THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Modeling the Potential for Carbon Removal in Agriculture: Integrating Farmer Perspectives

ANDREAS REHN

Department of Space, Earth, and Environment

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2023

Modeling the Potential for Carbon Removal in Agriculture:
Integrating Farmer Perspectives

ANDREAS REHN

Department of Space, Earth, and Environment
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000
www.chalmers.se

Cover: AI-generated illustration using DALL*E.
Search words include "1900s realism painter, Swedish agricultural landscape, fields of wheat and perennial ley, meadow, biodiversity, Anders Edelfelt"

Printed by Chalmers Digitaltryck
Gothenburg, Sweden 2023

Abstract

The overarching aim of this thesis is to provide insights into the dynamic processes governing SOC stocks and to identify viable paths for agricultural systems to contribute to climate change mitigation. By integrating current scientific knowledge of carbon sequestration in agriculture with feasible agricultural applications, this work proposes local realistic strategies for enhancing soil organic carbon (SOC) and presents a quantitative assessment of their potential for CO_2 removal. The thesis underlines the importance of considering both biophysical factors and farmer participation to ensure the successful implementation and permanence of any suggested climate mitigation strategies.

This thesis explores the potential of various agricultural techniques for enhanced SOC sequestration, in an agricultural landscape study site in central Sweden. It quantifies the carbon dioxide removal (CDR) potentials between various farming practices, together with the involvement of farmers. By analyzing updated databases and agricultural measures through two appended papers, this work provides insights that could inform policymakers and stakeholders in the process towards sustainable transition in agriculture and concretize climate change mitigation efforts.

Paper A investigates the relationship between crop rotational diversity, soil properties, and SOC content. Utilizing data from the Swedish Agricultural Soil Inventory and Swedish Integrated Administrative and Control System, this paper quantifies and analyzes the impact of temporary perennial leys on SOC stocks and the SOC/clay ratio—an indicator of soil structure quality. The findings suggest a significant positive correlation between perennial ley frequency in crop rotations and increased SOC content, underlining the importance of diverse crop sequences for SOC sequestration. Paper B expands on the findings of Paper A and utilizes the findings in an arable landscape setting. It specifically investigates three management practices—cover crops, increased perennial ley cultivation, and biochar production and application—from a landscape perspective, assessing their potential to enhance carbon sinks. A novel landscape model of arable land incorporating these practices was developed to simulate scenarios for CDR. The results highlight the efficacy of these strategies, with the potential for a combined carbon sequestration rate of 7.1 Mg C ha $^{-1}$ yr $^{-1}$ when maximizing ley crops, cover crops, and biochar application.

Keywords: Soil Organic Carbon (SOC), Carbon Dioxide Removal (CDR) Agricultural Practices, Crop Rotation, Perennial Ley Crops, Biochar, Landscape Modeling, Climate Change Mitigation, Stakeholder participation

Appended Publications

This thesis is based on the following papers:

Paper A A. Rehn, G. Berndes, C. Cederberg, E. Englund (2023). Combining continuous datasets on soil properties and land use to explore soil carbon changes and soil quality indicators
(Submitted Manuscript to European Journal of Soil Science (EJSS) 2023)

Paper B A. Rehn, G. Berndes, C. Cederberg, E. Englund (2023). Carbon removal potential in agricultural systems – Scenario-based model with suggested measures from farmer participation in Sweden
(Manuscript to be submitted to Carbon Management)

Author contributions

AR conceptualized the model framework and the model development, including main data analysis and data curation, with main conceptual support from BG and CC. AR led the data analysis and visualization with the support of OE. OE was the main supporting supervisor regarding data handling, software, and model development. CC and BG are the main supervisors in writing and conceptual development.

Paper A: introduces a method utilizing continuously updated geospatial datasets on soil and agricultural land use to assess the relationship between land use, particularly ley crop rotations, and SOC. By integrating 18 years of land use history, and monitoring changes in SOC and soil structure quality across Swedish agricultural fields, this study aims to increase our understanding of the impacts of land use and cultivated crops on SOC and soil structure quality.

Paper B: presents a model where the implementation of perennial ley, cover crops, and biochar production is introduced to an agricultural landscape in Sweden. This paper investigates the CDR potential of included carbon mitigation measures when introduced to current agriculture production systems (arable farms, dairy farms, beef farms, etc.) within the arable landscape. The analysis includes two scenarios where changes in cultivation measures are made based on farmers' participation in deciding viable measures, effectively creating a realistic model to quantify CDR potentials in agricultural landscapes.

