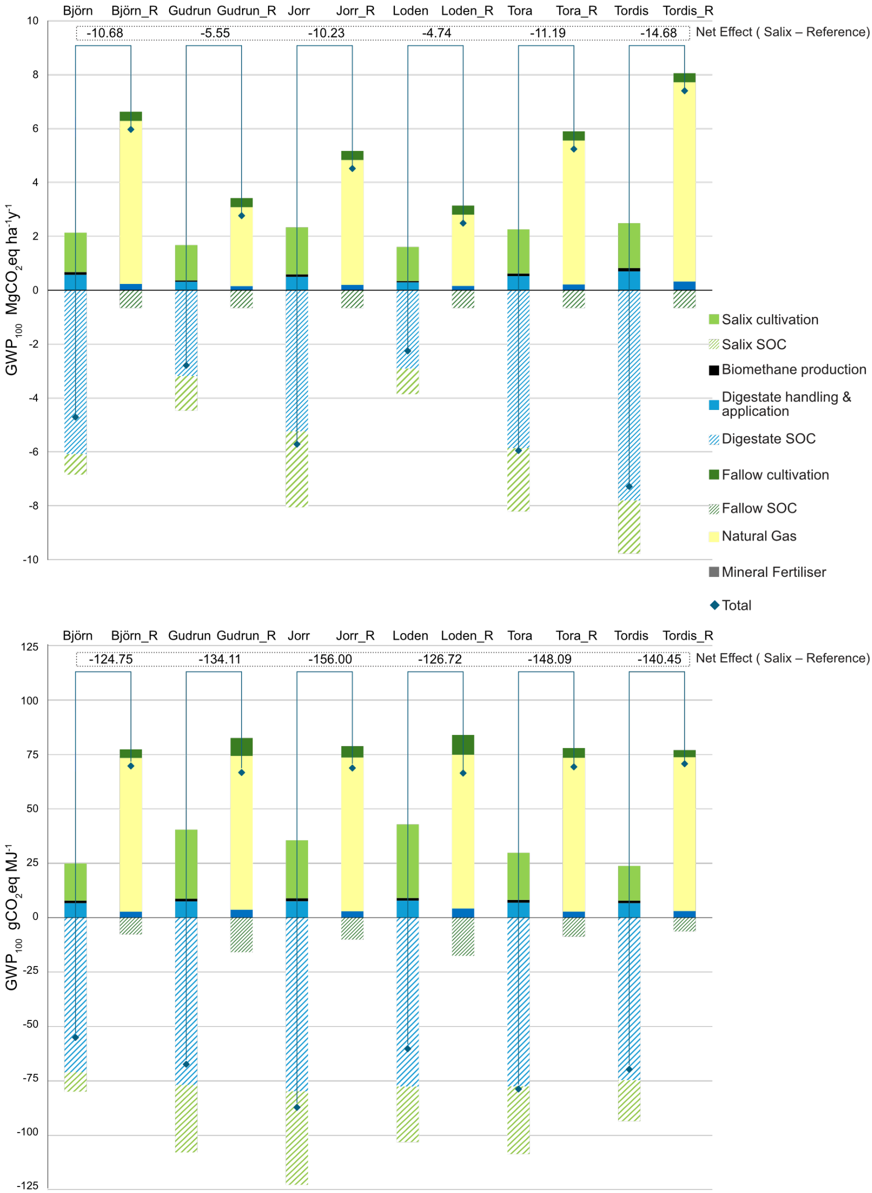

Figure 9. The global warming potential (GWP_{100}) for CBG production from the Salix varieties compared to an equivalent reference scenario in terms of two functional units of (a) per hectare and (b) MJ fuel energy. The reference scenario for the varieties is marked by the suffix 'R'. The net effect from substitution of the reference scenario is shown above the bars.

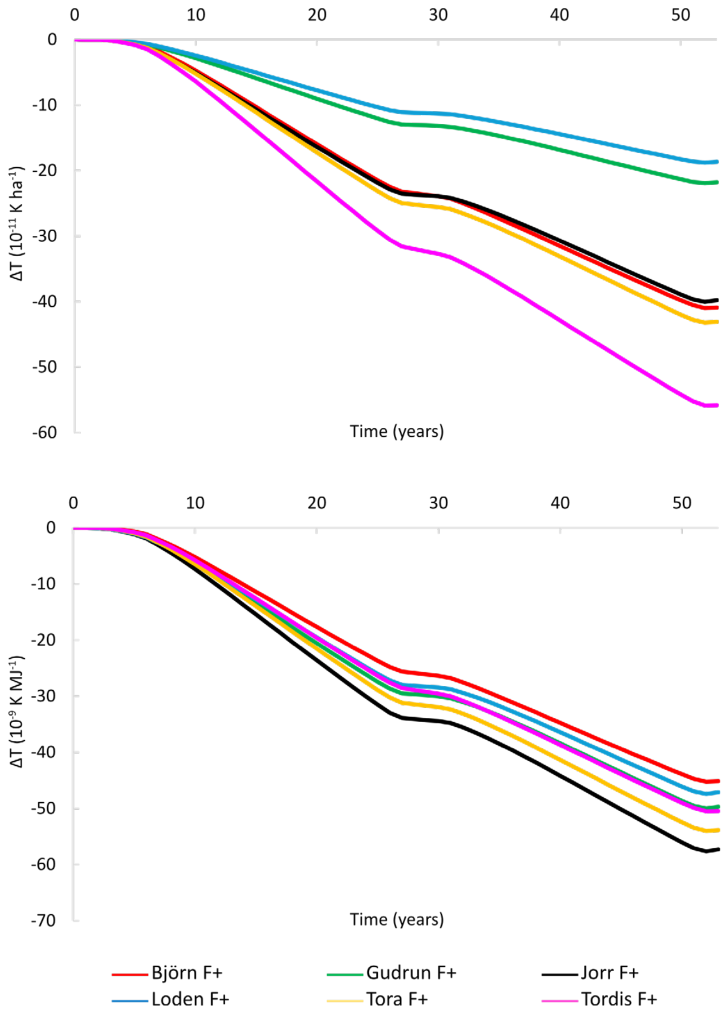

Figure 10. Time dependent climate impact in terms of temperature response (ΔT) for the total system, including the the substitution effect of CBG production from the Salix varieties in terms of two functional units of (a) per hectare and (b) MJ fuel energy.

A different trend is observed when comparing the varieties in terms of climate impact per MJ fuel energy (Figure 9b, Figure 10b). The variation of climate impact between the varieties was smaller for both climate metrics. This indicates that on basis of energy delivered, all varieties provide comparable climate benefits. However, when assessing performance in terms of land area, the selection of varieties had a larger influence on the climate impact of the overall system.

The GWP_{100} ranged from 23.81 gCO_2-eq. MJ^{-1} for Tordis to 42.87 gCO_2-eq. MJ^{-1} for Loden in the base scenario excluding biogenic carbon. When including the biogenic carbon and substitution effects, Jorr had the best climate mitigation potential, with a GWP_{100} of −156 gCO_2-eq. MJ^{-1} and ΔT of -57.30×10^{-9} K MJ_{CBG}^{-1}. The climate effect per MJ was primarily influenced by the SOC sequestration during Salix cultivation, as it varied greatly between the Salix varieties. While the effects of digestate SOC and the substitution effect were more consistent. The variety with the lowest climate benefit per MJ_{CBG} was Björn with GWP_{100} of −124.75 gCO_2-eq. MJ^{-1} and ΔT of -45.13×10^{-9} K MJ_{CBG}^{-1}.

The climate impact is dependent upon factors such as system boundaries, feedstocks and specifics of processes, which results in a wide range of reported values of GWP_{100} for biomethane across studies. The average GWP_{100} values of biomethane from waste streams are lower due to avoided emissions from waste management, varying from from 17.4 to 185 gCO_2-eq. MJ^{-1} (Oehmichen et al. 2021). A comprehensive analysis of biomethane supply chains reported values from −25 to 183 gCO_2-eq. MJ^{-1}, with median emissions of around 72 gCO_2-eq. MJ^{-1} (Bakkaloglu & Hawkes 2024). The GWP_{100} of CBG for the Salix varieties in our system was in the range of 23.81–42.87 gCO_2-eq. MJ^{-1} without including soil carbon and substitution effects. Including these effects, resulted in high climate mitigation effect with values of −156.00 to −124.75 gCO_2-eq. MJ^{-1}.

The sensitivity analysis showed that increasing h_{dig} and decreasing r_e resulted in a stronger cooling effect on the climate, while the opposite changes led to a weaker effect. The climate impact varied by about ±10% and ±20% from ±20% variation in h_{dig} and r_e respectively. The digestate SOC that ends up in the more stable old pool is proportional to h_{dig} — leading to a greater total SOC accumulation and increased cooling effect with a higher h_{dig} value. In contrast, higher r_e values accelerate carbon decomposition, increasing soil CO_2 emissions and the temperature response.

5.3.3 Salix to yeast oil

The climate impacts of producing yeast oil were calculated on the functional unit of 1 kg oil (Paper IV). The emissions from the Salix cultivation, transport, biorefinery operations, and soil emission accounted for GWP_{100}

values between 1.53–2.36 kgCO_2-eq. kg_{oil}^{-1} (Figure 11), comparable to the GWP_{100} estimated for Swedish rapeseed oil as 1.62 kg CO_2eq kg_{oil}^{-1} (Bernesson 2004). Salix cultivation had the major share in the GWP_{100} climate impact attributed to fertiliser use and related N_2O emissions. Low-yielding Gudrun and Loden exhibited lower biomass production efficiency, resulting in higher material and energy inputs per unit of biomass produced. Consequently, this resulted in the greater climate impact of the Salix cultivation phase for these specific clones. About half the emissions from the biorefinery stage was from ammonia usage for yeast propagation. The climate mitigation effect of SOC sequestration by Salix cultivation reduced the overall net GWP for all the varieties. In the case of Jorr, the SOC sequestration effect was large enough to have a net negative GWP_{100} of −0.28 kg CO_2eq kg_{oil}^{-1}. Yeast oil from Tora was nearly climate neutral from the GWP_{100} climate metric.

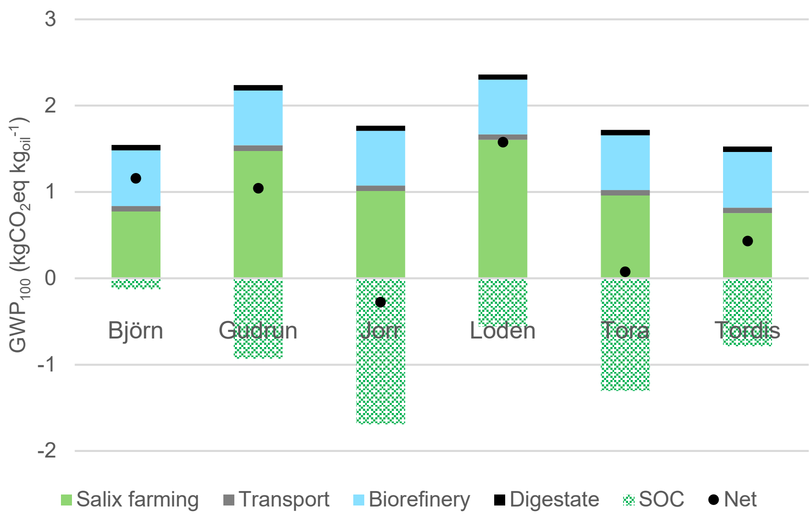

Figure 11. The global warming potential (GWP_{100}) of yeast oil produced from Salix biomass. The climate impact is calculated on basis of kg of oil produced.

The temperature response per kg of oil (Figure 12) from the Salix varieties followed the same trends as observed in the GWP_{100} climate impact. The contribution of biogenic carbon on a negative temperature response was clearer from the time-dependent ΔT metric. The net ΔT (K kg_{oil}^{-1}) was associated with the SOC sequestration effect, as seen with the varieties Jorr, Tora and Tordis. Jorr and Tora were the only varieties with a net cooling effect on the climate. Björn and Loden (with lower increase) in SOC showed a positive ΔT (warming effect) after the end of the first rotation period.

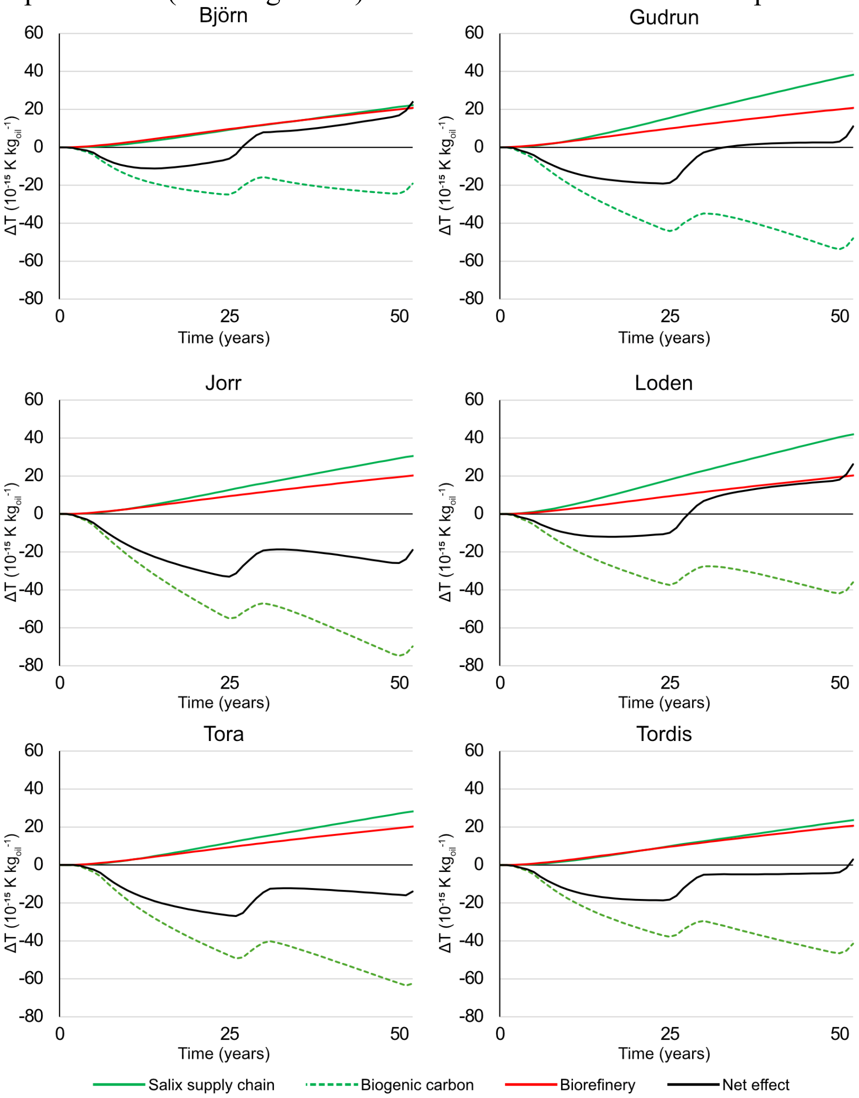

Figure 12. Time-dependent climate impact per kg of yeast oil from the different Salix varieties. The net temperature effect is marked with a solid line.

Sensitivity analysis on the variety 'Tora' showed that a 10% increase in yeast oil price led to a minor 2% rise in the GWP impact by affecting the economic allocation. Switching to allocation based on energy content reduced the GWP associated with yeast oil by nearly 30%. Reducing the amount of acid and base use in fermentation by 20% resulted in a minor (<1%) decrease in the system's net GWP. The GWP of the yeast oil increased by 3.9% when doubling the biomass transport distance.

5.4 Overall comparison of variety characteristics on conversion routes

The Salix varieties considered in the thesis exhibited differences in their yield, SOC sequestration potential, response to fertilisation, composition, and BMP values. The level of yield and SOC sequestration played an important role in determining factors for the climate impacts for the varieties. The perspective of comparison is based on the functional unit and determines which traits have a determining effect on the climate impact.

The comparison of conversion routes is complicated owing to the different nature and quality of the end product. From an energy performance perspective, conventional heat production (Paper I) has a higher energy output compared to CBG production (Paper III). However, CBG has higher energy quality, enabling multiple applications and replacement of fossil fuels in hard to abate sectors. The yeast oil production (paper IV) presents an advanced usage where composition and quality of the oil is the determining factor for the performance of system.

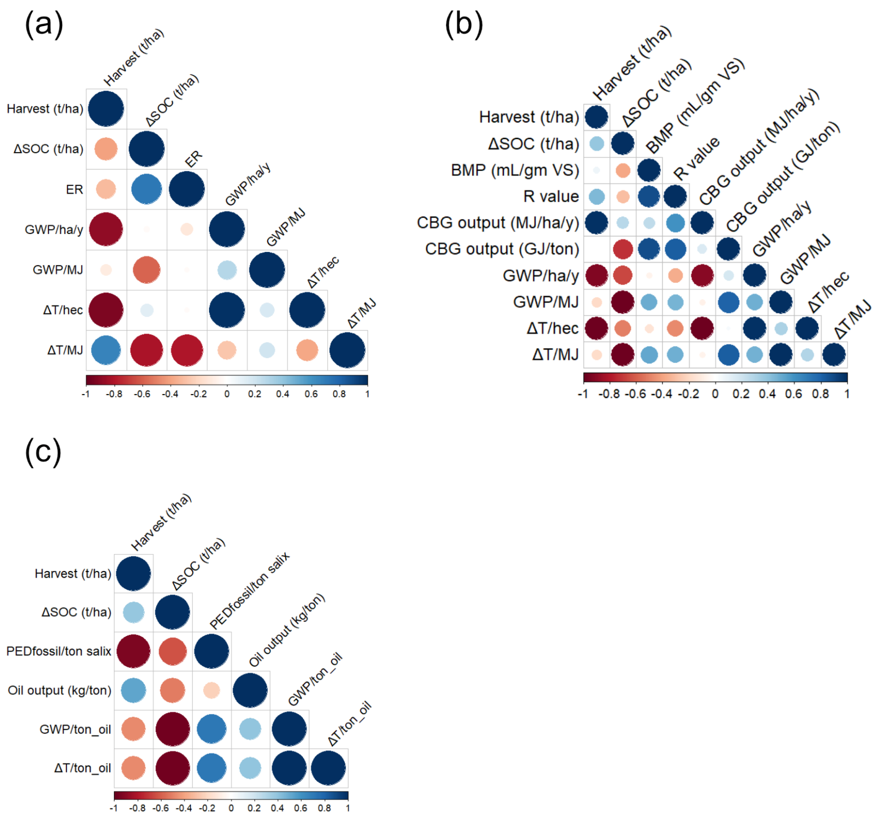

Figure 13. The Correlation matrix of Salix characteristics and climate impacts for the three conversion routes – (a) combustion (b) compressed biomass production, and (c) yeast oil production. A value of 1 defines a perfect positive liner relationship, while −1 defines a perfect negative linear relationship.

The choice of functional unit highlighted different aspects of the climate performance of Salix varieties. The same trends were observed across conversion routes (Figure 13). From a land use perspective, the climate impact (for both metrics) were highly negatively correlated to the harvest, and to SOC sequestration to a lesser extent. High yield levels led to a lower climate impact (or greater mitigation effect). Per hectare units emphasize the overall productivity and land use efficiency, favouring high-yielding varieties.

In contrast, per unit of product (MJ and kg_{oil}) units highlight the effect of carbon sequestration, and conversion efficiency per unit of biomass, favouring varieties with higher SOC sequestration. Climate impact and SOC sequestration had a strong negative correlation. Higher SOC sequestration led to a lower climate impact per unit product for all three conversion routes. This underscores the importance of selecting appropriate functional units based on the specific goals and priorities of the analysis.

6. General discussion

6.1 The influence of Salix variety characteristics on climate impact

Yield and SOC sequestration potential exert the greatest influence on the climate performance of Salix biomass utilisation. However, there is no linear relationship between these two characteristics (Paper I), which has been a common assumption in systems studies of energy crops like Salix (Hammar et al. 2014). Higher yields did not result in greater SOC sequestration potential. Rather, these two characteristics are dependent on Salix variety.

The relative importance of Salix characteristics on climate impact was based on the choice of functional units. From the land use perspective in Paper I and III, yield had the determining effect on the climate impact. The land perspective focusses on the productivity of per unit land. High yields lead to more biomass that can be converted to products, which contribute to lower associated emissions per hectare of land and a greater substitution effect.

While SOC sequestration effect of Salix cultivation had greater influence on the climate performance from the product perspective (Papers I, III and IV). Lower yield combined with greater SOC sequestered during cultivation resulted in greater SOC sequestered (and climate mitigation effect) per unit of harvested biomass. This contributes to a lower climate impact per unit product (MJ or kg_{oil}). However, if the yield is too low, the climate impact from cultivation phase on product will be higher. Hence, a balance between these aspects is important for a favourable climate impact.

In general, fertilisation led to greater yields in terms of harvestable (shoot) biomass, but lower increase in SOC across the varieties (Paper I). A greater amount of shoot biomass is also expected to produce more leaf litter amount. However, this did not contribute to higher soil carbon sequestration, which indicates that belowground biomass has a large effect on soil carbon. This suggests that belowground biomass (especially fine roots) production is negatively affected by fertilisation and is the most likely reason for the lower SOC sequestration in the fertilised treatments. Moreover, genetic differences can contribute to differences in allocation patterns between the different biomass parts. This reasoning is supported by other studies that have investigated the effect of fertilisation on aboveground and belowground biomass production and allocation on Salix plants (Heinsoo et al. 2009; Pacaldo et al. 2013; Rytter 2013). Variety and growing conditions have been seen to affect the growth and allocation patterns between Salix varieties (Sevel et al. 2012; Cunniff et al. 2015; Gregory et al. 2018).

Salix plants have been observed to have high root turnover rates (growth and death of biomass), even during winter months (Rytter 1999, 2001). Unlike most other energy crops, Salix species associate with ectomycorrhizal fungi, which contribute to plant nutrient supply and produce root exudates. The root and soil microbiological interactions can be variety specific, which can influence plant growth, SOC sequestration and soil ecology (Baum et al. 2009; Rooney et al. 2009; Weih et al. 2019).

The estimation of root biomass is challenging as it time-consuming, labour-intensive, expensive, and prone to variation from use of different measurement methods. Environmental influence on biomass growth and allocation patterns further complicates these estimations.

The annual production ratio of aboveground biomass to belowground biomass in Paper I aligns with the range of values reported for Salix species in various studies (Rytter 2001, 2013; Heinsoo et al. 2009; Pacaldo et al. 2013). Further research on belowground biomass is required to validate these figures, which would improve estimates of biomass inputs to soil and enhance the precision of soil carbon modelling estimates.

Crop characteristics and its interactions with the environment influence the environmental impact of the production and conversion routes. Genotypic variations within Salix are important to consider in systems analysis of biomass value chains.

In addition, there are variables besides the ones that have been investigated in this thesis that can differ between Salix varieties. For example, albedo change from establishing Salix plantations can have a substantial but short-lived effect on climate impact by changing the solar flux from the Earth's surface (Sieber et al. 2020). Physical and chemical characteristics are of special importance for a bio refinery approach where the composition of feedstock and product are of higher importance. As more variety specific traits are identified and measured, they can be incorporated into process simulations and impact assessments.

6.2 Soil carbon sequestration

The carbon sequestered as SOC played an important role in determining the climate impact across the three conversion processes of Salix biomass. The climate mitigation effect of SOC was especially strong in the biomethane system (Paper III) due to the high amount of C associated with the digestate. The results presented in this thesis contribute to a growing body of research supporting the importance of including SOC fluxes in LCAs, especially for biomass-based systems (Brandão et al. 2011, 2013; Bessou et al. 2020; Joensuu et al. 2021; De Feudis et al. 2022). In general, systems involving changes in land use and management can alter SOC stocks, impacting both GHG balances and soil quality. SOC fluxes are not always included in LCA studies, though the inclusion is becoming more common, especially in studies related to land use, agriculture, and bioenergy. The main challenges in incorporating SOC changes in LCA studies are lack of standardisation, data availability, modelling complexity, variability in soil types and management practices (Bessou et al. 2020; Joensuu et al. 2021). To ensure that SOC assessment methods are both feasible and practical for LCA practitioners, it is essential to strike a balance between accuracy and completeness without making the process overly complex or data-intensive(Goglio et al. 2015). As more LCA studies begin to incorporate SOC changes, it is likely to drive methodological advancements and improve the availability of relevant data.

