Drivers and Barriers for Biochar Deployment in Swedish Agriculture

- A Multi-Level Perspective on Sustainability Transitions

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Abstract

There are several sustainability challenges (e.g., environmental degradation, biodiversity loss, and food insecurity) that agro-food systems face. Simultaneously, agriculture is a major contributor to greenhouse gas emissions. Addressing these challenges requires socio-technical transformations in the agro-food system. Biochar can play a part in the solution because it is a carbon removal method with co-benefits for agriculture. Despite the goal of the Swedish government to achieve net-zero emissions by 2045, biochar has not been adopted widely in Swedish agriculture. Therefore, this study aims to investigate the drivers and barriers that facilitate or hinder biochar deployment in Swedish agriculture, and under what prerequisites an accelerated adoption can take place.

The study used a qualitative case study method. The data was collected through 9 semi-structured interviews and participation in a webinar. The data was analyzed with the use of thematic analysis. The multi-level perspective framework on sustainability transitions has been applied to interpret the empirical findings.

The results suggest that biochar holds promise to contribute to sustainable agriculture in Sweden, but that there are certain barriers that need to be overcome. Regarding drivers, biochar offers various agricultural and environmental benefits. The Swedish government's goal to reduce greenhouse gas emissions from agriculture further supports its deployment. However, there are barriers that hinder the widespread adoption of biochar. The high cost of biochar, along with volatility in biochar and carbon credit price makes it risky for farmers to invest in biochar technology. Financial incentives are essential to make biochar more affordable and attractive for on-farm use. The creation of a stable and farmer-friendly carbon market is crucial to reduce fluctuations in price and ensure economic viability for farmers. Knowledge gaps also exist, highlighting the need for research funding, knowledge sharing, and collaboration among stakeholders and countries. Farmers and researchers should work together to bridge the gap between scientific findings and practical on-farm use of biochar to find its ultimate applications in agriculture. Competition with other carbon removal technologies poses additional barriers as well as perceived resistance from fertilizer companies expressed by a few stakeholders. Lack of supportive legislation for using waste materials and side streams as biomass sources and inadequate financial support for production plant investments also hinder the diffusion of biochar technology. Overcoming these barriers requires learning processes and collective efforts to establish a sustainable and economically viable biochar market that benefits Swedish agriculture and contributes to the government's environmental goals. The results of this study can be utilized to guide policy-makers and biochar stakeholders on how to enable increased biochar adoption in Swedish agriculture.

Keywords: Biochar, Agriculture, Socio-technical transitions, Multi-level perspective

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Abbreviations

BCR	Biochar Carbon Removal
BECCS	Bioenergy with Carbon Capture and Storage
CEC	Cation Exchange Capacity
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
DAC	Direct Air Capture
EBC	European Biochar Certificate
EBI	European Biochar Industry
EU	European Union
GHG	Greenhouse Gases
MLP	Multi-Level Perspective
NET	Negative Emissions Technology
SLU	The Swedish University of Agricultural Sciences
SSA	Specific Surface Area

Introduction

Agricultural systems over the world are under increasing stress. Demand for food is projected by the FAO to increase by 70% by 2050, driven by the need to feed a growing population (FAO, 2009). Simultaneously, five out of the nine planetary boundaries that define the safe operating space for humanity to prevent irreversible damage to the Earth's system are significantly impacted by agricultural activities (Campbell et al., 2017). Three of these boundaries are at risk of being exceeded, with agriculture being the main driver for two of them; land-system change and freshwater use (Campbell et al., 2017). Further, agriculture is a significant contributor to the third, climate change. To demonstrate, the current food supply chain produces 26% of anthropogenic greenhouse gas (GHG) emissions, with agriculture accounting for 61% of those emissions (Poore & Nemecek, 2018). A radical change in the current food system is required to address the role of agriculture in the transgression of these boundaries (Campbell et al., 2017).

As a response, there has been a rise in the adoption of novel technologies in the agro-food chain, with the goal to mitigate the negative impact of agriculture on the environment (Nair et al., 2017). One of the technologies that has attracted attention over the last decade is biochar. Biochar is a solid product obtained from pyrolysis by heating biomass under an oxygen-free or oxygen-deficient environment at temperatures above 250 °C (Kamali et al., 2022). The unique physicochemical and biological characteristics of biochar as a soil amendment have been observed to enhance crop yield and soil quality (Kavithia et al., 2018). Furthermore, the Intergovernmental Panel on Climate Change (IPCC) recognized its potential as negative emissions technology (NET). To illustrate, it was described in the Special Report Global Warming of 1.5°C (SR1.5) as a relevant method for carbon dioxide removal (CDR) in the agricultural sector (IPCC, 2019).

The Swedish government has set ambitious goals to achieve net-zero emissions by 2045 (Government Offices of Sweden, 2021). The use of biochar aligns with this goal, as it can contribute to reducing greenhouse gas emissions while bringing co-benefits for agriculture. The necessity for Sweden to increase the implementation of carbon dioxide removal (CDR) and soil-enhancing technologies is illustrated by the major drought the country experienced in the summer of 2018. However, despite the agricultural and environmental advantages offered by biochar, its deployment in Swedish agriculture is still in an early stage of development.

For the large-scale adoption of biochar, soil characteristics are not the only relevant factors. To illustrate, Herrero et al. (2020) argue that a purely technological approach to food system transformation does not suffice, but rather that it requires changes in the component parts of the food system (technologies, infrastructure, and skills and capability) and a reform of the deeper system properties such as values, regulations, policies, markets and governance that surround it. This requires an understanding of the wider social and institutional factors that enable the deployment of novel technologies such as biochar.

Most of the currently available literature has a one-dimensional focus on the biological and technical prospects of biochar for agricultural use. However, other aspects that are needed for the actual implementation of biochar in agriculture, remain largely unstudied. This demonstrates a knowledge gap that is also recognized in the literature. For example, Otte and Vik (2017), argue that the implementation of biochar systems does not only require physical technology and economic benefits, but also the analysis of social and organizational factors, thus calling for a close collaboration between social science and natural science on biochar systems. Dorninger et al. (2020) argue that whereas sustainability transformation requires intervention to multiple system characteristics, deep system properties, such as world views, remain largely unaddressed in empirical studies.

There has been a previous master's study partially dedicated to studying the potential for large-scale implementation of biochar in agriculture in Sweden (Håkansson & Strömberg, 2022). The findings reported positive views of stakeholders on the economic and social benefits of biochar. Perceived challenges for large-scale implementation included knowledge gaps about the contexts in which biochar should be prioritized, and the cost and availability of biomass. Opportunities included increased collaboration between different stakeholders, synergies between biochar and bioenergy to improve resource efficiency, financial aid from the government, the establishment of a carbon crediting system, and the use of waste biomass (*Ibid*).

However, these results were not placed in a theoretical framework for analysis. Therefore, this master thesis adds to the current knowledge on the drivers and barriers for large-scale biochar deployment in Sweden by implementing a socio-technical transitions framework. This is needed, because “the current, unsustainable way in which important societal functions such as energy-, mobility, and healthcare are fulfilled presents a grand challenge”, which requires socio-technical transitions for these societal subsystems to become sustainable (Alkemade et al., 2011, p. 125).

1.1 Purpose and aim

Based on the identified knowledge gap, this study aims to apply a socio-technical systems approach to biochar deployment in Sweden, to gain knowledge on barriers and drivers for increased adoption and that integrates the technological considerations with the social, economic, and political processes that either impede or facilitate system innovation. This will give insight into new directions and desirable transformation pathways, thus guiding policy-makers on how to enable increased adoption of biochar in Swedish agriculture.

The objectives of this study are twofold: 1) to understand stakeholders' perspectives on the barriers and drivers for the widespread adoption of biochar in Swedish agriculture, and 2) to identify the socio-technical factors required to accelerate a sustainability transition towards increased biochar deployment. To achieve these objectives, the following research questions are formulated:

1. What do stakeholders perceive as the current main socio-technical factors that could either hinder or facilitate a sustainability transition in terms of increased biochar use in Swedish agriculture?
2. What are the socio-technical requirements to accelerate a sustainability transition towards increased biochar deployment in Swedish agriculture?

1.2 Outline

This thesis is constructed as follows: Chapter 2 provides background information about technological, economic, and legislative aspects that are related to biochar use in agriculture, with a focus on temperate regions. Chapter 3 presents the theoretical concepts used to analyze and discuss the research findings. In Chapter 4, the study design is described as well as the method of data collection and analysis that is used in this study. This chapter also includes ethical and quality considerations. The empirical findings are presented in Chapter 5 with the use of the theoretical framework. Chapter 6 discusses the research findings in relation to the theoretical framework. Further, it discusses the limitations of the study method and the theoretical framework that should be taken into account when evaluating the validity of the research findings. Chapter 7 presents the conclusions that are drawn from the results and provides answers to the research questions.

Background

The following paragraphs will provide relevant information on technological, economic, and legislative aspects that are related to biochar use in agriculture, with a focus on temperate regions. The technological aspects will be described in terms of biochar quality, and the effects of biochar as soil amendment.

2.1.1 Biochar quality

Biochar can be produced from a wide variety of biomass inputs (e.g., wood and its residues, agricultural waste, animal manure, sewage sludge, and food waste), and under varying pyrolysis conditions (Lévesque et al., 2021; Ippolito et al., 2020). In temperate regions, the quality of biochar as a soil amendment is primarily determined by physicochemical characteristics such as porosity, specific surface area (SSA), water-holding capacity, pH, cation-exchange capacity (CEC), and the type and concentration of mineral and toxic compounds (Lévesque et al., 2021). The following paragraphs will describe how these characteristics are influenced by the type of feedstock, the pyrolysis temperature, and the pyrolysis method (fast versus slow).

The composition of the used raw material as feedstock appears to have the largest influence on biochar properties (Ippolito et al., 2020). Wood-based biochars generally produce biochars with the highest carbon content, making them suitable soil amendments for carbon sequestration. Furthermore, woody biomasses generally have the greatest SSA, and larger pore volume, which is correlated to improved soil physical characteristics, including increased material adsorption and water-holding capacity (Lévesque et al., 2021). In comparison, straw- and manure-based biochars produce biochars with lower SSA and pore volume, but higher CEC which could lead to increased soil nutrient retention (Ippolito et al., 2020). Manure/biosolids feedstocks produce biochar with the highest nitrogen and phosphorus content (Joseph et al., 2021), providing them with an advantage in their use as fertilizer (Ippolito et al., 2020).

The pyrolysis temperature can affect the porosity, SSA, and stability of biochar, as it determines the particle size of the produced biochar (Lévesque et al., 2021). Higher temperatures are associated in biochars with higher carbon content, lower oxygen content, increased porosity, and increased SSA, which could enhance soil physicochemical improvements (Ippolito et al., 2020). Furthermore, biochars produced under higher pyrolysis temperatures (>500°C) tend to have higher longevity in soils (>1000 years), making them more effective for the mitigation of N_2O emissions and carbon storage (Ippolito et al., 2020). However, excessively high temperatures can form toxic compounds that can pose risks to the environment and human health, such as polycyclic aromatic hydrocarbons (Lévesque et al., 2021).

Lastly, the quality of biochar is affected by the pyrolysis method. Fast pyrolysis is conducted with shorter residence times (a few seconds or less), whereas slow pyrolysis is conducted with longer residence times (minutes to hours) (Lévesque et al., 2021). Slow pyrolysis generally produces biochars with greater surface area, CEC, porosity, carbon content, and pH when compared to fast pyrolysis (Ippolito et al., 2020).

2.1.2 Effects of biochar as a soil amendment

Crop productivity

There are contradicting results found on the effect of biochar on crop yields in regions with a temperate climate. The findings from a global-scale meta-analysis conducted by Jeffery et al. (2017), revealed a minimal effect of biochar application on crop yields in temperate climates, while it increased crop yields in tropical climates with an average of 25%. This is because arable soils in temperate climates, as opposed to those in tropical climates, have a moderate pH, higher fertility, and generally receive higher fertilizer inputs, resulting in limited additional benefits from biochar (*Ibid*).

Although the study by Jefferson et al. (2017) reported no general impact of biochar on crop yield in temperate climates, some studies demonstrate significant yield increases when fertilizers are included. To illustrate, a meta-analysis by Ye et al. (2020) found a 15% increase in average crop yields after one year when biochar was applied in combination with inorganic fertilizer as compared to the control which consisted of only inorganic fertilizer. This result is supported by the findings from a study by Meyer et al (2021) that examined the impact of two different biochar fertilizer blends on an asparagus plantation with sandy soils in Gotland (Sweden) with four different application rates. In the second harvest year after the application of the biochar fertilizer blend, the yield exceeded that of the control with an average of 7% from the four different treatments. This yield increase can likely be attributed to the impact of the biochar treatments on soil fertility, including increased soil organic content, increased plant available soil water storage capacity, and increased ammoniacal nitrogen content (Meyer et al., 2021).

Above described results correspond with the findings from a meta-analysis by Joseph et al. (2021), which demonstrated that the greatest crop responses to biochar are observed when it is applied in combination with fertilizer in acidic soils (common in the tropics) and on sandy soils (such as the Gotland trial field), due to increased nutrient retention and water-holding capacity (Joseph et al., 2021). Therefore, in the Swedish context, biochar application could be more desirable on less fertile sandy soils when considering crop productivity. However, further research is required over longer periods to confirm the effects of biochar on crop yield in temperate regions (Skogsstyrelsen, 2022).

Soil properties

Because of the contradicting results and lack of longitudinal data on the effect of biochar on crop yield, it is beneficial to shift the focus to soil health when discussing the effects of biochar in temperate regions. There is a multitude of meta-analyses and reviews that report positive effects of biochar, ranging from improved nutrient efficiency to increased soil pH, and improved water-holding capacity (Schmidt et al., 2021; Lévesque et al., 2021; Joseph et al., 2021).

As is the case with crop productivity, the effect of biochar on soil health and water availability depends on several factors, including feedstock type, pyrolysis conditions, amount of biochar applied, application method, soil type, the grown crop, and climate (Scott et al., 2014). Agricultural benefits are not guaranteed, and the wrong production and application method may even result in adverse effects on soil properties (Joseph et al., 2021). Therefore, it is important to consider these factors when applying biochar on arable land.

First, biochar can have beneficial effects on soil quality. Due to its porous structure, biochar can reduce the bulk density of the soil, increase the soil porosity as well as its water-holding capacity (Kamali et al., 2022), and plant available water (Schmidt et al., 2021). This can promote the resilience of agricultural systems to drought (Joseph et al., 2021), and enhance soil fertility (Kamali et al., 2022). For temperate regions such as Sweden, biochar could therefore be an especially valuable measure in drier seasons. However, Schmidt et al. (2021), note that large amounts of biochar (>10 t ha^{-1}) are necessary to achieve significant effects on soil water availability.

Biochar can also have beneficial effects on soil fertility. Its application can increase nutrient efficiency by accelerating biotic and abiotic soil reactions (Joseph et al., 2021), and hence stimulate plant development and crop resilience to disease and environmental stressors. According to Lévesque et al. (2021), the beneficial effects of biochar on the interactions between plants, soil, and microorganisms, can help limit mineral fertilizer and pesticide input and therefore offer a sustainable approach to agriculture in temperate regions.

Further, biochar also has a liming effect that can increase the pH of highly acidic soils which increases nutrient availability for plants (Lévesque et al., 2021). However, in more neutral temperate soils there is a risk of raising the soil pH too much (over-liming) which could lead to decreased mobilization of important nutrients (Jeffery et al., 2017), thus inhibiting plant growth. Therefore, it is important to consider what type of biochar and pyrolysis method suits the soil conditions. For example, wood-derived biochars tend to have higher pH than biochar produced from crop residues, as well as biochars produced at higher temperatures (Lévesque et al., 2021).

Recently, researchers from the Swedish University of Agricultural Sciences (SLU) developed a spatial map that helped identify suitable arable lands for biochar application in Sweden based on three priorities: improved soil quality, improved crop resistance, and reduced nitrogen leaching (Karan et al., 2022). The findings show that large proportions of Swedish arable land could potentially benefit from biochar application, with benefits of 25% from soil-improving qualities 39% from improved crop resilience, and 7% from reduced nitrogen leaching. These results strengthen the case for widespread adoption in the country.

Climate change mitigation

Most of the benefits from biochar on climate change mitigation in agriculture are derived from reduced N_2O and CH_4 soil emissions and increased carbon storage in soils (Azzi et al., 2022; Joseph et al., 2021). Biochar has high stability, staying in soils for hundreds to thousands of years (Joseph et al., 2021), and thus functions as a carbon sink. This makes biochar a valuable long-term method for CDR. The carbon sequestration potential of the production, use, and storage of biochar has been estimated to be in the range of 0.3-2 Gt CO_2 per year by 2050 (Fawzy et al., 2021). However the stability of biochar can vary between different biochars, depending on, among others, the feedstock material and production method (Azzi et al., 2022).