Acknowledgments

I would like to thank all of the people at the Department of Physical Resource Theory at the Institution of Space, Earth, and Environment (SEE) at Chalmers. In one way or another, everybody in this department puts in the effort to make it an amazing place to work. It is the people who make the department, and I have a hard time imagining a better place to do my Ph.D. At times, when the Ph.D. journey is inevitably hard, frustrating, and tedious – there is always a laugh to be found, an un-serious discussion to be held or a drink to be had that can make any bad day into a brilliant one.
Thank you all!

Thanks to my supervisors, Christel Cederberg and Göran Berndes. Thank you both for all your support and for making it possible for me to take on this battle that is a Ph.D. You both have a great ability to teach knowledge useful in the role of a researcher, the tacit knowledge that is not only centered on the research field. There are so many things beyond the actual scientific work that is a struggle of a Ph.D., and you guys help me and support me quite a lot.
I am looking forward to the upcoming projects and papers together after this licentiate!

I would like to thank Oskar Englund for your support in modeling, Python, and conceptual understanding of how a model could be constructed. You are really fun to work with and support me in many ways beyond technical skills. I hope for more intensive meetings where we can dive into the nitty-gritty of Python codes together.

Thank you, Martin Persson – for reading, listening, and talking to me about this licentiate, and everything else regarding the doctoral studies process.

To my family. It is a real privilege to have your love and support. This book is the reason I haven't called for a while, sorry about that. However, I know you always have my back, and that you will support me in whatever I take on, for which I am forever grateful.

Emma. My person, and my biggest supporter. The outcome of this thesis would have been much worse – and far less fun to put together without you in my life.
I love you endlessly.

List of Abbreviations

SOC	-	Soil Organic Carbon
SOM	-	Soil Organic Matter
SCS	-	Soil Carbon Sequestration
CDR	-	Carbon Dioxide removal (Atmospheric carbon removal)
NPP	-	Net Primary Production
GHGs	-	Greenhouse gases: carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O)
LULUCF	-	Land Use, Land-Use-Change, and Forestry refer to a category in greenhouse gas inventories. It encompasses changes in biomass and soil carbon stocks, and CO_2 emissions from deforestation and degradation, primarily looking at how specific land-use changes can impact carbon storage and greenhouse gas emissions.
AFOLU	-	Agriculture, Forestry, and Other Land Use. This term is broader than LULUCF as it encompasses all activities related to land use, including agricultural and forestry practices, and is used in the context of climate change mitigation across all land uses, including agriculture.

Table of Content

Abstract i

Appended Publications iii

Acknowledgments v

List of Abbreviations vi

CHAPTER 1 1

Introduction 1

CHAPTER 2 3

Background 3

Soil, soil organic carbon, and soil carbon sequestration 3
Agriculture and CO_2 emissions 6
Climate mitigation measures in agricultural systems 8
Farmer participation –insights for realistic implementation 11
Databases utilized in this study 11

CHAPTER 3 13

Summary and Results from Appended Papers 13

Paper A - SOC sequestration potential in agriculture 13
Paper B - Carbon removal potential in agricultural systems: A model with suggested measures from farmer participation in Sweden 17

CHAPTER 4 25

Conclusion 25

CHAPTER 5 27

Outlook and Future Studies 27

References 29

CHAPTER 1

Introduction

The Paris Agreement aims to keep the global average temperature increase to well below 2°C compared to pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C. To limit global warming to 1.5°C, there is a need for rapid action to reduce greenhouse gas (GHG) emissions (IPCC, 2018). To achieve this goal, decreasing emissions is not believed to be fast enough, and active removal of CO_2 from the atmosphere is necessary, as highlighted in nearly all scenarios mentioned in the IPCC report. This is also true for many of the scenarios in limiting global warming to below 2°C (IPCC, WG1, 2021). Among known strategies for atmospheric CO_2 removal (CDR), implementing measures to increase SOC storage, i.e., soil carbon sequestration (SCS), has gained significant societal and scientific attention in recent years (Moinet *et al*., 2023). Soils contain large amounts of soil, particularly in SOC. There is a continuous exchange of carbon between the atmosphere and the organic carbon stored in soils. Anthropogenic land use changes have had and will continue to have a significant impact on atmospheric carbon dioxide (CO_2) concentrations through their impact on the soil carbon pool based on historically poor management strategies (Carey, 2023).

Measures that increase and protect current SOC stocks stand out as natural mitigation options associated with low cost and immediate deployment (Fuss *et al*., 2018; Paustian *et al*., 2019a). This is especially the case when comparing SCS with technically oriented negative emission technologies (NETs) – such as bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS) which are highly discussed strategies for climate mitigation, however rather expensive and time-consuming to implement. Soils under agricultural management cover approximately 45% of the ice-free land surface directly affected by anthropogenic activities (IPCC, 2019), and these are also the most carbon-depleted (Paustian *et al*., 2019b). Herein lies an opportunity and increased SOC storage in agricultural land is recognized by researchers and policymakers as a viable complementary method to other NETs for CDR (Rumpel *et al*., 2020). The IPCC's special report "Climate Change and Land" (IPCC, 2019) emphasizes the strong links between land use and climate, further articulating this connection.