SOC sequestration is influenced by soil conditions, crop type, and management practices, which makes it challenging to directly extrapolate sequestration potential from one site to another. However, it can provide an indication of the capacity of the crop for climate mitigation. The initial SOC level at the Salix field study site was relatively low, which may have positively influenced SOC accumulation. Soils with a high initial SOC content will reach a steady state of carbon faster, which would reduce the capacity for additional carbon sequestration. Beyond its climate mitigation potential, increasing SOC can also enhance soil quality. Varieties like 'Jorr,' could effectively increase SOC stocks without the need for fertilisation, offer a cost-effective strategy for improving soils with a low carbon content while simultaneously enabling biomass production and delivering additional benefits (Paper I). Marginal and abandoned agricultural lands with a low organic matter content are particularly suitable for such interventions, providing an opportunity to restore soil quality and enabling them to be used for agricultural production in the future.

While SOC sequestration can effectively reduce atmospheric CO_2 and improve soil health, its permanence is less certain, as it is influenced by factors like climate, land management, and soil disturbance. Increasing temperatures are expected to accelerate SOC decomposition, thereby diminishing the sequestration rate and size of the carbon sink. The complexity of measuring and ensuring the permanence of carbon storage presents significant challenges for its inclusion in LCA studies and carbon credit schemes. Experts generally agree that more research, standardized methods, transparency, and robust policies are needed to fully realise the potential of SOC in carbon markets (Smith 2005; Oldfield et al. 2022; Leifeld 2023; Ogle et al. 2023; Paul et al. 2023; Dupla et al. 2024) . However, SOC sequestration is relatively easier to implement, making it a viable short-term climate mitigation strategy.

6.3 Advances in Salix breeding

The field study that is the basis of the varietal data used in this thesis was set up in 2001. Consequently, the Salix varieties included in the thesis were developed almost 20 years ago. Newer varieties of Salix continuously outperform older varieties in terms yield, climate adaptability and resistance to pests and diseases. Several of the varieties here are still offered commercially. Trials conducted in the 1990s and 2000s comparing Salix varieties from the UK and Sweden demonstrated a significant improvement in the yields of newer varieties (Lindegaard et al. 2001, 2013). Older varieties are also outclassed due to problems (such as failed disease resistance) that might emerge over time, and be removed from the market. The variety Björn, for example, has become outclassed and is removed from cultivation (Lindegaard et al. 2013).

A study conducted on marginal land in Poland demonstrated that how relatively newer willow variety Żubr achieved impressive biomass yields of 13.8 Mg ha^{-1} $year^{-1}$ (Matyka & Radzikowski 2020). In comparison, the variety Tordis, which was the highest yielding among the varieties examined in the study, produced 8.2 Mg ha^{-1} $year^{-1}$.

On-going projects such as Accelerating Willow Breeding and Deployment (AWBD) led by Rothamsted Research in the UK aim to accelerate breeding, multiplication and the deployment of newer varieties with lowered costs by using novel methods and techniques (Biomass Connect 2024; Rothamsted Research 2024). The project includes trials across five different environments in the UK.

Salix breeding programs are active in Sweden, the UK, Poland and the United States. There are about 30 commercial varieties of Salix available in the UK, Sweden and the United States, with ~90 more in the pre-commercialisation and development stages (Clifton-Brown et al. 2019). The journey from breeding to commercialisation is both long and expensive. This, coupled with the long payback period, has slowed the development of new Salix varieties (Baker et al. 2022). However, as the industry gains momentum, novel varieties offering a range of potential applications could enter the market. The genetic pool of commercial Salix varieties has expanded leading to varieties suited to drier and hotter climates—expanding the geographic potential of the crop.

6.4 Uncertainties

Uncertainties are unavoidable when utilising modelling approaches and conducting lifecycle assessments due to the broad nature and scope. The uncertainties arise due to multiple factors, including as data variability and quality from differences in measurement methods, temporal and spatial variations, assumptions when data is unavailable, methodological choices and system boundaries (Huijbregts 1998; Bamber et al. 2020). Models are a simplification of reality and assumptions made for the sake of computational feasibility introduce uncertainties. When making long-term assessments, natural variability and unpredictability arises due to factors like technological advancements and environmental changes. These limitations are not unique and occur across methods for environmental systems analysis. The inclusion of multiple varieties and field data in the studies here helps to tackle some aspects of variability arising due to different characteristics. The main uncertainties arising in the scope of this thesis are discussed below.

As discussed above (Section 6.2), SOC sequestration has a strong effect on the climate impact of the conversion routes. The lack of long-term data for validating the soil carbon models for different crop and soil types, along with the scarcity of knowledge on belowground biomass production is a challenge. The humification coefficient parameter in the ICBMr model are based on assumptions and calculations, as these are unavailable for the specific Salix varieties and digestate. The permanence of SOC has been discussed and debated intensely as it is subject to environmental conditions which are rapidly evolving due to climate change. While the absolute magnitude of SOC sequestered might be uncertain, the SOC sequestration potential patterns among varieties can be expected to be more robust.

Laboratory data on the composition and BMP values of Salix biomass were used when simulating biomethane production. The practical biogas production can vary from the BMP values obtained from experimental data, so a conservative estimate of 80% of the BMP value was used. Yeast oil production from Salix was estimated through process modelling based on compositional data. Yeast fermentation is an experimental process that has been used for similar lignocellulosic biomass and can become a prospective conversion route for Salix biomass. Data measured from pilot and industrial application are required for these processes for the accurate estimation of scaling up of these processes.

In Papers I and III, it was assumed that bioenergy (as heat or CBG) would replace fossil natural gas over the study period. The substitution contributed to a large environmental benefit from avoided GHG emissions in the net climate impact. The magnitude of substitution effect is dependent on the chosen reference. The share of energy sources is constantly evolving in response to policy, politics, and market forces. It can be expected that the share of renewables in the energy mix will increase over time, if the climate goals set at different institutional levels are followed. Assuming a dynamic reference energy scenario would lead to a reduction in the substitution effect of bioenergy over time. However, bioenergy has the advantage over other renewables of potentially replacing fossil fuels in hard to abate sectors due to its flexibility and ability to be used in existing infrastructure.

Similarly, the field machinery and transport vehicles involved in the operations (Papers I–IV) are diesel powered. Typically the transportation distance of biomass is a limiting factor as it has lower energy intensity compared to fossil fuels. The transition towards greater electrification and alternate fuels may lead to diesel replacement in some of these operations in the future. This can reduce the climate impact of transport, which would make it more feasible to transport biomass over larger distances.

6.5 Sustainability

Sustainability is commonly defined as a concept with three dimensions – environmental, economic and social (Purvis et al. 2019). While environmental sustainability is emphasised and primarily discussed, economic and social sustainability are complex to assess, and lacks a standardised framework for assessment. Sustainability is a normative concept, which evolves based on what is valued as desirable (Scoones 2016). There are aspects besides climate impact that will determine the use of Salix biomass as a sustainable resource. Salix has the potential to be more than just an energy crop due to the possible ecosystem services (discussed in the background section) it can provide. Variety will most likely play an important role in determining the strength of the ecosystem services, and the subsequent effects on the regional environment. Expanding the varietal differences to other impact categories in LCA will likely have a significant influence on the results. This will need more variety specific inventory data and associated flows of emissions and inputs for quantification.

The economic analyses of Salix biomass have mostly focussed on the monetary aspects of crop productivity and the costs of inputs. Salix biomass has typically been compared to wood fuel for combustion applications. The monetary value of Salix cultivation will evolve with technical advancements, novel conversion routes, market trends and policy. Interactions between policy and market factors (e.g., carbon crediting and a push towards a biobased economy) can change how the characteristics of productivity, SOC sequestration, and biomass composition are valued economically. There are efforts to go beyond monetary analyses to translate ecological, environmental, and social effects into economic terms. The social effects of Salix cultivation from the local to the international scale are less well researched. Biomass projects can have both positive (e.g., local job creation, energy security) and negative (e.g., land competition) socio-economic effects. Trans-disciplinary research is needed to integrate the environmental, social, and economic aspects and define the standard indicators to investigate overall sustainability (Brinkman et al. 2019).

The research also consolidates the view that generalised statements about biomass use and its associated impacts should be opposed. Sustainability of biomass for energy and other non-food uses is highly debated in the public. The debate in the popular press is prone to highly generalized and overblown statements from both sides. As supported by the analyses incorporating different Salix varieties in this thesis, the impacts arising from biomass-based systems are highly specific to temporal and spatial conditions, the variety of biomass selected and its characteristics, management practices, and conversion processes. These variations can lead to different outcomes in terms of greenhouse gas emissions, biodiversity, and sustainability, making it crucial to assess biomass systems individually to understand the specific climate and environmental effects.

7. Conclusions

This thesis investigates the influence of six different Salix varieties on the climate impact of three distinct conversion routes producing a range of outputs—heat, CBG (equivalent to natural gas), and yeast oil (equivalent to rapeseed oil). The study integrates soil carbon modelling with time dynamic LCA methodology to calculate the climate impact associated with these conversion routes. The analysis draws on variety-specific data, including yield, SOC measurements, composition, and BMP values, derived from field studies and laboratory experiments. The Salix plantations were modelled under conditions consistent with those of the field study conducted near Uppsala, Sweden. The differences between the Salix varieties influenced the overall climate impacts, with yield and SOC sequestration potential being the determining factors. This work contributes to the research on Salix as a biomass feedstock for a bio-based economy, highlighting the critical role of varietal differences in environmental impact assessments. The main conclusions can be summarised as follows:

- Soil carbon modelling showed that all six Salix varieties under both fertilised and unfertilised conditions contributed to an increase in SOC stocks in the 0–20 cm soil profile under the specific soil and climate conditions.
- There was no linear relationship between yield and soil carbon sequestration, which has been a typical assumption in several systems studies.
- Fertilisation was found to have both benefits and drawbacks
    - Fertilisation increased yields but led to lower SOC sequestration compared to unfertilised treatment of the same variety.

  - Additionally, the energy demand and GHG emissions per hectare of fertilisation were about three times higher compared to non-fertilisation.
  - However, higher yields from fertilisation represented greater land use efficiency and a stronger substitution effect of replacing fossil-based energy.
- Belowground biomass input (particularly from fine roots) is expected to have a substantial impact on soil carbon sequestration from Salix cultivation, as evidenced by the considerable variation observed across different varieties and treatments.
- The use of time dependent climate impact (ΔT) helps to capture the effect of biogenic carbon over time. The CO_2 uptake by the rapid growth of Salix biomass in the years after establishment has a strong but relatively short-lived effect on the global temperature. The slow accumulation and decomposition of SOC, however, has a longer lasting effect.
- The relative importance of Salix characteristics on the climate impact assessment was different depending on the functional unit used to compare the varieties:
  - From the land use perspective (per hectare) used in the production of heat (paper I) and CBG (Paper III), the yield of the Salix variety was the most important factor.
  - From the perspective of per unit of product (per MJ or kg_{oil}), the SOC sequestration potential was the determining factor.
- Direct combustion of Salix:
  - All varieties except 'Björn' exhibited a climate mitigation effect even when excluding the substitution effects of replacing natural gas based heat generation.
  - However, all varieties and treatments demonstrated climate change mitigation potential (both per hectare and MJ) when substitution effects were considered.
- CBG production from Salix:
  - SOC sequestration from digestate had a large climate mitigation potential as over 50% of the initial carbon ends up in the digestate.
  - Higher yields contributed to greater CBG amounts (consequently, a stronger substitution effect), and more

digestate per hectare leading to a greater climate mitigation effect.
  - The CBG production facility modelled has a high energy demand, but smaller contribution to climate impact due to the low emission factors of Swedish electricity mix.
  - The replacement of fossil natural gas by Salix based CBG lowered climate impact by 35%–60% per MJ under the study conditions.
- Yeast oil production from Salix:
  - The GWP_{100} of yeast oil from the Salix varieties was comparable to Swedish rapeseed oil even without including the SOC sequestration effect.
  - Salix cultivation was the major source of GHG emissions in the process chain.

These findings highlight the complexity of soil-plant interactions and the need for a nuanced selection of Salix varieties based on the specific goals of the biomass plantation, be it for optimal biomass production, carbon sequestration, or a balance of both. Moreover, these findings illustrate the importance of considering the trade-offs between yield and benefits (like SOC sequestration) in bioenergy crop cultivations.

8. Future research

The process of research often sheds light on new questions, which ultimately highlights the need for even more research. The analysis presented in this thesis is based on a combination of field and laboratory scale data, literature data and a healthy dose of assumptions. The robustness and accuracy of modelling approaches and LCA are dependent on the quality of data. There are several aspects where methodology, data quality and availability are a challenge and further research is required to fill the gaps.

Data on biomass production and allocation between different plant parts within different Salix varieties is scarce. Root biomass is assumed to play a major role in soil carbon sequestration, which needs to be measured and validated by experimental data that accounts for variety and site-specific factors. Long term soil measurements will help in the calibration and validation of soil carbon models, which will help in making better predictions.

Salix varieties can differ in other variables such as albedo, physical properties, inhibitory compounds, and resistance to pest and diseases. It will be interesting to explore and quantify more such differences across varieties, differences that can influence the impacts of the system.

Temporal and spatial influences on Salix biomass also need to be explored to determine the optimal cultivation regions and management practices relative to the desired outputs of the system. The expansion of Salix cultivation requires robust predictions of expected yields across different geographical regions. There have been efforts to develop yield maps of different willow varieties across different regions in the United States by combining data from field trials with modelling approaches (Volk et al. 2018). The advancement of such projection methods of yield levels across different geographic and climatic regions will help improve the accuracy of economic and productivity assessments of cultivations contributing to reduced uncertainty for farmers and decision makers.

The accurate estimation of energy and mass flows requires data from both pilot and industrial-scale biomass conversion plants. To determine the optimal Salix variety and its effectiveness as a sustainable resource, it is essential to go beyond climate impact and consider a broader range of impact categories. Expanding methodologies to encompass ecosystem services and social impacts is crucial to prevent unintended negative consequences.

There is a potential to explore the wide diversity within the Salix family to develop varieties intended for different end uses — from fuels to chemicals (Karp 2014). As our understanding of the physiological, chemical and growth characteristics of Salix progresses along with advanced breeding techniques, Salix can be expected to play an important role in our future.

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Popular science summary

A key strategy to mitigate climate is the reduction of greenhouse gas (GHG) emissions by replacing fossil fuels with renewable and sustainable biobased alternatives for energy and materials. It is however crucial to assess the emissions from the biological alternatives to ensure that they are indeed better from a climate perspective.

Salix (commonly known as willow) is a potential source of woody biomass with favourable characteristics — fast growth, high yields, low resource requirements, and the ability to thrive on lands of lower agricultural value. Moreover, they can also improve soil quality, remove metals and pollutants from the soil and supports local biodiversity. Salix plantations are typically harvested every three years, after which they regrow from the stumps and are replanted every 25th year. Research is exploring new potential uses of Salix biomass beyond combustion, such as production of biogas and other products. Salix breeders have developed several improved varieties with distinct characteristics over the years. It is important to understand how these differences between varieties might affect the climate from the use of Salix biomass to select the optimal variety for the specific uses.

This thesis examined how different Salix varieties and their traits influences the climate when used for various processes over two rotation periods of 25 years each. The analysis included six commercial Salix varieties for three processes: (a) combustion for heat, (b) the production of compressed biomethane gas as a natural gas alternative, and (c) fermentation with yeast to produce a 'yeast oil' with characteristics similar to rapeseed oil. The climate impacts were calculated using a life cycle assessment (LCA) perspective that aims to include the GHG emissions and removals throughout every stage of the life cycle of the system. Soil carbon modelling was used to account for the changes in the carbon stored in the soil, an effect which sometimes is ignored in climate assessments. Data on the Salix varieties was obtained from a field study near Uppsala, Sweden and from laboratory analyses at SLU.

One of the most significant findings was that the cultivation of the Salix varieties contributed to an increase in soil carbon under the site conditions. This potential to fix atmospheric carbon in the soil is vital because it helps to compensate for GHG emissions in other parts of the system. Interestingly, fertilisation produced greater yields, but a lesser increase in soil carbon compared to the unfertilised case of the same variety. This challenges the common assumption that yield and soil carbon increase are directly linked to each other. The significant increase in soil carbon despite lower crop yields suggests that root contributions are a key factor in soil carbon accumulation.

The results show that Salix for biomass-based systems in Sweden has potential for significant climate benefits. When it comes to specific processes, the results showed that:

(a) Heat production from Salix biomass (expect for the variety Björn) had a cooling effect on the climate even without considering the benefits of replacing fossil fuels. The climate mitigation effect is significantly higher if Salix replaces heat produced by natural gas.
(b) For compressed biomethane production, the soil carbon effect of digestate application had a very strong climate mitigation effect as more than half of the carbon initially present in the Salix ends up in the digestate. Replacing fossil natural gas with CBG from Salix could reduce the climate impact by 35% to 60% per unit of energy.
(c) The yeast oil produced from the Salix varieties had an overall climate impact similar to that of Swedish rapeseed oil, even without factoring in SOC sequestration.

The carbon stored by the live biomass in the Salix plantations contribute to a strong but temporary cooling effect on the climate. Overall, the variety played an important role in the climate impact of using Salix biomass. The two most important factors that determined the overall climate impact were yield, and the potential to capture carbon in the soil. Higher yields mean a greater amount of biomass to turn into useful products and more replacement of conventional fossil fuels, which results in lower emissions per unit of land. The potential for carbon storage in the soil by Salix was more important from an output product perspective. The more carbon is stored in the soil, the better it is for the climate, reducing the overall impact per unit product.

Populärvetenskaplig sammanfattning

En nyckelstrategi för att mildra klimatförändringarna är att minska utsläppen av växthusgaser genom att ersätta fossila bränslen med förnybara och hållbara biobasserade alternativ för energi och material. Det är dock avgörande att kvantifiera utsläppen från de biobaserade alternativen för att säkerställa att de verkligen är bättre ur ett klimatperspektiv.

Salix är en potentiell källa till biomassa med gynnsamma egenskaper — snabb tillväxt, hög avkastning, låga resurskrav och förmåga att trivas på marker med lägre jordbruksvärde. Dessutom kan den bland annat förbättra jordkvaliteten, avlägsna metaller och föroreningar från jorden och stödja den lokala biodiversiteten. Salixodlingar skördas vanligtvis vart tredje år varefter de växer upp igen från stubbarna och planteras om vart 25:e år. Forskning undersöker nya potentiella användningar av Salix-biomassa utöver förbränning, såsom produktion av biogas och andra produkter. Växtförädlare har under åren utvecklat flera förbättrade Salix-sorter med olika egenskaper. Det är viktigt att förstå hur dessa skillnader mellan sorter kan påverka klimatet vid användning av Salix-biomassa för att hitta den mest optimala sorten för varje användningsområde.

Denna avhandling undersökte hur olika Salix-sorter och deras egenskaper påverkar klimatet när dess biomassa används i olika processer under två rotationsperioder på 25 år vardera. Analysen inkluderade sex kommersiella Salix-sorter för tre processer: (a) förbränning för värmeproduktion, (b) omvandling till komprimerad biometangas som ett alternativ till naturgas, och (c) användning av jästceller för att producera en "jästolja" med egenskaper som liknar rapsolja. Klimatpåverkan beräknades ur ett livscykelperspektiv som syftar till att inkludera växthusgas-utsläpp och -upptag under alla stadier av systemets livscykel. Markkolmodeller användes för att kvantifiera förändringar i kol som lagras i marken, en effekt som ibland ignoreras i klimatberäkningar. Data för de olika Salix-sorterna erhölls från en fältstudie nära Uppsala och från laboratorieanalyser vid SLU.

Ett av de mest betydande resultaten var att odlingen av Salix-sorterna bidrog till en ökning av markkol under förhållandena på den studerade platsen. Denna potential att binda atmosfäriskt kol i marken är viktig eftersom den hjälper till att kompensera för växthusgasutsläpp i andra delar av systemet. Intressant nog gav gödsling högre avkastning men en lägre ökning av markkol jämfört med det ogödslade fallet för samma sort, vilket utmanar den vanliga uppfattningen att avkastning och markkoökning kopplade till varandra. Detta indikerar att bidraget av kol från rötterna troligen är större vid lägre avkastning.

Resultaten visar att Salix för biomassabaserade system i Sverige har potential för betydande klimatfördelar. När det gäller de specifika processerna visade resultaten att:

(a) Värmeproduktion från Salix-biomassa (med undantag för sorten Björn) hade en kylande effekt på klimatet även utan att beakta fördelarna med att ersätta fossila bränslen. Minskningen av klimatpåverkan är avsevärt större om Salix skulle ersätta värme producerad av naturgas.

(b) För komprimerad biometan produktion bidrog markkoleffekten från rötrestanvändning till en mycket omfattande minskning av klimatpåverkan, eftersom mer än hälften av kolet som ursprungligen fanns i Salix-biomassan hamnar i rötresten. Att ersätta fossil naturgas med CBG från Salix kan minska klimatpåverkan med 35% till 60% per energienhet.

(c) Jästoljan som producerades från Salix-sorterna hade en total klimatpåverkan jämförbart med svenska rapsoljan, även utan att inkludera markkolinlagring.

Kolinlagringen i levande Salix-biomassa hade en stark men kortvarig kylande effekt på klimatet. Sammantaget spelade sorten en viktig roll för klimatpåverkan vid användning av Salix-biomassa i de olika processerna. De två viktigaste faktorerna som avgjorde sortvalets effekter på klimatpåverkan var avkastning och potentialen att binda kol i marken. Högre avkastning innebär mer biomassa att omvandla till användbara produkter och mer ersättning av konventionella fossila bränslen, vilket resulterar i lägre utsläpp per arealenhet. Potentialen för kollagring i marken var viktigare ur produktperspektivet. Ju mer kol som lagras i marken, desto bättre är det för klimatet, vilket minskar den totala påverkan per mängd produkt.

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Soil Carbon Modelling in *Salix* Biomass Plantations: Variety Determines Carbon Sequestration and Climate Impacts

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Abstract: Short-rotation coppice (SRC) *Salix* plantations have the potential to provide fast-growing biomass feedstock with significant soil and climate mitigation benefits. *Salix* varieties exhibit significant variation in their physiological traits, growth patterns and soil ecology—but the effects of these variations have rarely been studied from a systems perspective. This study analyses the influence of variety on soil organic carbon (SOC) dynamics and climate impacts from *Salix* cultivation for heat production for a Swedish site with specific conditions. Soil carbon modelling was combined with a life cycle assessment (LCA) approach to quantify SOC sequestration and climate impacts over a 50-year period. The analysis used data from a Swedish field trial of six *Salix* varieties grown under fertilized and unfertilized treatments on Vertic Cambisols during 2001–2018. The *Salix* systems were compared with a reference case where heat is produced from natural gas and green fallow was the land use alternative. Climate impacts were determined using time-dependent LCA methodology—on a land-use (per hectare) and delivered energy unit (per MJ_{heat}) basis. All *Salix* varieties and treatments increased SOC, but the magnitude depended on the variety. Fertilization led to lower carbon sequestration than the equivalent unfertilized case. There was no clear relationship between biomass yield and SOC increase. In comparison with reference cases, all *Salix* varieties had significant potential for climate change mitigation. From a land-use perspective, high yield was the most important determining factor, followed by SOC sequestration, therefore high-yielding fertilized varieties such as 'Tordis', 'Tora' and 'Björn' performed best. On an energy-delivered basis, SOC sequestration potential was the determining factor for the climate change mitigation effect, with unfertilized 'Jorr' and 'Loden' outperforming the other varieties. These results show that *Salix* variety has a strong influence on SOC sequestration potential, biomass yield, growth pattern, response to fertilization and, ultimately, climate impact.

Keywords: biomass production; life cycle assessment; climate impact; soil organic carbon; *Salix*; willow; short rotation coppice; genotypic difference

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1. Introduction

It has been established that the current atmospheric concentrations of three major greenhouse gases (GHGs)—carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), are at the highest levels estimated for the past 800,000 years [1]. Most of this increase has happened post 1750, which was the beginning of the Industrial Revolution. The most alarming trend is that the decadal rate of increase in atmospheric CO_2 was highest in 2002–2011 since direct measurements began in 1958 [2]. There is consensus among the scientific community that the principal cause of this rapid increase is use of fossil fuels and land use change associated with the start of the Industrial Age. The increased atmospheric concentration of GHGs has enhanced radiative forcing, leading to higher average global temperatures and climate change.