Other applications in agriculture

Whereas the literature on the use of biochar in agriculture is mostly focused on its application as a soil amendment for CDR with co-benefits for arable soils, there are other opportunities for agricultural use, of which two examples will be described in the following paragraphs.

First, biochar can be used as an animal feed additive to improve the sustainability of animal husbandry. To demonstrate, a literature review by Schmidt et al (2019) revealed that co-feeding with biochar improved animal health, feed efficiency, and livestock housing climate, and reduced nutrient losses and GHG emissions. Moreover, during the digestion process, biochar gets enriched with nitrogen-rich organic compounds. This results in a valuable organic fertilizer when the biochar-containing manure is excreted, causing lower nutrient losses and GHG emissions during soil application. However, the need is recognized for further multi-disciplinary research to make generalized recommendations for co-feeding with biochar (*Ibid*).

Second, biochar can be used for odor control in livestock production and composting. In a study by Kalus et al. (2020), the effect of biochar addition to feed with rates of 2% and 4% was tested on laying hens' odor emissions from manure. This led to a 32% reduction in odor concentration from the litter headspace for the feed litter that contained 4% biochar when compared to the control. A study by Nguyen et al. (2023) demonstrated that adding biochar in quantities ranging from 5 to 20% to the compost mix resulted in accelerated aerobic microbial growth to degrade organic matter and reduce odor production.

2.1.3 Economic aspects

To enable the large-scale adoption of biochar as a soil amendment, it is important that it delivers economic benefits for agricultural producers. One of the main factors that drive acceptance of a new practice by farmers is yield increases, as this directly translates into better economic performance (Azzi et al., 2019). However, as temperate soils are inherently more fertile compared with tropical soils, a higher quantity of biochar may be needed to achieve a positive response in crop productivity (Borchard et al. 2014; Jeffery et al., 2011). This is not economically feasible for most agricultural producers due to the high cost associated with biochar production and the transport from its point of origin to its destination (Roberts et al., 2009). Schmidt et al. (2021) point out that optimized high-yield systems can still benefit from biochar because lower yield increases would be economically relevant and the same yields may be achieved but with fewer inputs and lower environmental costs.

Other options for agricultural producers to earn income in a biochar system are the sale of biochar as a product, or the use or sale of the heat and other energy produced during pyrolysis (Azzi et al., 2022; Skogsstyrelsen, 2022). Regardless, the benefits and costs of biochar should be mostly considered in the context of soil ecosystem services, such as minimizing carbon emissions (Latawiec et al., 2019). Multiple studies note the importance of policy measures providing payment for climate mitigation to provide economic incentives for the implementation of biochar-based soil management (Azzi et al., 2019; Song et al. 2022), for example by a national carbon trading system (Song et al., 2022). In Sweden, carbon removal efforts are currently taking place on the voluntary market, with biochar being sold at a price of €147.10 per tonne of CO_2 removed as of February 2023 (Puro Earth, n.d.). However, these market prices are highly volatile.

According to a life-cycle cost and economic assessment by Homogain et al. (2016), low-emission schemes can achieve the economic viability of biochar as a soil amendment for regions with temperate climates when efficient biochar production techniques are used. The study results demonstrated a break-even point of 12-13 years under the conditions that the biomass was available within a 200 km ratio and when the carbon sequestration was credited for by at least CAD 60 (around €42) per tonne of carbon dioxide equivalents (CO_2e).

2.1.4 Legislative aspects

There is limited regulation and policy in the European Union (EU) and Sweden regarding biochar. Biochar was authorized as a fertilizer in the EU Fertilizing Products Regulation (EU/2019/1009). It was approved in 2019 as a soil amendment in organic agriculture in the EU (Friedrich, 2020). Furthermore, biochar is included in a briefing from the European Parliament to set a regulatory framework for CDR in the EU climate mitigation legislation (Erbach & Andreo, 2021). However, in Sweden, biochar was excluded from the support system of the Swedish Energy Agency for bioenergy with carbon capture and storage (BECCS) (Skogsstyrelsen, 2020). This is on the basis that the climate benefit and negative emissions per unit weight of biomass are approximately 50% lower for biochar than for BECCS.

Until recently, Swedish companies, organizations, and entrepreneurs were eligible to receive financial support for their biochar investments from the Climate Leap Program (Klimatklivet): an investment aid scheme from the Swedish government aimed at reducing GHG emissions and promoting sustainable development (Naturvårdsverket, 2022). However, the application window is currently closed until autumn 2023.

The European Biochar Certificate

Currently, the European Biochar Certificate (EBC) is the most widely used standard used in Europe to help reduce the health and environmental risk associated with biochar production and use, with a focus on agriculture (EBC, n.d.). The EBC is a voluntary industry standard, except in Switzerland where it is mandatory. The EBC also offers certification for biochar-based carbon sinks. This carbon sink certification enables the CO_2e to be sold with carbon trading schemes and helps avoid double counting of the climate benefits (Carbon Standards International, n.d.).

With an increasing interest in biochar, Swedish private companies and government agencies have started similar initiatives to create national certification standards for carbon sinks. An example is the Biochar Carbon Removal (BCR) System developed by EcoEra (EcoEra, n.d.) in which biochar users and producers are given ownership of the CO_2e that are sequestered in Swedish soils. The Swedish Rural Economy and Agricultural Society (Hushållningssällskapet in Swedish) is also in the development of a certification standard for carbon sinks (Hushållningssällskapet, 2020). The aim is to create carbon sink rights locally in Sweden, to support an economically viable national biochar market.

Theoretical framework

The conceptual framework drives data collection and analysis as it provides a systemic approach to understanding the findings. The conceptual framework draws upon the literature available on sustainability transitions in the agro-food sector. It will start with an introduction to the biochar system and the agro-food system, to provide the needed background information to understand the interactions within both systems. Then it will describe the multi-level perspective (MLP) on socio-technical transitions that will be applied to present and analyze the research findings.

3.1 The biochar system

The flowchart in *Figure 1* depicts the different aspects of and processes within the biochar system.

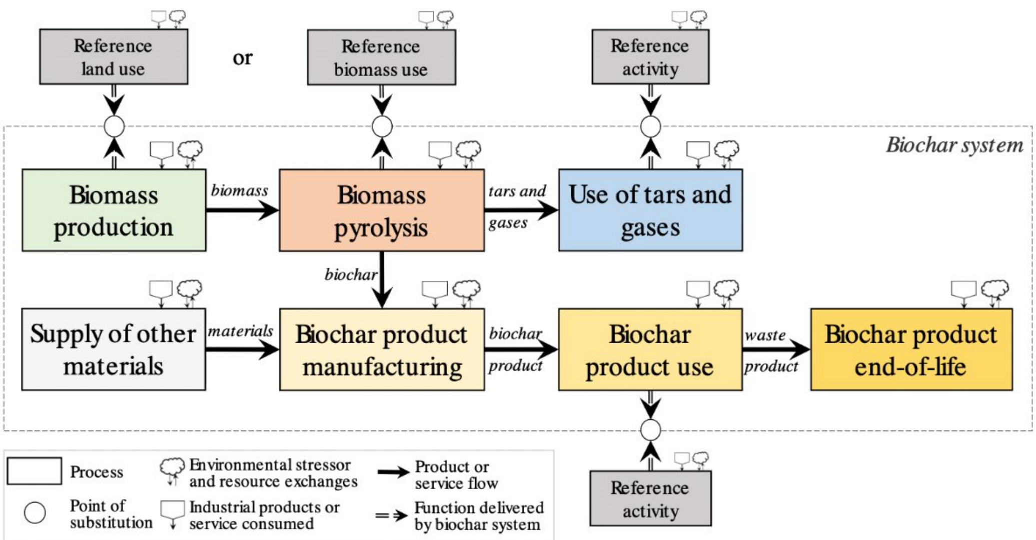

Figure 1. Flowchart of the biochar system (Azzi & Sundberg, n.d.).

The first step is 'biomass production' which refers to the processes required to create the feedstock, e.g., the cultivation of land, the application of fertilizers, the use of agricultural or forestry machinery, or the collection and preparation of a waste biomass stream (Azzi & Sundberg, n.d.). Once the feedstock is acquired, it is used in the next step 'biomass pyrolysis'. This process generates biochar, pyrolysis gas, and pyrolysis oil. The gases and oils are usually burnt to produce heating or electricity in the next step 'use of tars and gases'. Biochar is then combined with other materials to make a variety of biochar products in the 'biochar product manufacturing and supply of other materials' step. This is where agricultural applications such as soil blends or engineered fertilizers are made. This step is optional, as biochar can also be used directly. 'Biochar product use' involves the application of the manufactured biochar product, e.g. in agriculture. Lastly, 'biochar end-of-life' refers to the recycling, re-use, or disposal of biochar. This step can also be integrated with the previous step 'product-use' in case it remains in the soil (*Ibid*).

3.2 Sustainability transitions in agro-food systems

There are several 'wicked challenges' (e.g., environmental degradation, biodiversity loss, and food insecurity) that agro-food systems face, as they involve a large number of actors with conflicting demands (Dentoni et al., 2012). Alkemade et al. (2011) argue that socio-technical transformations are necessary to address sustainability challenges in societal subsystems such as the agro-food system. This involves several stakeholders, as it requires extensive, long-term transformation across entire production, consumption, and behavior chains (Geels, 2004).

The agro-food system is dynamic and has a large number of interdependencies between social and technical elements, visualized in *Figure 2*, that need to be understood to achieve a more sustainable system (Smith et al., 2010). Socio-technical agro-food systems do not only involve technological elements of food production, but also wider social, political, institutional, cultural, and organizational elements. On the technical side, there is the opportunity for innovation on parts of the entire supply chain (e.g., agricultural inputs, plant-breeding techniques, pesticide use, and harvesting technologies). There are a number of social factors that interact with the technical side since they give societal meaning to technical innovation. Examples include prevailing attitudes towards different farming methods, opinions about what is healthy, governmental agricultural policy and price-support mechanisms, food consumption trends, and concerns about the environmental impacts of food production and consumption. The structure of the food system is determined by the co-evolution of these social and technical elements (*Ibid*).

Thus, agricultural innovation does not only require technological change, but also wider institutional, economic, and social co-innovations by heterogenous actors (Klerkx et al., 2012; Geels, 2004), and only by understanding how these interact, it is possible to foster a transition to an inherently more sustainable system

(Smith et al., 2010). The success of innovative technologies, such as biochar, is dependent on their co-evolution with other factors, including market structures, policy measures, and societal preferences, and is shaped by a large number of actors with different ideas and objectives.

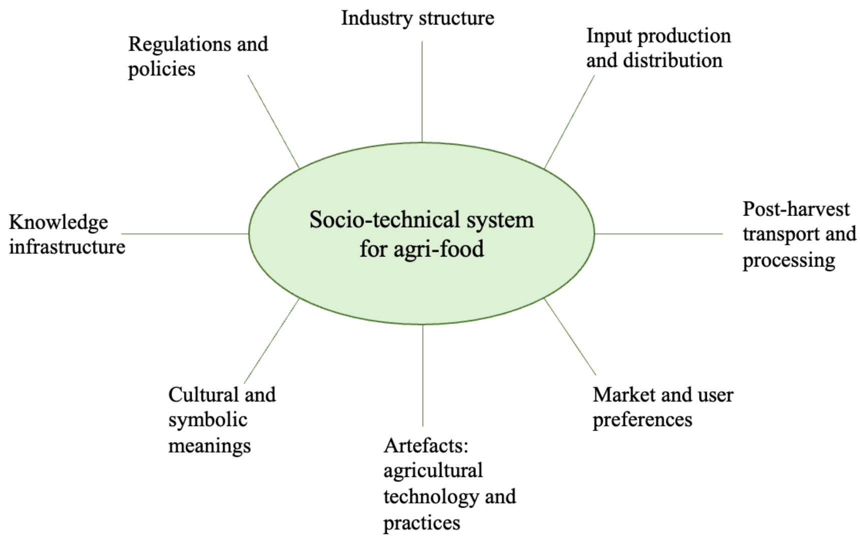

Figure 2. Representation of the socio-technical elements that the agro-food system consists of (adopted from Schiller, 2023)

According to El Bilali (2019a), sustainability transitions are required to move towards sustainable agriculture and food systems. Loorbach et al. (2017, p.600) describe sustainability transitions as "large-scale disruptive changes in societal systems that emerge over a long period of decades". As they present opportunities for radical, systematic, and accelerated change, they pose a risk to currently existing systems.

Several frameworks can be applied to study sustainability transitions, one of which is predominantly used is the multi-level-perspective (MLP) (Markard et al., 2012; Loorbach et al., 2017). This framework will be used in this study as a systematic approach to identify the factors that impede or facilitate a sustainability transition in the Swedish agro-food system towards increased biochar deployment.

3.3 Multi-Level-Perspective on Sustainability Transitions

The MLP framework can be used as a tool to understand sustainability transitions, by analyzing and addressing the multi-dimensional complexities of socio-technical systems (Geels, 2010). The MLP suggests that transitions involve alignments of processes within and between three analytical levels: niche innovations, socio-technical regimes, and an external socio-technical landscape (Schot & Geels, 2008). Transitions can be described as regime shifts that result from interactions and alignment within and between these levels (Geels, 2010; El Bilali, 2019a). The interactions between the three levels are visualized in *Figure 3.* The MLP can help identify how the factors from the different levels of the socio-technical system interact that either support or hinder the adoption of biochar as a soil amendment.

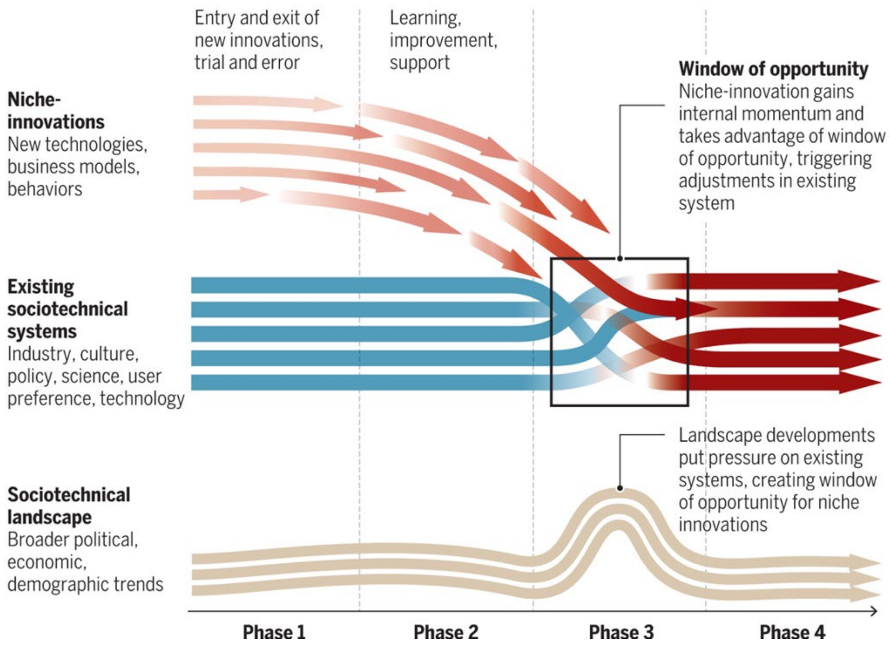

Figure 3. A visualization of the three different levels in the MLP, and their interactions (Geels et al., 2017).

3.3.1 Niche innovations

Niches are protected spaces where radical innovations are created (Geels, 2010; Bünger & Schiller, 2022), or small market niches with users that have specific needs and that are willing to support emerging innovations (Darnhofer, 2015). According to Darnhofer (2015), niches emerge from the activities of actors at the local level, such as the invention of radical new technologies or by entrepreneurs developing a new market. Niche innovations can develop due to a mismatch with the existing regime, lack of appropriate infrastructure, regulations, or incompatibility with consumer routines (Darnhofer, 2015).

The purpose of niche innovations is to become embedded in the existing regime or to replace it (Geels, 2012). Whether niche innovations can gain momentum and break into the regime level is influenced by the ability of niches to stabilize over time (Darnhofer, 2015). There are a number of social processes through which niches can stabilize over time which are described in the strategic niche management framework. These include: "*the articulation of expectations and* *visions"*, *"the building of social networks"*, and *"learning processes"* about technical design, market and user preferences, cultural meanings, infrastructure, regulations and government policy, and societal and environmental effects (Schot & Geels, 2008).