In addition to climate change mitigation by CO_2 removal and subsequently enhancement of SOC storage, land use and management practices on agricultural land can provide benefits such as improved agroecosystem resilience, food security, and climate change adaptation (Smith *et al*., 2016; Sykes *et al*., 2020). A strong motivation for this thesis is to improve understanding of the crucial role that soils and soil carbon play in mitigating climate change, while also enhancing essential soil functions such as fertility and water retention (Dignac *et al*., 2017). Increasing SOC content has been linked to decreasing yield losses in unfavorable weather events, i.e., supporting a more resilient production (Droste *et al*., 2020). The role of soils and SOC stocks in natural climate solutions (NCS) further presents dual climate benefits: strategies can be implemented to increase SOC in carbon-depleted soils, while others can be used to protect existing SOC stocks (Bossio *et al*., 2020). However, even though there are known principles and practices that can sequester CO_2 from the atmosphere, the practical feasibility comes with challenges. Recent studies suggest that management practices should be site-specific based on both current agricultural practices and farmers' willingness to implement changed actions, as well as pedoclimatic factors, such as clay content, temperature, and precipitation as well as soil pH (Büchi *et al*., 2022).

Soils SOC storage and therefore its CDR potentials vary between agricultural systems (Henryson *et al*., 2022), what the motivating factors behind implementing mitigation measures are (Farstad *et al*., 2022), and how the practice affects the soil structure quality (Mattila *et al*., 2022). Farmers' decisions on land-use change are complex and include a multitude of considerations such as private economy, food market, and crop insurance (Paustian *et al*., 2019a). To this, social and cultural values and institutions are highly important to acknowledge when suggesting changes in an agricultural system (Davidson *et al*., 2016). This complexity adds many dimensions to the issue of how a transition can be suggested and performed in an arable landscape to create a sustainable CDR potential. Even though management principles are highly important, unmanageable pedoclimatic factors such as silt and clay content are site-specific key factors for carbon stabilization and long-term permanence (Büchi *et al*., 2022; Wiesmeier *et al*., 2019). It is therefore important to acknowledge these factors in any attempts to understand the transition of agricultural practices in attempting to increase CDR potentials. Including important soil metrics, such as SOC and SOC/clay ratio (Johannes *et al*., 2017; EU Commission, 2023), knowledge about land use history and initial SOC content (Rehn *et al*., 2023), as well as farmers´ perspectives (Paustian *et al*., 2019a) are important to implement a long-lasting sustainable transition in agriculture. Ignoring these aspects in climate mitigation policies in agriculture may hinder the successful deployment of a climate mitigation strategy.

The first step in understanding the CDR potential in various agricultural practices is to understand the initial starting point of the soil, the baseline at which measure(s) can be implemented. This involves understanding important aspects such as land use and cultivation systems, and soil properties such as clay and SOC content. Due to the spatial heterogeneity in arable soils´ SOC content, many soil samples are usually required to quantify and verify changes in SOC content at the individual farm site. This thesis proposes a landscape modeling approach to incorporate soil metrics while considering farmers´ interest and willingness to adopt CDR mitigation strategies.

The aim of this thesis can be summarized into three main research questions: How can existing continuously updated datasets be utilized to better understand SOC stock dynamics in arable land? How can agricultural production systems change to sequester more atmospheric carbon? What would be the quantitative result of a feasible transition in terms of removed CO_2? With these central questions, the two papers included in this licentiate aim to contribute valuable insights and showcase the effect of suggested measures. By quantifying the CDR potential across various farming practices, this work contributes to insights towards a sustainable transition of agriculture.

Thesis disposition

Following this introduction, the thesis will proceed with Chapter 2, which provides an overview of agriculture and its greenhouse gas (GHG) emissions, carbon sequestration, CO_2 removal (CDR), and soil organic carbon (SOC). Chapter 3 will then go deeper into the foundation of this thesis by summarizing the two included papers. This chapter will thoroughly outline the methodology and modeling framework utilized in both papers and discuss their limitations. Chapter 4 will offer a conclusion and the contributions of this thesis and Chapter 5 finally presents an outlook and future work.