Countries and organizations worldwide have set certain regulations and targets to limit the increase in average global temperatures to avoid the negative impacts of climate change. The European Commission has set targets to cut GHG emissions by at least 40% below 1990 levels and to increase renewable energy share to at least 32% by 2030 [3]. The long-term strategy is to reach a climate-neutral EU by 2050 [4]. Sweden has made an ambitious commitment to phase out all GHG emissions completely by 2045 [5,6]. The climate crisis induced by increased GHG emissions has led to a quest for different strategies to mitigate the problem. Bioenergy from sustainable biomass can be part of a viable climate mitigation strategy by replacing fossil fuels for heat and electricity generation. At the global scale biomass accounted for 9% of renewable electricity generation and 96% of renewable heat generation in 2018 [7].

The cultivation of plant species such as *Salix* (willow) and *Populus* (poplar) in short-rotation coppice (SRC) systems has emerged as an interesting approach to sustainably produce renewable biomass [8,9]. *Salix* SRC systems are characterized by short growth cycles of 2–5 years, after which the stems are harvested, and shoots regrow from the stumps left in the soil [10]. SRC plantations can have a positive effect on soil organic carbon (SOC) sequestration, because of the addition of large amounts of root and leaf litter to the soil, which are better incorporated into the soil due to minimal soil disturbance compared with annual crops [11]. *Salix* propagates easily via cuttings and is well suited to growth in temperate and Arctic climatological conditions. Commercial plantations of *Salix* are gaining interest worldwide for use as a biomass crop, with the largest cultivated areas (as of 2015) in China and Argentina, followed by North America and Europe [12]. There is high interest in European countries such as Sweden, where commercial *Salix* plantations were established in the 1990s, with policies proposed to increase energy crop cultivation to 40,000 hectares by 2030 [13].

In Sweden, the area under SRC plantations reached a peak of about 18,000 hectares in the mid-1990s, which decreased to about 12,000 hectares by 2015 [14,15]. This was attributed to a combination of factors such as poor management, inefficient policy and low prices—which meant that the practical results did not meet the high expectations [16,17]. New varieties and better management practices adapted to Swedish conditions have emerged in the past two decades. These, combined with the ambitious Swedish emission reduction targets, make SRC *Salix* an interesting prospect for biomass feedstock in the Swedish context.

The SOC sequestration potential of SRC plantations is gaining attention among researchers for its climate mitigation effects. Multiple studies [18–22] have found that SRC *Salix* systems sequester more carbon than conventional cropping systems. However, the SOC sequestration of *Salix* established on grasslands is more uncertain and can be lower [23,24]. The magnitude and potential for SOC change depend on previous land use, soil and climate conditions [18,24,25]. This, combined with the different soil profile depths considered in different studies leads to variation in reported SOC stock change rates. Long-term field data, and especially those on belowground biomass production rates, are necessary to validate and improve the accuracy of SOC sequestration estimates for SRC *Salix* plantations under different growth and soil conditions.

Biomass for bioenergy utilization can be considered carbon neutral as CO_2 emitted from its conversion phase is recaptured by new growth. However, there is a need to assess the climate impact in a system perspective including changes in SOC and land use, and impacts from site preparation, production of inputs, machinery operations, transports and energy conversion. Quantification of the potential effects and impacts of biomass use over spatial and temporal horizons is needed to ensure its sustainability.

There are several tools for environmental impact evaluation, and one of the most commonly used is Life Cycle Assessment (LCA). LCA is a well-established and standardized tool for estimation of potential environmental impacts from a product or service over its whole lifespan. The LCA methodology was originally designed for industrial processes and products but has been expanded in recent decades to evaluate and compare agricultural, forestry and bioenergy processes and products [26,27]. In the context of bioenergy production system evaluation, LCA helps by expanding the perspective beyond the production system itself. This is important as the environmental consequences of a bioenergy production system frequently depend more on the impacts on other parts of the value chain than on the production system itself. Thus, the broad system perspective makes LCA a suitable tool for planning of bioenergy systems and policymaking, especially in the context of the potential effects of bioenergy production systems on climate change mitigation. However, when modelling large and often complicated systems in LCA studies, parts of the data are often more uncertain and some subjective aspects may be handled in order to reach the broad system perspectives [28,29]. These limitations are not unique to LCA, and similar problems occur even in other methods for environmental systems analysis. The decisions on data quality requirements play an important role in the results of the assessment. Ambitions about completeness of data must be balanced against availability of resources and workload. These are intrinsic and accepted aspects of LCA studies, as long as the relevance, data quality and relevant major assumptions are appropriately described [30]. The LCA methodology is constantly evolving as understanding of climate and environmental impacts develops.

The most common climate impact metric used in LCA is global warming potential (GWP_{100}), which is based on radiative forcing and captures the integrated impacts over a single time horizon of 100 years [31]. It does not capture the effect of timing and persistence of GHG fluxes and temporal changes in SOC [32]. It does not represent the actual impacts on ecosystems such as temperature change, sea level change or biodiversity loss.

Using a time-dependent method can counter this by expressing the climate metric as a function of time. Several studies have developed such alternative methods and applied them in LCA to capture the emissions and fluxes of carbon flows between the atmosphere, biomass and soil [17,32–34]. An absolute time-dependent climate metric such as the absolute global temperature change potential (ΔTs) developed by Ericsson et al. [35] represents the impact on global mean surface temperature from emission or removal of a GHG at a particular point in time. This can aid in better understanding of climate impacts of bioenergy as biomass systems capture and emit carbon at different points in time. Several LCA studies have assessed *Salix* cultivation for bioenergy utilization [17,32,33,36–40]. However, studies looking at the magnitude of impact of differences between *Salix* varieties on the overall bioenergy system are rare.

Differences between *Salix* varieties can have a significant impact on physiological traits, biomass quality, growth patterns and soil ecology. Weih and Nordh [41] showed that key traits and shoot biomass production are variety-specific and that there is a need to account for these variety differences at the field level. Adegbidi et al. [42] found that biomass production, nutrient use efficiency and nutrient removal are strongly influenced by variety in *Salix* plantations. Cunniff et al. [43] observed significant differences in allocation between aboveground and belowground biomass in different varieties and at different locations in the UK. Data from *Salix* field trials in Sweden have demonstrated that the effects of fertilization on soil ecology are also affected by variety [44]. *Salix* varieties have been found to differ significantly in their response to fertilization and in carbon storage potential in shoots and soil [44].

Despite of the many plant-and field-scale reports indicating significant impacts of *Salix* varieties on plant traits that potentially affect their environmental performance, there is a lack of systems-scale research (such as LCAs) accounting for these differences. Thus, there is a need to address the differences between *Salix* varieties regarding the impact on soil carbon sequestration and climate impact when assessing bioenergy systems in a life cycle perspective

This study aimed to analyze the effects of *Salix* variety and fertilization treatment on SOC dynamics, and subsequent effects on climate impacts of *Salix* cultivation for bioenergy on a commercial scale, with a 50-year time horizon. A field trial established in 2001 is the source of the harvest and SOC data for the selected *Salix* varieties in this study [44,45]. Unfortunately, root biomass data over time from field-grown trees were not available from the trials used here, and we therefore used indirect methods to estimate root biomass allocation over time from published reports using pot and lysimeter experiments, in which root biomass can be assessed more easily. Other data are either taken from literature and studies on *Salix* systems where available, or based on assumptions derived from other biomass systems.

Specific objectives of the study were to:

1. Estimate the potential for soil carbon sequestration for the selected *Salix* varieties under the specific site conditions of Vertic Cambisols by using soil carbon modelling;
2. Assess the climate impact from utilizing *Salix* grown on existing fallow land as feedstock in an incineration plant using two metrics—GWP_{100} and a time-dependent climate metric (ΔTs);
3. Calculate the energy balance and performance (in terms of energy ratio) for the selected *Salix* varieties.

It is expected that quantification of the magnitude of varietal effects will highlight the importance of their inclusion in systems analysis studies of bioenergy. The intention was to provide a basis for comparison of *Salix* varieties in terms of energy and climate performance, which can aid in the consideration of optimal *Salix* variety selection for a particular purpose, e.g., maximized carbon sequestration potential.

We believe that studies like this investigation will motivate the need for variety- and location-specific root and belowground data to make realistic, accurate and detailed assessments of the environmental performance of bioenergy systems.

2. Materials and Methods

The effect of *Salix* variety on the climate impact and energy performance of a *Salix*-biomass production system under Swedish conditions (Uppsala region) was analyzed using LCA methodology. Two functional units (FU) of 1 MJ of heat and 1 hectare of land were chosen to describe the two different functions of the system—generation of heat and use of land as a resource for mitigating climate impacts. The energy FU compares the relative impact of using the *Salix* varieties as an energy source, while the land FU unit compares the different impacts from a land use perspective considering land as a restricted resource.

The climate impact calculation considers three major GHGs (CO_2, N_2O and CH_4) and is expressed in terms of two metrics—global warming potential (GWP_{100}) and a time-dependent climate impact (ΔTs) as defined in [35], with a one-year time step. The flux of carbon in the soil due to addition and decomposition of biomass was modelled with the carbon model ICBM developed by Andrén and Kätterer [46]. Annual net flux of the selected GHGs was estimated for each source and sink, and the associated emission impulses were based on the timing of the emissions.

2.1. Plant Material, Field Trial and Data Collection

The analysis was based on data collected from a field trial during the period 2001−2017 at Pustnäs, near Uppsala in central Sweden by Weih and Nordh [45]. The following six commercial *Salix* varieties were part of the study: 'Björn' (*Salix schwerinii* E. Wolf. × *S. viminalis* L.), 'Gudrun' (*S. burjatica* Nasarow × *S. dasyclados* Wimm.), 'Jorr' (*S. viminalis*), 'Loden' (*S. dasyclados*), 'Tora' (*S. schwerinii* × *S. viminalis*) and 'Tordis' ((*S. schwerinii* × *S. viminalis*) × *S. viminalis*). There were two experimental treatments—fertilized (approx. 100 kg N, 14 kg P, 47 kg K ha^{-1} yr^{-1}) and unfertilized. Plots were 6.75 m × 7.00 m in size and contained 84 plants each, corresponding to a planting density of about 18,000 plants per hectare. Each variety and treatment had four replicate plots. The dominating soil type was a vertic cambisol with a sandy loam as topsoil (0–20 cm soil depth) with 66% sand, 16% silt and 18% clay. Initial SOC content at 0–10 cm soil depth was 11.1 g kg^{-1}, with a bulk density of 1.3 g cm^{-3}. Further details of the field trial can be found in Weih and Nordh [45].

After establishment of the plantation in 2001, the plantation was managed in three-year cutting cycles with shoots harvested during winter in 2004, 2007, 2010, 2013 and 2016. Mean air temperature during the growing season (April to October) in the years relevant to this study was 12.5 °C, and the corresponding mean annual precipitation sum was 841 mm [44].

For the present analysis, the average yield for the first harvest (2004) and for subsequent harvests (average value for 2007–2016 harvests) were calculated. The first yield after planting is usually lower, as the plant root system is still establishing. The shoot growth and biomass yield figures after the field measurement period (post-2017) were assumed to follow the average values calculated from the field trial data. Table 1 presents the average harvest values from the field study used as input to the modelling work.

Table 1. Average harvested biomass yield (dry weight, DW) and standard deviation (SD) of the six commercial *Salix* varieties grown under two fertilization regimes in central Sweden from 2001 to 2018. F0 and F+ refer to the unfertilized and fertilized treatment, respectively.

Variety and Treatment	1st Harvest		2nd–5th Harvest	
	Average (DW Mg ha^{-1})	SD	Average (DW Mg ha^{-1})	SD
Björn F0	7.4	3.8	31.9	8.3
Björn F+	15.5	4.3	42.7	16.0
Gudrun F0	8.8	4.1	20.8	5.9
Gudrun F+	11.6	1.2	20.6	5.2
Jorr F0	4.5	1.3	14.4	7.6
Jorr F+	16.9	0.9	36.9	6.0
Loden F0	3.9	1.2	14.4	4.1
Loden F+	10.4	4.9	18.3	10.2
Tora F0	6.7	4.7	18.2	8.7
Tora F+	16.6	6.1	38.3	11.1
Tordis F0	10.8	5.1	28.5	13.0
Tordis F+	19.8	6.4	48.5	9.0

The field site was ploughed shortly before planting of the *Salix* stem cuttings. The soil in each plot was sampled (five replicates per plot) with a soil corer (3 cm diameter), to a depth of 10 cm in spring 2001 and to a depth of 20 cm in 2018. The initial soil sampling was performed prior to laying out the plots. The field site is characterized by a flat surface without relief-promoted erosion, which contributed to the lack of significant differences in soil properties between the different plots. An additional follow-up soil sampling in 2002 showed no significant differences in the bulk density and SOC content among the plots. As such, the ploughing did not cause a measurable difference between the first (2001) and second year (2002). The SOC content in the 0–10 cm layer was recorded and is reported by Baum et al. [44], who provide full details of the soil sampling and analysis procedures.

As the plough depth was about 25 cm during the year of establishment of the field trial, the topsoil (0–20 cm soil depth) was assumed to be homogenous and to have similar characteristics. Hence, the initial SOC stock in the 10–20 cm soil layer in 2001 was assumed similar to that in the 0–10 cm soil layer. The bulk density in 2018 had not changed significantly from the initial value of 1.3 g cm^{-3}, which can be expected as consequence of combined lack of loosening by tillage under the perennial crops, but improved aeration of the soil by increased SOC content. The SOC stock in the 10–20 cm soil layer from 2018 was analyzed following the same methodology as was described by Baum et al. [44] for the 0–10 cm soil layer. The resulting SOC stocks in the 0–10 cm, 10–20 cm and 0–20 cm layers in 2001 and 2018 are displayed in Table 2. The reduction in SOC content in the 10–20 cm layer for some of the *Salix* varieties is not unexpected under SRC as evidenced by similar results reported by Kahle et al. [47].

Table 2. Soil organic carbon stock (Mg ha^{-1}) in the 0–10 and 10–20 cm soil layers measured in field trials on six *Salix* varieties at Pustnäs, Sweden, in 2001 (pre-establishment) and in 2018. F0 and F+ refer to the unfertilized and fertilized treatments respectively.

Variety and Treatment	Soil Carbon Stock 2001 (Mg ha^{-1})			Soil Carbon Stock 2018 (Mg ha^{-1})			Increase in SOC Stock (Mg ha^{-1})
	0–10 cm	10–20 cm	0–20 cm	0–10 cm	10–20 cm	0–20 cm	0–20 cm
Björn F0	14.4	14.4	28.9	24.3	15.3	39.7	10.8
Björn F+	14.4	14.4	28.9	20.9	12.1	33.0	4.2
Gudrun F0	14.4	14.4	28.9	22.3	21.3	43.6	14.7
Gudrun F+	14.4	14.4	28.9	21.9	12.8	34.8	5.9
Jorr F0	14.4	14.4	28.9	31.7	18.6	50.3	21.5
Jorr F+	14.4	14.4	28.9	27.5	14.3	41.8	12.9
Loden F0	14.4	14.4	28.9	26.8	17.3	44.2	15.3
Loden F+	14.4	14.4	28.9	20.5	12.7	33.2	4.4
Tora F0	14.4	14.4	28.9	25.4	16.1	41.6	12.7
Tora F+	14.4	14.4	28.9	25.8	14.2	40.0	11.2
Tordis F0	14.4	14.4	28.9	26.9	16.9	43.9	15.0
Tordis F+	14.4	14.4	28.9	23.9	14.6	38.5	9.6

2.2. System Boundaries

The system studied comprised the steps from preparation of the field site for *Salix* cultivation to production of heat in a boiler in a heating plant (Figure 1). Energy flows and emissions from field operations, production of inputs, biomass transportation and thermochemical conversion were included within the system boundaries. Downstream losses and emissions after production of heat and ash at the incineration plant were considered as outside the system boundaries. Belowground changes and biomass inputs (from leaf, stumps, fine roots and coarse roots) to 20 cm depth were within the system boundaries as the SOC values from the field studies were determined with accuracy within the 0–20 cm soil layer. Highest litter input from fine roots and leaf litter are within this soil profile [48]. As the SOC changes in the sub-20-cm-profile are not part of the study system, a higher total carbon sequestration in the complete soil profile can be assumed.

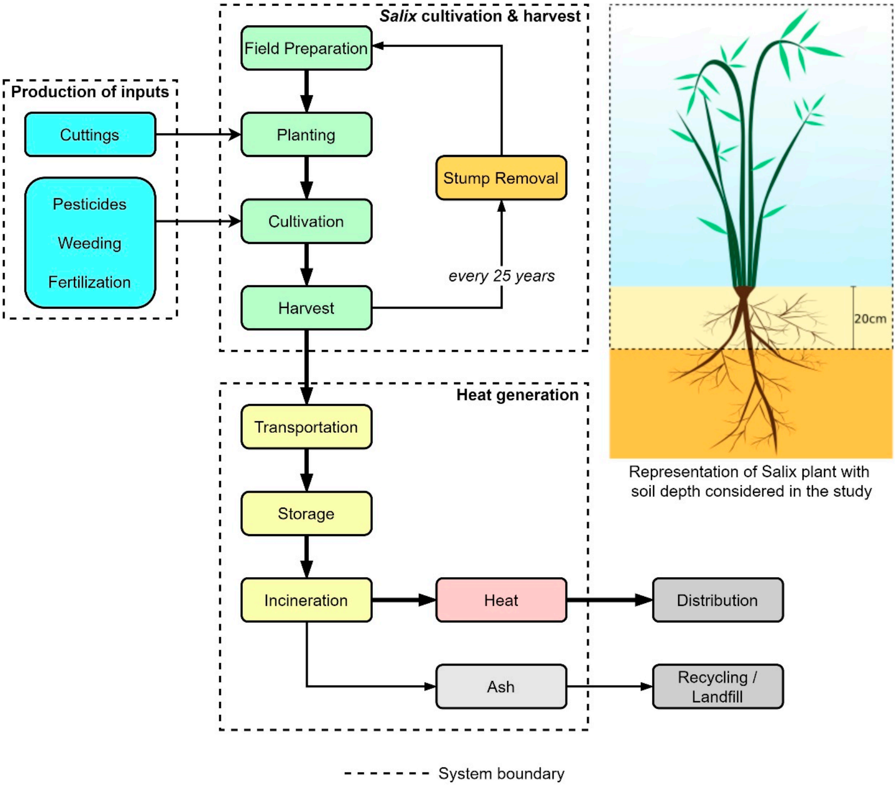

Figure 1. System boundaries (dotted lines) showing the processes considered within the study. Greenhouse gas and energy fluxes associated with the processes within the system boundaries were included in the analysis.

2.3. Field Operations and Management

The SRC *Salix* system followed a typical three-year cutting cycle, with the *Salix* harvested and chipped on-site at the end of every third growth cycle. The *Salix* then regrew from the stumps left in the field. According to current practical recommendations [49], one rotation period was assumed to last 25 years, after which the stumps would be broken up and removed and a new rotation would be established with new cuttings. The study period for the system was set to 50 years, which resulted in two rotation cycles. Technologies and management practices were assumed unchanged during this period. The data and assumptions used to calculate energy and emissions associated with the production of inputs and processes can be found in the Supplementary Material (Tables S6 and S7).

The harvest period for SRC systems is usually during winter months because the biomass is drier, the plant is dormant and the hard frozen soil provides a higher machinery carrying capacity [49,50]. It was assumed that the conventional method of harvesting and direct chipping was followed. Thereafter, the chips were transported to a heating plant for production of heat. The average road transportation distance was set as 40 km in this study.

2.4. Thermochemical Conversion

The higher heating value (HHV) of the *Salix* chips was considered to be 19.9 GJ/Mg DM (dry and ash-free), based on which the lower heating value (LHV) adjusted for moisture content was calculated [51,52]. The average storage period of the chips was 30 days, during which 3% dry matter loss occurred. The heating plant produces heat from biomass incineration and is equipped with flue gas condensation, which raises the overall efficiency. The energy efficiency for heat and flue gas condensation is 84% and 10% respectively (LHV basis), which gives an overall energy efficiency of 94%. The ash produced from biomass incineration was assumed to be transported by road for an average distance of 100 km. Calculation of ash quantities was on ash content of 3% in the *Salix* biomass [53]. The downstream processing and end-use of the ash were deemed outside the system boundaries.

2.5. Reference System

The reference energy system in this study was a fossil fuel-based energy generation system. A natural-gas-powered incineration plant supplied heat equivalent to the amount generated in the same year from the SRC *Salix* system. The alternative land use scenario was green fallow. The modelled SOC increase and use of fossil fuel for topping the land annually were included in the LCA. Assumptions concerning emissions and energy modelling are included in the Supplementary Material (Table S8).

2.6. Energy Performance Indicator

Energy performance was quantified by the indicator energy ratio (*ER*), which is the ratio between the delivered usable energy (thermal energy in this case) and the total primary energy input to the system [54,55]:

$$ER = \frac{Delivered\ energy\ (E_{out})}{Energy\ Inputs\ (E_{in})} \tag{1}$$

The delivered energy (E_{out}) is the energy produced (as heat) from the heating plant. Energy inputs (E_{in}) is the sum of all primary energy inputs associated with field processes and management, machinery operation, and production of inputs (fertilizers, pesticides and cuttings). E_{in} excludes the energy contained in the *Salix* biomass produced by cultivation.

This means that the losses in the thermochemical conversion process are excluded, but they indirectly reduce the delivered energy (E_{out}). The ER metric is dimensionless and describes the useful energy produced per unit of energy consumed.

2.7. Mineral Fertiliser

Addition of nitrogen in the form of mineral fertilizers and biomass entering the soil lead to direct and indirect emissions of N_2O. The amount of fertilizer was set according to the levels used in the field studies, where all fertilized treatment plots received 100 kg N, 14 kg P, 47 kg K per hectare annually, excluding the year of establishment [44].

The direct (N_2O_{direct}) and indirect ($N_2O_{indirect}$) emissions were calculated as:

$$N_2O_{direct} = EF_N \cdot \left(N_{applied} + N_{litter} + N_{roots}\right) \cdot \frac{44}{28} \tag{2}$$

$$N_2O_{indirect} = N_{applied} \cdot (F_A \cdot EF_D + N_{leached} \cdot EF_L) \cdot \frac{44}{28} \tag{3}$$

where $N_{applied}$ is the nitrogen applied by mineral fertilizer, N_{litter} and N_{roots} is the nitrogen contained in aboveground litter and roots respectively, and $N_{leached}$ is the nitrogen lost by leaching. EF_N, EF_D and EF_L are emission factors for direct emissions from applied nitrogen, indirect emissions from volatilization and re-deposition, and leaching respectively. F_A represents the fraction of applied nitrogen emitted as ammonia. The fraction $\frac{44}{28}$ converts nitrogen to N_2O. The emissions are calculated using default parameter values from IPCC [56], and are presented in Table A1, Appendix A. The same methodology was followed to calculate emissions from the fallow reference case.

N_2O emissions from biomass residues were based on the nitrogen content in *Salix* leaf litter reported for the selected varieties by Weih and Nordh [41] (details in Table S4 in Supplementary Material) and for stems as 0.43% (of total solids) [41]. Root nitrogen content was calculated from a dataset by Manzoni et al [57]. The estimated mean nitrogen content of roots from plants with low and high fertilization was 0.83% and 1.76% (of total solids) respectively (Table S5 in Supplementary Material). There are few studies on nitrogen content between different plant components, especially among different *Salix* varieties.

2.8. Soil Carbon

Soil carbon balances were calculated using the regional Introductory Carbon Balance Model (ICBMr) [46,58]. While the field trials provide measured SOC change for the first 17 years, the soil carbon modelling was used to estimate the SOC sequestration over the study period of 50 years. The model calculates the carbon flux based on variable annual inputs and regional differences. The ICBM model compartmentalizes the soil carbon into two pools, a young pool (Y) and an old pool (O), and the dynamics are governed by five parameters (i, k_y, k_o, h and r_e). The annual carbon input, denoted i, enters the young pool primarily in the form of leaf litter and dead roots. Both the young and old carbon pools undergo decomposition according to first-order kinetics as determined by decay constants k_y and k_o, respectively. The humification coefficient h denotes the fraction of the young pool that enters the old pool, while the remainder returns to the atmosphere as CO_2 emissions. The variable r_e represents the effect of external factors (mostly climatic and edaphic) on the decomposition rates. The initial calibration of the model was carried out using data from the Ultuna long-term field trial [59]. The ICBM parameters from the long-term trials are the basis of the parameters used in our study for SOC modelling as the long-term field trials are in the same region as our study.