The agricultural innovation systems (AIS) framework has recently gained popularity in research as an approach to understanding the diffusion of novel technologies for agricultural innovation. According to a report from the OECD (2013), AIS are crucial to improving the sustainability, economic, and social performance of food systems as it can help understand the relevance of novel technologies to users' demands and priorities, as well as their cost-efficiency. The focus of AIS is on networks of actors from diverse fields (research, business, civil society, and government) that co-produce a range of technological, social, and institutional innovations that shape future food systems (Klerkx & Begemann, 2020), see *Figure 4*. Further, an ASI approach helps find focus points for strengthening coordination and governance to facilitate the diffusion of technology. Therefore, this study applies the AIS framework at the niche level, to explore the development and diffusion of biochar technology and to identify actors, networks, and organizations that are involved in this process, and the collaborations and interactions between those.

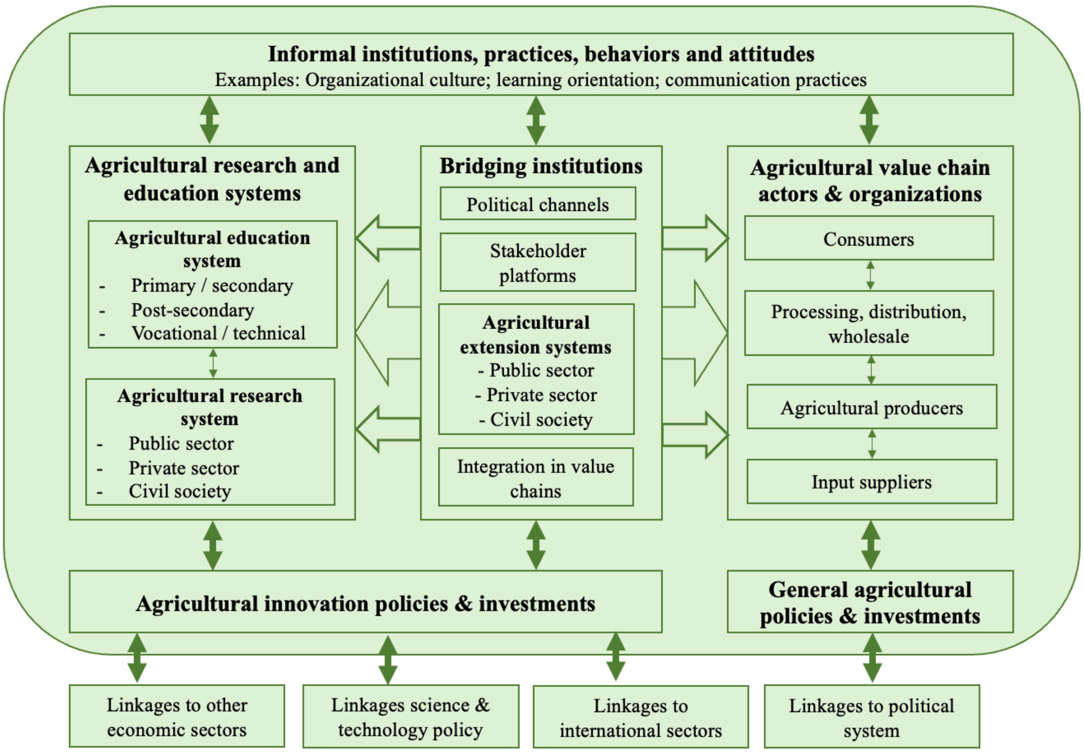

Figure 4. The agricultural innovation system (adapted from Ludemann et al., 2012).

3.3.2 Socio-technical regime

The regime represents the meso-level of the MLP and refers to the predominant way that socio-technical systems are organized in a particular industry. The regime includes the currently established actors and deep structures made up of practices, routines, policy paradigms, social expectations, and norms (Geels, 2011). Bünger and Schiller (2022), describe the regime as ‘established power centers’, due to the persistence of dominant structures. Based on this description, in agriculture, a regime can be understood as the practices, policies, and procedures that are followed to maintain agricultural productivity, e.g. fertilizer use.

Regimes are often characterized by lock-in because they function on well-aligned and stable rules regarding cognitive routines, shared beliefs, capabilities and capacities, institutional regulations, legally binding contracts, and lifestyle and user practices (Darnhofer, 2015). Lock-in also occurs when positive outcomes are provided for the users with the adoption of already established technologies, for example in the form of decreased production cost (Klitkou et al., 2015). Hence, established technologies have advantages because they are diffused at a greater level.

Further, due to transformational resistance socio-technical regimes tend to follow a dependent path and undergo incremental changes rather than radical ones (Geels, 2010; Markard et al., 2012; Lachman, 2013). According to Lachman (2013), the regime continues to build stronger alignment between the elements of the system in which it operates as long as regimes themselves are stable and there is no external pressure exerted from the landscape level. This adds to its path dependency and locked-in character. However, incremental changes are not deemed sufficient to solve the prevailing societal sustainability challenges (Loorbach et al., 2017; Lachman, 2013). For this, a sustainability transition at the regime level is required, which can be achieved with pressures from landscape-level, or from within a social-technical regime (Geels, 2010). Darnhofer (2015) explains that external pressures often emerge as a result of the inability of the regime to solve persisting problems, such as disagreement on various issues, debate, and internal conflict. This results in the creation of a window of opportunity for niche innovations to break through and be diffused in the regime (Darnhofer, 2015).

3.3.3 Socio-technical landscape

The landscape level of the MLP refers to the external factors that influence the diffusion of new technologies, for example, market conditions, energy policy, and climate change. According to Lachman (2013), niches and regimes have little to no influence on the landscape level, whereas the landscape level can have a significant impact on the other levels. In the absence of landscape pressures, the regime will remain stable and continue to change incrementally (Lachman, 2013). However, if the trends and changes in the landscape are strong enough, a window of opportunity can be created for a niche to break through and change the structure of the regime (Lachman, 2013), possibly leading to the creation of new regimes with new actors or rules (Geels, 2010). The ability of the niche to take advantage of this window of opportunity is dependent on the timing of landscape pressure on the regime with regard to the state of niche developments (Geels & Schot, 2007). The niche has to be fully developed at the time that landscape pressure occurs, to make use of this window before it closes.

Methodology

This chapter describes and justifies the study design and qualitative methods, i.e. semi-structured interviews and the participation in a webinar, that are used to discover the main barriers and drivers for increased biochar deployment in Swedish agriculture. It also describes how data collection and analysis were carried out and how the researcher relates to quality criteria for qualitative methods.

4.1 Research design

The research design can be described as a logical sequence that guides the researcher in the process of collecting, analyzing, and interpreting observations (Yin, 2009). The main purpose is to help connect the empirical data to the research questions. The research design of this study can be described as an exploratory deductive case study.

According to Yin (2009), a case study method is used when the objective is to gain an in-depth understanding of a complex phenomenon by studying it within its real-life context. Thus, this study can be characterized as a case study, as it aims to understand the context and complexity of a transition toward increased biochar deployment in Sweden. The case study method "allows investigators to retain the holistic and meaningful characteristics of real-life events" (Yin, 2009, p.4).

Case studies can be carried out with three different approaches, i.e. descriptive, explanatory, and explorative (Yin, 2009). As this study aims to seek new insights and knowledge on relatively broad research questions and a complex phenomenon, an exploratory approach was utilized. According to Saunders et al. (2009, p. 139), the objective of exploratory research is to find out "what is happening," "seek new insights," and "assess phenomena in a new light". Explorative research focuses mostly on "what" questions, with the purpose to develop relevant hypotheses and propositions for further investigation (Yin, 2009). The approach starts within a developed theory, that both facilitates the data collection phase of the case study, as well as helps relate the research findings to the research questions (Yin, 2009). This approach was followed in this study by relating the empirical data to the theoretical framework.

Further, research can be inductive, deductive, or abductive. According to Makri and Neely (2021), a deductive approach starts within the existing theory to formulate research questions or hypotheses, to subsequently help organize and guide data collection and analysis. This study uses a deductive approach as data analysis and interpretation derived from the MLP explained in the theoretical framework.

4.2 Data collection

The empirical data of this research was mainly collected with a qualitative method through semi-structured interviews. Interviews are the most commonly used method in qualitative research (Bryman & Bell, 2015). In semi-structured interviews, the researcher follows an interview guide that the researcher intends to follow, which includes a list of predetermined topics related to the research subject (Bryman & Bell, 2015).

The potential of semi-structured interviewing lies in its ability to address specific dimensions of the research question by including questions that are informed by theory, while simultaneously allowing participants to offer new meanings to the study topic (Galetta, 2013). This aligns with the purpose of this study, as it allows new valuables to be explored and already-known variables to be confirmed or rejected. Moreover, as this study aims to investigate individuals' attitudes, beliefs, and perspectives of individual actors, this method is beneficial for the investigation of the research topic (Creswell & Creswell, 2018). It helps understand the complexity of the research topic as it allows for in-depth information and allows the mapping of the actors that are involved in various societal levels (niche, landscape, and regime). Additional data was assembled during an online webinar.

4.2.1 The semi-structured interviews

Sampling

As opposed to quantitative research, in qualitative research participants are purposefully selected based on their ability to increase understanding and provide valuable information about the problem and the research question (Creswell & Creswell, 2018). To collect a wide variety of information on the research subject, different relevant actors were sampled that are involved in biochar for agricultural use in Sweden. A report by the OECD (2013) identified a number of actors that play a role in the support, creation, facilitation, and adoption of innovation in the agricultural sector. These include governments, researchers, private businesses, farmers, advisors, and other intermediaries, charities and non-governmental agencies, and markets and consumers. This study partially used this description and pursued research participants from governments, researchers, private businesses, farmers, advisors and other intermediaries, charities, and non-governmental agencies. Charities and non-governmental agencies, markets, and consumers were found less relevant to the research topic and were therefore excluded from the sample.

Initial interview respondents were identified with the help of the network of the thesis supervisor and by asking respondents to recommend other individuals who may possess useful information about the research subject. This method is known as snowball sampling and is useful in situations when it is difficult to reach the right people who have the needed information (Patton, 2002).

There was no predetermined set number of research participants, which allowed the researcher to be receptive to whether new interviews would contribute to the empirical insight. According to Kahlke (2017), a level of empirical saturation is achieved once new research participants do not offer new perspectives to the understanding of a problem. The sampling in this study was concluded before this level was reached to ensure completion within the given time limit. Regardless, the conducted interviews yielded substantial and valuable information that was deemed sufficient to provide comprehensive answers to the research questions.

The interview process

Potential participants were invited to participate in the research with a recruitment message that was sent over e-mail. The sample for this study consisted of ten stakeholders, presented in *Table 1*.

Table 1. Overview of conducted interviews (February-March, 2023) and interviewees.

R	Date	Organization	Relevance	Duration (min)
1	23-02	Waila – research	Involved in consultancy and research about biochar.	40
2	01-03	CEO of biochar consultancy agency	Offers consultancy on biochar projects.	55
3	02-03	Jordbruksverket – The Swedish Board of Agriculture	Swedish government's expert authority in the field of agricultural and food policy.	34
4	03-03	Hushållningssälskapet – The Rural Economy and Agricultural Society	A Swedish organization focused on promoting sustainable agriculture through advisory services and education.	54
5	09-03	Farmer	Agricultural producer, biochar user, biochar producer, and reseller of BioMacon production plant.	51

6	10-03	LRF – The Federation of Swedish Farmers	Member organization for Swedish farmers that offers knowledge-based advice. Functions as spokesperson of the farmers.	23
7+8	13-03	Klimatklivet – The Climate Leap Program	Financial aid scheme from the Swedish government that invests in different projects that with the focus to reduce the emissions of carbon dioxide, and other greenhouse gas gases.	41
9	16-03	CEO of EcoEra	Created and sells a carbon dioxide removal certificate (CORC) so that biochar carbon sinks can be sold on the voluntary carbon market.	32
10	28-03	Farmer	Agricultural producer, biochar producer.	36

In total, there were nine interviews conducted. The discrepancy in the number of interview participants and the number of conducted interviews can be explained by the fact that in one interview, two participants were interviewed simultaneously. Conducting a joint interview with two participants at the same time, allowed the research participants to complement each other and fill in any gaps in the provided information. Seven of the interviews were conducted on the video conferencing software Microsoft Teams, one interview was conducted face-to-face, and one was conducted over the phone. Bryman and Bell (2015) note that non-verbal communication is important in the interpretation of interviews. Therefore, during the interviews that were conducted over Microsoft Teams, the camera of both the researcher and the research participants were turned on.

The duration of the interviews ranged from 30 to 50 minutes, which can be explained by the varying levels of knowledge and articulacy about the research topic among the different stakeholders. The interviews were audiotaped and hand-written notes were taken to capture the participants' responses, to enable subsequent analysis. The interviews were conducted with the help of an interview protocol (Appendix 1) that included questions prepared in advance of the interview. Further, it included introductory information about the topic and closing instructions. The questions were open-ended to allow for rich and in-depth responses.

4.2.2 The webinar

The webinar took place after the completion of the interviews on the 4th of May. The webinar was organized by the Rest till Bäst platform for the Residues to Best Use project. This project aims to minimize the environmental impact of organic residues from society, by turning them into biochar, while simultaneously creating a carbon sink (Rest till Bäst, n.d.). The purpose of the webinar was to share information among different participating stakeholders and to discuss various topics concerning the project work and other important issues identified by the project partners. The results were retrieved from the section of the webinar that discussed 'how to make biochar cheaper for farmers'. The webinar was not audiotaped as sensitive topics were discussed. Instead, detailed notes were taken.

4.3 Data analysis

The empirical data gathered from the semi-structured interviews and the webinar were analyzed with a method called thematic analysis. According to Bryman and Bell (2015), this is one of the most commonly used methods for analyzing qualitative data. This method helps identify, analyze, organize, describe, and report patterns and recurring themes found within the data (Braun & Clarke, 2006). There are a number of advantages of thematic analysis that made it a compelling choice of method for this study. First, thematic analysis is a suitable method for researchers that are new in their careers, as there are relatively few procedures to follow (Nowell et al., 2017). Further, this method helps understand similarities and differences in the perspectives of different research participants, which is useful for this study as it explores the perspectives of different stakeholders (Nowell et al., 2017). Lastly, according to Robson (2002), this analysis method is particularly suitable for explorative studies, because the themes that arise from the analysis emerge from the data and are not influenced by any preconceived ideas or assumptions.

Following the approach proposed by Creswell (2013), the thematic analysis was carried out with six sequential steps, including organizing and preparing the data for analysis, reviewing the data, coding the data, generating themes, interrelating themes, and interpreting the meaning of themes.

In the first step, organizing and preparing the data for analysis, transcriptions of the interviews were produced with the use of transcription software, Otter.ai. The notes taken from the webinar were organized. The second step, *reviewing the data*, involved re-listening to the audiotapes while simultaneously re-reading the transcriptions to ensure accuracy. This also helped to create a general understanding of the data. In this stage, the data from the interviews and the webinar were compiled. In the third step, data coding, important statements were highlighted by keywords, to represent specific categories (codes). In this stage, codes were eliminated that had no relevancy when referred to the research questions. The identified codes were then grouped together based on their similarities into overarching themes in the fourth step, *generation of descriptions and themes*. In the fifth step, *interrelating theme*s, these were compared and contrasted to identify any similarities or differences between the stakeholders' perspectives. The themes were evaluated on their relevance to the research questions and their applicability to the theoretical framework, which resulted in the final themes that were used in Chapter

4, Research Findings. During the final step, *interpreting the meaning of themes*, the themes are analyzed and interpreted in light of the research questions and theory, which is discussed in Chapters 5 and 6, Discussion and Conclusions. The codes and themes that resulted from the thematic analysis can be found in Appendix 2.

4.4 Ethical considerations

It is important to consider ethical issues when conducting a qualitative study that involves human participants (Chowdhury, 2015). According to Sanjari et al. (2014, p.4), ethical concerns include *"respect for privacy, the establishment of honest and open interactions, and avoiding misrepresentation"*. There were several measures taken in this study to address these ethical concerns.

First, informed consent was obtained from all interview participants. To achieve this, a document containing information about data collection at SLU was sent to all participants prior to the interviews. This document contained information about the purpose of the study, participants' right to withdraw from the study at any time, and contact information of the researchers in case of concerns. The interviewees were also informed that the interviews would be recorded. Providing this information, helped participants to make an informed decision about their participation in the study, which contributed to the establishment of honest and open interaction. All participants gave their consent, and therefore all interviews were audiotaped.

In addition, confidentiality and anonymity of the interview participants' identities are maintained throughout the study to protect the privacy of participants. To achieve this, identifiers are used when referring to specific stakeholders, instead of names. This ensures that participants' personal information and opinions are not revealed to the public or linked to the research findings. Likewise, the identities of the individuals that participated in the webinar are not specified.

Moreover, consent was obtained from interview participants with the use of email contact before using direct quotes in the results. Consent for the use of the notes taken during the seminar was also obtained from the organizer. This had the purpose to accurately reflect participants' views in the research findings, and to avoid misrepresentation and deception.