CHAPTER 2

Background

This section of the thesis aims to provide the background knowledge needed to comprehend the main themes. It contains a review of crucial topics concerning soil, soil organic carbon, climate mitigation strategies in agricultural systems, sources and databases used, and measures that can enhance soil carbon content. Each of these subjects is covered in separate sections and provides essential information related to the investigation and analysis of increasing atmospheric carbon removal in arable land in Sweden, as presented in papers A and B.

Soil, soil organic carbon, and soil carbon sequestration

Soils are formed through several intricate processes, including weathering of parent rocks, deposition of organic matter, and interaction with living organisms. The composition of the soil influences its texture, structure, pH, and nutrient availability, which in turn affects the types of plants and animals that can inhabit the area (SGU, 2023). Beyond this, soils provide vital ecological functions, such as water retention and filtration, along with carbon storage (Wiesmeier *et al*., 2019). Soil derives its fertility from both atmospheric sources, such as carbon dioxide (CO_2), and nitrogen (N), as well as geological sources, such as phosphorus (P), potassium (K), and minor and trace nutrients (Sposito, 2008). Due to inadequate attention to soils and intensive management practices, soil degradation occurs as a result of diminished soil fertility, and one of the key elements upholding a soil's fertility is soil organic carbon (Mosier *et al*., 2021).

Diverse soil types are created from different parent materials and therefore consist of various minerals. This mineralogical constitution, inherently rooted in its parent material, greatly impacts the abundance of mineral surfaces available, which directly correlates with the stabilization of carbon in soils. Specifically, this variability dictates the type and concentration of iron-oxide and clay minerals present, both of which play critical roles in the physical (Paul *et al*., 2023) and chemical stabilization mechanisms of carbon (Angst *et al*., 2021). While the influence of mineralogy on carbon stability is undeniable, quantifying the exact mineral content is both labor-intensive and costly. That is one of the reasons clay contents are used to the extent it is – soils rich in clay, characterized by a high specific surface area, can be robust reservoirs for SOC storage (Wiesmeier *et al*., 2019).

Soil organic carbon is a part of soil organic matter (SOM) which comprises litter, microorganisms, microbial, and root exudates. SOC specifically refers to the carbon content within the SOM. SOC is dynamic and a crucial aspect of soil health, with microorganisms playing a key role in maintaining its stability and permeability. One of the main reasons for SOC loss is the decomposition of organic matter, which is primarily carried out by microorganisms. As these microorganisms break down organic matter, they release carbon in the form of CO_2 back into the atmosphere, contributing to the loss of SOC (Tao *et al*., 2023). From sustainable ecosystem services (ES) to influencing soil properties, SOC forms the backbone of soil health and is closely linked to essential soil attributes, and frequently serves as an indicator of sound soil quality and function (Büchi *et al*., 2022; Johannes *et al*., 2017; Wiesmeier *et al*., 2019).

There is a vast amount of organic carbon in the soil. Soil contains large amounts of SOC, around 1700 Gt C down to 1 m (Friedlingstein *et al*., 2022) (Figure 1). This exceeds the total mass of carbon in both the atmosphere and vegetation put together and 160 times as much as the current annual rate of anthropogenic CO_2 emissions (Friedlingstein *et al*., 2022). Even though known estimates of soil carbon stocks are associated with uncertainty, the immense reservoir of carbon exists in both inorganic and organic forms and has multifaceted and important roles in the ecosystem. The inorganic carbon, which is not further discussed in this thesis is formed of primary or lithogenic parent material weathering secondary carbonates and pedogenic processes (Lal, 2023). Soil organic carbon is influenced not only by land use and management but also by the properties of the soil itself, especially its fine fraction content (clay, silt). Hence, understanding the interplay between these factors is essential for effective soil management.