The humification factor (h) varies depending on biomass quality and studies have indicated that roots can contribute more to SOC than aboveground residues [60]. *Salix* fine roots specifically have been shown to have higher turnover rates [48]. Therefore, the model was modified to represent the two different input biomass types—aboveground inputs (i_a) and belowground inputs (i_b), with separate humification coefficients (h_a and h_b). Hence, there were two parallel young pools, a young pool representing the aboveground biomass input (Y_a) and a young pool representing the belowground input (Y_b). Equations (4) and (5) were used to calculate the SOC stock with an annual time step:

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

$$\begin{aligned} O(t) = {} & \left(O_{t-1} - \left(\frac{h_a.k_y}{(k_o - k_y)}\left(Y_{a_{t-1}} + i_{a_{t-1}}\right) + \frac{h_b.k_y}{(k_o - k_y)}\left(Y_{b_{t-1}} + i_{b_{t-1}}\right)\right)\right) \cdot exp^{-k_o r_e} \\ & + \left(\frac{h_a.k_y}{(k_o - k_y)}\left(Y_{a_{t-1}} + i_{a_{t-1}}\right) + \frac{h_b.k_y}{(k_o - k_y)}\left(Y_{b_{t-1}} + i_{b_{t-1}}\right)\right) \cdot exp^{-k_y r_e} \end{aligned} \tag{5}$$

The aboveground input, i_a, consists of the leaf litter. The belowground input, i_b, consists of the yearly fine root turnover and the accumulated coarse roots and stumps broken up and added to the soil after each 25-year rotation. The sum of the young and old pools represents the total SOC content at the specific point in time. Based on Kätterer et al. [60], h_b was assumed to be 2.3 times the value of h_a. The parameters were estimated from previous SOC studies [17,33,35,38] on *Salix* using the same methodology. The parameter details of the ICBM model are included in supplementary material (Tables S1 and S2).

2.9. Biomass Production Allocation

The standing biomass in *Salix* plants was divided into two major pools, aboveground and underground. The aboveground pool consisted of the stems (S) and leaves (L), while the underground pool consisted of the fine roots (F) and coarse roots (C). The stump material was included in the coarse root pool. The biomass growth allocation for these pools in a 3-year growing cycle are included in the Supplementary Material (Table S3). The ratio of 3-year accumulated net primary production (NPP) of aboveground biomass to belowground biomass, denoted as η was calculated as:

$$\eta = \frac{S+L}{F+C} = \frac{(1+a)S}{(1+b)F} \tag{6}$$

where S, L, F and C are the net production of stems, leaves, fine roots and coarse roots (including stumps), respectively over the 3-year cutting cycle period, a is the ratio of leaves to stems and b is the ratio of coarse roots to fine roots.

The differences in growth patterns between the various *Salix* varieties and treatments can be expected to lead to variation in values of η between them. Thus, varying the ratio η would lead to different input parameters (i_a and i_b), resulting in different SOC values calculated by the ICBM model. This would lead to differences in biomass input between the varieties and variations in SOC accumulation. The ratios a and b were determined from lysimeter studies on *Salix* growth by Rytter [61] to be 0.244 and 0.238, respectively, and are considered to remain unchanged between the different *Salix* varieties. Introduction of the factor η was an attempt to represent the impact of genetic differences between *Salix* varieties on plant growth and biomass allocation.

Rytter and Hansson [62] found that around 70% of total fine root biomass lies in the upper 20 cm of the soil profile. Based on this, annual root biomass input in the 0–20 cm soil layer was set to 70% of annual root NPP. For the equivalent green fallow reference case, the root biomass was 60% of the root NPP in the 0–20 cm layer [63].

The ICBM model was used to calculate the SOC change in the 0–20 cm soil layer for the 17-year period. The above-to-below ground accumulation ratio (η) was adjusted until the calculated SOC values from the ICBM model matched the measured SOC values from the field trials for all six varieties and treatments. The η values obtained by this method are presented in Table 3.

Table 3. Ratio of aboveground to belowground biomass accumulation (η) over 3-years for the different *Salix* varieties and treatments obtained from optimization of the ICBM soil carbon model with field-based soil organic carbon measurements. F0 and F+ refer to the unfertilized and fertilized treatments respectively.

Parameter	Treatment	Björn	Gudrun	Jorr	Loden	Tora	Tordis
η	F0	1.80	0.85	0.40	0.55	0.80	1.20
	F+	8.00	1.85	1.85	2.00	2.30	3.75

2.10. Climate Impact

In the normalized GWP_{100} metric, the cumulative warming potential of a GHG emission is represented relative to that of CO_2 for a 100-year period [64] and expressed in CO_2-equivalents. The emissions of CO_2, CH_4 and N_2O are multiplied by their respective characterization factors and summed to arrive at the total GWP_{100}. While this is a simplified and popular metric for representation of climate impacts, GWP_{100} does not capture the effects of timing of the emissions and their absolute impacts on the ecosystem [30,54].

Absolute global temperature change potential (AGTP), also referred to as ΔTs, is a metric that takes into account the timing of emissions and represents the climate impact as a change in temporal global mean surface temperature [65]. Using an absolute metric like AGTP displays the climate impact from a GHG emission as change in temperature (ΔTs), which approaches the actual physical effect on global temperature but increases uncertainty. This time-dependent LCA methodology, developed by Ericsson et al. [35], was used here as a climate impact indicator in addition to GWP_{100}.

Emission of a GHG at a particular point in time leads to a change in its atmospheric concentration which affects the radiative forcing (RF). This leads to a change in the energy balance on Earth, which results in an increase or decrease in temperature represented as ΔTs [35,56]. GHGs vary in their radiative efficiency and atmospheric residence time, e.g.,

N_2O and CH_4 have atmospheric residence times of 12.1 and 12.4 years, respectively, while CO_2 stays in the atmosphere until it is absorbed by the ocean or biosphere [66]. The lifetime of CO_2 is modelled based on the Bern carbon cycle. The temperature response of a GHG ($AGTP_x$) is defined as:

$$AGTP_x(H) = \int_0^H RF_x(t) R_T(H-t)dt \left(\mathrm{K\ kg_{gas}}^{-1} \right) \quad (7)$$

which represents the complex interaction between radiative forcing (*RF*) and the temperature response function (R_T) caused by a unit change in RF due to a pulse emission of a GHG '*x*' at a specific time interval (*t*), and '*H*' is the timeframe of the study. The parameter R_T captures the change in temperature due to the change in RF because of emission or uptake of a GHG (*x*) from the atmosphere at time interval (*t*). Integrating over the studied period '*H*' gives the temperature response for a particular GHG ($AGTP_x$) in terms of K kg_{gas}^{-1}. The overall temperature response (ΔTs, measured in K) is the summation of the AGTP of the individual GHG emissions over the study timeframe '*H*'. A detailed explanation of the methodology is given in Ericsson et al. [35].

The time-dependent climate impact methodology requires the creation of an inventory of GHG emissions and uptakes distributed over time of the study. Individual temperature responses of each emission are calculated from this inventory. The total system response (ΔTs) is obtained by summing the individual responses and can be plotted as the change in temperature over time.

2.11. Sensitivity Analysis

Even with accurate data collection and standardized methods, uncertainties are unavoidable due to the multiple assumptions and variability involved in modelling and LCA approaches. Sensitivity analysis makes it possible to understand how different factors influence the final results of the analysis [67].

The setting of the system boundary to 20 cm of soil depth is a source of uncertainty. This is a type of parameter uncertainty and model uncertainty, as change in depth of soil profile changes the system boundaries of the model and related parameters such as SOC values and inputs from BGB. To assess how a greater soil profile would influence the SOC modelling and climate impacts from the different *Salix* varieties, a one-at-a-time sensitivity analysis was performed. The system boundary was adjusted to include a soil depth of 25 cm and related parameter of below ground input (i_b) and initial and final SOC values were changed, while other parameters in the analysis remained constant. The average plough depth of 20–25 cm was the motivation for limiting the soil profile depth, as the subsoil characteristics at the site (both before and after establishment of *Salix*) were not known.

In soil carbon modelling, the average SOC stock in the 20–25 cm layer was estimated to be half of the stock in the 10–20 cm layer for each of the varieties described in the previous sections. The root biomass input for *Salix* and the reference fallow case was 80% and 65% of the annual belowground NPP, respectively based on studies of root distribution for *Salix* [48] and grasses [63,68]. The root distribution is subject to variability due to factors such as soil and climate, and hence is a potential source of uncertainty.

3. Results

3.1. Energy Use and Efficiency

Regarding energy performance, the fertilized treatments of varieties 'Tordis', 'Björn', 'Tora' and 'Jorr' performed best in the ambient conditions, with ERs (GJ_{out} GJ_{in}^{-1}) of 28.2, 26.5, 25.1 and 24.7, respectively (Table 4). Among the unfertilized varieties, 'Tordis' and 'Björn' gave the best energy performance, with ERs of 47.7 and 48.2, respectively. Average annual net heat output varied from 69 to 234 GJ ha^{-1} $year^{-1}$ between the different *Salix* varieties and treatments. Fertilized 'Tordis' had the highest primary energy input of all the varieties as it had the highest yield levels, leading to high biomass and heat output

(234 GJ ha^{-1} $year^{-1}$). Fertilization of 'Gudrun' and 'Loden' did not lead to major improvement in their yield over the unfertilized treatment, which resulted in relatively poor energy performance of the fertilized treatment of these two varieties. Among the unfertilized treatments, the variety 'Björn' had the highest annual heat output, 150 GJ ha^{-1} $year^{-1}$. The energy output from the heating plant is directly proportional to the biomass yield, which was higher when the plots were fertilized. Hence, the energy outputs in the form of heat were consistently higher for the fertilized treatment compared with the unfertilized treatment. The primary energy input for the fertilized treatment of each variety was about 2.5–4.6 higher than in the equivalent non-fertilized treatment. Consequently, ERs for the unfertilized cases was much higher than in the fertilized cases.

Table 4. Primary energy input, heat output, energy in biomass and energy ratio for the six SRC *Salix* varieties in fertilized and unfertilized treatments during two rotation periods (years 0–50). F0 and F+ refer to the unfertilized and fertilized treatments, respectively.

Variety and Treatment	Energy in Biomass (GJ ha^{-1})		Primary Energy Input (GJ ha^{-1})		Net Heat Output (GJ ha^{-1})		Energy Ratio (GJ_{out} GJ_{in}^{-1})
	Total	Annual Average	Total	Annual Average	Total	Annual Average	
Björn F0	8245	165	156	3	7518	150	48.2
Björn F+	11252	225	388	8	10259	205	26.5
Gudrun F0	5525	111	110	2	5038	101	46.0
Gudrun F+	5562	111	290	6	5071	101	17.5
Jorr F0	3769	75	79	2	3437	69	43.3
Jorr F+	9834	197	364	7	8967	179	24.7
Loden F0	3757	75	79	2	3426	69	43.2
Loden F+	4956	99	280	6	4519	90	16.1
Tora F0	4789	96	97	2	4366	87	45.1
Tora F+	10177	204	369	7	9279	186	25.1
Tordis F0	7526	151	144	3	6863	137	47.7
Tordis F+	12859	257	415	8	11725	234	28.2

The contribution of the individual cultivation, transportation and handling processes to the total primary energy input over the study period are described in Table 5. The primary energy associated with pesticides, field preparation, production and planting of seedlings, and stump removal were the same for all six *Salix* varieties and treatments, as these processes are independent of variety type and fertilization. These are presented on a per hectare basis. The processes of harvesting, chipping, forwarding and transportation are directly proportional to the amount of shoot biomass produced, and hence are presented on basis of per GJ of energy in biomass. Production and spreading of fertilizers were the greatest contributor to primary energy input for fertilized cases, while it was zero for non-fertilized cases.

Table 5. Primary energy inputs by process category associated with the bioenergy system of six *Salix* varieties in fertilized and unfertilized treatments over the 50-year study period.

Process	Energy (GJ ha^{-1})	Unit
Pesticides [a]	4	GJ ha^{-1}
Field preparation [a]	6	GJ ha^{-1}
Planting & seedlings [a]	4	GJ ha^{-1}
Stump removal [a]	1	GJ ha^{-1}
Fertilizer [b]	0 or 180	GJ ha^{-1}
Harvest & chipping [c]	7.33×10^{-3}	GJ $GJ_{biomass}^{-1}$
Forwarding (field transport) [c]	3.58×10^{-3}	GJ $GJ_{biomass}^{-1}$
Road transport [c]	6.22×10^{-3}	GJ $GJ_{biomass}^{-1}$

[a] Processes which are equal for all varieties. [b] Primary energy associated with fertilization is zero for the unfertilized treatment. [c] These processes are proportional to the amount of biomass produced in the field.

3.2. Soil Organic Carbon

Soil carbon modelling results showed that all varieties and treatments led to an increase in SOC over the initial level in the topsoil (0–20 cm) during the study period (50 years) consisting of two rotation periods (Table 6). The SOC stock calculated by the ICBM model at the end of both the first rotation period (after 25 years) and second rotation period (after 50 years) are shown in Table 6. Fertilized 'Loden' and 'Björn' showed the lowest net increase in SOC during the 50-year period, 15.8 and 13.3 Mg ha^{-1}, respectively. These values were only slightly greater than the SOC increase for the fallow reference case (9.5 Mg C ha^{-1}).

Table 6. Initial, total and net soil organic carbon increase in the 0–20 cm soil layer after two rotation periods (50 years), as calculated by the ICBM soil carbon model. F0 and F+ refer to the unfertilized and fertilized treatments, respectively.

Variety and Treatment	Initial SOC Stock (0–20 cm) (Mg ha^{-1})	SOC Stock after 25 Years (0–20 cm) (Mg ha^{-1})	Total SOC Stock after 50 Years (0–20 cm) (Mg ha^{-1})	Net SOC Increase (0–20 cm) (Mg ha^{-1})	Annual SOC Increase (0–20 cm) (Mg ha^{-1} yr^{-1})	Change in SOC after 50 Years (%)
Björn F0	28.9	52.0	66.1	37.2	0.74	129
Björn F+	28.9	37.2	42.2	13.3	0.27	46
Gudrun F0	28.9	60.4	79.4	50.5	1.01	175
Gudrun F+	28.9	42.1	49.8	20.9	0.42	73
Jorr F0	28.9	74.6	102.4	73.6	1.47	255
Jorr F+	28.9	56.7	73.7	44.9	0.90	155
Loden F0	28.9	61.1	80.4	51.5	1.03	178
Loden F+	28.9	38.9	44.6	15.8	0.32	55
Tora F0	28.9	57.3	74.3	45.5	0.91	158
Tora F+	28.9	52.3	66.6	37.7	0.75	131
Tordis F0	28.9	60.4	79.6	50.7	1.01	176
Tordis F+	28.9	48.7	60.9	32.1	0.64	111
Reference-Fallow	28.9	34.3	38.4	9.5	0.19	33

The carbon modelling results also showed that the unfertilized treatment for each variety was able to sequester about 1.6 to 3.3 times more SOC than the fertilized case, except for 'Tora'. Both treatments of 'Tora' led to a similar increase in SOC stock in the topsoil.

The low-yielding variety 'Jorr' showed the greatest potential for net carbon sequestration, capturing 73.6 Mg C ha^{-1} and 44.9 Mg C ha^{-1} over 50 years in the unfertilized and fertilized treatments, respectively. The variety 'Gudrun' had similar biomass yields for both the fertilized and unfertilized treatments (Table 1), but net SOC increase in the unfertilized case was almost double that in the fertilized case. 'Björn' had high biomass yields, but the SOC increase was at the lower end of the spectrum. Thus, no clear correlation between biomass yield and net SOC increase was established. These results indicate that the impacts on SOC are variety-specific, and that fertilization in general leads to lower net SOC increase.

3.3. Time-Dependent Climate Impact

3.3.1. Impact Per Hectare of Land (Including Substitution Effects)

All *Salix* varieties and treatments gave a negative temperature response (ΔTs) over the study period, which equated to a lowering of the global mean temperature when substituting reference fossil energy (natural gas) and reference land use (fallow) (Figure 2). There was great variation in temperature response between the varieties, from -2.15×10^{-10} K ha^{-1} for fertilized 'Loden' to -5.99×10^{-10} K ha^{-1} for fertilized 'Tordis'. Fertilized 'Tordis', 'Björn', 'Tora' and 'Jorr' had the greatest negative ΔTs per hectare of land, which is explained by the high levels of yield combined with an increase in SOC stocks. These cases represent the best use of land area under the study conditions for climate change mitigation.

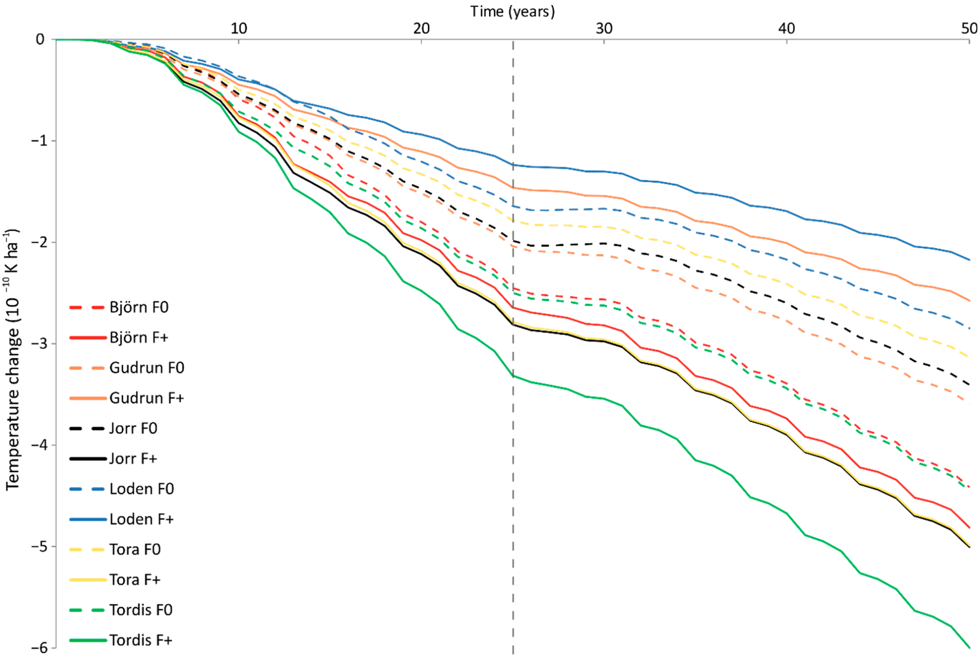

Figure 2. Time-dependent temperature response of the *Salix* SRC systems with substitution effects included. The vertical dashed line represents the end of the first rotation and start of the second (at 25 years). F0 and F+ refer to the unfertilized and fertilized treatments, respectively.

Although the unfertilized treatment of each variety had greater CO_2 sequestration potential, the increase in biomass output achieved by fertilization led to higher replacement of fossil energy. As a result, fertilized cases had lower ΔTs values. 'Loden' and 'Gudrun' were exceptions, as their fertilized cases showed a greater temperature response than the unfertilized cases. These two varieties gained little to no improvement in their yield from fertilization, so the additional energy and material input through fertilization led to a lower climate mitigation potential.

3.3.2. Impact Per Unit of Heat Output (Including Substitution Effects)

A different picture emerges when the climate impacts from all cases were expressed based on their function of delivering energy services (per MJ_{heat}) and replacing fossil-generated heat (Figure 3). Unfertilized 'Jorr' showed the greatest climate mitigation effect (-5.11×10^{-15} K MJ^{-1}), while fertilized 'Björn' (-2.39×10^{-15} K MJ^{-1}) had the lowest. The non-fertilized varieties showed a greater negative temperature response (per MJ_{heat}) than the fertilized varieties. This can be attributed to the higher primary energy demand for the fertilized treatments, combined with the greater SOC increase for the unfertilized cases.

The unfertilized cases were more favorable for climate change mitigation on comparing when the climate impacts per unit of energy delivered (MJ_{heat}) by the biomass systems. This is relevant when comparing energy generation systems and land is not a restricted resource. Unfertilized 'Jorr' and 'Loden' were the best-performing varieties in terms of potential for temperature reduction per unit of energy, although they had the lowest biomass yield. Fertilized 'Loden', 'Gudrun' and 'Björn' had the lowest temperature decrease (ΔTs per MJ_{heat}) over the study period. Those cases also had the lowest SOC increase over the study period.

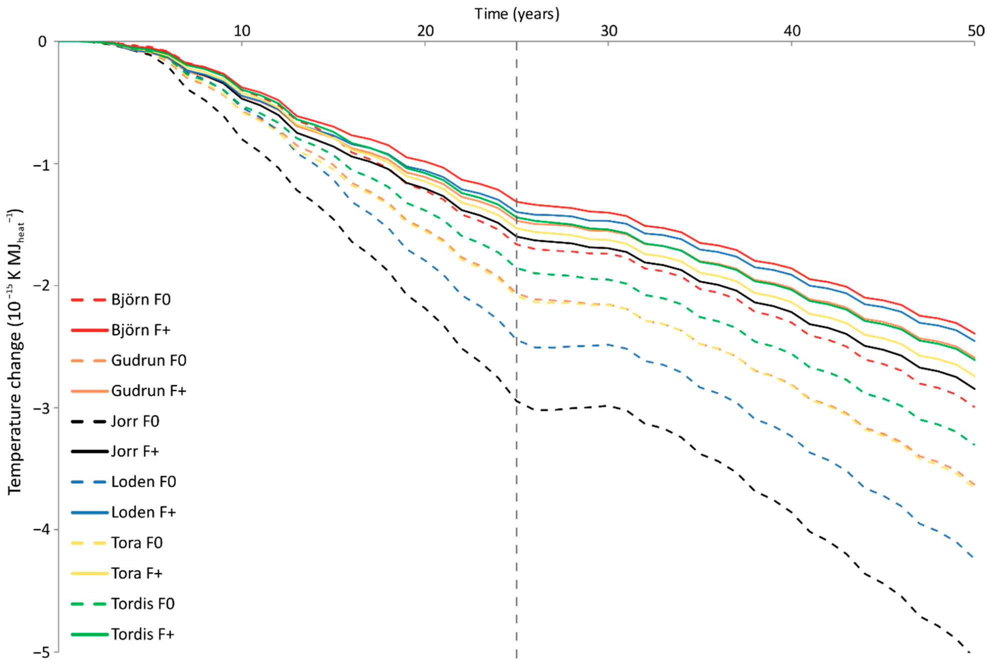

Figure 3. Temperature response per MJ of heat for the *Salix* SRC systems, with substitution effects included. The vertical dashed line represents the end of the first rotation and start of the second (at 25 years). F0 and F+ refer to the unfertilized and fertilized treatments, respectively.

3.4. Global Warming Potential

The life cycle impact assessment of the different varieties under the two fertilization regimes showed varying climate impacts. A negative value of the GWP_{100} metric means that there is a net reduction of atmospheric GHG concentration, leading to a climate mitigation effect. In absolute terms (not including the effect of substituting the reference case), unfertilized 'Jorr' had the lowest GWP_{100} (−333 Mg CO_2-eq. ha^{-1}), while fertilized 'Björn' had the highest total GWP_{100} (30 Mg CO_2-eq. ha^{-1}) (Table 7).

Among the fertilized varieties, 'Björn' and 'Loden' were the worst performing in terms of climate mitigation effects per hectare over 50 years. These varieties had the lowest increase in SOC among the fertilized varieties, which contributed to their poorer climate performance. Fertilized 'Tora' and 'Jorr', which had the highest increase in SOC among fertilized varieties, showed the greatest reduction in GWP, indicating the importance of soil carbon sequestration for achieving a climate change-mitigating effect.

Considering the effects of substitution of a natural gas-based reference system for the SRC *Salix*, all varieties showed a climate-mitigating effect during the study period. The magnitude of the mitigation effect ranged from −312 Mg CO_2-eq.ha^{-1} for fertilized 'Loden' to −858 Mg CO_2-eq. ha^{-1} for fertilized 'Tordis'. On considering the substitution effects, the yield level influenced GWP. High yields contributed to a greater climate mitigation effect, as seen for fertilized 'Tordis', 'Björn', 'Jorr' and 'Tora'. This is a result of avoided equivalent emissions from heat produced in the fossil reference system.

Table 7. Global warming potential (GWP_{100}) for the *Salix* cropping systems and fossil-powered reference system and effect of substitution when *Salix* was assumed to replace the reference system. The GWP is expressed in both Mg CO_2-eq per hectare and g CO_2-eq per MJ of heat during the 50-year study period. F0 and F+ refer to the unfertilized and fertilized treatments, respectively. A positive value indicates emissions to atmosphere, and a negative value indicates reduction.