4.5 Research quality

According to Yin (2003), the quality of a case study can be evaluated in terms of validity (internal and external), and reliability, which will be used to discuss the quality of this study.

4.5.1 Validity

Internal validity refers to the ability of the researcher to provide a causal relationship between the research variables and results, to justify the research's conclusions (Gibbert et al., 2008). In this study, the data collected in the interviews was supplemented and supported by data acquired in the webinar, which can be described as triangulation. Triangulation is a valid and reliable way to gain an understanding of a complex social situation (Bryman & Bell, 205), thus increasing the internal validity of this study. Moreover, the semi-structured format of the interviews increased validity, as it ensured that key questions were addressed in each interview. Additionally, the study used purposive sampling, which helped ensure that the stakeholders selected had relevant expertise within the studied field. Further, the wide range of stakeholders in the sample reduced the risk of biased outcomes. Lastly, the researcher was involved in member checking, where the use of quotes was validated with participant verification (Kahlke, 2017).

External validity refers to the extent to which the results can be generalized (Yin, 2009). According to Yin (2009), external validity poses a challenge for single case studies, as the results refer to a specific context and are not necessarily applicable in other settings. Since this study is focused on the deployment of biochar in a specific sector (agriculture) and a specific country (Sweden), the results might not be generalizable to other sectors or countries. Regardless, the results of a single case study provide value in the form of increased understanding (Robson, 2002), in this case about the main factors that can hinder or facilitate increased biochar deployment in Swedish agriculture.

4.5.2 Reliability

Reliability relates to the replicability of the case study, with the goal that the same results would be achieved if the same methods were used by another researcher (Yin, 2009; Gibbert et al., 2008). To improve the reliability of the study, all the procedures that the study used were clarified and documented, for example by following an interview guide and by using the six-step approach to thematic analysis. Also, the interviews were transcribed and reviewed to ensure accuracy.

Results

This chapter gives an overview of the results from the empirical data acquired through the semi-structured interviews and the webinar. It will place these themes into the different levels of the MLP, to understand the forces that are facilitating or hindering increased biochar use.

The overall opinion from the interviewed stakeholders on biochar use in Swedish agriculture is positive. Biochar is described as a win-win solution for carbon storage with agricultural benefits. In Sweden, biochar is currently predominantly used in industry and urban environments, but there is a general consensus among respondents that the agricultural sector is the desired end destination for its use.

> "The final goal for biochar, where it can really be used, is the agricultural soils". (R2)

Farmers can play a role as both producers and consumers of biochar since they can produce biochar on their farms and use the same biochar by applying it on their land. However, biochar as a physical product is currently perceived as too expensive to motivate its use for agriculture, and therefore stakeholders view agriculture as more important for biochar production at present and use in the future. Most of the biochar produced on farms is sold to industry and municipalities for use in urban areas. Stakeholders expect an increase in the production of biochar in the future, and that the excesses will most possibly be used in agriculture.

While the agricultural market for biochar in Sweden is still underdeveloped, certain drivers and factors must be considered, which will be categorized in the following sections under niche, and regime and landscape forces. Niche factors that emerged from the interviews are described in the themes 'technical drivers and barriers', 'knowledge', and 'economic drivers and barriers'. Regime and landscape forces are grouped under the themes 'dominant structure' and 'synergies between production systems', 'policy and legislation', 'certification', and 'market forces'. The reason for grouping regime and landscape together is because for some themes it is not so clear to which level they belong. This will be addressed in the discussion chapter.

5.1 Niche innovations

5.1.1 The biochar AIS

In the interviews, respondents were asked to identify the main actors and networks that are currently playing a role in the diffusion of biochar technology and the development of the use of biochar in Swedish agriculture. These are visualized in *Figure 5*. A short description of some of these stakeholders and their activities and role in the diffusion of biochar technology can be found in Appendix 3.

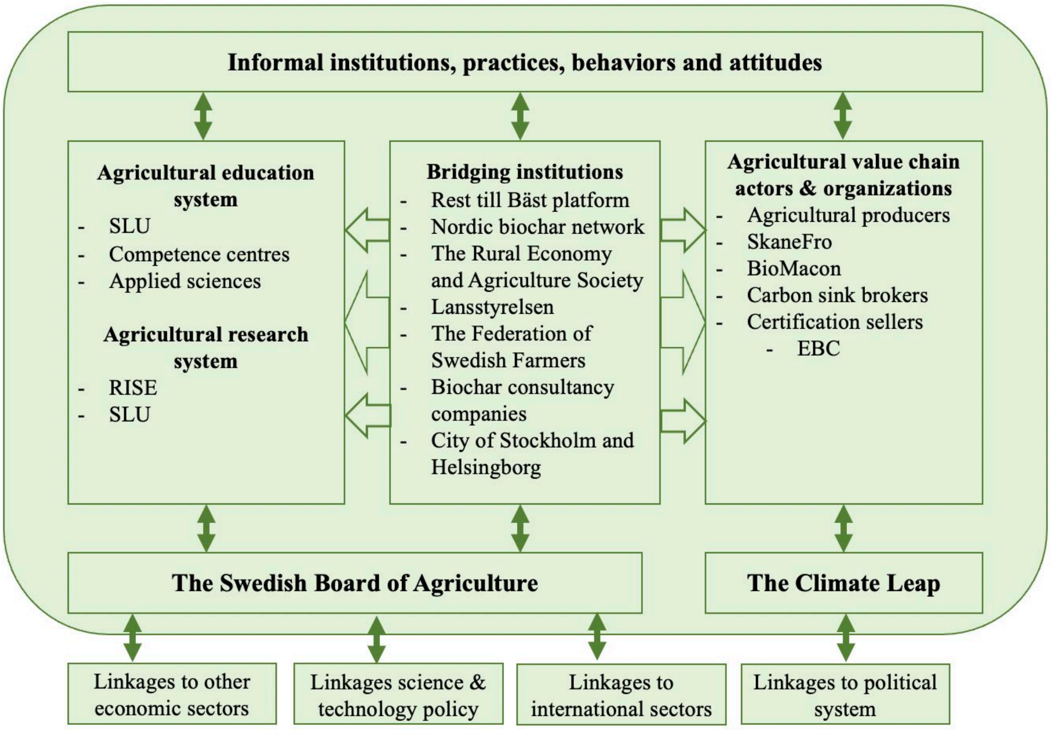

Figure 5. AIS of the agricultural biochar system in Sweden (own image).

It was frequently mentioned that biochar deployment in Swedish agriculture has been driven by passionate individuals that operate at the niche level. As a result, the information flow used to be relatively informal. However, over recent years the interest in biochar has increased. With an increased number of involved actors, there is a need for the establishment of formal networks so that information sources and flows are clear. This is necessary to make information accessible to new farmers that want to start using biochar in their farm operations. One interviewee gave an example of the creation of extension services to provide farmers with knowledge on biochar to farmers, with an emphasis on accessibility.

> "I think the farmers and the agricultural sector is one of the trickiest to both reach and reach in the right way because most of them are not going to read articles in their free time." (R4)

Another example of how the knowledge flows about biochar can be improved is by creating competence centers. Lastly, in the webinar, the opportunity was emphasized for collaboration between different countries on how to increase the use in different sectors. In Sweden, biochar finds most applications in urban areas, whereas in Germany its use is more widespread in agriculture. Germany can learn how to use biochar in urban areas from Sweden, and Sweden can learn from Germany how to use biochar in agriculture, thereby increasing the markets in both countries. Knowledge sharing and collaboration between different stakeholders and nations are currently happening within the European Biochar Industry (EBI) Consortium and the Rest till Bäst platform.

5.1.2 Technical drivers and barriers

There are a number of technical barriers and drivers mentioned throughout the interviews that could either facilitate or hinder the development of the use of biochar in the agricultural sector in Sweden.

First, the interviewees expressed a couple of benefits derived from biochar application on soil that could act as a driver for agricultural use. The most frequently named benefits of biochar include its ability to increase water-holding capacity and therefore offer better drought resistance. This is exemplified by the experience of one of the interviewed farmers that saw a 30% higher crop yield during the drought in 2018 on fields where biochar was applied compared to where biochar was not applied. The interviewees expect drought resistance to become increasingly important in the future. Other benefits that were mentioned throughout the interviews include less compact soil, better root systems, improved nutrient retention, and phosphorus cycling from sludge-based biochars. Some of the interviewees also referred to higher crop yields, although it was acknowledged that these effects were smaller in Sweden due to fertile soils with high carbon content. The application of biochar was perceived as most effective in sandy soils and intensive crop production systems (e.g., vegetable and fruit production) in comparison to conventional crops.

One key takeaway from the interviews is that it is important to consider the sustainable use of feedstock. The participants mentioned a variety of feedstocks that are currently used feedstocks in Sweden, including straw, forest residues, and crop residues. Multiple interviewees see an opportunity in the underutilized side- and waste streams to use as biomass for biochar production. These include side streams from food production (seeds, nuts, shells), grain residues, wood residues from thinning, bushes, biochar grown on fallow land, municipal waste from gardens and trees, sewage sludge, and wood affected by beetles. Furthermore, it was mentioned that it is important to avoid using feedstocks that have a long regrowth time and to avoid displacing agricultural production for feedstock production. The social acceptability of feedstock type was also a factor that came up in the interviews when discussing sludge-based biochars with the opinions on the use of sewage sludge as feedstock being divided. One respondent has the opinion that sludge char does not meet the requirements to be classified as biochar, because it can contain heavy metals and harmful substances that can be damaging to the soil. However, the majority of the respondents support the use of biochar derived from sewage sludge and see it as a valuable resource. In addition, according to the webinar participants, biochar derived from sludge gains value due to the cost saving for municipalities on dewatered sludge disposal and the carbon sink.

> ”If we make biochar from sludge, we will see phosphorus recycling, which will bring a lot of benefits because farmers don't have to purchase phosphorus inputs… the carbonization of the sludge will remove all the poisons and toxins and pathogens.” (R9)

A barrier to increased biochar adoption in agriculture that was highlighted in the majority of the interviews is the shortage of production plants. The production plants that are currently used for agricultural production are made by the German company BioMacon. One interviewee explained that this specific plant is most suitable for agricultural use, due to its smaller size and lower electricity usage. The shortage of production plants is a logistical issue that results in long waiting times (up to a couple of years) for farmers and has therefore been a significant hinder to starting production in the agricultural sector. Thus, there is a clear need for an increased supply of production plants that are suitable for agricultural use.

A driver for biochar adoption in agriculture that several interviewees pointed out is that biochar can provide major environmental benefits through converting fossil fuel boilers to biochar boilers for heat production. For both interviewed farmers the heat produced by the biochar plant was sufficient to supply for the entire on-farm facilities. Excess heat can be supplied to the local power grid.

Another driver that was highlighted by multiple interviewees is the opportunity to use biochar in niche applications. An example that was frequently given is to use biochar in livestock production. Applications that were discussed included: 1. The use of biochar in bedding material to reduce smell and create a better work environment in the stable, 2. Using biochar as an animal feed additive to get biochar-enriched manure that can be applied to the field, 3. The direct addition of biochar to manure to charge it with nutrients that are favorable for crop production. One of the farmers had the perspective that biochar should first be used as a filter for sewage sludge, before being applied to farmland. It was emphasized that a prerequisite for the application of this solution is that farmers receive reimbursement. These solutions contribute to the creation of a more circular farm system.

"To me, it's a bit of a waste to take this super material that's actually feed classed. Why don't use it at least once before, as a filter material and let it do its job and get some nutrients into it." (R10)

Further, the carbon sink of biochar was considered a major opportunity for its increased use in agriculture. However, there are also some issues related to carbon sinks. First of all, an interviewee mentioned the issue of additionality, which relates to whether the carbon sink would have been created even without getting compensated. However, according to this interviewee, the lack of additionality is not necessarily a negative thing as the carbon sink is needed regardless. Second of all, there is the risk of double counting, as there are three places where the carbon sink can be counted: at the carbon-neutral production facility, by the farmer that applies it in soil, and by the company that buys the carbon sink. Several interviewees proposed dividing the physical biochar product from the carbon credit to prevent this and to ensure that both the producer and the user get their fair share of the compensation. Further, there is an overall lack of trust and a need for credibility in the way that carbon credits are accounted for. This can be avoided by tracing the entire process from cradle-to-grave to ensure that biochar has a beneficial final application instead of being disposed of.

Lastly, multiple interviewees see potential in merging biochar production with existing production systems to promote resource efficiency and circularity. One proposed solution is to add biochar to animal feed and insert the resulting biochar-enriched manure into a biogas plant. Subsequently, the biogas slurry that contains biochar can be applied to the field. Another suggestion is to convert existing biomass heating plants to biochar production plants in the summer when there is lower heat demand. Both solutions could also help reduce the cost of biochar to make it more available to farmers and promote efficient use of resources and energy.

5.1.3 Knowledge

From early on in the interviewing process it became apparent that there are a large number of knowledge gaps and knowledge needs that are necessary to address to facilitate biochar deployment in Swedish agriculture. The most frequently mentioned knowledge gap is the effect of biochar on crop yield in Swedish agriculture. Interviewees also expressed uncertainty about how biochar works under different agricultural conditions (e.g., soil, crops, pesticide use, feedstocks), about how much biochar should be applied, and about the positive effects of biochar in livestock production. To fill in these knowledge gaps, there is an urgent need for evidence-based research studying biochar, to find the ultimate application for the production and use of biochar in agriculture.

"You need to have practical examples of pilot scales and real scale setups, to show that it [biochar production] actually works. People won't just take your word for it as there is a lot of money involved in an investment like this" (R4).

Multiple interviewees noted that it is important to conduct long-term trials because the effects of biochar take more than one growing season to manifest. However, stakeholders recognize that this is hindered by a lack of research funding. To illustrate, both interviewed farmers expressed that they are interested in doing large-scale long-term trials with biochar, but that they are unable to receive funding or find interested researchers that are required to conduct these trials. One respondent highlighted that farmers should not wait for the results from research to start integrating biochar in their operations, but that research should rather develop in parallel to that. Similarly, the webinar highlighted the potential role of farmers in developing small-scale trials to demonstrate the effects of biochar on different soils and crops. This approach could be advantageous due to the wide variation in crop and soil types, and the deep understanding that farmers possess of their land. An opposing view was expressed by an interviewee that *"they (farmers) can put the biochar out there, but the farmer is not going to make academic reports to show the true effects" (R2).* This demonstrates a need for collaboration between researchers and practitioners. One interviewee proposed that SLU should start their own biochar production and biochar use to demonstrate the effectiveness.

5.1.4 Economic drivers and barriers

The majority of respondents mentioned profitability as a prerequisite for increased agricultural deployment. There are three main sources of income identified in the interviews that are associated with the production of biochar in agriculture. First, the heat generated from biochar boilers can be sold or used to heat on-farm facilities to reduce energy costs. Second, farmers can receive profits by selling the carbon credits from the carbon sink. Third, selling biochar to other sectors creates revenue for farmers. According to several interviewees, the installation of a production plant would require additional revenue streams from heat production and the sale of carbon credits to be financially viable.

Multiple respondents noted that the price of biochar is too high for farmers to use on their land at the moment. One of the interviewed farmers has only applied the biochar they have produced in small quantities on their land. The other farmer has not used the biochar they produce on their land at all because the payoff is too small compared to the investment. Instead, they sell the biochar to companies that make planting material for urban areas. The reason for this is that compared to on-farm use, selling the biochar to other sectors results in immediate and higher profits, which are needed to pay off the investment and bank loans, thus preventing the use in agriculture.

> "Farmers are perfect producers. They know how to handle these types of machines, they are at the farm all day and walk past the plant, and they can easily integrate it with everyday work". (R2)

The use of biochar has been shown to increase yield in certain areas, providing an additional source of income for farmers. Yet, at the moment biochar is too expensive to purchase for on-farm use, without having the economic benefits that come with the installation of a production plant in the form of heat production and the opportunity to sell biochar to other sectors. This makes the agricultural sector *"the perfect place for producing biochar now and for use in the future, since you have the excess of biomass, you have the use of heat and you have the use of biochar" (R2).*

During the webinar, it was mentioned that biochar offers many co-benefits to animal and environmental welfare (animal health, compositing, soil health, reduced nitrogen, and CH_4 emissions), which are not offered by carbon capture and storage (CCS) technologies. These should be taken into account when considering the cost-effectiveness of biochar, as they give carbon credits from biochar a higher value. However, at present it is nearly impossible to valorize these co-benefits.

A profitability calculation by one of the respondents demonstrated that the primary investment in biochar pays off within 10 years and receives a return on investment of around 10%. This demonstrates the investment will pay off in the long term, which could suit the future vision the interviewed farmers have of giving their farms to their children. However, two respondents pointed out that biomass availability and accessibility are important conditions for the profitability of biochar. During the webinar, there were additional factors identified that impact the economic outcome of biochar production, including transport distance, feedstock type, and production plant size. When discussing plant size, larger plants were considered to be more cost-effective. However, there are limits to scaling. For example, from a carbon emissions and cost perspective, it is preferable to locate plants near biomass sources.