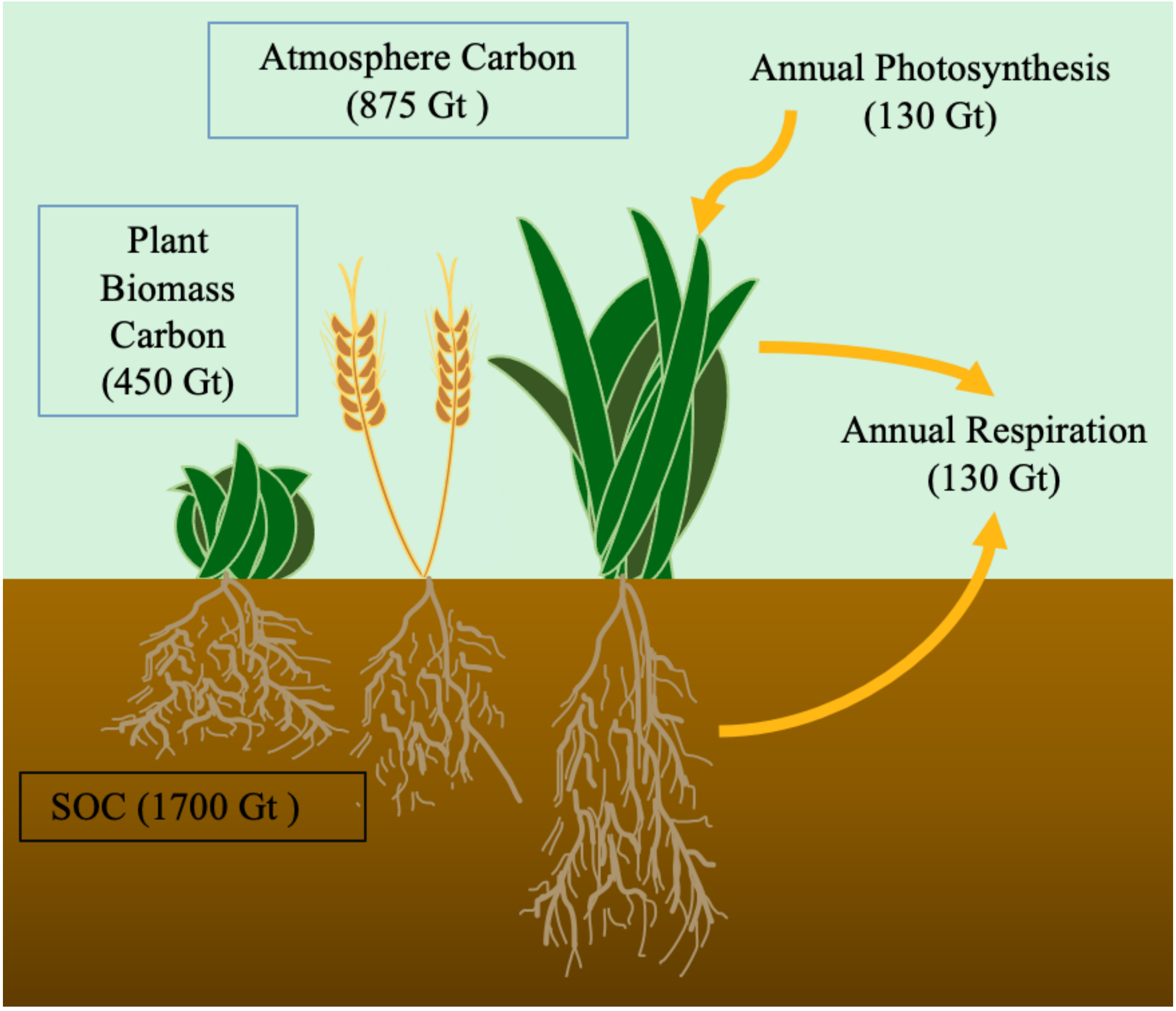

Figure 1. Schematic illustration of carbon stocks (Gt C) and annual flow of photosynthesis (sequestration) and respiration from plant biomass Carbon (Gt C /y). Data is combined from (Friedlingstein et al.*, 2022).*

The interaction of mineral surfaces is a major mechanism for stabilizing carbon within organic matter, establishing a clear connection to SOC storage. This interaction serves as a crucial factor in SOC storage, reflecting the importance of understanding soil properties in addition to land management (Wiesmeier *et al*., 2019). Because the mineral surfaces are a major stabilizing mechanism or SOC, the amount of fine fraction (clay and silt) materials in soils are important.

Built on this, – clay in relation to SOC content has started to be used as a soil quality indicator. Many experts have included the content of clay as a covariable when studying the impact of soil components on soil physical properties since a considerable amount of soil organic carbon is bound to clay minerals (Johannes *et al*., 2017: Prout *et al*., 2021).

One way this is done is to look at the ratio of SOC/ Clay and to classify soil samples according to that ratio at different thresholds. In a study on Swiss soils, Johannes *et al* (2017) developed thresholds of 1/8 as a field optimum for 'Very good structure quality, between 1/8 and 1/10 as "good structure quality", 1/10 as 'improvements suggested' and 1/13 as a threshold below which the 'structure quality is most likely unacceptable and in need for improvement' (Johannes *et al*., 2017). These thresholds were further implemented in a larger study in England and Wales by Prout *et al*., 2021), and the interest in using SOC/clay ratio to better understand soil structural quality in agricultural soils is receiving more interest. In 2023, the European Commission presented a proposal for a directive on soil monitoring. Here, the SOC/clay ratio is considered as a criterion for healthy mineral soils (threshold 1/13 as Degraded) to measure the extent of soil degradation (EU Commission, 2023).