Variety and Treatment	Global Warming Potential (GWP_{100})					
	SRC System [a]		Reference System [b]		Substitution Effect [c]	
	Mg ha^{-1}	g MJ^{-1}	Mg ha^{-1}	g MJ^{-1}	Mg ha^{-1}	g MJ^{-1}
Björn F0	−143	−19	514	68	−657	−87
Björn F+	30	3	707	94	−677	−91
Gudrun F0	−220	−44	339	67	−558	−111
Gudrun F+	−31	−6	340	68	−372	−74
Jorr F0	−333	−97	225	65	−558	−162
Jorr F+	−114	−13	616	179	−730	−192
Loden F0	−231	−68	225	66	−456	−133
Loden F+	−10	−2	301	88	−312	−90
Tora F0	−198	−45	291	67	−489	−112
Tora F+	−84	−9	638	146	−722	−155
Tordis F0	−210	−31	467	68	−678	−99
Tordis F+	−47	−4	811	118	−858	−122

[a] Climate impact of SRC *Salix* system without substitution effect. [b] Climate impact of reference system—heat from natural gas and green fallow land use. [c] Climate impact of SRC *Salix* system including substitution effects of reference system.

From the perspective of heat delivered with substitution effects, fertilized 'Jorr' had the highest climate mitigation effect, −192 g CO_2-eq.MJ_{heat}^{-1} produced, while fertilized 'Gudrun' was at the other end of the spectrum, with −74 g CO_2-eq.MJ_{heat}^{-1} produced.

The contribution of the *Salix* production chain emissions, SOC sequestration and substitution effects to the overall net GWP_{100} per hectare for the different *Salix* varieties are presented in Figure 4. The production chain leads to GHG emissions while SOC sequestration and substitution effects remove or replace GHG emissions. Emissions from the production chain (field operations, transportation, fertilizer and soil emissions) are higher for fertilized varieties due to fertilizer production and greater soil N_2O emissions. The substitution effects are the main contributor to the overall negative GWP_{100} for all *Salix* varieties, except for unfertilized Loden and Jorr. These two varieties showed a greater potential of SOC sequestration relative to harvest yields in comparison to the other *Salix* varieties. Alternatively fertilized Gudrun and Loden have a higher GWP_{100} compared to their unfertilized counterparts due to relatively lower improvement in yield.

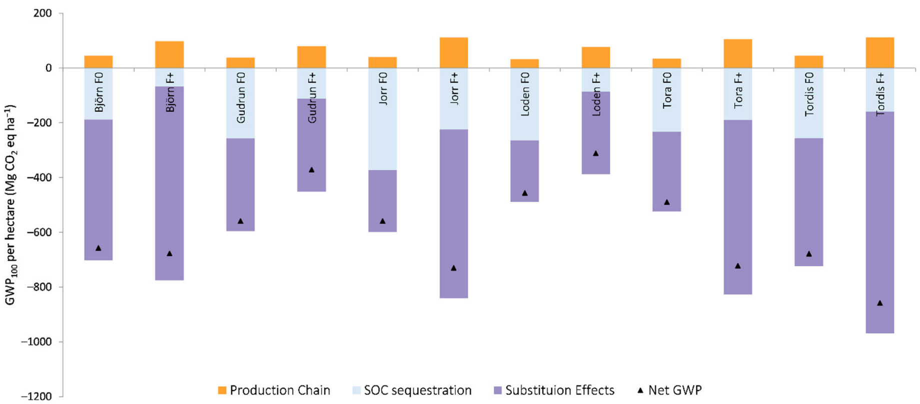

Figure 4. Contribution of the *Salix* production chain, SOC sequestration, substitution effects (from replacing green fallow and fossil energy) to the net GWP_{100} per hectare of each of the *Salix* bioenergy system.

3.5. Sensitivity Analysis

The sensitivity analysis results for net SOC increase and climate impacts (GWP_{100}) from considering a soil depth of 25 cm, compared with the base case of 20 cm, are shown in Table 8. Generally, a deeper soil layer gave a greater net SOC increase within the system boundary, leading to a lower climate impact. Fertilized 'Björn', 'Gudrun' and 'Loden' were exceptions to this, as the net SOC increase in the 0–25 cm layer was smaller than in the 0–20 cm layer. Consequently, the climate impacts for these three cases were also greater.

Table 8. Sensitivity analysis of soil organic carbon (SOC) sequestration and global warming potential (GWP_{100}) for the six *Salix* varieties in the fertilized and unfertilized treatments, when soil depth considered was increased from 20 to 25 cm. F0 and F+ refer to the unfertilized and fertilized treatments, respectively.

Variety and Treatment	0–20 cm Soil Layer				0–25 cm Soil Layer			
	Net SOC Increase	Annual SOC Uptake	GWP_{100}	GWP_{100}	Net SOC Increase	Annual SOC Uptake	GWP_{100}	GWP_{100}
	(Mg ha^{-1})	(Mg ha^{-1} yr^{-1})	(Mg ha^{-1})	(g MJ^{-1})	(Mg ha^{-1})	(Mg ha^{-1} yr^{-1})	(Mg ha^{-1})	(g MJ^{-1})
Björn F0	37.2	0.74	−143	−19	40.1	0.80	−100	−13
Björn F+	13.3	0.27	30	3	10.8	0.22	58	6
Gudrun F0	50.5	1.01	−220	−44	64.1	1.28	−193	−38
Gudrun F+	20.9	0.42	−31	−6	19.7	0.39	9	2
Jorr F0	73.6	1.47	−333	−97	82.0	1.64	−258	−75
Jorr F+	44.9	0.90	−114	−13	45.7	0.91	−55	−6
Loden F0	51.5	1.03	−231	−68	57.1	1.14	−175	−51
Loden F+	15.8	0.32	−10	−2	13.9	0.28	26	6
Tora F0	45.5	0.91	−198	−45	50.1	1.00	−147	−34
Tora F+	37.7	0.75	−84	−9	50.1	1.00	−34	−4
Tordis F0	50.7	1.01	−210	−31	58.2	1.16	−165	−24
Tordis F+	32.1	0.64	−47	−4	33.6	0.67	−9	−1

Fertilized 'Björn', 'Gudrun' and 'Loden' showed the lowest SOC increase in field measurements from 2001–2018, which led to lower SOC sequestration rates. On considering a deeper soil layer, the starting SOC level prior to *Salix* establishment was also higher. In absolute terms, the final SOC stock was greater with a deeper soil layer, but the net increase was lower for these three cases when compared with a shallower (20 cm) layer. Thus, a lower sequestration rate combined with a greater initial SOC level led to a smaller SOC increase for these fertilized varieties with increased soil depth. Overall, the changes in SOC stock and climate impacts were not highly influenced by considering a deeper soil layer of 25 cm.

4. Discussion

The analysis revealed that cultivation of the selected *Salix* varieties for bioenergy to substitute equivalent fossil fuels (under the given environmental and site conditions) can potentially mitigate climate change as it has a net cooling effect on global mean surface temperature over a 50-year time horizon. *Salix* variety had a major influence on the climate change mitigation potential. The *Salix* varieties in this study varied in some key factors derived from measured field data (SOC sequestration, biomass yield and response to fertilization) and these factors affected the overall climate impact between the different varieties. The major contribution to the climate mitigation effect comes from substitution of fossil fuels and SOC sequestration. While fossil fuel replacement is relatively easy to estimate using harvest yields, estimation of SOC change over time is complicated as it is subject to various environmental conditions and uncertainties.

The flue gas condensation technology assumed in the incineration plant with heat recovery gives high energy efficiency, leading to a greater output of energy delivered which puts the energy ratio in the higher range. This is a common technology in Swedish power plants [64], although it might not be common in other countries. The conversion efficiency of the thermochemical processes selected in a study determines the amount of useful energy production from the system and its subsequent ER. The ER in this study was within the range 16.1–28.2 for fertilized *Salix* varieties and 43.2–48.2 for non-fertilized varieties. Values of ER reported in the literature range from 16 to 79 in energy performance analysis studies [69–76], which are indicative of different methods and assumptions considered in individual studies.

The results in the present study indicate that *Salix* variety and fertilization regime strongly affect the NPP distribution between aboveground and belowground biomass. The ratio of NPP of annual aboveground biomass (AGB) to belowground biomass (BGB) in our study was estimated at 0.4–1.8 for unfertilized treatments and 1.9–8.0 for fertilized treatments (Table 3). The estimation of these values is based on the well-established conception that variety and fertilization influence the production of BGB relative to AGB, which leads to variation in SOC change.

Data on AGB and BGB production and allocation for *Salix* from some studies are presented in Table 9. Heinsoo et al. [77] reported large differences in the magnitude of the ratio between AGB and fine root production for fertilized and control plots in an Estonian *Salix* plantation with two species (*S. viminalis* and *S. dasyclados*). This study reported a significant reduction in annual production of fine root biomass under fertilization, while AGB production was greatly improved. The AGB to BGB production ratio for *S. viminalis* was 1.04–2.07 for lysimeter-grown *Salix* in sandy and clayey soils [61]. Rytter [78] found significant differences in biomass allocation to fine-roots between N-limited and unlimited growing conditions (*for S. viminalis*) but no change in annual turnover rates of fine roots. These studies support the idea that fertilization can lead to lower BGB production that leads to very different AGB to BGB ratios between unfertilized and fertilized treatments.

Table 9. Aboveground to Belowground biomass production and allocation ratios of *Salix* varieties reported under different environmental conditions.

Study	Description	Value
Heinsoo et al., 2009 [77]	Ratio of aboveground to fine root annual production	
	S. viminalis control	1.16–1.09
	S. viminalis fertilized	14.28–12.5
	S. dasyclados control	2.85–1.51
	S. dasyclados fertilized	20–16.67
Rytter, 2001 [61]	Ratio of total aboveground to belowground production of *S. viminalis L*	
	Year 1	1.04–0.73
	Year 2	1.73–2.07
	Year 3	1.63–1.5
Rytter, 2013 [78]	Ratio of annual production of stem to fine root of *S. viminalis L*	
	N limited	0.65
	Unlimited	1.84
Pacaldo et al., 2013 [79]	Ratio of biomass allocation of Aboveground biomass (Stem + Leaf) to Belowground biomass (FR + CR + stool) of *S. dasyclados*	0.32–0.61

Pacaldo et al. [79] reported biomass allocation for a single *Salix* variety (*S. dasyclados*) from two locations with different plantation ages and soil conditions; based on their data, the AGB to BGB allocation ratio was 0.32–0.61. The ratio of annual production of AGB to BGB in our study falls within the range of values reported for *Salix* in different studies, but these figures need to be validated by further studies on belowground biomass to increase accuracy in soil carbon modelling estimates.

Salix roots are characterized by high growth and mortality rates [80] and are not bound by seasonal patterns, with some growth and decay observed even during winter [61]. This indicates that root production is relatively higher under a non-fertilized regime, which combined with unchanged turnover rates would lead to higher belowground biomass input to the soil compared with a fertilized treatment, which can lead to greater SOC stocks.

The few previous studies on how biomass growth and allocation differ between *Salix* varieties [43,81,82] have shown that variety and growing environment can have significant impacts on biomass allocation and growth patterns. Cunniff et al. [43] found that belowground allocation differed up to 10% between *Salix* varieties and up to 94% between locations. Furthermore, a study by Gregory et al. [81] found significant differences in root density between *Salix* varieties, especially in the upper layers.

There is a scarcity of data on belowground biomass allocation and its variation between *Salix* varieties and environmental conditions. Only a few studies measured the production and turnover of roots (especially fine roots) as these analyses are time-consuming, labor-intensive and expensive [83]. Furthermore, the estimation of root growth and number can greatly vary due to the measurement method used [84]. A study including two *Salix* varieties [85] has also shown differences in decomposition rates of fine root litters, which further stresses the need for variety focused studies. This makes it difficult and complicated to compare data on aboveground to belowground biomass accumulation from different sources, as variations can occur owing to multiple factors. This is a source of variability in determining especially belowground biomass growth and its contribution to SOC sequestration. There is need for further research and standardization of methods to enable comparisons and calibration of soil carbon models to make more reliable long-term predictions.

In spite of the uncertainties regarding the variety-related input variables for soil carbon modelling, this investigation provides useful insights into the expected variety-related SOC changes over a longer period of time and based on measured data of above ground biomass and soil SOC over an 18-year period. While these uncertainties might affect all investigated varieties in a similar way, they are likely to result mostly in an uncertain absolute magnitude of SOC after a certain period of time, whereas the variety-specific pattern of SOC change is expected to be more robust. Thus, we believe that the use of *Salix* variety-specific data from the field study in this analysis is a clear improvement over previous studies dealing with SOC modelling in *Salix*. The scaling and extrapolation of soil carbon models is a challenge due to lack of long-term data and the complexity of SOC sequestration mechanisms. Despite the challenges, such approaches with assumed data are a necessary part of making sustainable management decisions. The accuracy of the models and their predictions can be constantly adjusted by feedback of new measured data and advancing knowledge of SOC.

The carbon modelling based on measured SOC levels from the measured field trial data, showed that non-fertilization led to a greater increase in SOC compared with fertilization of the same variety under the same soil conditions. A relationship between shoot biomass yield and increase in SOC was expected from other studies, but was not seen in our study, as greater yield did not correlate with more CO_2 being sequestered in the soil. For example, unfertilized 'Jorr' had one of the lowest shoot biomass yields among all varieties investigated here, but showed the highest increase in SOC in the top 20 cm soil layer; while fertilized 'Björn', with high biomass output, had one of the lowest increases in SOC stocks. This result questions the common assumption of higher shoot biomass yield leading to a greater increase in SOC due to higher production of leaf and root litter. While greater shoot biomass may lead to increased leaf litter production, root litter production might show a differential pattern. Interestingly, Pappas et al. [86] found that in boreal forests, aboveground biomass growth is decoupled from the carbon input to the ecosystem, highlighting the significance of belowground carbon inputs independent from aboveground growth. Also, Khan et al. [87] conclude that N-fertilization increases harvests for crops but can have a negative effect on SOC sequestration.

The SOC accumulation rate in our study was 0.24–1.29 Mg ha^{-1} yr^{-1} for the 0–20 cm soil layer over 50 years. Direct comparisons of SOC changes reported in different studies are difficult, because of variations in initial soil conditions, study period, growing conditions, methodology and depth of soil profile considered in the study. The test site had a clay content of 18%. This clay content promotes long-term carbon sequestration by stabilization of SOC against decomposition [88]. SOC sequestration rates of 1.44–2.27 Mg ha^{-1} yr^{-1} for the top 30 cm soil layer have been reported for two *Salix* varieties during a 6-year study period in the UK [81]. Other recent studies have recorded SOC sequestration rates of 1 Mg ha^{-1} yr^{-1} in the upper 10 cm in Italy [89] and high levels of 6.7–10.2 Mg ha^{-1} yr^{-1} in the upper 60 cm in Belgium [90]. In a meta-analysis by Agostini et al. [18], SOC accumulation rates in the range −0.06 to 3.57 Mg ha^{-1} yr^{-1} Mg ha^{-1} yr^{-1} were found for *Salix*. However, the studies in the meta-analysis varied greatly in methodology, soil conditions and length of study period, impeding comparisons. Greater accumulation rates have been reported for *Salix* grown on former arable land compared with grassland [91]. The amount and rate of SOC change are highly dependent on the previous land use, which consequently plays a major role in the climate impact. In any case, the annual SOC accumulation rates in our study clearly fall within the range reported from other sources. However, there is a need for further investigation of root production, turnover and decay based on soil types, plant variety, and nutrient regimes because the soil carbon change has an important effect in determining the climate impacts and should therefore be included in systems studies

From a land use perspective, the climate impact was governed by the *Salix* biomass yield. Higher biomass yields contributed to a greater replacement of fossil energy, thereby contributing to a greater cooling effect. Exceptions to this were the varieties 'Gudrun' and 'Loden', which showed almost no improvement in yield from fertilization. Thus, for optimum climate mitigation per unit land area, a high-yielding variety needs to be selected. However, on comparing the varieties from the functional unit of energy output (per MJ of energy output), the SOC sequestration potential played the major role in determining the climate impact. In this regard, the unfertilized varieties with good yields and SOC sequestration potential offered greater potential cooling effects. Hence the basis of comparison (land use or energy output) also plays an important role in the interpretation of climate impact results.

A literature review by Djomo et al. [54] reported that LCAs of short-rotation bioenergy crops often use very different system boundaries, impact indicators and conditions, which makes comparisons between studies difficult. All scenarios analyzed in the present study showed a GWP reduction potential of 95 to 237% compared with the fossil reference system (Table 7). This is much higher than the 90–99% reduction potential presented in the review by Djomo et al. [54], but only one study in that review had considered the effects of soil carbon sequestration. The high yield levels for unfertilized *Salix* varieties in the present study, combined with SOC sequestration, explain the much higher GWP reduction potential estimated in our study. However, the soil is not an endless C sink and increasing temperatures under climate change will accelerate the degradation of SOC, thereby reducing the size of the sink. Thus, the SOC sequestration potential is expected to decrease over time because of climate change. It is difficult to predict technological change during a long period, so in this study the systems were assumed to remain static during the 50-year period. Assuming a constant level of cultivation of *Salix* at the same location, the cooling effect from an increasing SOC pool will eventually decline, but the warming effect due to GHG emissions from the production system will continue to increase over time. The major sources of emissions are production of fertilizers and N_2O soil emissions. From a longer time perspective, these emissions will be of uppermost importance in improving the climate performance of *Salix* production systems.

Default IPCC values for calculation of nitrogen leaching from mineral fertilizers were used in this study, due to lack of site-specific data. *Salix* has been shown to have lower nitrogen leaching rates than other crops [40,92], and thus the default values used here might be on the higher side for *Salix* cultivation. In the field trials, all fertilized plots were enriched with the same quantity of mineral fertilizer, which might be higher or lower than the optimal fertilization level of the plant. Fertilization studies can help to determine the optimum fertilization by variety, which will greatly influence the emissions and energy input of the fertilization phase and the AGB to BGB production ratio.

The scarcity of complete data that are site- and variety-specific for all aspects of the *Salix* bioenergy production and decomposition poses some limitations. The SOC changes and climate impacts from one study should not be directly extrapolated to other cases as there are several factors (such as environmental conditions and previous land use) which can lead to different results. The results of this study stress the importance of accounting for variety and fertilization effects when estimating SOC changes and climate impacts of *Salix* bioenergy systems. As such, these effects should not be ignored in planning for bioenergy systems of the future. There is potential to develop varieties with high levels of both shoot and root biomass with efficient fertilizer utilization, which would give a greater climate mitigation benefit.

5. Conclusions

Soil carbon modelling based on Swedish field trial data showed that all *Salix* varieties tested can potentially increase the SOC stock in the soil over a period of 50 years under given soil conditions of vertic cambisols. *Salix* variety and fertilization treatment determined the magnitude of CO_2 sequestration. No clear relationship was found between biomass yield and SOC sequestration potential across the varieties and soil type used in this study, which indicates that belowground biomass accumulation and decomposition should not be directly estimated from shoot yield alone. High production and turnover rate of fine roots was estimated to be the major contributor to SOC inputs by *Salix*. Fertilization led to an increase in biomass yield (and therefore energy output), but a decrease in SOC sequestration potential, across all varieties.

The fertilized 'Björn' biomass systems showed a warming effect on the climate (positive GWP) without inclusion of substitution effects from replacing a natural gas-based reference case. However, all varieties and treatments showed the potential to mitigate climate change (negative GWP and $\Delta T s$) on inclusion of substitution effects. High-yielding *Salix* varieties had the greatest potential to mitigate climate change when looking from a land-use perspective. When comparing per energy unit, the SOC sequestration effects become more prominent in determining the overall magnitude of the climate change mitigation potential of the different *Salix* varieties. System analysis approaches like LCA should incorporate SOC effects, which can significantly affect the climate impacts of biomass cultivation systems, as seen here for six *Salix* varieties.

Initial soil conditions are very important for biomass productivity because they influence the amount of leaf and root litter produced, which in turn influence the SOC accumulation rate. Hence, previous land use needs careful consideration when evaluating climate impacts. Results in previous studies, combined with our findings, show that there is some uncertainty about SOC sequestration rates, which makes it important to research belowground biomass production, including varietal and location effects.

The results from this study highlight the effects of variety on SOC sequestration, biomass yield, response to fertilization and, ultimately, climate impact. This shows the importance of selecting the appropriate variety of *Salix* and management practices based on the desired outcome from the bioenergy system.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/f12111529/s1, Table S1: Parameters used to model SOC changes in ICBM. Table S2: Initial values of aboveground (Y_a) and belowground (Y_b) young pool, and old pool (O) used in the ICBM calculation. Table S3: Values used to calculate the biomass allocation between the different pools (stems, leaves, fine roots and coarse roots) at stages of growth as a percentage of their 3-year net primary production. Table S4: The nitrogen content in leaf litter was calculated according to the abscission leaf N content by variety and fertilization as reported by Weih and Nordh, 2002. Table S5: The nitrogen (N) content of roots was calculated from the dataset by Manzoni et al., 2021. Table S6:

Energy input and emissions associated with production of pesticides, cutting, fertilizer and fossil fuels. Table S7: Data used to estimate emissions and energy usage for operations in the biomass procurement chain. Table S8: Data used to model emissions and energy for the reference case.

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Appendix A

Table A1. Default parameters used in Equations (2) and (3) to calculate N_2O emissions as described in IPCC 2019 [56].

Parameter	Description	Value	Unit
EF_N	Direct emissions from applied N	0.01	kg N_2O-N kg^{-1} N
EF_D	N_2O emissions from volatilization and re-deposition	0.010	kg N_2O-N kg^{-1} NH_3-N
EF_L	N_2O emissions from N leaching	0.011	kg N_2O-N kg^{-1} N leached
F_A	Fraction of applied N lost as ammonia (for ammonia-N based fertilizer)	0.05	kg NH_3-N + NO_x-N kg^{-1} applied N
$N_{leached}$	Fraction of N lost by leaching	0.24	Kg N kg^{-1} applied N

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Supplementary Material

Soil carbon modelling in *Salix* biomass plantations: variety determines carbon sequestration and climate impacts

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Table S1 Parameters used to model SOC changes in ICBM [46,58,60]

	k_Y	k_O	r_e	h_a	h_b	i_a	i_b
Green fallow	0.8	0.0085	1	0.17	0.39	0.72	0.86[1]
Salix[2]	0.8	0.0085	1	0.17	0.39	-	-

[1]belowground biomass input adjusted for 20cm soil depth
[2]Above and belowground input for *Salix* varieties calculated based on yield levels and biomass allocation

Table S2 Initial values of aboveground (Y_a) and belowground (Y_b) young pool, and old pool (O) used in the ICBM calculation. The initial SOC stock was divided between the different pools (Y_a, Y_b and O) by using the ratio of each individual pool to the total SOC pool at steady state.

	Y_a	Y_b	O
Green fallow	0.31	0.62	27.92
Salix	0.31	0.62	27.92

Table S3 Values used to calculate the biomass allocation between the different pools (stems, leaves, fine roots and coarse roots) at stages of growth as a percentage of their 3-year net primary production [61].

	Annual biomass allocation (% of 3-year total accumulation)			
Year	Stems (S)	Leaves (L)	Fine Roots (F)	Coarse Roots (C)[1]
n.1	11%	13%	19%	24%
n.2	47%	39%	38%	49%
n.2	41%	48%	42%	26%

[1] Coarse roots include the stumps and cuttings

Table S4 The nitrogen (N) content in leaf litter was calculated according to the abscission leaf N content by variety and fertilization as reported by Weih and Nordh, 2002[41] . (Suffixes F0 and F+ denotes unfertilized and fertilized treatments)

Salix variety and treatment	Abscission leaf N concentration
Björn F0	1.04%
Björn F+	1.15%
Gudrun F0	0.66%
Gudrun F+	0.65%
Jorr F0	1.38%
Jorr F+	1.22%
Loden F0	0.94%
Loden F+	0.89%
Tora F0	0.90%
Tora F+	0.88%
Tordis F0	0.84%
Tordis F+	0.93%

Table S5 The nitrogen (N) content of roots was calculated from the dataset by Manzoni et al., 2021[57]. As data for individual varieties included in our study are unavailable, mean root N-content of *Salix* cultivated in low nutrient (F0) and high nutrient (F+) conditions were calculated. *Salix* grown under low frequency watering were excluded from the calculation.