However, as there is uncertainty on the effects of biochar on soils as described under the previous theme, 'knowledge', primary investment in the biochar production plant is seen as a high-risk endeavor. Multiple respondents highlight the importance of financial aid schemes to mitigate this risk and incentivize farmers to install a production unit. Moreover, biochar heating systems are more expensive than other types of heating, which poses *"a hefty sum to pay for sole actors"* (R7+8). This again illustrates the importance of financial aid to *"help provide some of the cost to help their ability to make this investment"* (R7+8).

5.2 Socio-technical regime and landscape

5.2.1 Dominant structures

The interviews revealed forces from two dominant structures that impede the acceleration of biochar deployment in Swedish agriculture. The first one is a perceived resistance from fertilizer companies as expressed by two interviewees, as the implementation of biochar improves soil health and therefore reduces the need for fertilizer. Further, feeding biochar to animals can create biochar-enriched fertilizer. One of the interviewed farmers had the opinion that a lot of research is funded by fertilizer companies and while this force is subtle and subliminal, two interviewees recognize this resistance. However, during the webinar, it was highlighted that there is also an opportunity for fertilizer companies and biochar producers to benefit from each other. Companies producing or selling fertilizers can replace rock phosphate in fertilizer production with sludge-based biochar because of its high phosphorus content. Nevertheless, current biochar production capabilities do not meet the input demand for fertilizer companies, demonstrating the need for a higher number of production units.

The second identified barrier is competition from other NETs in the heat and energy sector. For instance, one interviewee mentioned that direct air companies (DAC) are applying direct pressure to include in EU legislation that carbon should be stored away deep underground as a requirement to receive payment for carbon storage. Oil companies work in partnership with DAC, forming an *"unholy alliance"* (R9) which gives them more leverage. However, it was stated that incorporating this as a requirement in EU legislation for carbon storage would be counterproductive for the deployment of biochar in agriculture due to the loss of soil benefits resulting from injecting biochar deep underground. Additionally, in the webinar and multiple interviews, it was mentioned that there is competition from large-scale CCS production plants. Due to the larger production size, the price can be reduced, making the carbon credits more competitive than that of the generally preferred smaller scale of biochar production. However, it was also mentioned that a drawback to these large-scale production plants is that they require more electricity.

5.2.2 Policy and legislation

The interviews revealed that on a national level, Swedish agricultural policy has the goal to reduce emissions from the agricultural sector, which is reflected in the willingness of the government to pay for carbon removal.

"I think the Government is interested in paying for the carbon storage because that's something we want." (R3)

This view is opposed by another interviewee that sees more potential in the use of biomass in other methods, such as for the production of biogas.

> "The most important task at this moment is to reduce the use of fossil fuels. From our perspective, we can use biomass in a more efficient way than digging it in the ground. And also, we can also see that biochar, it's not really increasing or improving the fertility of the soil." (R6)

Additionally, one interviewee pointed out that the current political climate does not allow for long-term goals. Changes in the government influence the support given to farmers. As a result of the recent change of government in autumn 2022, funding from Klimatklivet is momentarily put on hold. The application window is closed until autumn 2023. This poses a barrier to biochar deployment in agriculture, as the financial aid from Klimatklivet is an important factor in farmers' decision to make the primary investment in a biochar production plant and biochar boiler. One interviewed farmer received 50% of the required investment from this financial aid scheme. The other farmer mentioned that this financial support was a prerequisite to building the biochar boiler on a large enough scale to allow the heat from the boiler to be used in their district heating. A solution that was proposed by two respondents was to offer a large-scale deal on biochar and offer it as a package. An example was given that farmers could receive financial support from companies such as Arla and Lantmännen.

Swedish national policy is strongly influenced by legislation and directives from the EU. To illustrate, EU state aid laws restrict the types of projects Klimatklivet can fund. The impact of EU legislation was explored throughout the interviews and it was found that these can either facilitate or hamper the deployment of biochar in Swedish agriculture. For instance, the acceptance of the use of biochar in organic agriculture was seen as a driver for its increased adoption in Sweden. In contrast, the EU carbon removal framework that is currently under development favors large production units and was seen as a potential barrier. This is because most interviewees were of the opinion that biochar production in the agricultural sector is better suited for smaller-scale production.

> "Biochar is perfect for small to medium-sized production because it fits within an agricultural system. You have the biomass there, you don't need to transport it from all over, you have everything there". (R2)

In addition, the renewable energy directive from the EU could hinder the use of byproducts from forestry as a feedstock source, which could be a limitation for Sweden due to its large amount of forest residues. This directive is expected to become more complicated in the future, due to the envisioned addition of biodiversity as one of the assessment criteria. Lastly, EU legislation currently excludes the use of certain waste streams, such as sewage sludge, in their approved feedstock list, which was mentioned as a hindrance by some interviewees.

> "There is a gap in what the legislation wants to do and what we see that our actors want to do." (R7+8)

5.2.3 Certification

The respondents agree that certification is important to ensure the quality of biochar. One interview respondent has the opinion that all biochar should be EBC certified, to prevent the use of biochar that contains heavy metals and other substances that could damage soils. Therefore, analysis of the feedstock quality should always be required when it is applied in agriculture, to avoid adverse effects.

However, there are several disadvantages that farmers face in the certification process. First, certification is costly, with one farmer mentioning they have to pay a yearly fee of 50.000 kronor to be EBC-certified. This is a high cost to bear, especially for smaller operations. Second, there is a large amount of paperwork and documentation required to be certified, putting extra work pressure on the farmer. Further, EBC feedstock list does not include sewage sludge, hindering the development of regulations that could support the use of this.

The creation of a national carbon sink standard could help establish a credible carbon credit market so that it becomes a reliable revenue stream for farmers. This standard is currently under development in a project by Hushållningssalskapet. The idea is to offer the carbon sink as a package deal together with biochar as a physical product for a low price to the farmer. The farmer can then use the biochar in its soil and sell the carbon credits to companies. This standard could offer a big driver for farmers, as it contributes to the development of a credible and more stable carbon credit market.

> "When we sell biochar carbon sinks to tech companies, architectural companies, and real estate companies that need to compensate for their climate footprint, they could finance the farmers' practices to put biochar on the farm. That is a real game changer." (R2)

5.2.4 Market forces

The interviews revealed that biochar supply does not meet demand at present. Meanwhile, demand is rising, but mostly for use in urban areas. This results in a high market price for the physical product of biochar, posing a hindrance to the deployment of biochar in Swedish agriculture. Further, the demand for biochar is unstable and there is a high volatility in the carbon sink market, creating a highly insecure environment for farmers.

> "It's a quite new technology, which is creating risk in different ways. There is a high price because small-scale production makes each unit more expensive than if it was larger scale. There are uncertainties in the market: risks as to, is there any demand for it? What will the price be? It's still difficult to foresee the price on the market for these carbon sink certificates" (R10)

A proposed solution is to extend the market of biochar by promoting its use in a wide variety of sectors and a larger variety of niche applications in agriculture (e.g. as a filter, or animal feed additive). This will create a stable demand and a local market with short transportation distances to ensure the economic and environmental sustainability of biochar.

> "There's too little biochar to go around. It's the seller's market. Though, we need to create more biochar in Sweden to make it more available to all kinds of buyers. That would push the price down and open up for new buyers."(R4)

Although most interviewees express a preference for small-scale decentralized biochar production, it was expressed during the webinar that scaling in volume (large production units) is more cost-effective than scaling by number. There is a general agreement that there should be a higher quantity of production units to increase production and lower the price of the physical biochar product.

> "If we can build more facilities based upon the carbon removal certificates, we can then create more biochar on the market and lower the price. It's a matter of the price for the farmer." (R9)

Discussion

This section starts with delineating the socio-technical regime and landscape to operationalize these levels of the MLP. It then explores interactions between niche, regime, and landscape-level, and investigates the processes the niche must undergo to accelerate a sustainability transition. Further, it discusses the limitations of the theoretical framework and the study method, that should be taken into account when evaluating the validity of the research findings. The section concludes with suggestions for future research.

6.1 Theoretical delimitations

Reviewing the empirical findings, various barriers and drivers have been identified that either facilitate or hinder the deployment of biochar in Swedish agriculture. Before discussing the interactions between these factors on the different levels of the MLP, it is important to distinguish between regime and landscape forces.

6.1.1 Delineating the socio-technical regime

First, the regime has to be conceptualized within the context of this study as Holtz et al. (2008) describe that this is *"usually not given through clear system boundaries but is a matter of framing and deliberation"* (p. 623).

According to El Bilali (2019b), in studies that focus on sustainability transitions in the agro-food sector, the regime is most often defined as *"the intensive, conventional, industrial agro-food sector and its associated rules and practices"* (p. 8). In the case of this study, this refers back to the dominant practice of fertilizer use. In the opinion of two interviewees, the deployment of biochar in Swedish agriculture is restrained by research being funded by fertilizer companies. However, there was also a perceived opportunity for collaboration as sludge-based biochar can be used in fertilizer production. Also, according to Ngo Ndoungh et a. (2021), there are limitations to the exclusive use of biochar, such as a lack of nutrients. This shows opportunities for fertilizer companies and biochar producers to work together to combine biochar and fertilizer in an optimal way. In this sense, biochar has a rather synergistic character for the fertilizer industry and thus has the potential to be embedded into the incumbent socio-technical agro-food system (based on fertilizer use), rather than replacing it.

A second regime that was less explicitly mentioned in the interviews is that of incumbent energy and heat production systems. Currently, this regime is receiving pressure from novel negative emissions technologies (NET) in Sweden, including biochar, CCS, BECCS, direct air capture for carbon capture and storage (DACCS) (Bojö & Edberg, 2021). What CCS, BECCS, and DACCS have in common is that they capture and store the emitted CO_2 in geological formations (Buss et al., 2019), as opposed to biochar which is applied on the soil surface. The interviews revealed that stakeholders perceive these other NET as a threat to biochar deployment for two reasons: 1. The larger scale of production which can create cost efficiencies, and 2. The pressure from DAC companies on the EU to only compensate for carbon removal if it is stored deep underground.

These concerns are valid as it seems like the incumbent actors (i.e., the Swedish Energy Agency) in the Swedish heat and energy regime are taking a favorable position towards BECCS. To illustrate, in the report "Road to a Climate Positive Future" BECCS was identified by the Swedish Energy Agency as one of the measures that Sweden can use to achieve the goal of negative GHG emissions in 2045, whereas biochar was excluded (Regeringskansliet, 2022). The strong support of the Swedish government for BECCS is evident from the decision to allocate a state aid of SEK 10 million per year from 2023-2025 and a total of 36 billion from 2026-2046. This enables the creation of large carbon sinks, therefore possibly threatening the economic competitiveness of the carbon sink created by smaller-scale biochar. This resistance from BECCS is also recognized in a recent doctoral thesis by Olsson (2023a) that assessed how some CDR methods with co-benefits, including biochar, can be assessed and potentially supported by policy. The author writes that "the Swedish Energy Agency is evaluating biochar based on the agency's role to supply energy commodities and this regime inclusion is reflected in its decision not to include biochar in the same support scheme as BECCS" (Olsson, 2023a, p.76).

From a technical perspective, biochar has a few benefits over other NETs, because it delivers agricultural benefits and requires less electricity. However, as emerged from the interviews, the small scale of biochar production could make it difficult to compete in price with larger-scale CCS production plants. This could contribute to a future lock-in since large-scale CCS methods could provide benefits in the form of decreased production costs when they become embedded in the regime (Klitkou et al., 2015). However, Olsson (2023a) points out that the different focus of small-scale biochar and large-scale BECCS could present an advantage. This is because biochar producers can utilize locally available biomass that has little to no value to society while BECCS can operate in a large-scale setting.

6.1.2 Delineating the socio-technical landscape

It is a more challenging task to delineate the socio-technical landscape. Some landscape forces are very evident as they go beyond the direct influence of the niche and regime actors (Levidow & Upham, 2017). Based on this description, EU legislation can be considered a landscape force, as it goes beyond the actors operating in the niche and regime whose influence is confined to Sweden. Other examples from the interviews that match this description of the landscape are an increased need for drought resistance, market forces, certification, and growing concerns from the government about the environmental impacts of industrial agriculture.

Further, According to El Bilali (2019b), the landscape plays a key role in ensuring the protection of niches against the dominant regime, by shielding them from initial competition. This can be achieved by supporting the niche-associated innovation system with capacity building and networking, or by empowering the niche innovation with the introduction of new regulations that are in favor of the niche (Hinrichs, 2014). Using this description, the following barriers and drivers are also delineated to the landscape level, although they are not outside of the direct influence of niche and regime actors: Klimatklivet government funding, and the development of a national carbon sink certification standard.

6.2 Niche-regime-landscape interactions

As explained in the theoretical framework, a transition must take place at the regime level for a sustainability transition to occur within a socio-technical system (Geels, 2010). Such a transition requires pressures from either the landscape level or from within the regime itself so that a window of opportunity is created for the niche innovation to break through (Geels & Schot, 2007), to displace the regime or be embedded into it (Geels, 2012).

One landscape force that was identified from the interviews that puts pressure on the regime is the urgency of the Swedish government to reduce agricultural emissions. According to Lachman (2013), this pressure, if strong enough, can destabilize the regime which opens a window of opportunity for the niche to break through. However, there are some counterproductive landscape forces identified in the interviews that hinder the diffusion of biochar technology in Swedish agriculture. First, the current political climate does not allow for long time goals. Second, EU legislation restricts the use of sewage sludge, other side-and waste streams, and forest residues as feedstock. Further, instabilities on the market for the price of biochar and for the biochar carbon credit result in farmers feeling financially secure to initiate investments in production plants without receiving financial aid from the government.

In addition, there are a few landscape factors that can facilitate increased biochar deployment in Swedish agriculture by shielding the niche from the initial competition through the introduction of new regulations. One example of this is the former financial aid offered by Klimatklivet. The interviews demonstrated that this aid scheme was essential for farmers to install a biochar production plant. This finding is confirmed by a recently published that highlights the Klimatklivet as significant for the existence of biochar production plants in Sweden and that without it there would be little to no domestic production (Olsson, 2023b). Thus, it is extremely important for the diffusion of biochar technology in Swedish agriculture that this funding will be re-started in autumn 2023.

Another example is the national carbon sink standard that Hushållningssälskapet is developing. A recent press release stated that this standard will deliver benefits to the farmers, which will be ensured through third-party accreditation (Hushållningssällskapet, 2023). The standard will create a credible market for carbon sinks that adapts the international guidelines to suit the Swedish context. This incentive creates a supportive environment for the niche to thrive and promotes the adoption of biochar.

To accelerate biochar deployment in Swedish agriculture, it is important to consider the timing of landscape pressure and the niche's ability to provide a valid solution as this has a direct impact on the possible change path outcomes (Geels & Schot, 2007). From the interviews, it emerged that at the moment there is no urgency for using biochar in agriculture, due to the high fertility of Swedish soils. However, this need might emerge in the future from climate change as it is projected that with every +1 °C of global warming, the average high-exposure area in the Northern Hemisphere will experience a 16% increase in the occurrence of warm and hot spells (Vogel et al., 2019). This would enable the emergence of a landscape force favoring the use of biochar with biochar offering a valuable solution to address the need for drought resistance, which the current agricultural practices in the agro-food regime may struggle to fulfill. Also, it creates a strong advantage in the choice of biochar for heat and energy generation over other NETs. The niche must be sufficiently developed to seize this opportunity when it arises. Processes that can contribute to the development of the niche will be described in section 6.4., Niche processes to accelerate a sustainability transition.

El Bilali (2019b) stresses that niche development is not sufficient to initiate a regime shift, or in other words, a transition. This also requires collaboration and eventually negotiation between actors from the niche and the regime. This collaborative process can take place in various settings, such as innovation platforms, where different stakeholders (e.g., farmers, policymakers, and researchers) engage in collective action and interaction (El Bilali, 2019b).

6.3 Niche processes to accelerate a sustainability transition

It is evident from the interviews that the niche needs to undergo several processes to stabilize to such an extent that it can break into regime-level, which are described in the strategic niche management framework by Schot and Geels (2008). This framework can help uncover the conditions for successful emergence, and different pathways to establish a sustainability transition towards increased biochar deployment in Swedish agriculture (Loorbach & Van Raak, 2006). Also, according to Olsson (2023a), the bottom-up character of this framework may result in different outcomes on whether biochar is an important CDR method when compared to the top-down approach of the Swedish Energy Agency. Therefore, this framework is useful in the assessment of how policymakers can support the biochar niche.