The act of increasing SOC in soils is referred to as soil carbon sequestration (SCS). It is often regarded as an efficient and relatively inexpensive option for CDR and can be defined as the net uptake of CO_2 from the atmosphere into the soil of a land unit via plant photosynthesis and other organic solids, increasing SOC storage (Keel *et al*., 2023; Olson *et al*., 2014). Whether increased carbon storage results in SCS and consequently leads to negative emissions, hinges on the current land use, SOC content, and management specific to a location. The carbon inputs needed to maintain the soil in a steady state are proportional to the initial SOC stock, and subsequently, the annual change of SOC stock. A boost in carbon storage following a management shift aids climate change mitigation either through genuine SCS or by mitigating the SOC loss that would occur without the implemented change (Kätterer & Bolinder, 2023).

The potential to increase SOC stock in agricultural land begins with net primary production (NPP), the conversion of carbon fixed by photosynthesis into biomass. The proportion of this carbon that enters the soil influences its SOC balance and depends on various factors, such as crop type, management strategies, and carbon retention in the field (Kätterer & Bolinder, 2023). The permanence of carbon in the soil, controlling how long existing carbon can remain stable, is a critical aspect. The carbon needs to be stabilized to ensure long-term carbon storage, and if climate change mitigation by removal of atmospheric carbon is the goal – then the removal should be permanent which SOC pools are not (Paul *et al*., 2023). To preserve soil carbon levels without depletion, continuous inputs, and proper management practices are essential for effective control.

Carbon content in soils is often referred to as being stored in different pools. The pool analogy is often used to depict the decomposition kinetics of the carbon existing in fast turnover pools and slow turnover pools with higher permeance (Zacháry *et al*., 2023). These pools, with varying permanence, are influenced by numerous factors, both manageable and unmanageable. The permanence of these pools is diverse and depends on many factors, most importantly unmanageable pedoclimatic factors such as clay content, temperature, and precipitation (Büchi *et al*., 2022), where silt and clay are found to represent the key factors (Wiesmeier *et al*., 2019) as stabilizing mechanisms protecting the carbon from mineralization.

The soil's carbon balance is a delicate equilibrium between inputs of organic carbon from photosynthesis, governed by farming practices, including rhizodeposition from plant roots, harvest residues, and organic amendments like manure (Kätterer & Bolinder, 2023) — and outputs from the loss of carbon as CO_2 or CH_4 due to the biotic metabolism of accumulated carbon (Janzen *et al*., 2022). The balance of carbon is controlled by these opposed processes and even if SOC levels are to remain the same or increase – the carbon always needs to be refilled by inputs (Paul *et al*., 2023).

It is foremost in the input of carbon where suggested mitigation measures can have a significant impact, as the output of carbon is controlled by regional pedoclimatic conditions, such as soil texture and weather, which are harder to manage (Kätterer *et al*., 2012; Büchi *et al*.,2022).

Agriculture and CO_2 emissions

It is estimated that the global agricultural soils have lost about 135 Pg carbon from the SOC stock since agriculture was born 12,000 years ago (Carey, 2023), and the rate of this loss has intensified dramatically in the past 200 years (Sanderman *et al*., 2017: Lal, 2023). The current rate of SOC stock loss is still significant, estimated to be about 21.80± 0.91 g C m^{-2} $year^{-1}$ (Abdalla *et al*., 2020). Depletion of SOC stocks, especially when the carbon content in soils becomes low (1.5 – 2% C by weight in the root zone), is the main driver of soil degradation, subsequently hurting the soil's capacity to provide ecosystem services (Lal, 2023). Ecosystem services, or ES, could be defined as the benefits, both physical and non-physical, that humans obtain from ecosystems (MEA, 2005). Within the context of agricultural land, these ESs include supporting services such as nutrient cycling, soil structure and fertility, water quality, biodiversity, and carbon sequestration, as well as cultural services like recreational purposes (Vidaller & Dutoit, 2022). Additionally, agricultural land – or rather, agroecosystems – provides provisioning services such as food, water, and bioenergy (Power, 2010). These ecosystem services are of critical importance for humans, as they directly affect food security and are therefore essential for human welfare.

By continuing to degrade the world's soils, e.g., by ongoing depletion of SOC stocks, these supporting and provisioning ES are put at risk, jeopardizing not only ecological stability but also social and economic well-being. Soils and their carbon content are central to supporting vital ecosystem functions, delivering benefits that sustain and enhance our environment (Berryman *et al*., 2020). SOC content in the soils benefits the entire system and its many vital ecological functions (Mosier *et al*., 2021) and should therefore be acknowledged in agricultural strategies. To address these multifaceted challenges, it becomes vital to integrate ecosystem-based strategies with practical farm practices to develop resilient farming systems (Rockström *et al*., 2017). Healthy soils and sustainable agriculture are not only important for climate change mitigation but also for the future of farming and food security for humans.