	Mean N-content of roots		
	mg N/g dry wt.	Std dev.	% dry wt.
	13.02	5.0	1.30%
Salix_F0	8.35	1.3	0.83%
Salix_F+	17.6	2.1	1.76%

Table S6 Energy input and emissions associated with production of pesticides, cutting, fertilizer and fossil fuels

Input	Amount	Energy [MJ/ha]	CO_2 [g/ha]	CH_4 [g/ha]	N_2O [g/ha]	Reference
Pesticide						
- Roundup	5 l/ha	481.38	11958	0.4374	3.6693	(Ahlgren, 2004; Nilsson and Bernesson, 2008)
- Cougar	1 l/ha	118.86	2952.6	0.108	0.906	
Cuttings	18000 /ha	1120.98	1014369	158.40		Adapted from Nilsson and Bernesson, 2008
Fertilizer		Energy [MJ/kg]	CO_2 [g/kg]	CH_4 [g/kg]	N_2O [g/kg]	Adapted from GaBi Database
- N (Ammonium Nitrate based)	100 kg/ha	35.2	2839	8	2	("GaBi Process data set: AN," 2018)
- P	14 kg/ha	7.79	489	1	0	("GaBi Process data set: TSP," 2018)
- K	47 kg/ha	5.54	342	0	0	("GaBi Process data set: KCl," 2018)
Fuel production			CO_2	CH_4	N_2O	
Diesel			[g/MJ]	[g/MJ]	[g/MJ]	
			5.78	0.0338	0.0000555	(Öman et al., 2011)
Natural Gas			5.53	0.275	2.6E-12	(Gode et al., 2011)

Table S7 Data used to estimate emissions and energy usage for operations in the biomass procurement chain

Operation	Diesel [MJ/ha]	Energy [MJ/ha]	CO_2 [g/ha]	CH_4 [g/ha]	N_2O [g/ha]	Reference
Field Preparation						
- Plowing	1870	1870	154000	129.8	0	(Börjesson, 2006; Nilsson and Bernesson, 2008)
- Harrowing	262	286	81400	68.2	0	
Planting	660	55000	46.2	0.00		(Börjesson, 2006)
Fertilizer Application	28.1	30.6	2186.4	0.95	0.0016	(Nilsson and Bernesson, 2008)
Stump Removal	674.5	735.2	52464	22.8	0.0374	(Nilsson and Bernesson, 2008)
Harvest & Chipping	Harvest with self-propelled forage, Claas Jaguar 695					(Nilsson and Bernesson, 2008)
	Capacity [ton/h]				24.4	
	Fuel Consumption [l/h]				40.0	
Field Transport	Forwarding with Tractor 4WD, 100kW Capacity					(Nilsson and Bernesson, 2008)
	Capacity [ton/h]				11.4	
	Fuel Consumption [l/h]				19.0	
Road Transport	Capacity [ton/load]				34.6	(Baky et al., 2009)
	Fuel Consumption [l/km]				0.58	(Andersson and Frisk, 2012)
	Load rate [% of distance]				54%	
Incineration	Emission factors in large scale heating plant (50-300 MW)					(Paulrud et al., 2010)
	N_2O [g/GJ]				6	
	CH_4 [g/GJ]				11	

Table S8 Data used to model emissions and energy for the reference case

Green Fallow	Annual Yield (tons/ha)	4.8	Based on Aronsson et al., 2009
	N-content	2.81%	(Phyllis 2, 2009)
Annual mowing of green fallow	Mower-conditioner (Valtra 6600 tractor)		
	Fuel Consumption (kg/h)	12.9	(Lindgren et al., 2002)
	Cutting rate (ha/h)	2.53	
Natural Gas (NG) combustion	CO_2 [g/MJ]	56.8	(Gode et al., 2011)
	CH_4 [g/MJ]	0.001	
	N_2O [g/MJ]	0.0001	
Energy efficiency of NG heat plant	Heat efficiency	90%	(Börjesson et al., 2010)
	Flue gas heat recovery efficiency	10%	
	Total efficiency	100%	

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RESEARCH

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Energy performance of compressed biomethane gas production from co-digestion of *Salix* and dairy manure: factoring differences between *Salix* varieties

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Abstract
Biogas from anaerobic digestion is a versatile energy carrier that can be upgraded to compressed biomethane gas (CBG) as a renewable and sustainable alternative to natural gas. Organic residues and energy crops are predicted to be major sources of bioenergy production in the future. Pre-treatment can reduce the recalcitrance of lignocellulosic energy crops such as *Salix* to anaerobic digestion, making it a potential biogas feedstock. This lignocellulosic material can be co-digested with animal manure, which has the complementary effect of increasing volumetric biogas yield. *Salix* varieties exhibit variations in yield, composition and biomethane potential values, which can have a significant effect on the overall biogas production system. This study assessed the impact of *Salix* varietal differences on the overall mass and energy balance of a co-digestion system using steam pre-treated *Salix* biomass and dairy manure (DaM) to produce CBG as the final product. Six commercial *Salix* varieties cultivated under unfertilised and fertilised conditions were compared. Energy and mass flows along this total process chain, comprising *Salix* cultivation, steam pre-treatment, biogas production and biogas upgrading to CBG, were evaluated. Two scenarios were considered: a base scenario without heat recovery and a scenario with heat recovery. The results showed that *Salix* variety had a significant effect on energy output–input ratio (R), with R values in the base scenario of 1.57–1.88 and in the heat recovery scenario of 2.36–2.94. In both scenarios, unfertilised var. Tordis was the best energy performer, while the fertilised var. Jorr was the worst. Based on this energy performance, *Salix* could be a feasible feedstock for co-digestion with DaM, although its R value was at the lower end of the range reported previously for energy crops.

Keywords *Salix*, Energy analysis, Biogas, Lignocellulosic biomass, Short-rotation coppice willow, Systems perspective, Biomethane, Energy balance

Introduction

Fossil fuels are the major source of primary energy across the world [1] and are also the main source of anthropogenic emissions of greenhouse gases (GHGs) leading to global warming [2]. To limit global warming to 1.5 °C, global GHG emissions need to peak before 2025, be reduced by 43% by 2030, and reach net zero by the early 2050s, according to the latest IPCC assessments [3]. Countries, regions, cities and companies representing

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85% of the world's population and 90% of GDP (PPP) have set net zero targets or have pledged to limit global warming within this century [4]. Another problem with fossil fuels is the unequal distribution of reserves, leading to inequalities in supply and demand and dependence on producing nations. This leads to energy insecurity, geopolitical issues and conflicts.

Sustainable bioenergy is an important part of fossil-fuel free energy production and energy security efforts, by providing viable replacements for solid, liquid and gaseous fossil fuels. Bioenergy can be particularly important in sectors where fossil fuels are difficult to replace (e.g. heavy industry, aviation, heavy transportation). In pathways to reach net-zero emissions by 2050, bioenergy supply is predicted to grow from 65 EJ in 2020 to 100–248 EJ by 2050 [3, 5]. Biogas produced by anaerobic digestion of organic matter can be used for heat and power production and can be upgraded to biomethane by removing CO_2 and trace gases. It can use existing gas infrastructure and technologies, such as pipelines [6] and natural gas engines. Biomethane can be compressed in a similar way to natural gas to make compressed biomethane gas (CBG), as an alternative to compressed natural gas. This makes biomethane an attractive fossil-free vehicle fuel option. In the IEA net zero emissions scenario [5], biogas use reaches 14 EJ in 2050, from 2.1 EJ in 2020. The REPowerEU action plan envisions boosting biomethane production to 35 bcm by 2030 to reduce dependence on Russian natural gas [7]. Therefore, there is interest in increasing biogas production in a sustainable manner to reduce natural gas use.

Different feedstocks are being investigated to meet the growing demand for bioenergy and realize its potential. Energy crops have played an important role in increasing biogas production in some countries such as Germany [8], but use of conventional energy crops such as sugar beet and maize can lead to conflicts with food production and supply. Therefore, there is a need for alternative feedstocks, such as waste streams, short-rotation lignocellulosic crops and feedstocks, that can be cultivated on non-agricultural land and which are not used for food and feed. In both the EU [9] and Sweden [10, 11], organic residues and energy crops offer the greatest potential for increasing biogas production. According to the IEA roadmap for net zero emissions by 2050 [5], organic waste streams and short-rotation woody crops will be the main sources of the future global bioenergy supply.

Animal manure has great potential for biogas production, with the added benefit of avoiding atmospheric methane emissions from manure decomposition [12], which makes it an attractive option for meeting climate targets. However, manure usually has a very high moisture content, leading to low organic loading rate (OLR), resulting in low volumetric biogas production. A co-digestion system to supplement manure with another feedstock, such as lignocellulosic material, can achieve an increase in volumetric biogas yield without compromising hydraulic retention time (HRT) [13].

Lignocellulosic biomass is a very abundant type of biomass and is relatively economical to produce, but typically has higher recalcitrance than other biomass sources [14]. Recalcitrance can be defined as the resistance of the biomass to release of sugars for fermentation or degradation, which is the major barrier to their conversion to biofuels [15]. Pre-treatment methods can help reduce recalcitrance in lignocellulosic biomass by increasing the accessibility of holocellulose (cellulose and hemicellulose) to microorganisms, improving both the rate and yield of biogas production [16].

Potential sources of sustainable and renewable lignocellulosic biomass include short-rotation coppice systems such as *Salix* plantations. *Salix* plantations have the benefits of relatively short growth cycles of 2–5 years, multiple harvests from the same plantation for 20–25 years, vegetative propagation, simple management practices and high net energy return. They can also provide the additional benefits of soil carbon sequestration, phytoremediation, acting as flood barriers and windbreaks, increased biodiversity and pollinator attraction. *Salix* biomass is thus a promising feedstock for biogas production systems, where it can be co-digested with other substrates such as animal manure [17, 18].

In recent decades, breeding programmes have developed several newer varieties of *Salix*. Studies show that there are significant differences between these *Salix* varieties in terms of biomass yield [19], biomass quality [20, 21], physiological and morphological traits [22, 23], biomethane potential (BMP) [24], soil ecology and response to fertilisation [25]. It is common practice to assume average characteristics for energy crops such as *Salix* in systems studies. There is a lack of analyses that consider varietal differences when examining the energy and mass flow of biogas production systems. These differences should be taken into account when exploring the potential of *Salix*-based biogas production systems, as they can have a significant influence on system parameters and performance.

This study analyzed a biomethane production system using co-digestion of pre-treated *Salix* biomass with dairy manure. The aims were to evaluate energy and mass flows along the total process chain for six selected *Salix* varieties, cultivated under fertilised and unfertilised conditions, and to compare the energy performance of the varieties. A broad cradle-to-grave scope was applied in the analysis starting with *Salix* cultivation and ending with final production of CBG and digestate application to soil.

Materials and methods

System boundaries and description

A life-cycle perspective was used to identify and determine the mass and energy flows in a biomethane production system involving co-digestion of steam pre-treated *Salix* biomass and dairy manure (DaM) to produce CBG as a final product. The analysis considered a Swedish context, with the study region assumed to be in Uppsala, central Sweden. The system was assumed to handle a feeding rate of 300 kg/h of dry *Salix* biomass, with all other flows calculated based on this parameter. The system boundaries used in the analysis are shown in Fig. 1, where arrows indicate the material flows within the different sub-systems. The system was divided into five stages:

1. Stage 1 (Raw materials): Cultivation and harvest of the different *Salix* varieties and transportation to the biogas plant. Transportation of DaM from farms to the biogas plant was also included, while its production was excluded from the system.
2. Stage 2 (*Salix* pre-treatment stage): Pre-treatment of *Salix* by SO_2-catalysed steam explosion of *Salix* at 185 °C for 4 min.
3. Stage 3 (Biogas production): Hygienisation of DaM at 70 °C before adding it to the pre-treated *Salix* for co-digestion in an anaerobic digester at 37 °C. DaM and *Salix* substrates were mixed in a 1:1 volatile solids (VS) ratio with 10% TS content for feeding the anaerobic digester, and a HRT of 45 days was assumed. The biogas produced progressed to stage 4 for upgrading, while the digestate was directed to a storage tank under ambient conditions. The digestate was assumed to be stored in the tank for 30 days, during which further degradation occurred, leading to secondary production of biogas. This secondary biogas was added to the primary biogas flow for upgrading.
4. Stage 4 (Upgrading): The raw biogas was upgraded to bio-methane by removing CO_2 using a wet scrubber and compressed to transport-grade CBG.
5. Stage 5 (Digestate use): The digestate was transported from the storage tank to agricultural fields and spread as a liquid fertiliser.

Raw materials

Salix biomass

Use of biomass from six commercial *Salix* varieties grown under fertilized and unfertilized conditions was compared. The varieties were: 'Björn' (*Salix schwerinii* E. Wolf. × *S. viminalis* L.), 'Gudrun' (*S. burjatica* Nasarow × *S. dasyclados* Wimm.), 'Jorr' (*S. viminalis*), 'Loden' (*S. dasyclados*), 'Tora' (*S. schwerinii* × *S. viminalis*) and 'Tordis' (*S. schwerinii* × *S. viminalis*) × *S. viminalis*). *Salix* growth and cultivation data were obtained from a field trial in Uppsala during 2001–2017 [26]. The varieties cultivated under fertilised conditions received 100 kg N, 14 kg P and 47 kg K per ha and year. The suffixes F0 and F+ are used hereafter to refer to unfertilised and fertilised conditions, respectively. The plantations were managed in a three-year cutting cycle, with winter harvests.

Salix biomass samples were collected in 2019 and chipped with a compost chipper, after which compositional analysis and BMP assays were performed, the details of which are presented in the supplementary material (SM). Compositional analysis was performed on the extractives, carbohydrate and lignin components of the *Salix* samples. For the BMP assay tests, samples were first steam-exploded under process conditions of 185 °C for 4 min with 2% (mass/mass) SO_2 as a catalyst. A BMP assay was performed on the samples using inoculum from a wastewater treatment plant, with an inoculum-to-substrate ratio of 3:1 on a volatile solids basis. Cellulose and inoculum controls were included in the assay. Full details of sample preparation and BMP test conditions can be found in the SM.

The composition of untreated *Salix* biomass (cellulose and hemicellulose content of the *Salix* varieties) was calculated from analyzed sugar composition after acid hydrolysis for the different varieties (Additional file 1: Table S1). The cellulose content was considered equivalent to the sum of glucose and cellobiose content. Hemicelluloses were considered to be the polysaccharide forms of xylose, arabinose, mannose and galactose in the concentrations reported. The concentration of polymeric sugars was calculated using anhydro correction factors from the corresponding monomeric sugar as described by Sluiter et al. [27]. Lignin was expected to remain unchanged between untreated and steam-treated samples, as lignin generally does not depolymerise under mild steam treatment conditions. The composition of the untreated *Salix* biomasses and their BMP values are presented in Table 1. The composition values were used as inputs for the process modelling.

Analysis of *Salix* cultivation and harvest included field preparation, management operations, harvesting and transportation (Fig. 2). Production of fertilisers, pesticides and *Salix* cuttings used as inputs to cultivation was also included. The harvested *Salix* biomass was in the form of chips and was assumed to be transported an average distance of 100 km to the biogas production plant. Energy and material flows for the varieties (Additional file 1: Tables S2–S4) were based on the *Salix*

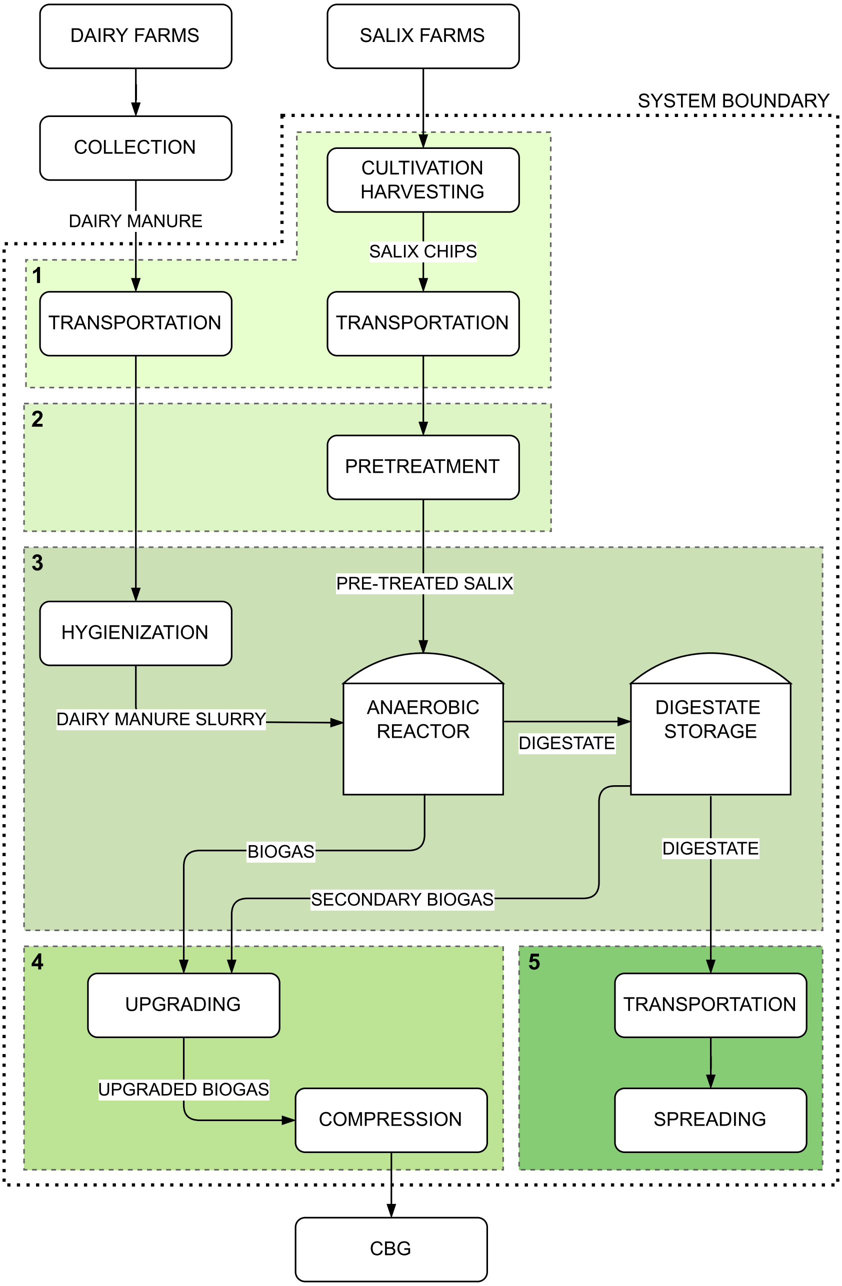

Fig. 1 System boundaries of the compressed biomethane gas (CBG) production system analysed in this study

production system covered by Kalita et al. [28]. All agricultural, transport and processing machinery were presumed to use fossil diesel as fuel.

Dairy manure

The composition and BMP characteristics of the DaM used as the second feedstock in the co-digestion system (Table 2) were based on averages of DaM data in the literature. Using proportions calculated from reported yields of manure hydrolysis by Chen et al. [29] and Wen et al. [30], the hemicellulose content was divided into arabinose, galactose and xylose. Literature sources [31–35] report BMP values within the range 51–264.3 mL CH_4/gVS, with an average value of 211.5 ml CH_4/gVS. The DaM was assumed to be collected from the farms in the form of slurry with 10% TS content. Handling operations and storage of DaM on-farm were outside the system boundaries of the study.

Dairy farms supplying DaM were assumed to be an average distance of 30 km from the biogas plant (Fig. 3). DaM was transported using 40-ton trucks with fuel consumption of 0.74 MJ/tkm, with an empty return trip included [36]. The digestate produced at the end of biogas production was transported to agricultural fields

Table 1 Polysaccharide composition, volatile solids (VS) content and biomethane potential (BMP) of the six selected Salix varieties under unfertilised (F0) and fertilised (F+) conditions (adapted from analytical values in Additional file 1: Table S1)

Variety	Lignin (%VS)	Cellulose (%VS)	Hemi-cellulose				VS (%TS)	BMP (mL/gm VS)
			Xylan (%VS)	Galactan (%VS)	Arabinan (%VS)	Mannan (%VS)		
Björn F0	24.5	54.0	9.4	1.9	0.4	1.8	97.9	194
Björn F+	24.7	51.3	8.9	1.6	0.4	1.6	98.1	232
Gudrun F0	28.0	50.0	9.2	1.6	0.6	1.6	97.7	246
Gudrun F+	28.7	48.8	8.3	1.7	0.6	1.5	97.3	235
Jorr F0	28.1	49.3	8.6	2.4	0.8	2.3	97.7	216
Jorr F+	27.8	46.9	7.8	2.0	0.9	2.2	98.1	190
Loden F0	29.0	47.3	8.4	1.7	0.7	1.8	96.9	236
Loden F+	29.6	47.3	8.5	1.8	0.8	2.0	97.3	251
Tora F0	29.1	48.0	9.4	2.1	0.7	1.9	97.3	246
Tora F+	26.7	46.1	9.0	1.6	0.6	2.1	97.8	248
Tordis F0	26.0	52.3	9.0	1.9	0.5	2.1	98.1	271
Tordis F+	26.2	50.4	8.9	1.6	0.4	1.8	98.2	268

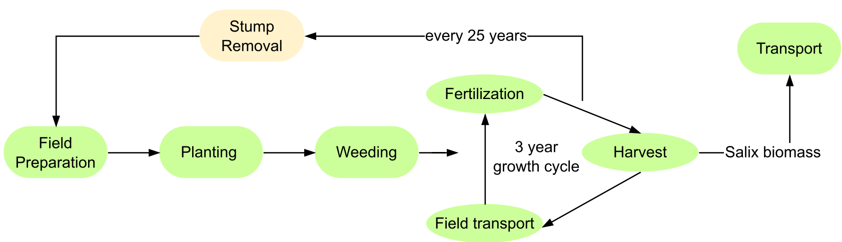

Fig. 2 Illustration of the Salix cultivation system analysed

Table 2 Compositional data (volatile solids (VS) basis) and biomethane potential (BMP) values for dairy manure used in the present study

Lignin (%VS)	Cellulose (%VS)	Xylose (%VS)	Arabinose (%VS)	Galactose (%VS)	Crude protein (%VS)	Lipid (%VS)	Others (%VS)	VS (%TS)	BMP (mL/gVS)
16.9	32.7	11.9	4.8	2.4	21.2	3.9	31.2	80	211.5

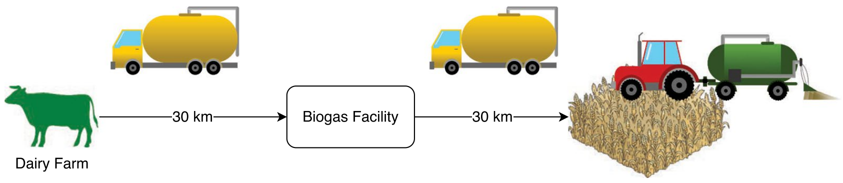

Fig. 3 Schematic representation of transport of manure and digestate and field application of digestate

over an average transport distance of 30 km, using the same configuration of 40-ton trucks (Fig. 3). As the digestate was not de-watered, it was assumed that it would be handled similarly to liquid fertiliser. Fuel energy use was determined for transport of DaM and digestate to and from the biogas facility, respectively. The energy needed to spread liquid digestate on agricultural fields was assumed to be 17 MJ per ton of wet digestate at an average spread dose of 30 tons/hectare [37]. Fossil diesel fuel was assumed for all vehicles and machinery involved.

Process modelling

The energy and mass flows were simulated for stages 2–4 in Fig. 1, comprising steam pre-treatment of *Salix*, co-digestion of *Salix* and hygienized manure to produce biogas, and upgrading of biogas to CBG, using the Aspen Plus process simulation software. Values for the heating, cooling, and electricity energy requirements of these stages were obtained from the Aspen simulation. The facility was designed to process 300 kg of *Salix* dry matter per hour. Dairy manure was added for the co-digestion process, in a 1:1 ratio on a VS basis. The process was modelled in three parts (Fig. 4):

1. Acid-catalysed steam pre-treatment of *Salix* biomass.
2. Anaerobic co-digestion of pre-treated *Salix* and DaM to produce biogas and digestate.
3. Upgrading of biogas to biomethane and compression to CBG.

The process model was adapted from the Aspen model for biodiesel production used by Karlsson et al. [38]. All processes used the NRTL property method in the Aspen simulation.