The first process refers to the *"articulation of expectations and visions"*. At the moment, the visions of different actors do not seem to align with some actors recognizing the potential of biochar whereas others are more hesitant due to the lacking evidence on the effects of biochar on crop yields. However, it is crucial for the development of the niche that stakeholders unite on the articulation of expectations and visions as these give steer learning processes (Schot & Geels, 2008).

The second process refers to *"the building of social networks"* (Geels & Schot, 2008). For the case of biochar adoption in Swedish agriculture, this seems to be an ongoing process, with an increasing number of initiatives being taken to engage in networking and research (e.g., with the Rest till Bäst platform). However, the results of this study point to a missing link in the dissemination of research to the final applicants of biochar technology, the agricultural producer, demonstrating the need for further extension services. Therefore, there should be an increased emphasis in the niche on the building of social networks to facilitate interactions between relevant stakeholders to accelerate the production and use of biochar in Swedish agriculture.

The last process that is important for the development of the niche is *"learning processes at multiple dimensions"* (Schot & Geels, 2008). To stimulate the development of the niche, these learning processes must occur in multiple dimensions, including *"technical aspects and design specifications", "market and user preferences", "cultural and symbolic meaning", "infrastructure and maintenance networks", "industry and production networks", "regulations and government policy",* and *"societal and environmental effects"*.

Considering the technical aspects and design specifications, there is an ongoing learning process on the ultimate applications of biochar in agriculture. This study revealed the opportunity to have real-life experiments with the use of biochar as an animal feed additive or as a filter, to learn about the technical and economic feasibility and environmental gains of these different application options. Further, this study revealed uncertainty related to the long-term effects of applying biochar to agricultural soil. There is a need for more research and eventually education to overcome these uncertainties and to create valuable knowledge about the practical implementation of biochar technology. This is confirmed by a study by Otte and Vik (2017) that revealed that 70% of the surveyed Norwegian farmers perceived increased knowledge of the use and effect of biochar as crucial for its adoption. In addition, according to Olsson (2023a), the lack of scientific support for the co-benefits of biochar complicates policymaking. Hence, increasing knowledge can help niche actors advocate for government policies and regulations that promote the use of biochar to facilitate its integration into mainstream agricultural practices.

Regarding industry and production networks, this study demonstrated the need for an upscaling of biochar production, to achieve cost-efficiency. However, this is currently being restricted by a shortage in production plants. This is no surprise as, according to Schot and Geels (2008), niche innovations rarely match the existing regime in terms of appropriate infrastructure. Thus, an increased supply of biochar production plants is key for a sustainability transition to take place within the socio-technical agrio-food system in Sweden towards increased biochar use. Further, it is important to explore and capitalize on the opportunity for synergies between BECCS and biochar. One way to avoid competition between biochar and other NETs to be embedded into the regime is to increase coordination between the niches and synergize with each other (Immink et al., 2013), for example, by using a byproduct from BECCS (ash from wood production) as an additive in biochar production (Buss et al., 2019). This way, instead of competing, the two niche innovations can strengthen each other.

In terms of market and user preferences, there are certain barriers to be solved. Currently, biochar is too expensive for farmers to apply on their land, resulting in them selling it off to other industries. This is in line with the results of a study on the social acceptance of biochar from the farmer's perspective that identified high costs as the main constraint on its adoption (Latawiec et al., 2017). The survey by Otte and Vik (2017) demonstrated that 28% of Norwegian farmers consider subsidies as an important factor for their deployment of biochar. 30% of the farmers expressed that their interest in biochar would increase in case they are compensated for carbon sequestration. This shows the need for learning processes concerning regulations and government policy, as the research findings of this study, as well as Otte and Vik's (2017) study, suggest that these are required to incentivize farmers to use biochar on their farms.

6.4 Limitations

There are several points of critique on the MLP of which three will be discussed that are important when reviewing the empirical data of this particular study. First of all, critics argue that the descriptive nature of the framework gives rise to discrepancies in the researcher's interpretation of mechanisms, patterns, and relationships when applying the MLP framework (Markard & Tuffer, 2008; Smith, Voß & Grin, 2010). This can result in empirical differences between case studies (Genus & Cole, 2008). According to Genus and Cole (2008), there is a need for increased specification and operationalization at the regime level in particular, to improve the identification of actors within the socio-technical regime and the robustness of the MLP framework. In this study, the delineation between regime and landscape forces was considered an extremely challenging task. Therefore, it is important to consider the impact of the researcher's creative interpretation on the results.

Another often-received criticism in transition literature is that most case studies focus on a single regime that faces pressures from niche innovations and landscape developments (Geels, 2010). Geels (2010) advocates for a focus shift to multi-regime interactions. This study applied this multi-regime focus with the identification of two regime interactions: the dominant practice of fertilizer use in the agro-food system, and competition with other NETs in the heat and energy regime.

In addition, the MLP has been criticized for downplaying the role of agency in transitions. To illustrate, according to Smith et al. (2005), *"existing approaches tend to be too descriptive and structural, leaving room for greater analysis of agency as a means to more informed, deliberate and effective processes of regime transformation"* (p. 1492). The authors argue for more attention to the role of governance in socio-technical transition, with an emphasis on agency and power. In the case of sustainability transitions in the agro-food sector, Hargreaves et al. (2013) emphasize the tendency in the innovation literature to focus on the market-based actors, while neglecting the impact of civil society actors. However, by applying the AIS framework on the niche level, this study took a wide range of actors into consideration that was deemed important by the research participants.

There are also limitations to this study that are important to consider and that are not related to the theoretical framework. First, the qualitative character of this study could potentially elude research bias. This could be from the interviewer as well as the interviewees as the skills, experience, and commitment of both the researcher and the research applicants affect the quality of the data acquired from the interviews (Creswell, 2013). Further, it is important to consider that biochar is a new technology and that new national and European-level legislation is rapidly evolving. For example, the certification for the carbon sink that is under development by Hushållningssällskapet will be launched in the near future. As a result, the landscape might have experienced changes by the time of publication which is important to keep in mind when interpreting the results.

6.5 Suggestions for future research

This study identified many knowledge gaps that can give direction to future research studies. First of all, there should be a focus on long-term impact and real-scale studies to assess the effects of biochar application on soil fertility and crop productivity in different regions in Sweden. Further, it would be beneficial to study the crop-specific effects of biochar application in the Swedish context. This can increase understanding of biochar's potential benefits, challenges, and optimal application rates in different agricultural contexts. The empirical findings also highlight the importance of the engagement of farmers in participatory research to meet their knowledge needs. Addressing knowledge gaps is crucial, as this study demonstrated that they pose a significant barrier to increased biochar deployment.

For the identification of realistic pathways and solutions for a transition to sustainable food systems, it is important to uncover possible synergies and conflicts among proposed solutions and priorities for action from different actors (Röös et al., 2023). To achieve this it is recommended to conduct multi-stakeholder research to align visions from different actors within the biochar system. Such research could help strengthen cooperation in the niche by contributing to the process of *"articulation of expectations and visions"*.

Conclusion

To conclude, there are multiple barriers and drivers that can either hinder or facilitate a sustainability transition in terms of increased biochar deployment in Swedish agriculture, as well as prerequisites to accelerate this transition identified in this study. Drivers include the agricultural benefits biochar delivers, heat production, the opportunity for biochar use in niches solutions (i.e., in livestock production and as a filter), the possibility to receive reimbursement from the carbon sink, the merging of the biochar system with other production systems to achieve recourse efficiency, and the goals of the Swedish government to reduce GHG emissions from the agricultural sector. As the farm is a suitable place for production, the next step is to make its on-farm use more attractive. For this, multiple barriers have to be addressed.

The main barrier to biochar deployment in Swedish agriculture that this study identified is the high cost of biochar. This, together with the volatility in the price of biochar and carbon credits, creates an environment of high uncertainty for farmers to adopt biochar on their farms. Thus, the establishment of financial incentives such as Klimatklivet is considered a prerequisite for biochar deployment. Further, there is a need for the creation of a credible carbon market to reduce volatility in the carbon credit market. This carbon credit system should be in favor of the farmer to incentivize them to use the biochar on their own land instead of selling it to other industries. It is also important to find logistical solutions for the lack of production units so that biochar supply can be increased to further reduce its market price.

Another barrier is the existence of knowledge gaps, emphasizing the need for research funding and increased knowledge sharing and collaboration between different stakeholders and countries to support evidence-based biochar use in agriculture. Strengthened collaboration between farmers and researchers can bridge the gap between academic research and on-farm application, to find the ultimate applications for biochar in Swedish agriculture.

Competition with other NETs in the heat and energy regime also poses barriers to biochar implementation. This combined with an unfavorable landscape in the form of the absence of legislation to support the use of waste or side streams as feedstock, and the current absence of financial incentives to help with the investment in a production plant hinders the diffusion of biochar technology.

Overall, these barriers can be overcome through various learning processes and collective efforts. By addressing financial, knowledge, and market-related challenges, a sustainable and economically viable biochar market can be established that benefits Swedish agriculture and contributes to the government's environmental goals.

References

Alkemade, F., Hekkert, M.P. & Negro, S.O. (2011). Transition policy and innovation policy: Friends or foes? *Environmental Innovation and Societal Transitions*, 1(1), pp. 125–129. https://doi.org/10.1016/j.eist.2011.04.009.

Azzi, E.S., Karltun, E. & Sundberg, C. (2019). Prospective Life Cycle Assessment of Large-Scale Biochar Production and Use for Negative Emissions in Stockholm. *Environmental Science & Technology*, 53(14), pp. 8466–8476. https://doi.org/10.1021/acs.est.9b01615.

Azzi, E.S., Jungefeldt, L., Karan, S. & Sundberg, C. (2022). *Biochar in Swedish agriculture – Straw pyrolysis as a first step towards net-zero*. Uppsala: Swedish University of Agricultural Sciences.

Azzi, E.S. & Sundberg, C. (n.d.) *Biochar systems analysis*. [online] Biochar Systems. Available at: https://biochar.systems/modules/ [2023-05-10]

Bojö, E. & Edberg, V. (2021). Carbon Storage in Sweden : A study on CCS, BECCS, DACCS and biochar from a 2045 perspective. Msc. Thesis. KTH Royal Institute of Technology: DiVa. http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1568409&dswid=-8116. [[2023-05-15]

Borchard, N., Siemens, J., Ladd, B., Möller, A. & Amelung, W. (2014). Application of biochars to sandy and silty soil failed to increase maize yield under common agricultural practice. *Soil and Tillage Research*, 144, pp. 184–194. https://doi.org/10.1016/j.still.2014.07.016.

Braun V. & Clarke V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3, pp. 77–101. doi:10.1191/1478088706qp063oa

Bryman, A. & Bell, E. (2015). *Business research methods*. Oxford: Oxford University Press.

Bünger, A. & Schiller, D. (2022). Identification and characterization of potential change agents among agri-food producers: regime, niche and hybrid actors. *Sustainability Science.* https://doi.org/10.1007/s11625-022-01184-1.

Buss, W., Jansson, S., Wurzer, C. & Mašek, O. (2019). Synergies between BECCS and Biochar—Maximizing Carbon Sequestration Potential by Recycling Wood Ash. *ACS Sustainable Chemistry & Engineering*, 7(4), pp.4204–4209. https://doi.org/10.1021/acssuschemeng.8b05871.

Campbell, B.M., Beare, D.J., Bennett, E.M., Hall-Spencer, J.M., Ingram, J.S.I., Jaramillo, F., Ortiz, R., Ramankutty, N., Sayer, J.A. & Shindell, D. (2017). Agriculture production as a major driver of the Earth system exceeding planetary

boundaries. *Ecology and Society*, 22(4). https://doi.org/10.5751/es-09595-220408.
Carbon Standards International. (n.d.). *Standards and Services*. [online] Available at: https://www.carbon-standards.com/en/standards-and-services?open=101 [2023-04-02]
Chowdhury, I.A. (2015). Issue of quality in a qualitative research: An overview. *Innovative Issues and Approaches in Social Sciences*, 8(1), pp.142-162.
Creswell, J.W. (2013). *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. 4th ed. London: SAGE Publications, Inc.
Creswell, J. W. & Creswell, J. D. (2018). *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. 5th ed. Thousand Oaks CA, SAGE Publications, Inc.
Darnhofer, I. (2015). Socio-technical transitions in farming: key concepts. Transition pathways towards sustainability in agriculture: case studies from Europe, pp. 17–31. https://doi.org/10.1079/9781780642192.0017.
Dentoni, D., Hospes, O. & Ross, B. R. (2012). Managing Wicked Problems in Agribusiness: The Role of Multi-Stakeholder Engagement in Value Creation. *International Food and Agribusiness Management Review*, 15(B).
Dorninger, C., Abson, D.J., Apetrei, C.I., Derwort, P., Ives, C.D., Klaniecki, K., Lam, D.P.M., Langsenlehner, M., Riechers, M., Spittler, N. & Von Wehrden, H. (2020). Leverage points for sustainability transformation: a review on interventions in food and energy systems. *Ecological Economics*, 171, p.106570. https://doi.org/10.1016/j.ecolecon.2019.106570.
EcoEra. (n.d.). *About Us*. [online] Available at: https://ecoera.se/pages/about-us [2023-04-02]
El Bilali, H. (2019a). Research on agro-food sustainability transitions: A systematic review of research themes and an analysis of research gaps. *Journal of Cleaner Production*, 221, pp. 353–364. https://doi.org/10.1016/j.jclepro.2019.02.232.
Erbach, G. & Andreo, G. (2021). *Carbon dioxide removal: Nature-based and technological solutions*. [online] Available at: https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/689336/EPRS_BRI(2021)689336_EN.pdf [2023-03-01]
European Biochar Certificate (EBC) (n.d). *Introduction*. [online] Availble at: https://www.european-biochar.org/en/ct/26-Introduction [2023-04-02]
FAO. (2009). *2050 graphics-all languages*. [online] Available at: http://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf [2023-02-18]
Fawzy, S., Osman, A.I., Yang, H., Doran, J. & Rooney, D.W. (2021). Industrial biochar systems for atmospheric carbon removal: a review. *Environmental Chemistry Letters*, 19(4), pp. 3023–3055. https://doi.org/10.1007/s10311-021-01210-1.
Friedrich, S. (2020). *Approval for organic farming in the EU | Blog PYREG*. [online] PYREG GmbH. Available at: https://pyreg.com/biochar-approved-for-organic-farming-throughout-the-eu/ [2023-02-25].

Galletta, A. (2013). *Mastering the semi-structured interview and beyond: From research design to analysis and publication.* New York University Press.

Geels, F.W. (2004). From Sectoral Systems of Innovation to socio-technical Systems. *Research Policy*, 33(6-7), pp. 897–920. https://doi.org/10.1016/j.respol.2004.01.015.

Geels, F.W. & Schot, J. (2007). Typology of sociotechnical transition pathways. *Research Policy*, 36(3), pp. 399–417. https://doi.org/10.1016/j.respol.2007.01.003.

Geels, F.W. (2010). Ontologies, socio-technical transitions (to sustainability), and the multi-level perspective. *Research Policy*, 39(4), pp. 495–510. https://doi.org/10.1016/j.respol.2010.01.022.

Geels, F.W. (2011). The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation and Societal Transitions*, 1(1), pp. 24–40. https://doi.org/10.1016/j.eist.2011.02.002.

Geels, F.W. (2012). A socio-technical analysis of low-carbon transitions: introducing the multi-level perspective into transport studies. *Journal of Transport Geography*, 24, pp. 471–482. https://doi.org/10.1016/j.jtrangeo.2012.01.021.

Geels, F.W., Sovacool, B.K., Schwanen, T. & Sorrell, S. (2017). Sociotechnical transitions for deep decarbonization. *Science*, 357(6357), pp.1242–1244. https://doi.org/10.1126/science.aao3760.

Genus, A. & Coles, A.M. (2008). Rethinking the multi-level perspective of technological transitions. *Research Policy,* 37(9), p. 1436–1445.

Gibbert, M., Ruigrok, W. & Wicki, B. (2008). What passes as a rigorous case study? *Strategic Management Journal*, 29(13), pp. 1465–1474. https://doi.org/10.1002/smj.722.

Government Offices of Sweden (2021). *Sweden's climate policy framework*. [online] Regeringskansliet. Available at: https://www.government.se/articles/2021/03/swedens-climate-policy-framework/ [2023-02-10]

Håkansson, M. & Strömberg, L. (2022). The potential for large-scale implementation of biochar in the agricultural sector. Msc. Thesis. The Swedish University of Agricultural Sciences. Alnarp: Epsilon. https://stud.epsilon.slu.se/18404/1/hakansson-m-et-al-2022-10-18.pdf. [2023-02-10]

Herrero, M., Thornton, P.K., Mason-D'Croz, D., Palmer, J., Benton, T.G., Bodirsky, B.L., Bogard, J.R., Hall, A., Lee, B., Nyborg, K., Pradhan, P., Bonnett, G.D., Bryan, B.A., Campbell, B.M., Christensen, S., Clark, M., Cook, M.T., de Boer, I.J.M., Downs, C. & Dizyee, K. (2020). Innovation can accelerate the transition towards a sustainable food system. *Nature Food*, 1(5), pp. 266–272. https://doi.org/10.1038/s43016-020-0074-1.