It is well-established that the agricultural sector is considered a major source of GHG emissions and subsequently a significant contributor to anthropogenic global warming (IPCC, 2018; Lynch *et al*., 2021; Springmann *et al*., 2018). Agriculture and land use emit carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) as the largest global warming contributors and the sector is responsible for 23 % of annual anthropogenic net GHG emissions (Agriculture, Forestry, and Other Land Use (AFOLU)) (IPCC, 2019).

Sweden's agricultural sector was responsible for 6.9 Mt of Mt CO_2-e greenhouse gas (GHG) emissions (2021), which is equal to 15% of the total territorial emission (Naturvårdsverket, 2022). These emissions are largely from methane and nitrous oxide released by livestock digestion and manure management. Nearly half (49%) of these emissions stem from agricultural lands, with a significant portion due to nitrous oxide released during manure application to fields. Land use activities associated with agriculture (within the Land Use, Land-Use-Change, and Forestry (LULUCF) specifically on arable land and pastures, contributed to 3.1 Mt CO_2-e emissions in 2020, predominantly from organogenic soils on arable lands (Naturvårdsverket, 2022).

One way to mitigate the large emissions attributed to the agriculture and land use sector is to protect and potentially increase SOC stocks in agricultural land. With management changes, SCS could be accomplished (Kätterer & Bolinder, 2023) or at least mitigate the SOC loss of already depleted soils. Arable soils that are deemed depleted are so compared to their pre-agricultural state, indicating a potential that SOC stocks can be increased if managed properly (Lal, 2015). A current and ongoing threat to agriculture systems is poor management practices, causing SOC depletion (Edlinger *et al*., 2023: Keel *et al*., 2019). To this, global warming might have an intensifying effect on SOC depletion as it causes an acceleration of SOC decomposition in the upper soil layer (Crowther *et al*., 2016; Wiesmeier *et al*., 2019). However, the SOC in mineral arable soils in Sweden is increasing, and analysis of Swedish mineral soils indicates that the content of organic matter experienced an average increase of 7.7% nationwide over roughly two decades (Poeplau *et al*., 2015). This translates to net sequestration ranging from 1 to 2 million tons of CO_2 annually (Bolinder *et al*., 2018). One reason for this substantial net sequestration could be explained by the strong increase in ley cultivation observed over the past three decades. During this period, the population of horses has more than doubled, which likely drives the heightened demand for ley, and subsequent SOC stocks (Poeplau *et al*., 2015).

Agriculture is not only a great contributor to GHG emissions and thus climate change but also stands as one of the sectors at the highest risk of negative impacts (Tubiello *et al*., 2022). With global warming comes increased environmental variability and with it an increased risk to agricultural systems which can have repercussions on food supply and the associated supply chains at various scales, from local to global. Characterized by increased warming, altered precipitation patterns, spikes in humidity (Shah *et al*., 2021) as well as fluctuations in drought and temperature, climate change has accelerated soil degradation in regions where soils are increasingly exposed to these factors (IPCC, 2019). Increased environmental variability introduces a higher risk of food insecurity, especially when there are limited available substitutes or alternative sources (Davis *et al*., 2021). In Sweden, the large impact of drought was strikingly evident in the summer of 2018. During this period, the total cereal harvest was drastically reduced, registering 43% lower than the average of the preceding five years (Jordbruksverket, 2018).

Mitigating strategies at the production level i.e., on farms and fields, involves focusing on enhancing farms' resilience, ensuring they can produce sufficient quantities of quality food despite the challenges posed by environmental variability (Davis *et al*., 2021) Strategies may include adopting sustainable farming practices, and aligning with local ecological conditions to create a more adaptable and robust agricultural system. The connection between environmental stability and food security emphasizes the importance of careful resource management and sustainable practices within the agricultural sector. Ultimately, one essential element in accelerating the transition of food systems toward desired, sustainable states is fostering societal dialogue (Herrero *et al*., 2020). Including farmers and local stakeholders early on in research about agricultural transition can help to bridge the implementation challenges and enable sustainable transition pathways. The link between agriculture, climate change, and soil degradation is a pressing and important topic.

The depletion of SOC stocks and the role of agriculture in GHG emissions call for immediate, sustainable measures. By embracing soil-improving practices and collaborative efforts, a sustainable transition in agriculture can be performed and resilient farming systems can be developed to meet global needs without further harm to agroecosystems vital services or food security.