Steam pre-treatment of Salix

Steam explosion pre-treatment is one of the most common and efficient pre-treatment methods used commercially for reducing the recalcitrance of lignocellulosic biomass [39, 40]. *Salix* biomass was assumed to be pre-treated by acid-catalysed steam explosion at 185 °C for 4 min, with 2% SO_2 as catalyst. The pre-treatment conditions were set to be same as those in pre-treatment of the *Salix* samples before BMP assays (SM). The *Salix* pre-treatment process flow analyzed is shown in Part I in Fig. 4. A side-effect of most pre-treatment methods is formation of inhibitory compounds affecting the microorganisms and enzymes responsible for conversion to biofuel [41], and higher pre-treatment severity can lead to increased production of inhibitory compounds [42]. Steam pre-treatment at 180–200 °C for 4–10 min is reported to be favourable for *Salix* [17, 42, 43]. Thus the relatively mild pre-treatment conditions assumed in this study can be expected to minimise the formation of inhibitory compounds. Mild steam pre-treatment primarily affects the hemicellulose content in biomass, and results in the breakdown of polysaccharides (xylan, arabinan, galactan and mannan) to simpler carbohydrates (xylose, arabinose, galactose and mannose). The lignin and cellulose content remains largely unchanged relative to the starting material. Under low-severity pre-treatment conditions, 55–75% of xylan and 60–80% of arabinan are converted [43]. In the steam treatment reactor used in the simulation in this study, conversion of xylan to xylose was assumed to be 60%, and that of arabinan, galactan, and mannan 76%. Composition after pre-treatment of the *Salix* biomasses is shown in Table 3. The steam released after pre-treatment was condensed and added back to the biomass stream. Additional water was assumed to be added to the steam-exploded *Salix* to reach a solids content of 10%, giving a pumpable slurry for the anaerobic digestion process.

Biogas production

Dairy manure hygienisation DaM was added in a 1:1 VS ratio to the *Salix* biomass and, as the different *Salix* varieties had varying VS content in biomass, the corresponding amount of DaM added to the co-digestion process also changed. There is a known risk of microbiological

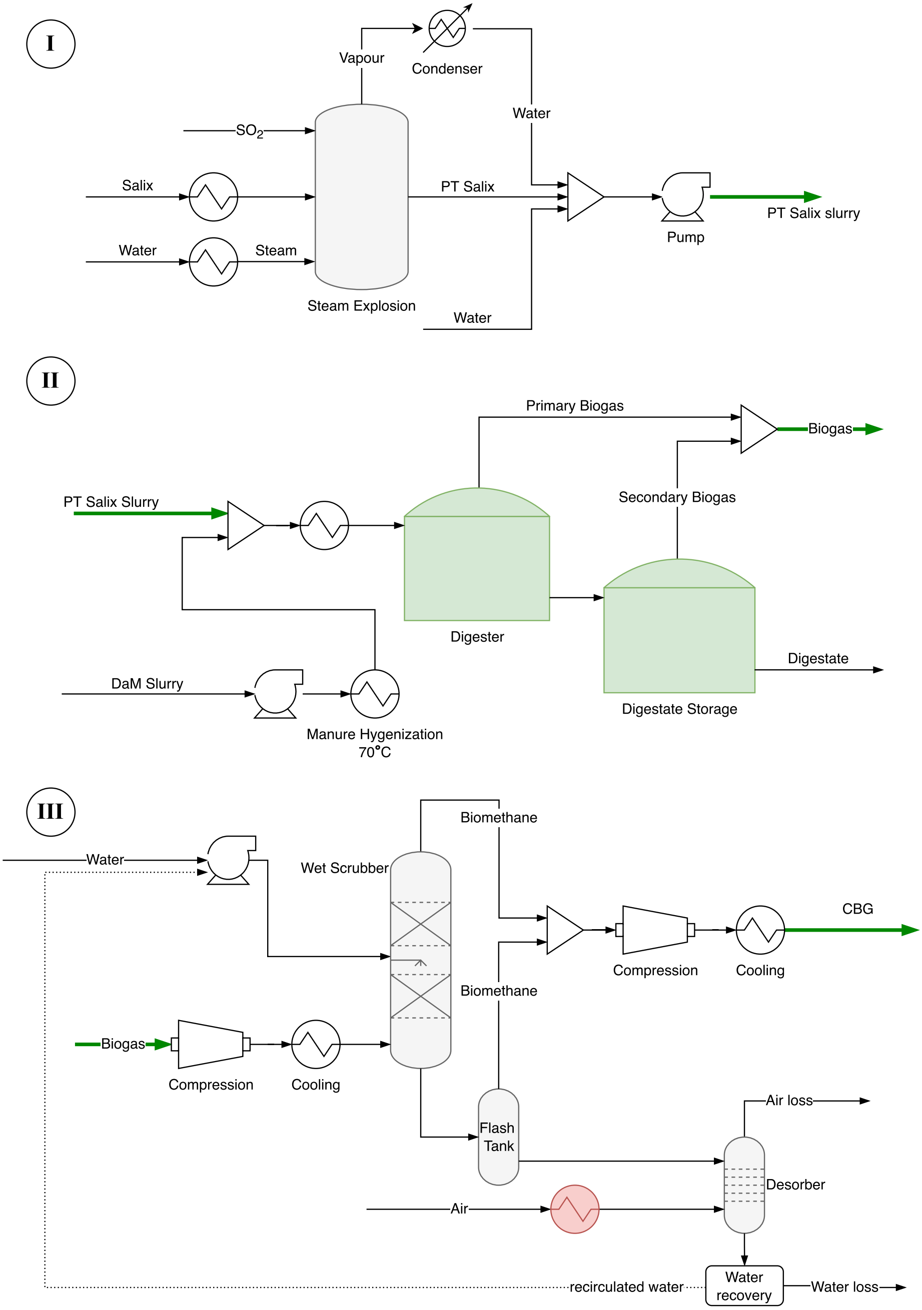

Fig. 4 Simplified process flow diagram of stages modelled in Aspen Plus in this study

Table 3 Composition of six varieties of unfertilised (F0) and fertilised (F+) Salix as percentage of total solids (%TS) after steam pretreatment with 2% SO_2 at 185 °C for 4 min

Variety	Lignin	Cellulose	Xylan	Xylose	Arabinan	Arabinose	Mannan	Mannose	Galactan	Galactose
Björn F0	24.0	58.7	4.2	6.3	0.1	0.4	0.5	1.5	0.5	1.5
Björn F+	24.2	55.9	4.0	6.0	0.1	0.4	0.4	1.3	0.4	1.3
Gudrun F0	27.3	54.3	4.1	6.1	0.2	0.5	0.4	1.3	0.4	1.3
Gudrun F+	27.9	52.8	3.7	5.5	0.2	0.5	0.4	1.2	0.4	1.4
Jorr F0	27.4	53.5	3.8	5.8	0.2	0.7	0.6	1.9	0.6	2.0
Jorr F+	27.2	51.1	3.5	5.2	0.3	0.8	0.6	1.8	0.5	1.7
Loden F0	28.1	50.9	3.7	5.5	0.2	0.6	0.5	1.5	0.4	1.4
Loden F+	28.8	51.2	3.8	5.6	0.2	0.7	0.5	1.6	0.5	1.4
Tora F0	28.3	51.9	4.2	6.3	0.2	0.6	0.5	1.6	0.5	1.7
Tora F+	26.1	50.1	4.0	6.0	0.2	0.5	0.6	1.8	0.4	1.3
Tordis F0	25.5	57.0	4.0	6.0	0.1	0.4	0.6	1.7	0.5	1.6
Tordis F+	25.7	55.0	4.0	5.9	0.1	0.4	0.5	1.5	0.4	1.3

infection and contamination of the food chain from use of animal manure for production of human and animal feed [44]. Therefore, DaM was assumed to undergo hygienisation at 70 °C for 1 h to reduce the epidemiological risk when digestate from the system was applied to agricultural land. The hygienised DaM stream joined the pretreated *Salix* stream to produce a combined feedstock slurry, which was fed to the anaerobic digester for biogas production after adjusting to the digester temperature of 37 °C.

Anaerobic co-digestion The anaerobic digester was modelled as a stoichiometric digester in Aspen Plus. A retention time in the digester of 45 days was assumed. Fractional anaerobic conversion of individual components in the digester was determined using biodegradability (BD) ratio as follows: The Buswell equation [45] was used for stoichiometric calculation of anaerobic digestion products from complete conversion of a generic organic material of composition CaHbOcNd, as shown in Eq. 1. Maximum theoretical methane yield (TMY, ml/g VS) was calculated based on the composition of the *Salix* and manure substrates as shown in Eq. 2, using the Buswell equation. While BMP values are a predictor of potential methane production, a direct relationship for prediction of methane production in digesters from BMP values is lacking in the literature [46, 47, 49]. Based on comparative studies [48, 49], real methane yield (RMY) was conservatively estimated to be 80% of the laboratory-scale BMP values. Biodegradability (BD) was defined as the ratio between RMY and TMY (Eq. 3) and determined how much of the substrate is converted into biogas, while the unconverted fraction ended up in the digestate. The TMY, RMY and BD ratios for the different co-digestion mixes of *Salix* varieties and DaM are shown in Table 4. The digester contents were assumed to be agitated

Table 4 Total methane yield (TMY) and real methane yield (RMY) values for each unfertilised (F0) and fertilised (F+) Salix variety-dairy manure (DaM) co-digestion mix and its biodegradability (BD) ratio

Feedstock	TMY (L/kg feed)	RMY (L/kg feed)	BD (%)
Björn F0 & DaM	63.40	35.38	55.80
Björn F+ & DaM	62.82	41.06	65.36
Gudrun F0 & DaM	55.47	37.76	68.0
Gudrun F+ & DaM	54.71	37.41	68.38
Jorr F0 & DaM	56.09	35.35	63.03
Jorr F+ & DaM	60.25	35.89	59.57
Loden F0 & DaM	54.05	36.77	68.02
Loden F+ & DaM	55.17	39.16	70.99
Tora F0 & DaM	57.71	39.68	68.76
Tora F+ & DaM	57.35	40.51	70.64
Tordis F0 & DaM	55.71	40.19	72.15
Tordis F+ & DaM	57.91	42.32	73.08

with a long-shaft agitator with power consumption of 5.76 $kWh/100m^3$/day [50].

$$C_aH_bO_cN_d + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4}\right)H_2O \rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8}\right)CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8}\right)CO_2 + dNH_3 \quad (1)$$

$$TMY = \frac{22.4 \times 1000 \times \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8}\right)}{12a + b + 16c + 14d} \quad (2)$$

$$BD = \frac{RMY}{TMY} \times 100\% \quad (3)$$

The digestate from the anaerobic digester was assumed to be sent to the digestate storage tank (DST), where further microbial activity was expected to take place, producing a secondary biogas flow. The average temperature of DST was taken to be 20 °C, with HRT of 30 days. Hence, the storage tank was simulated as another stoichiometric digester similar to the anaerobic digester and a further 10% degradation of the remaining organic components was assumed. The biogas from the anaerobic digester and secondary biogas from the DST were sent to the upgrading stage. The digestate stream from the DST was assumed to be pumped to an outlet, after which it was transported via trucks for field application.

Upgrading & compression

The upgrading stage was assumed to comprise a water scrubber section to dissolve and remove CO_2 from the biogas stream, increasing the methane content to more than 95%. This was followed by a compression stage in which biomethane was cooled and compressed at 200 bar and 21 °C to produce CBG. The energy content of the CBG output was calculated using the lower heating value of methane (50 MJ/kg at 25 °C).

Potential energy savings – Heat recovery (HRE) scenario

The base scenario did not consider any internal heat exchange, with all heating and cooling needs fulfilled with external energy. Stages 2–4 had significant heating and cooling requirements, providing an opportunity to exchange heat between different hot and cold streams to lower the need for external hot and cold utilities. An additional heat recovery (HRE) scenario was designed to reduce the heating demand for hygienisation of DaM slurry. Heat was recovered from three streams within the processes and exchanged with the cold DaM slurry stream as shown in Fig. 5.

Digester sizing

The volume of the digester (V_d) was determined from the chosen retention time (T_r) and daily volumetric input of substrate (S_d) as:

$$V_d = S_d \times T_r$$

The *Salix*-DaM slurry fed to anaerobic digester had a solids content of 10%. Due to the high water content of the slurry, a density value of 1 ton/m3 was used to convert the mass flow rate of the slurry to volumetric flow. The volume was calculated based on maximum volumetric flow rate for the different *Salix* and manure combinations. A 45 day retention time gave a digester volume of 7216 m^3 with an organic loading rate (OLR) of 1.96 kg VS/m3/day (Table 5).

Energy performance calculations

While there is no single standardised method for calculating the energy performance of biogas plants, output–input ratio I is one the most commonly used metrics [51]. Generally, the higher the R value, the better the energy performance of the system. The energy flows included within the input and output categories depend on the system boundaries, and conventions set by the authors of individual studies. The R value of the CBG production system in this study was defined as the ratio of the

Table 5 Size and related parameters of the biogas digester and digestate storage tank (DST)

Maximum daily flow rate of slurry mixture	160.36 tons/day
Max volumetric flow rate of slurry mixture	160.36 m^3/day
Retention time of digester	45 days
Digester volume	7216 m^3
Organic loading rate	1.96 kg VS/m^3/day
Retention time of digestate storage tank	30 days
Digestate storage tank volume	4811 m^3

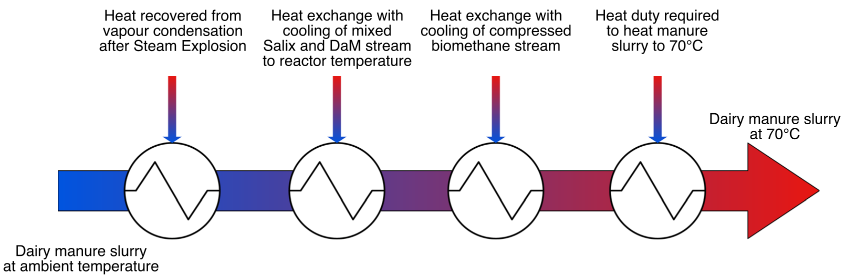

Fig. 5 Representation of heat exchanges assumed in the heat recovery (HRE) scenario

output energy in the CBG produced (E_{cbg}) to the secondary energy input in stages 1–5 of the system:

$$R = \frac{E_{cbg}}{E_{1,f} + E_{2-4,h} + E_{2-4,c} + E_{2-4,el} + E_{5,f}}$$

where $E_{1,f}$ and $E_{5,f}$ are the fuel (diesel) energy demand of stages 1 and 5, and $E_{2\text{-}4,h}$, $E_{2\text{-}4,c}$ and $E_{2\text{-}4}$,el represent the heating, cooling and electricity inputs in stages 2–4 of the system.

The energy inputs (or demands) were represented in terms of heating, cooling and diesel fuel. The inherent energy contained in the material flows of the feedstocks (*Salix* and DaM) was not included in the input energy, as they were considered to be material inputs to the system undergoing transformation. The *R* value was calculated and is reported for both the base scenario and HRE scenario. The energy used in manufacture and maintenance of infrastructure, vehicles and management was not included in the calculations.

Results

Process inputs

The system under study was designed with an input rate of 300 kg/h dry matter of *Salix* biomass. The energy inputs at each stage of the process chain for the base scenario are shown in Table 6 for the different feedstock combinations.

Energy demand as diesel in cultivation and transport was higher for all fertilised varieties compared with their unfertilised counterparts. This was due to the additional energy usage in production and application of fertilisers to fields. However, as fertilisation usually results in a greater amount of shoot biomass, fertilised *Salix* requires less land per unit mass of biomass produced. Reported average land area required to produce a ton of *Salix* biomass varies from 0.06 ha for the highly productive variety Tordis to 0.21 ha for the low-producing Jorr and Loden [28]. There was slight variation in amount of DaM added to the different *Salix* feedstock mixtures in this study as VS % differed between the varieties and the two feedstocks were combined in a 1:1 VS ratio. This led to minor variations in the energy demand for transportation of DaM.

The biogas facility encompassed stages 2–4, i.e., steam pre-treatment of *Salix*, manure hygienisation and anaerobic digestion, and upgrading of biogas to compressed biomethane. The energy demands of these stages were obtained from the process model created in Aspen Plus. The average energy flows of modelled unit processes are shown in Additional file 1: Table S5. The inputs in the pre-treatment phase varied slightly between the different *Salix* varieties, as the net mass of biomass treated was the same, but with some variations in composition. A large amount of heat was required in the steam explosion process as a result of production of superheated steam. The hygienisation process was the most energy-intensive step in the entire process chain, due to the high energy demand for heating DaM to 70 °C. The hygienised manure was mixed with the pre-treated *Salix* slurry and the combined feedstock stream needed cooling to the digester operating temperature of 37°C before anaerobic digestion.

Deviations in the composition of feedstocks and in BD between the manure and *Salix* mixtures resulted in variations in the amount of biogas generated and its composition. Higher BD led to greater conversion of organic matter to biogas, leading to greater flow rates of biogas. Higher amount of biogas produced meant that more electricity and cooling were required in the upgrading and compression steps. The water used in wet scrubbing of biogas to remove CO_2 was recirculated with a loss of 3%, reducing the need for addition of fresh water. The heat demand in the upgrading stage was for heating air used to remove dissolved gases from the water, which was then released from the system. Since compression of gases generates heat, the compressed gases needed to be cooled between stages, leading to high cooling demand in Stage 4.

Transportation of digestate to agricultural farms and spreading of digestate were performed using machines with diesel fuel as their energy source. Diesel energy demand for these activities was similar between the different varieties.

Biogas output

There were large variations in simulated biogas yield between the different *Salix* feedstock combinations studied because of the variation in composition and BMP, as reflected in the BD ratios. Primary and secondary biogas flows produced in the biogas digester and DST were upgraded and compressed to CBG. Feedstock mixtures with the varieties Gudrun and Tordis were the most productive CBG producers, while var. Jorr was the least productive (Table 7). In terms of CBG produced per unit of VS in the system, fertilised Jorr and unfertilised Björn showed lowest conversion of VS to the final product (Table 7).

Annual energy balance

The annual energy inputs and outputs (energy contained in the final CBG) with an annual operating time of 8000 h for the two scenarios are shown in Table 8. The energy performance was calculated based on energy output–input ratio (R).

Table 6 Hourly energy demand (MJ/h) in each stage and sub-stage of the process chain in the base scenario (without heat recovery) for the different feedstock combinations of Salix varieties and dairy manure (DaM)

	Björn F0 & DaM	Björn F+ & DaM	Gudrun F0 & DaM	Gudrun F+ & DaM	Jorr F0 & DaM	Jorr F+ & DaM	Loden F0 & DaM	Loden F+ & DaM	Tora F0 & DaM	Tora F+ & DaM	Tordis F0 & DaM	Tordis F+ & DaM
Stage 1												
1.1 Salix cultivation and transport												
Diesel	130.9	214.4	135.2	308.9	141.4	227.7	141.5	331.8	137.3	224.1	131.7	202.8
1.2 Dairy manure transport												
Diesel	81.5	81.7	81.4	81.0	81.3	81.7	79.4	80.9	81.0	81.4	81.7	81.7
Stage 2												
2. Pre-treatment												
Heat	383.8	364.2	371.8	358.8	409.2	407.9	376.4	396.2	390.6	400.2	402.2	382.5
Electricity	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Stage 3												
3.1 Manure hygienisation												
Heat	852.4	854.2	850.9	847.4	850.8	854.0	844.1	847.1	847.6	851.7	854.3	854.9
Electricity	1.11	1.11	1.11	1.10	1.11	1.11	1.10	1.10	1.10	1.11	1.11	1.11
3.2 Anaerobic Digestion												
Cooling	246.6	247.0	245.5	243.0	245.7	246.8	241.1	243.1	243.9	245.4	247.8	247.5
Electricity	62.2	62.2	62.2	62.2	62.2	62.2	62.2	62.2	62.2	62.2	62.2	62.2
Stage 4												
4.1 Upgrading												
Heat	20.3	20.3	20.3	20.3	20.3	20.3	20.3	20.3	20.3	20.3	20.3	20.3
Cooling	95.4	104.5	107.4	105.1	100.6	93.4	103.0	107.5	106.4	106.4	115.5	113.8
Electricity	124.8	133.4	136.1	133.9	129.7	122.8	131.9	136.1	135.1	135.1	143.7	142.1
4.2 Compression												
Cooling	139.1	150.1	153.4	150.6	145.2	136.3	147.9	153.4	152.1	152.1	163.4	161.2
Electricity	138.7	149.6	153.0	150.1	144.8	135.9	147.5	152.9	151.7	151.6	163.0	160.8
Stage 5												
5.1 Digestate transport												
Diesel	149.7	149.3	148.8	148.6	149.2	150.0	147.1	148.4	148.6	149.0	148.6	148.8
5.2 Digestate spreading												
Diesel	114.6	114.3	114.0	113.8	114.3	114.8	112.7	113.7	113.8	114.1	113.8	114.0

Table 7 Biogas and compressed biomethane gas (CBG) yield on an hourly basis from the anaerobic digester and digestate storage tank (DST) (F0 & F+ indicate unfertilised and fertilised Salix, respectively, DaM is dairy manure)

Feedstock	Biogas flow (kg/h)		Compressed biomethane gas flow		
	DIGESTER	DST	Kg/h	Nm^3/h	kg/kg VS
Björn F0 & DaM	228	15	85	118	0.14
Björn F+ & DaM	256	12	92	128	0.16
Gudrun F0 & DaM	264	11	94	131	0.16
Gudrun F+ & DaM	259	11	92	128	0.16
Jorr F0 & DaM	278	14	89	124	0.15
Jorr F+ & DaM	224	13	83	116	0.14
Loden F0 & DaM	254	11	90	126	0.16
Loden F+ & DaM	266	10	94	131	0.16
Tora F0 & DaM	262	11	93	130	0.16
Tora F+ & DaM	262	10	93	130	0.16
Tordis F0 & DaM	288	10	100	139	0.17
Tordis F+ & DaM	283	10	99	137	0.17

All *Salix* and DaM-based co-digestion systems had a R value greater than 1, which means that more energy was obtained in the final product (biomethane) than was demanded in the complete system. Unfertilised Tordis-based systems had the highest R value (1.88), while fertilised Jorr had the lowest (1.57). Most of the energy demand was in the form of heating, which can be attributed to the large energy requirement for hygienisation of DaM and steam explosion of *Salix* biomass. As the manure had a moisture content of 90%, a significant amount of energy was required to heat it to 70°C to reduce the risk of pathogen contamination from field application of digestate. The cooling demand was also high, indicating potential for heat exchange between the heating and cooling functions to reduce the overall demand of the facility.

Under the HRE scenario, there was a significant reduction in energy demand for heating and cooling owing to heat exchange between selected hot streams and the cold DaM feed stream (Table 8). Heat recovery did not affect the energy output in terms of CBG, which remained the same as in the base scenario. This led to improved energy performance in the HRE scenario, resulting in higher *R* values for all cases (Table 8). Energy performance improved by 46–61% in the heat recovery scenario compared with the base scenario. Biomethane production from co-digestion of unfertilised Tordis with DaM had the highest R value in the HRE scenario (2.94), while the fertilised Jorr with DaM system had the lowest (2.36).

Energy demand by process

The average energy requirement by type as diesel, electricity, heat and cooling across the different processes in the whole production chain for the different feedstock cases are presented in Fig. 6. In the base scenario, manure hygienisation and steam pre-treatment had the largest energy demand in the form of heating. The HRE scenario greatly reduced the heat demand for manure hygienisation. Diesel energy demand was sensitive to transportation distance, especially in the case of digestate disposal, as transportation of large volumes of wet digestate over greater distances greatly increased the diesel energy demand. Thus longer transport distances will require alternate strategies for the digestate to maintain desirable energy performance.

Discussion

This study analyzed the effects of *Salix* variety on energy and mass flows co-digested with DaM to produce biomethane. The results from the literature, laboratory experiments and process modelling were useful in identifying factors and parameters affecting energy output and performance of the anaerobic digestion process. Overall, the results showed good potential for biomethane production and can serve as a guideline for future assessments to determine biomethane output in relation to amount of *Salix* processed. Site-specific data that include spatial and temporal aspects are needed to refine the results further to provide exact figures for real biogas applications.

The results in the present case showed that the energy output was higher than the energy demand of the *Salix*-to-biomethane systems, but with differences between varieties, highlighting the importance of including varietal effects in such analyses. The wide system boundary chosen in the study (Fig. 1) also provided a more holistic picture of the performance of the system, as all steps from cultivation of *Salix* to digestate disposal were included.