Hinrichs, C.C. (2014). Transitions to sustainability: a change in thinking about food systems change? *Agriculture and Human Values*, 31(1), pp.143–155. https://doi.org/10.1007/s10460-014-9479-5.

Holtz, G., Brugnach, M. & Pahl-Wostl, C. (2008). Specifying ‘regime’ — A framework for defining and describing regimes in transition research. *Technological Forecasting and Social Change*, 75(5), pp.623–643. doi:https://doi.org/10.1016/j.techfore.2007.02.010.

Homagain, K., Shahi, C., Luckai, N. & Sharma, M. (2016). Life cycle cost and economic assessment of biochar-based bioenergy production and biochar land application in Northwestern Ontario, Canada. *Forest Ecosystems*, 3(1). https://doi.org/10.1186/s40663-016-0081-8.

Hushållningssällskapet. (2020). *Kolsänksrätter med biokol*. [online] Available at: https://hushallningssallskapet.se/?projekten=kolsanksratter-med-biokol [2023-04-02]

Hushållningssällskapet. (2023). *Sigill Kvalitetssystem i nytt samarbete om biokol*. [online] Available at: https://hushallningssallskapet.se/pressrum/sigill-kvalitetssystem-i-nytt-samarbete-om-biokol/ [2023-05-18].

Immink, V.M., Van Tulder, M.R. & Van Trijp, J.C.M. (2013). The livestock sector and its stakeholders in the search to meet the animal welfare requirements of society. *Journal on Chain and Network Sciences*, 13(2), pp.151–160. https://doi.org/10.3920/jcns2013.1005.

IPCC. (2019). Global Warming of 1.5 °C: an IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Available at: https://www.ipcc.ch/site/assets/uploads/sites/2/2022/06/SR15_Summary_Volume_HR.pdf [2023-06-12]

Ippolito, J.A., Cui, L., Kammann, C., Wrage-Mönnig, N., Estavillo, J.M., Fuertes-Mendizabal, T., Cayuela, M.L., Sigua, G., Novak, J., Spokas, K. & Borchard, N. (2020). Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. *Biochar*, 2(4), pp. 421–438. https://doi.org/10.1007/s42773-020-00067-x.

Jeffery, S., Verheijen, F.G.A., van der Velde, M. & Bastos, A.C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems & Environment*, 144(1), pp. 175–187. https://doi.org/10.1016/j.agee.2011.08.015.

Jeffery, S., Abalos, D., Prodana, M., Bastos, A.C., van Groenigen, J.W., Hungate, B.A. & Verheijen, F. (2017). Biochar boosts tropical but not temperate crop yields. *Environmental Research Letters*, 12(5), p. 053001. https://doi.org/10.1088/1748-9326/aa67bd.

Joseph, S., Cowie, A.L., Van Zwieten, L., Bolan, N., Budai, A., Buss, W., Cayuela, M.L., Graber, E.R., Ippolito, J.A., Kuzyakov, Y., Luo, Y., Ok, Y.S., Palansooriya, K.N., Shepherd, J., Stephens, S., Weng, Z.H. & Lehmann, J. (2021). How biochar works, and when it doesn’t: A review of mechanisms controlling soil and plant responses to biochar. *GCB Bioenergy*, 13(11), pp. 1731–1764. https://doi.org/10.1111/gcbb.12885.

Kahlke, R. (2017). The qualitative quality conversation. *Medical Education*, 51(1), pp.5-7.
Kalus, K., Konkol, D., Korczyński, M., Koziel, J.A. & Opaliński, S. (2020). Effect of Biochar Diet Supplementation on Chicken Broilers Performance, NH3 and Odor Emissions and Meat Consumer Acceptance. *Animals*, 10(9), p. 1539. https://doi.org/10.3390/ani10091539.
Kamali, M., Sweygers, N., Al-Salem, S., Appels, L., Aminabhavi, T.M. & Dewil, R. (2022). Biochar for soil applications-sustainability aspects, challenges and future prospects. *Chemical Engineering Journal*, 428, p.131189. https://doi.org/10.1016/j.cej.2021.131189.
Karan, S., Osslund, F., Azzi, E.S., Karltun, E. & Sundberg, C. (2022). *A Spatial Framework for Prioritizing Biochar Application to Arable Land: A Case Study for Sweden*. [online] papers.ssrn.com. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4144164. [2023-02-18]
Kavitha, B., Reddy, P.V.L., Kim, B., Lee, S.S., Pandey, S.K. & Kim, K.H. (2018). Benefits and limitations of biochar amendment in agricultural soils: A review. *Journal of Environmental Management*, 227, pp.146–154. https://doi.org/10.1016/j.jenvman.2018.08.082.
Klerkx, L., Van Mierlo, B. & Leeuwis, C. (2012). Evolution of systems approaches to agricultural innovation: concepts, analysis and interventions. In: Darnhofer, I., Gibbon, D., Dedieu, B. (eds) Farming Systems Research into the 21st Century: The New Dynamic. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-4503-2_20.
Klerkx, L. & Begemann, S. (2020). Supporting food systems transformation: The what, why, who, where and how of mission-oriented agricultural innovation systems. *Agricultural Systems*, 184, p. 102901. https://doi.org/10.1016/j.agsy.2020.102901.
Klitkou, A., Bolwig, S., Hansen, T. & Wessberg, N. (2015). The role of lock-in mechanisms in transition processes: The case of energy for road transport. *Environmental Innovation and Societal Transitions,* 16, pp. 22–37. https://doi.org/10.1016/j.eist.2015.07.005.
Lachman, D.A. (2013). A survey and review of approaches to study transitions. *Energy Policy,* 58, pp. 269–276. https://doi.org/10.1016/j.enpol.2013.03.013.
Latawiec, A., Królczyk, J., Kuboń, M., Szwedziak, K., Drosik, A., Polańczyk, E., Grotkiewicz, K. & Strassburg, B. (2017). Willingness to Adopt Biochar in Agriculture: The Producer's Perspective. *Sustainability,* 9(4), p.655. https://doi.org/10.3390/su9040655.
Latawiec, A.E., Strassburg, B.B.N., Junqueira, A.B., Araujo, E., D. de Moraes, L.F., Pinto, H.A.N., Castro, A., Rangel, M., Malaguti, G.A., Rodrigues, A.F., Barioni, L.G., Novotny, E.H., Cornelissen, G., Mendes, M., Batista, N., Guerra, J.G., Zonta, E., Jakovac, C. & Hale, S.E. (2019). Biochar amendment improves degraded pasturelands in Brazil: environmental and cost-benefit analysis. *Scientific Reports*, 9(1). https://doi.org/10.1038/s41598-019-47647-x.

Lévesque, V., Oelbermann, M. & Ziadi, N. (2021). Biochar in temperate soils: opportunities and challenges. *Canadian Journal of Soil Science*, pp. 1–26. https://doi.org/10.1139/cjss-2021-0047.

Levidow, L. & Upham, P. (2017). Linking the multi-level perspective with social representations theory: Gasifiers as a niche innovation reinforcing the energy-from-waste (EfW) regime. *Technological Forecasting and Social Change*, 120, pp.1–13. https://doi.org/10.1016/j.techfore.2017.03.028.

Loorbach, D., Frantzeskaki, N. & Avelino, F. (2017). Sustainability Transitions Research: Transforming Science and Practice for Societal Change. *Annual Review of Environment and Resources*, 42(1), pp. 599-619. https://doi.org/ 10.1146/annurev-environ-102014-021340

Ludemann, R., Dorp, M., Kormelinck, A. & Chancellor, T. (2012). Capacity Development in Agricultural Research for Development. Available at: https://www.researchgate.net/figure/Agricultural-Innovation-System_fig1_293798711 [2023-04-25].

Makri, C. & Neely, A. (2021). Grounded Theory: A Guide for Exploratory Studies in Management Research. *International Journal of Qualitative Methods*, 20, pp.1–14. https://doi.org/10.1177/16094069211013654.

Markard, J., Raven, R. & Truffer, B. (2012). Sustainability transitions: An emerging field of research and its prospects. *Research Policy*, 41(6), pp. 955–967. https://doi.org/10.1016/j.respol.2012.02.013.

Meyer, S., Fischer, D., Meyer, A., Karltun, E. & Silvén, M.P. (2021). Biochar-Fertilizer Blends—a Valuable Soil Amendment for Asparagus Cultivation? *Journal of Soil Science and Plant Nutrition*, 22(1), pp. 691–705. https://doi.org/10.1007/s42729-021-00678-8.

Nair, V.D., Nair, P.K.R., Dari, B., Freitas, A.M., Chatterjee, N. & Pinheiro, F.M. (2017). Biochar in the Agroecosystem–Climate-Change–Sustainability Nexus. *Frontiers in Plant Science*, 8. https://doi.org/10.3389/fpls.2017.02051.

Naturvårdsverket. (2022). *Klimatklivet vill öka produktionen och användningen av biokol i Sverige.* [online] Available at: https://www.naturvardsverket.se/om-oss/aktuellt/nyheter-och-pressmeddelanden/klimatklivet-vill-oka-produktionen-och-anvandningen-av-biokol-i-sverige/ [2023-04-01]

Ndoung, O.C.N., Figueiredo, C.C., & Ramos, M.L.G. (2021). A scoping review on biochar-based fertilizers: enrichment techniques and agro-environmental application. *Heliyon*, 7(12), p.08473. https://doi.org/10.1016/j.heliyon.2021.e08473.

Nguyen, M.K., Lin, C., Hoang, H.G., Bui, X.T., Ngo, H.H., Le, V.G. & Tran, H.T. (2023). Investigation of biochar amendments on odor reduction and their characteristics during food waste co-composting. *Science of The Total Environment*, 865, p. 161128. https://doi.org/10.1016/j.scitotenv.2022.161128.

Nowell, L.S., Norris, J.M., White, D.E. & Moules, N.J. (2017). Thematic analysis: Striving to Meet the Trustworthiness Criteria. *International Journal of Qualitative Methods*, 16(1), pp.1–13. https://doi.org/10.1177/1609406917733847.

OECD. (2013). *Agricultural Innovation Systems: A Framework for Analysing the Role of the Government*, OECD Publishing. [online] Available at: https://read.oecd-ilibrary.org/agriculture-and-food/agricultural-innovation-systems_9789264200593-en#page15 [2023-03-19]

Olsson, A. (2023a). Assessing Carbon Dioxide Removal methods amid uncertainty: soil carbon sequestration, biochar and harvested wood products as methods for climate change mitigation. PhD. Thesis. KTH Royal Institute of Technology. Stockholm: http://kth.diva-portal.org/smash/record.jsf?aq2=%5B%5B%5D%5D&c=13&af=%5B%5D&searchType=LIST_COMING&sortOrder2=title_sort_asc&query=&language=en&pid=diva2%3A1736998&aq=%5B%5B%5D%5D&sf=all&aqe=%5B%5D&sortOrder=author_sort_asc&onlyFullText=false&noOfRows=50&dswid=8381. [2023-06-14].

Olsson, A. (2023b). The potential for large-scale implementation of biochar in the agricultural sector. PhD. Thesis. KTH Royal Institute of Technology. Stockholm: DiVa. https://kth.diva-portal.org/smash/get/diva2:1736998/FULLTEXT01.pdf. [2023-05-15].

Otte, P.P. & Vik, J. (2017). Biochar systems: Developing a socio-technical system framework for biochar production in Norway. *Technology in Society*, 51, pp. 34–45. https://doi.org/10.1016/j.techsoc.2017.07.004.

Patton, M. Q. (2002). *Qualitative research and evaluation methods*. 3rd ed. Thousand Oaks, CA: SAGE Publications, Inc.

Poore, J. & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science*, 360(6392), pp. 987–992. https://doi.org/10.1126/science.aaq0216.

Puro.earth (n.d.). *Carbon price*. [online] puro.earth. Available at: https://puro.earth/carbon-removal-index-price/ [2023-03-01]

Regeringskansliet. (2022*). Stor satsning görs på infångning av biogen koldioxid.* [online] Available at: https://www.regeringen.se/pressmeddelanden/2022/11/stor-satsning-gors-pa-infangning-av-biogen-koldioxid/ [2023-05-12].

Rest till Bäst. (n.d.). *Biochar.* [online] Available at: https://biokol.org/english [2023-05-10].

Roberts, K.G., Gloy, B.A., Joseph, S., Scott, N.R. & Lehmann, J. (2010). Life Cycle Assessment of Biochar Systems: Estimating the Energetic, Economic, and Climate Change Potential. *Environmental Science & Technology*, 44(2), pp. 827–833. https://doi.org/10.1021/es902266r.

Robson, C. (2002). *Real World Research*. 2nd ed. Malden, USA: Blackwell publishing.

Röös, E., Wood, A., Säll, S., Abu Hatab, A., Ahlgren, S., Hallström, E., Tidåker, P. & Hansson, H. (2023). Diagnostic, regenerative or fossil-free - exploring stakeholder perceptions of Swedish food system sustainability. *Ecological Economics,* 203, p.107623. doi:https://doi.org/10.1016/j.ecolecon.2022.107623.

Sanjari, M., Bahramnezhad, F., Fomani, F.K., Shoghi, M. & Cheraghi, M.A. (2014). Ethical challenges of researchers in qualitative studies: the necessity to develop a specific guideline. *Journal of medical ethics and history of medicine*, [online] 7(7), p.14. Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4263394/.

Saunders, M., Lewis, P. & Thornhill A. (2009). *Research methods for business students*. 5th ed. Pearson Education.

Schmidt, H.P., Hagemann, N., Draper, K. & Kammann, C. (2019). The use of biochar in animal feeding. *PeerJ*, 7, p.7373. https://doi.org/10.7717/peerj.7373.

Schmidt, H., Kammann, C., Hagemann, N., Leifeld, J., Bucheli, T.D., Sánchez Monedero, M.A. & Cayuela, M.L. (2021). Biochar in agriculture – A systematic review of 26 global meta-analyses. *GCB Bioenergy*, 13(11), pp. 1708–1730. https://doi.org/10.1111/gcbb.12889.

Schot, J. & Geels, F.W. (2008). Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy. *Technology Analysis & Strategic Management,* 20(5), pp. 537–554. https://doi.org/10.1080/09537320802292651.

Scott, H.L. Ponsonby, D. & Atkinson, C.J. (2014). Biochar: an improver of nutrient and soil water availability - what is the evidence? *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources*, 9(019). https://doi.org/10.1079/pavsnnr20149019.

Skogsstyrelsen. (2022). *Underlag för strategisk planering för ökad kolsänka Regeringsuppdrag*. Available at: https://www.skogsstyrelsen.se/globalassets/om-oss/rapporter/rapporter-20222021202020192018/rapport-2022-14-underlag-for-strategisk-planering-for-okad-kolsanka.pdf [2023-03-10].

Smith, A., Voß, J.P. & Grin, J. (2010). Innovation studies and sustainability transitions: The allure of the multi-level perspective and its challenges. *Research Policy,* 39(4), pp.435–448. Available at: https://ideas.repec.org/a/eee/respol/v39y2010i4p435-448.html [2023-05-9]

Song, B., Almatrafi, E., Tan, X., Luo, S., Xiong, W., Zhou, C., Qin, M., Liu, Y., Cheng, M., Zeng, G. & Gong, J. (2022). Biochar-based agricultural soil management: An application-dependent strategy for contributing to carbon neutrality. *Renewable and Sustainable Energy Reviews*, 164, p. 112529. https://doi.org/10.1016/j.rser.2022.112529.

Vogel, M.M., Zscheischler, J., Wartenburger, R., Dee, D. & Seneviratne, S.I. (2019). Concurrent 2018 Hot Extremes Across Northern Hemisphere Due to Human-Induced Climate Change. *Earth's Future*, 7(7), pp. 692–703. https://doi.org/10.1029/2019ef001189.

Ye, L., Camps-Arbestain, M., Shen, Q., Lehmann, J., Singh, B., Sabir, M. & Condron, L.M. (2020). Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls. *Soil use and management*, 36 (1), 2–18. https://doi.org/10.1111/sum.12546

Yin, R.K. (2009). *Case Study Research: Design and Methods*. 4th ed. Thousand Oaks, CA: SAGE Publications, Inc. [online] Available at: http://cemusstudent.se/wp-content/uploads/2012/02/YIN_K_ROBERT-1.pdf.