There were large variations in energy demand of the *Salix* production chain between the different varieties, due to fertilisation and differences in yield. Fertilisation increased the energy demand per unit mass of biomass produced, but also gave higher biomass yield in most cases. The productivity of *Salix* crop varieties is an important parameter, as there is reported to be a 3.5-fold difference in land requirement between the lowest- and highest-producing varieties [28]. Arable land is a scarce resource in the majority of countries worldwide, so it is important to strike a balance between the amount of land needed for production and the energy input per unit of biomass. The productivity level of unfertilised crops is also questionable in the long run, as it is very likely that the soil nutrients will deplete over time. Thus,

Table 8 Energy balance and energy ratio (R) of unfertilised (F0) and fertilised (F+) Salix varieties and dairy manure (DaM) co-digestion feedstocks in the biogas system under base and heat recovery (HRE) scenario

Feedstock	Björn F0 & DaM	Björn F+& DaM	Gudrun F0 & DaM	Gudrun F+& DaM	Jorr F0 & DaM	Jorr F+& DaM	Loden F0 & DaM	Loden F+& DaM	Tora F0 & DaM	Tora F+& DaM	Tordis F0 & DaM	Tordis F+& DaM	Unit
Net energy output*	9.43	10.19	10.42	10.22	9.85	9.24	10.04	10.41	10.33	10.32	11.10	10.95	GWh
Base scenario													
Net diesel demand	1.06	1.24	1.07	1.45	1.08	1.28	1.07	1.50	1.07	1.26	1.06	1.22	GWh
Net heating demand	2.79	2.75	2.76	2.73	2.85	2.85	2.76	2.81	2.80	2.83	2.84	2.79	GWh
Net cooling demand	1.07	1.11	1.13	1.11	1.09	1.06	1.09	1.12	1.12	1.12	1.17	1.16	GWh
Net electricity demand	0.73	0.77	0.79	0.78	0.75	0.72	0.77	0.79	0.78	0.78	0.83	0.82	GWh
Output–input ratio	1.67	1.73	1.81	1.69	1.71	1.57	1.77	1.68	1.79	1.72	1.88	1.83	
HRE scenario													
Net diesel demand	1.06	1.24	1.07	1.45	1.08	1.28	1.07	1.50	1.07	1.26	1.06	1.22	GWh
Net heating demand	1.62	1.56	1.56	1.54	1.66	1.68	1.56	1.61	1.60	1.63	1.61	1.57	GWh
Net cooling demand	0.24	0.26	0.27	0.26	0.25	0.23	0.26	0.27	0.26	0.26	0.29	0.28	GWh
Net electricity demand	0.73	0.77	0.79	0.78	0.75	0.72	0.77	0.79	0.78	0.78	0.83	0.82	GWh
Output–input ratio	2.59	2.66	2.83	2.54	2.63	2.36	2.75	2.50	2.78	2.62	2.94	2.82	
Improvement in HRE scenario over base scenario	55.1%	53.6%	56.0%	50.6%	54.2%	51.0%	55.5%	49.2%	55.1%	52.1%	55.9%	54.0%	

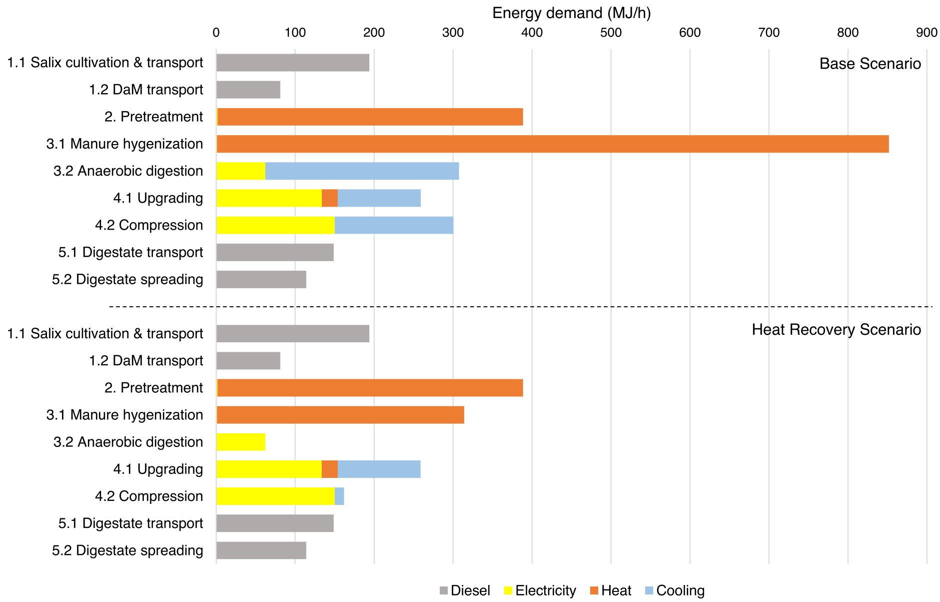

Fig. 6 Average energy demand (diesel, electricity, heating and cooling) of the different processes in the compressed biomethane gas (CBG) production chain for the different Salix varieties and dairy manure (DaM) co-digestion feedstocks

fertilisation is beneficial to ensure a steady and secure supply of *Salix* biomass.

The biomethane facility studied comprised steam pre-treatment, hygienisation of manure and anaerobic digestion, and biogas upgrading (stages 2, 3 and 4 in Fig. 1). The hygienisation process had the highest energy demand, for heating liquid dairy manure to deactivate pathogens. This increased the energy input of the system, but rendered the digestate safe as a fertiliser. Although optimisation of energy performance is important, it is not always the main objective of biogas plants. Use of digestate on fields reduces the need for mineral fertilisers and can contribute to increased soil carbon sequestration. This is favourable from the perspective of climate change mitigation and waste management. Climate impact studies on the system scale (e.g., LCA) are needed to calculate the climate benefit of such processes. Based on the N-P-K content of *Salix* biomass and DaM reported in the literature (Additional file 1: Table S6), annual application of 30 tons/hectare of digestate can add about 60 kg, 12.5 kg and 59 kg of N-P-K per year (Additional file 1: Table S7).

Co-digestion of the *Salix* varieties Gudrun and Tordis with DaM gave the highest biomethane output in this study. In both fertilised and unfertilised form, these two varieties produced more than 100 kg/h of biomethane from co-digestion of 300 kg/h of *Salix* feedstock with DaM in a 1:1 VS ratio. The biomethane output was modelled in reactors in Aspen Plus, using stoichiometric reactions and BD ratio calculated from laboratory-scale BMP studies. Different approaches in modelling biogas reactors can lead to varying results and there is uncertainty regarding how biogas production in industrial-scale plants compares with laboratory-scale experiments. Anaerobic digestion is a simple process but has complex dynamics, as it involves intricate microbiological interactions, so it is difficult to upscale laboratory-scale BMP values to methane production in large-scale plants. In this study, RMY was conservatively assumed to be 80% of the BMP value. Depending on anaerobic digester conditions and management practices, RMY can be higher. Liquid digestate recirculation could be an interesting strategy to increase biomass degradability and reach higher methane yields as some studies as reported [52, 53]. For instance, liquid digestate could be utilized instead of water to increase water content of the pretreated *Salix* biomass to make it pumpable. Experimentation is required to determine optimal recirculation ratios for the feedstocks studied and to avoid negative effects such as inhibitor accumulation or accumulation of solids. Pilot-scale studies are needed to identify the reaction dynamics and interactions, which will allow more accurate modelling and extrapolation of such processes to industrial scales.

Due to the lack of a standardised method for measuring energy performance, it is challenging to make direct comparisons of different systems. Output–input ratio is one of the most common indicators used in energy performance calculations for biogas production [51], but differences in system boundaries between studies determine what are included as input and output energies in respective systems. To conduct an accurate energy balance analysis, direct and indirect energy requirements should be established for all stages of the crop-based energy production cycle. The *R* values in this study ranged from 1.57 to 1.88 for the base scenario without heat recovery, and from 2.36 to 2.94 in the heat recovery scenario. These values are at the lower end of the range of R values reported in the literature, e.g., for *Salix* biogas production in Denmark values of 7.3 without pre-treatment and 12.3 with pre-treatment have been reported [54]. Those higher R values can be due to omission of biomethane upgrading and manure hygienisation processes in their system. The *R* values in that study were higher for *Salix* than for maize and miscanthus, although total energy output was higher from maize without pre-treatment. The perennial energy crops (*Salix* and miscanthus) had significantly lower energy inputs for cultivation and harvest than maize, and pre-treatment improved biogas yield [54]. A similar analysis of biomethane production from untreated hemp (*Cannabis sativa* L.) in Sweden reported a R value of 2.6 [55], which is comparable to the R values of *Salix* in the HRE scenario in our study. Another study analysing biomethane production from maize, fodder beet, lupin and perennial ryegrass, with heat and electricity demand fulfilled from the biogas produced, reported *R* values of 2.0 to 2.9 for crops in the system [54]. However, the results of such systems analyses are dependent on site-specific conditions and modelling choices such as system configuration, secondary feedstock selection, and pretreatment conditions. Hence, it is important to consider these factors when interpreting the results.

The heating demand for the pretreatment and manure hygienization processes is one of the main energy consumers in the system. Reduction of the pretreatment energy consumption for pre-treatment, while maximising the release of sugars, is critical for improving the energy performance of biomass to biofuel systems [56]. Achieving such an improvement could make lignocellulosic materials such as *Salix* an efficient and attractive feedstock for sustainable production of biofuels and biogas [57]. The lower energy demand in the HRE scenario improved the energy performance of the system in this study. Process design to maximise heat recovery while balancing the economic costs of a more complex set-up is necessary to ensure the success of industrial-scale production.

The heating value of the raw materials was not considered in this study, as the energy performance of different energy carriers other than biomethane or other conversion pathways (e.g., combustion or gasification) for the feedstocks were not compared. The focus was on biomethane production and the system performance of different feedstock combinations. Differences in energy conversion efficiency must be included when comparing different conversion pathways.

Upgrading and compression of biogas to biomethane had a high demand for electricity and cooling, which negatively affected the overall energy balance, as these steps did not increase the net energy output of the system. The increased energy demand for upgrading biogas can be justified, as it improves fuel quality and enables direct use of biogas as a vehicle fuel or injection into gas grids as biomethane. If biogas is to replace natural gas as fuel, upgrading is necessary to remove the non-combustible CO_2 fraction from biogas. Reducing the energy demand for upgrading would greatly benefit the energy performance of the system, but might not be as relevant from an economic standpoint if cheap electricity and cooling are available on-site. Various upgrading technologies (in addition to water scrubbing) are undergoing constant improvement in their energy and environmental performance, but their actual performance will depend on site-specific and economic conditions, which must be taken into account when selecting the best technique [58].

In addition to replacement of fossil natural gas by biomethane, potential for soil carbon sequestration by *Salix* cultivation [25] and digestate application [59] make co-digestion of *Salix* an interesting strategy to mitigate climate change. In future work, we will extend the mass and energy analysis to a LCA to evaluate and compare the climate performance of biomethane production from *Salix* varieties.

Conclusions

A CBG production system based on a 1:1 VS mix of pre-treated *Salix* and DaM was analyzed to evaluate the energy performance of different *Salix* varieties. Biomethane production varied between different combinations of *Salix* and DaM, based on BMP values and composition. The energy demand of the biomethane production chain in terms of heating, cooling, and electricity demand was assessed in scenarios without and with heat recovery. Output–input ratio varied from 1.57 to 1.88 in the scenario without heat recovery, while including heat recovery to meet some of the heating and cooling requirements increased the *R* value to 2.36–2.94. A system based on unfertilised var. Tordis performed best, fertilised Jorr was the worst in both scenarios. The hygienization of DaM was the greatest contributor to the heating demand, followed by upgrading and compression of biogas to biomethane. The heat recovery scenario greatly reduced the energy demand; however, upgrading still represented a high energy demand owing to the higher electricity demand. A reduction in the energy required for upgrading can significantly improve energy performance. The energy performance showed that, *Salix* could be a potential feedstock for biogas production, although its *R* value was at the lower end of the reported range for biogas from energy crops. However, direct comparison between studies is difficult due to differences in system boundaries and conditions. Further work will focus on determining the climate impacts of these *Salix*-based biomethane systems, to assess their potential to mitigate climate change.

Abbreviations

BD	Biodegradability
BMP	Biomethane potential
CBG	Compressed biomethane gas
DaM	Dairy manure
DST	Digestate storage tank
EU	European Union
F+	Fertilised
F0	Unfertilised
GDP	Gross domestic product
GHG	Greenhouse gas
HRT	Hydraulic retention time
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
NRTL	Non-random two liquid
OLR	Organic loading rate
PPP	Purchasing power parity
RMY	Real methane yield
SM	Supplementary material
TMY	Theoretical methane yield
TS	Total solids
VS	Volatile solids

Supplementary Information

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Additional file 1: Table S1. Composition data for the six Salix varieties under unfertilised (F0) and fertilised (F+) conditions. Values are based on total solids content. Values are means of three biological replicates. **Table S2.** Average yield of Salix varieties in tons (t) of dry matter (DM) per hectare (ha) per 3-year harvest cycle and annual average [5]. **Table S3.** Material inputs per hectare in Salix cultivation. Cuttings and pesticide were used during establishment of a new rotation every 25 years. Fertilisers were applied annually from the second year of establishment. The values were obtained from a field study by Weih and Nordh [6] at Uppsala, Sweden. **Table S4.** Energy input in terms of diesel fuel for processes involved in Salix cultivation per ton dry matter (t DM) of harvested biomass [5]. **Table S5.** Energy in terms of electricity, heating and cooling for the unit processes modelled using Aspen Plus. **Table S6.** Nitrogen (N), Phosphorus (P) and Potassium (K) content (% in dry matter) for Salix shoot biomass (dry) for fertilised and unfertilised varieties, and manure. **Table S7.** Amounts of N P K added and area needed for digestate spreading when digestate is spread at a rate of 30 tons/hectare annually.

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Author contributions

All authors contributed to the conception, design and methodology of the study. JO generated the biogas data for the *Salix* varieties. SK carried out the energy and mass analysis with inputs and guidance from all other authors. SK wrote the first draft of the manuscript and prepared the figures, and all authors reviewed the previous versions. All authors read and approved the final manuscript.

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Availability of data and materials

The data presented in this study are available the supplementary material and within the article. If required, further relevant details are available from the corresponding author on request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

All authors have approved the manuscript and consent to its publication in the journal.

Competing interests

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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Additional file 1

Salix Compositional Analysis Data

The milled and sieved biomass samples were Soxhlet extracted according to the NREL procedure TP-510-42619. Samples underwent extraction with boiling water for 6 hours and ethanol (95%) for an additional 6 hours. All extracted samples were then dried, and the monomeric carbohydrates contents of the samples were determined by quantitative saccharification upon acid hydrolysis and subsequent HPLC analysis, based on the NREL procedure 510-42618. The sugar compositions were determined by HPLC (Chromaster) equipped with an evaporative light scattering detector (ELSD-go), and a Metacarb 87P column operated at 80°C. Ohlsson, 2021 [1], presents the details of the compositional analysis. Mohamed Jebrane at Department of Forest Biomaterials and Technology, SLU carried out the compositional analysis tests.

Biomethanation Potential Assays

Biomass was chipped using a compost chipper (MTD90 Chipper Shredder). The chipped material was steam pretreated using relatively mild conditions (185 °C for 4 minutes, 2% SO_2 as a catalyst), equalling a severity factor ($\log_{10} R_0$) of 3.1. The steam pretreatment was performed in a 10-L reactor (Process & Industriteknik AB, Kristianstad, Sweden) described previously by Palmqvist et al. (1996) [2]. The material was stored in –20°C before and after steam pretreatment, and thawed at 4°C prior to BMP assays.

The BMP assay was performed using steam pretreated Salix biomass. In 1120-ml serum bottles, 1.2 g volatile solids (VS) were mixed with inoculum from a wastewater treatment plant in Uppsala, Sweden. Inoculum to substrate ratio was 3:1 on a VS basis, and tap water was added to reach a final liquid volume of 400 ml. Total solids (TS) and VS were measured by drying at 105°C followed by incineration at 550°C. Inoculum TS was 3.7% and VS was 2.4%, based on wet weight. Bottles were sealed with butyl rubber seals and aluminium caps and incubated at 37°C on a rotary shaker set to 100 rpm. Gas production was evaluated manometrically, and methane contents analysed using gas chromatography as previously described by [3], [4] . Triplicate cellulose (1.2 g VS per bottle; medium fibers; Sigma-Aldrich) and inoculum controls were included in the assay. Due to very low BMP values, indicating an issue with the assay, the Jorr F+ samples were re-evaluated on an AMPTS system using the same parameters as above.

Table S1 Composition data for the six Salix varieties under unfertilised (F0) and fertilised (F+) conditions. Values are based on total solids content. Values are means of three biological replicates.

Variety & treatment	Lignin (%)	Cellobiose (%)	Glucose (%)	Xylose (%)	Galactose (%)	Arabinose (%)	Mannose (%)
Björn F0	24.0	0.1	58.6	10.4	2.0	0.5	2.0
Björn F+	24.2	0.1	55.8	9.9	1.7	0.5	1.7
Gudrun F0	27.3	0.0	54.3	10.2	1.8	0.7	1.8
Gudrun F+	27.9	0.1	52.7	9.2	1.8	0.7	1.6
Jorr F0	27.4	0.7	52.8	9.6	2.6	0.9	2.4
Jorr F+	27.2	0.3	50.7	8.7	2.2	1.0	2.4
Loden F0	28.1	0.1	50.8	9.2	1.8	0.7	1.9
Loden F+	28.8	0.1	51.1	9.4	1.9	0.9	2.2
Tora F0	28.3	0.1	51.8	10.4	2.3	0.8	2.1
Tora F+	26.1	0.0	50.1	10.0	1.8	0.7	2.3
Tordis F0	25.5	0.1	57.0	10.1	2.1	0.6	2.3
Tordis F+	25.7	0.0	55.0	9.9	1.7	0.5	2.0

Input Data for Salix Cultivation and harvest

Table S2 Average yield of Salix varieties in tons (t) of dry matter (DM) per hectare (ha) per 3-year harvest cycle and annual average [5]

Variety and treatment	Harvest (t DM/ha)	
	3-year rotation	Annual average
Björn_F0	31.9	10.6
Björn_F+	42.7	14.2
Gudrun_F0	20.8	6.9
Gudrun_F+	20.6	6.9
Jorr_F0	14.4	4.8
Jorr_F+	36.9	12.3
Loden_F0	14.4	4.8
Loden_F+	18.3	6.1
Tora_F0	18.2	6.1
Tora_F+	38.3	12.8
Tordis_F0	28.5	9.5
Tordis_F+	48.5	16.2

Table S3 Material inputs per hectare in Salix cultivation. Cuttings and pesticide were used during establishment of a new rotation every 25 years. Fertilisers were applied annually from the second year of establishment. The values were obtained from a field study by Weih and Nordh [6] at Uppsala, Sweden.

Input	Value	Unit per hectare
Cuttings[1]	18000	Cuttings/rotation
Pesticide		
Roundup	5	l/rotation
Cougar	1	l/rotation
Mineral Fertiliser		
N	100	kg/year
P	14	kg/year
K	47	kg/year

[1]Salix was planted at a density of 18000 cuttings per hectare

Table S4 Energy input in terms of diesel fuel for processes involved in Salix cultivation per ton dry matter (t DM) of harvested biomass [5]

Variety & treatment	Pesticides	Field preparation	Seedling production & planting	Fertiliser production and application	Harvest and chipping	Forwarding	Stump removal	Transport to biogas facility
	MJ/ t DM	MJ/ t DM	MJ/ t DM	MJ/ t DM	MJ/ t DM	MJ/ t DM	MJ/ t DM	MJ/ t DM
Björn F0	7.0	12.2	7.5	-	120.2	58.7	2.9	227.7
Björn F+	5.1	8.9	5.5	286.3	120.2	58.7	2.1	227.7
Gudrun F0	10.5	18.2	11.1	-	120.2	58.7	4.4	227.7
Gudrun F+	10.4	18.1	11.1	579.2	120.2	58.7	4.3	227.7
Jorr F0	15.3	26.7	16.3	-	120.2	58.7	6.4	227.7
Jorr F+	5.9	10.2	6.3	327.5	120.2	58.7	2.5	227.7
Loden F0	15.4	26.8	16.4	-	120.2	58.7	6.4	227.7
Loden F+	11.7	20.3	12.4	650.0	120.2	58.7	4.9	227.7
Tora F0	12.1	21.0	12.9	-	120.2	58.7	5.0	227.7
Tora F+	5.7	9.9	6.0	316.5	120.2	58.7	2.4	227.7
Tordis F0	7.7	13.4	8.2	-	120.2	58.7	3.2	227.7
Tordis F+	4.5	7.8	4.8	250.5	120.2	58.7	1.9	227.7

Energy of unit processes determined from process model

The electricity, heating and cooling duties in Table 7 were obtained from the process models created using Aspen Plus V11.

Table S5 Energy in terms of electricity, heating and cooling for the unit processes modelled using Aspen Plus

Unit process	Electricity req.	Heat req.	Cooling req.
Pretreatment			
Salix heating		7 kW/h	
High pressure steam generation		39 kW/h	
Steam Explosion		54 – 68 kW/h	
SO2 pump	0.18 kW/h		
Water pump	0.28 kW/h		
Recoverable heat from steam post steam explosion			42.6 kW/h
Anaerobic Digestion			
Manure Hygenization		234 – 237 kW/h (base scenario) 84 – 91 kW/h (heat recovery scenario)	
Manure pump	0.31 kW/h		
Excess heat in digestate (Cooling)			67 – 69 kW/h (base scenario)
Digestate pump	2 kW/h		
Upgrading			
Compressor block 1	17 – 21 kW/h		14 – 17 kW/h
Compressor block 2	7 – 9 kW/h		12 – 15 kW/h
Air heating		5.63 kW/h	
Water pump	10 kW/h		
Compression			
Compression block 3	38 – 45 kW/h		38 – 46 kW/h (base scenario) 29 – 36 kW/h (heat recovery scenario)

Nutrient (N-P-K) content in feedstock and digestate

Table S6 Nitrogen (N), Phosphorus (P) and Potassium (K) content (% in dry matter) for Salix shoot biomass (dry) for fertilised and unfertilised varieties, and manure

	Treatment	N (%)	P (%)	K (%)
Björn	F0	0.19	0.08	0.27
Björn	F+	0.19	0.08	0.27
Gudrun	F0	0.20	0.08	0.27
Gudrun	F+	0.25	0.08	0.27
Jorr	F0	0.22	0.08	0.27
Jorr	F+	0.18	0.08	0.27
Loden	F0	0.23	0.08	0.27
Loden	F+	0.29	0.08	0.27
Tora	F0	0.21	0.08	0.27
Tora	F+	0.19	0.08	0.27
Tordis	F0	0.22	0.08	0.27
Tordis	F+	0.23	0.08	0.27
DaM		3.5	0.7	3.4

Nitrogen content in Salix shoot biomass is based on data from field study by Weih and Nordh [6], and the phosphorus and potassium content is estimated by data from Phyllis database [7]. NPK content of DaM is based on mean of literature values [8]–[13]. The N P K amounts in the mixed feed of Salix and DaM is assumed to end up in the digestate in calculation of the nutrient content of the digestate. Considering an annual digestate application rate of 30 tons/hectare, the potential NPK added to per hectare of land and the annual area needed to spread this digestate are calculated and presented in Table 6.

Table S7 Amounts of N P K added and area needed for digestate spreading when digestate is spread at a rate of 30 tons/hectare annually

Digestate	Treatment	N (kg/ha)	P (kg/ha)	K (kg/ha)	Area needed (ha)
Björn + DaM	F0	59.7	12.5	59.1	1968.8
Björn + DaM	F+	60.0	12.5	59.4	1963.8
Gudrun + DaM	F0	60.1	12.5	59.4	1957.3
Gudrun + DaM	F+	60.6	12.5	59.2	1954.7
Jorr + DaM	F0	60.2	12.5	59.2	1962.7
Jorr + DaM	F+	59.6	12.5	59.1	1972.5
Loden + DaM	F0	60.7	12.6	59.6	1935.4
Loden + DaM	F+	61.2	12.5	59.3	1952.5
Tora + DaM	F0	60.1	12.5	59.3	1954.0
Tora + DaM	F+	59.9	12.5	59.4	1959.2
Tordis + DaM	F0	60.7	12.6	59.7	1955.1
Tordis + DaM	F+	60.8	12.6	59.7	1957.3

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This thesis explored the influence of Salix variety on the climate impact of three conversion routes — producing heat, compressed biomethane, and yeast oil. A life cycle perspective incorporating time dynamic climate impact, soil carbon modelling, and field and laboratory data was used. The results found that Salix variety played a key role in determining the climate impact. The yield and soil carbon sequestration were the most important characteristics. The findings can be used to optimise selection of Salix varieties.

Saurav Kalita received his postgraduate education at the Department of Energy and Technology, Swedish University of Agricultural Sciences (SLU), Uppsala. He holds a Master of Science degree in Innovative Sustainable Energy Engineering from KTH and Aalto University.

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