Popular science summary

Environmental degradation, biodiversity loss, and food insecurity: these are some examples of the challenges that agro-food systems over the world face. At the same time, agricultural production emits a large amount of greenhouse gas emissions. To solve these challenges, radical changes are needed. There has been a rise in the adoption of new technologies in the agro-food chain, with the goal to reduce the negative impact of agriculture on the environment, of which biochar is one. Biochar is a type of charcoal that is made by burning organic materials, such as wood, crop residues, or agricultural waste, in an environment with little to no oxygen. Biochar can be applied to farmland to store carbon in the soil while also delivering agricultural benefits, making it an environmentally friendly solution. However, regardless of these advantages, biochar is not widely used in Swedish agriculture. Therefore, this study investigates what is facilitating and hindering biochar deployment in Swedish agriculture. This study also explores what the requirements are to accelerate its adoption. To gain insight into this, a wide variety of stakeholders that are involved in some way with biochar in agriculture were interviewed. The results indicate that biochar has the potential to play a large role in making the Swedish agro-food system more sustainable because of its technical advantages, but that there are challenges that need to be addressed. For example, there are financial barriers, including the high cost of biochar and an unstable demand for biochar. Knowledge gaps also exist, highlighting the need for research funding, knowledge sharing, and collaboration among stakeholders. The lack of supportive policies for using waste materials and side streams as biomass sources and inadequate financial support for production plant investments also hinder the deployment of biochar in Swedish agriculture. Overcoming these barriers requires collective efforts to establish a viable biochar market that benefits Swedish agriculture and contributes to the government's environmental goals.

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Appendix 1. Interview protocol

Introduction to topic

My research is focused on understanding the current barriers and drivers that hinder or facilitate biochar use in Swedish agriculture, and to find out the requirements for its widespread adoption. I interview diverse actors that operate in the biochar system to discover what are differences in the drivers and barriers they perceive, as well as possible synergies and conflicts that exist between different actors' priorities for action.

Introduction to protocol

Today I will have a semi-structured interview with you. I will start off by asking some background questions. Subsequently, I will ask you about the actors and networks that operate in the biochar sector in agriculture in Sweden. Lastly, I will ask about your perception of the main barriers and drivers for biochar deployment in Swedish agriculture.

This interview is estimated to last between 30 and 50 minutes. During this time, I will cover several questions. If time runs short, it may be necessary to interrupt you in order to push ahead and complete this line of questioning.

Background questions:

1. Can you shortly describe how are you involved with biochar, and can you tell me about the journey on how you got there?
2. How would you describe your professional role?

Actors and networks:

1. Can you describe the main actors and organizations involved in the development and implementation of biochar in agriculture in Sweden?
2. Who is driving the change toward increased biochar use?
3. How does knowledge get exchanged between different stakeholders?
4. What are opportunities for collaboration between different stakeholders in the agricultural sector to promote the wider use of biochar in Sweden?

Drivers and barriers:

1. What is the current state of biochar production and deployment in Swedish agriculture?
2. How do you see the demand for the agricultural sector?
3. How do you see the role of biochar in the promotion of the sustainable development of the agricultural sector in Sweden?
4. What is your future vision of biochar for Swedish agriculture: how would you like to see it be used?
    - Probe: What initiatives and efforts do you see from the sector to achieve this?
5. What are the current policies and regulations related to the use of biochar in agriculture in Sweden?
6. How can the government and other stakeholders support the deployment of biochar in Swedish agriculture?
7. Are there any technical and infrastructure requirements to scale up the production and use of biochar in Swedish agriculture?
8. What are the main sources of information and knowledge about biochar for farmers and agricultural stakeholders in Sweden?
    - Probe: How can the availability and accessibility of information be improved?
9. What is the cause of the low adoption of biochar in Swedish agriculture?
10. What do you consider to be the main challenges to the increased adoption of biochar in Swedish agriculture?

Appendix 2. Thematic analysis

Table 2. Thematic analysis of the theme "technical drivers and barriers".

R	Code	Sub-theme	Theme
1	Importance to use feedstock with short regrowth time	Sustainable and clean feedstock	Technical drivers and barriers
1	Avoid displacing agricultural production for biomass production		
1, 2, 5, 8, 10	Importance to utilize a wide variety of waste-, and side-streams as feedstock		
2, 5, W, 9	Contrasting opinions on using sewage sludge as feedstock		
2, 3, 4, 5	Effects of biochar on water-holding capacity and thus drought resistance seen a one of the most important	Biochar as soil amendment	
5	Less compact soil, better root systems, more worms		
5	Experienced 30% higher crop yield during drought in 2018 on field where biochar was applied compared to where biochar was not applied		
1, 9	Biochar leads to increased crop yields, even in Sweden		
6, 10	Low effects in Swedish agriculture on crop yield and soil fertility, due to fertile and high carbon content soils		
9	Better effects in sandy soils due to water-holding capacity		
4, 5, 9	Increasingly important in drought management		
1	Difficult to measure the effect of biochar on soil		
1, 10	Different soils, feedstocks, and crops have different outcomes		

2, 3, 5	Use of biochar in animal production	Niche solutions for biochar	
9, 10	Biochar can be used as filtering system		
10	Niche solutions give financial incentive for agricultural use		
2, 7 + 8, 10	Heating system with co-benefits	Biochar as heating solution	
5, 7+8, 10	Biochar heating system is sufficient to heat on-farm facilities		
7+8	Can contribute to electricity production		
6	Using biomass for biogas as more effective in creating energy on farms		
3, 6, 7+8	Biochar has the potential to contribute to carbon storage with co-benefits	Carbon sink	
6	Carbon sequestration as an opportunity to reduce agricultural emissions		
6	Other methods seen as more efficient		
4	Issue of additionality		
2, 3, 4	Need for clarity who produces and owns the carbon credit to avoid risk of double counting		
3, 4	Lack of trust on the amount of carbon that is stored		
2, 4, 9	Need for credibility, e.g. by third party auditing		
2, 4, 10	Importance of traceability from cradle-to-grave		
2, 5, 9, 10	Biogas production can be included with biochar production to apply biogas slurry on field	Integrating biochar production in biogas production system	Synergies between production systems
9	Biochar can be used in anaerobic digesters		
1	Opportunity to convert biomas heating plants to produce biochar in summer when there is low heat demand	Produce biochar in biomass heating systems	

Table 3. Thematic analysis of the theme "knowledge".

R	Code	Sub-theme	Theme
3, 4, 10	Unclarity about effects on crop yield	Knowledge gaps	Knowledge
6	Unclarity on how biochar works		
3	Uncertainties about the efficiency of carbon storage		
2	Researchers are behind		
7+8	Difficult to keep up with research: fast pace		
1, 10	Importance of educational resources for farmers	Knowledge needs	
1, 9	Need for knowledge sharing on the positive effects of biochar on crop yield in Sweden		
4	Need for competence centres where knowledge can be created and diffused.		
4	Need for extension services to provide accessible knowledge to farmers		
1, 3, 10	Need for evidence-based research on the impact of biochar on different agricultural conditions (e.g., soils, crops, feedstocks, pesticide use)		
3, 10	Need for evidence-based research on the quantity in which biochar has to be applied		
3, 5	Need for evidence-based research on the benefits of biochar in animal production		
4, 7+8	Need to find the ultimate applications for biochar in agriculture		
2, 3, 4, 5, 10	Need for long-term field studies and real-scale studies to demonstrate the effectiveness of biochar		
2, 3	Importance of research in risk reduction for farmers and enabling government aid schemes		
2	SLU should play a role in demonstrating the effectiveness of biochar		
2, 3, 5	Lack of research funding for large-scale, long-term trials	Research funding	

Table 4. Thematic analysis of the theme "economic drivers and barriers".

R	Code	Sub-theme	Theme
2, 4, 5, 10	Price is currently too high to motivate agricultural use	Cost	Economic drivers and barriers
5, 10	Biochar is not used (daily) on farm, due to cost		
7+8	Biochar heating systems are expensive		
5, 10	Higher profits from selling biochar to other sectors than using it on the land		
1, 4, 10	Primary investment can be a huge risk for farmers due to high-uncertainty		
1, 5, 10	Importance of financial aid to incentivize farmers		
4, W	Difficult to valorize co-benefits of biochar to nature and animal welfare		
4, 5, 9	Profitability as prerequisite for increased biochar deployment in agriculture		
1, 5	Biochar is profitable under certain conditions: biomass availability	Opportunities	
1, 5, 10	Long-term vision farmers		
4	Farmers have multiple sources of income from biochar production and use: heat, carbon sink, and increased yield in some areas		
4, 5, 9, 10	Opportunity to establish financing through the carbon sink		
4	Possibility to buy the carbon credits and biochar in a package deal to reduce cost of biochar		
2, 3, 7+8	Climate positive impact of biochar can be used to receive government funding		
4	Biochar use could incentivice banks to give loans to farmers		

Table 5. Thematic analysis of the theme "policy and legislation".

R	Code	Sub-theme	Theme
2, 4	EU accepted the use of biochar in organic agriculture	EU policy and legislation	Policy and legislation
9	Carbon removal certification is under development		

2, 3, 4	European standard on carbon sink could incentivice Swedish government to create a national standard	
4	Eu carbon sink framework will affect voluntary standards	
4	Voluntary standards are faster	
2, 4	Lack of knowledge among EU legislation makers	
4, 7+8	EU legislation and directives influence national policy and legislation	
7+8	EU state aid laws restricts the types of projects Klimatklivet can fund	
7+8	EU legislation hinders the use of certain feedstocks, i.e. sewage sludge	
7+8	The renewable energy directive from the EU could hinder use of byproducts from forestry	
2	EU legislation favors large production units, whereas biochar is better suited to small-scale/ medium-sized	
6	Swedish agricultural policy has the mission to reduce emissions from agriculture	National policy and legislation
3	Interest from government to pay for carbon removal	
7+8	Biochar is recognized by Klimatklivet as carbon removal measure with potential	
6, 5, 7+8	Government changes influence support given to farmers: aid from Klimatklivet momentarily on hold	
5	Current political climate does not allow for long-term goals	
5	Received 50% of production plant installation cost from Klimatklivet	
10	Klimatklivet as prerequisite to build the biochar boiler on big enough scale for the district heating	
10	Need for regulations that allow biochar as a filter for sewage water	

Table 6. Thematic analysis of the theme "certification".

R	Code	Sub-theme	Theme
2, 3, 5, 10	EBC certification is costly for a small operation and there is lots of rules to adhere to	EBC certification	Certification
10	EBC certification costs around 50.000 SEK yearly	as obstacle	
2, 5	Certification brings pressure on farmers in terms of paperwork and documentation		
9	Sewage sludge is currently not included in EBC approved feedstock list		
2, 5, 9	EBC certification is important to ensure quality	EBC as necessary	
2	Everyone should be certified		
2	Helps prevent use of feedstock that contains heavy metals and could damage soils		
4, 5, 9	Hushållningssälskapet is developing a national carbon sink certificate	Carbon sink	
4	Carbon sink certificate cost money	certification	
4, 5	Allows farmers to buy biochar for a cheap price, could be offered as package deal		

Table 7. Thematic analysis of the theme "market forces".

R	Code	Sub-theme	Theme
4, 9	Supply of biochar is too low	Demand and supply	Market forces
2	Demand is rising, but mostly for urban applications		
10, 4, W	Need for stable demand, created by extending the market and allowing biochar use in other sectors (e.g. as filter material)		
2	Importance to create a local market		
2, 3, 4, 5	Long waiting times production plant		
2, 4, 5	Limited availability to production unit		

2, 4, 9	Offer compensation to farmers for biochar carbon credits, which helps finance biochar use on farmland	Climate compensation	
2	Companies need to buy carbon credits to compensate for their climate footprint		
10	High volatility on biochar price and carbon sink market	Price of biochar	
9, 10	High price as cause for low use in soils		
1, 10	High production unit price due to small scale production		
9, 10	Need for increased quantity of production units to increase supply, and lower the price		

Table 8. Thematic analysis of the theme "dominant structures".

R	**Code**	**Sub-theme**	**Theme**
5	Biochar could increase soil health and reduce need for fertilizer	Fertilizer companies	Dominant structures
5	Feeding biochar to animals can create biochar enriched fertilizer		
5	Research is funded by fertilizer companies		
5, 9	Subtle and subliminal resistance from companies that make nitrogen out of fossil gas		
W	Fertilizer companies can use sludge based biochar as input		
9	Pressure from direct air capture companies to store away carbon deep underground to receive payment for carbon removal	Other CDR methods	
2	Different carbon storage should not work against each other		
2	Competition from centralized large-scale CCS		
9	Injecting biochar deep underground would lose agricultural benefits		
9	Oil companies working with CDR technologies, such as DAC		

Appendix 3. Biochar AIS descriptions

In this Appendix, a short description will be provided of the activities of the stakeholders that are denoted with a '*' in *Figure 6*, as their role within the diffusion of biochar technology and relevancy to the subject are not clearly stated in the thesis.

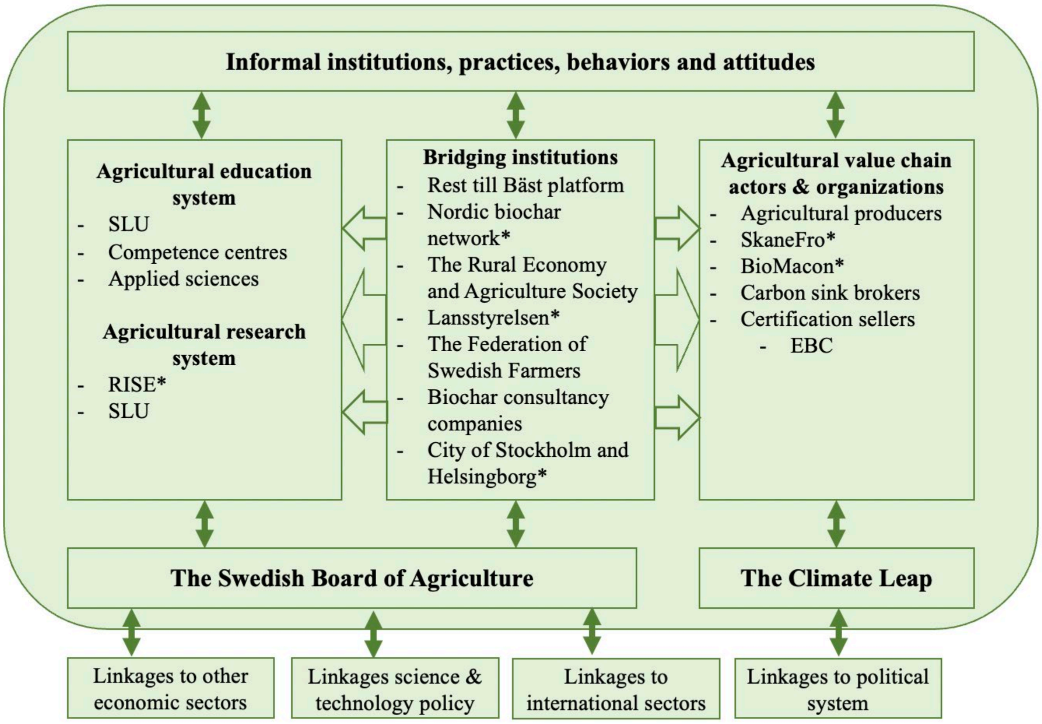

Figure 6. AIS of the agricultural biochar system in Sweden, stakeholders with a "" will be explained (own image).*

RISE (Research Institute of Sweden) is an independent state-owned research institute that aims to contribute to making society more sustainable through international collaboration with industry, academia, and the public sector. They worked on a project related to biochar in 2019-2021, called "Biomass to energy and biochar", with the purpose to increase the knowledge about available techniques to produce biochar, heat, and electricity at farms, and increase knowledge about the possible uses of biochar in agriculture.

The Nordic biochar network is a collaborative initiative from researchers from the Nordic countries that focuses on promoting the understanding and use of biochar technology.

Lansstyrelsen is a government agency that is responsible for implementing national policies at the regional level. In the interviews, their role in biochar is described as helping farmers with their applications for Klimatklivet funding. Also, as they function regionally, they play a role in guiding the government on where applications of biochar are most needed as they have connections to the local actors.

Municipalities were mentioned by multiple interviewees as important actors in the diffusion of biochar technology. For example, the City of Stockholm included in their guidelines that the soil used in municipalities should be enriched with biochar. The City of Helsingborg also has projects related to biochar and organized a seminar for multiple stakeholders about biochar.

On the value chain actors level, Biomacon is an important actor. Biomacon is a German company that specializes in the production of the biochar production plant that is most suitable for agricultural production. Another value chain actor is Skånefrö: a Swedish company that specializes in the production of seeds for agricultural production. One interviewee told that they have built one of the largest biochar production plants in Europe and are producing biochar in Skåne that can be used as a soil amendment. This is sold to individuals, companies, and municipalities.

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