Climate mitigation measures in agricultural systems

In agricultural land, various carbon sequestration practices are discussed in the context of climate mitigation strategies, and one example of this is to increase SOC content in cultivated arable land. These measures include perennial ley cultivation in the crop rotation, cover crops, agroforestry cultivation, and increasing the share high yielding - cereal crops (Naturvårdsverket, 2022) as well as management strategies like using organic amendments (e.g., manure), 'no-tilling' practice and producing and using biochar (Poeplau & Don, 2015; Paul *et al* 2023; Kätterer & Bolinder 2023). Land use management practices have a significant impact on the storage of soil organic carbon (SOC), and one influential factor is the diversity of crop rotations (Wiesmeier *et al*., 2019).

However, the unique characteristics of agricultural fields, such as location, climate, and soil type are important in determining soil properties. This emphasizes the need to identify and consider the main parameters that influence soil quality at field sites as specific as possible to guide management decisions and enhance soil functionality in agriculture (Büchi *et al*., 2022). Many previous studies have investigated the SOC dynamics and the main drivers of SOC storage, as well as viable practices to increase SOC storage as a climate mitigation option (Paustian *et al*., 2019b). Increased SOC storage has also been shown to increase yields as found in an over five-decade long-term field trial (LTE) in Sweden (Droste *et al*., 2020) even though any effect should be regarded as context-dependent (Moinet *et al*., 2023).

Quantifying different measures´ effects on SCS can be challenging as they are influenced not only by management principles but also by uncontrollable pedoclimatic conditions. Estimations of SCS effect from different crops or cultivations can be performed in multiple ways and many studies have attempted to estimate the amount of carbon that can be sequestered in soil organic matter, fixed by photosynthesis (Kätterer *et al*., 2011; Poeplau *et al*., 2015; Bolinder *et al*., 2020). One tool that can be used for this is carbon allocation coefficients to estimate the carbon input effect of different plant parts based on measured crop yields as seen in Bolinder *et al*. (2007). This method is often combined with empirical data and estimations to model SOC effects over time, which is subsequently associated with great uncertainties (Keel *et al*., 2017). To investigate the real change in SOC storage over time, studies using long-term field trials (LTEs) can be used. In these, carbon input is controlled over extended periods to analyze the impact of each applied measure, making them highly suitable for understanding the effects of agricultural management in the short and long term (Kätterer *et al*., 2011). It should however be noted that any effect of measures expressed in an amount of carbon sequestered annually comes with high uncertainty and there is a need for estimations and equations that are adapted to local crop types and agricultural practices (Keel *et al*., 2017).

By including a higher variety of crops that offer complementary effects with deeper root systems, different growth seasons, and soil coverage, agriculture systems can enhance soil carbon levels (Wiesmeier *et al*., 2019; Paul *et al*., 2023). The positive effect of ley farming for carbon storage is well known and well investigated.

In a comparison with crop rotations solely composed of annual cultivars, it has been demonstrated that a higher share of ley within the crop rotation directly correlates with increasing SOC stocks (Bolinder *et al*., 2020). A (2013) large meta-study by Kätterer *et al*. covering 5 countries and 8 publications, found that arable systems with perennial leys in crop rotation retained an average of 0.52 Mg C ha^{-1} (range 0.3–1.1 Mg C ha^{-1} $year^{-1}$) more carbon in soils than cropping systems with only annual crops.

One of the reasons behind this is that perennial ley crops allocate more of their net primary production in below-ground (BG) residues compared to annual crops (Bolinder *et al*., 2007), and root-derived carbon has been found to contribute more to stable soil carbon pools than above ground residues (Ghafoor *et al*., 2017). Historically, annual plants have been selectively bred to allocate their resources toward seed production. In contrast, perennial species necessitate substantial investment in their root system as a survival strategy to endure winter conditions, effectively leading to more below-ground biomass subsequently increasing carbon stock. This implies that ley significantly enhances BG carbon content since root-derived carbon contributes more to the stable SOC pool than above-ground additions (Kätterer *et al*., 2011). It has also been found that the inclusion of legumes and canola in wheat production crop rotations has the potential to increase the SOC stock (He *et al*., 2021).

The schematic illustration (Figure 2) depicts the carbon dynamics of arable lands planted with perennial ley or with a cereal crop. On one side, wheat, for example, a typical cereal and food crop, has a relatively smaller root system. This means that less BG carbon is returned to the soil (in comparison with a ley crop) and this can result in a reduced SOC stock. Conversely, perennial crops such as leys, with more extensive root systems, return relatively more BG carbon to the soil. This enhancement in root biomass can contribute to securing higher SOC stocks, emphasizing the potential of perennial crops in carbon sequestration, and mitigating atmospheric CO_2 levels.

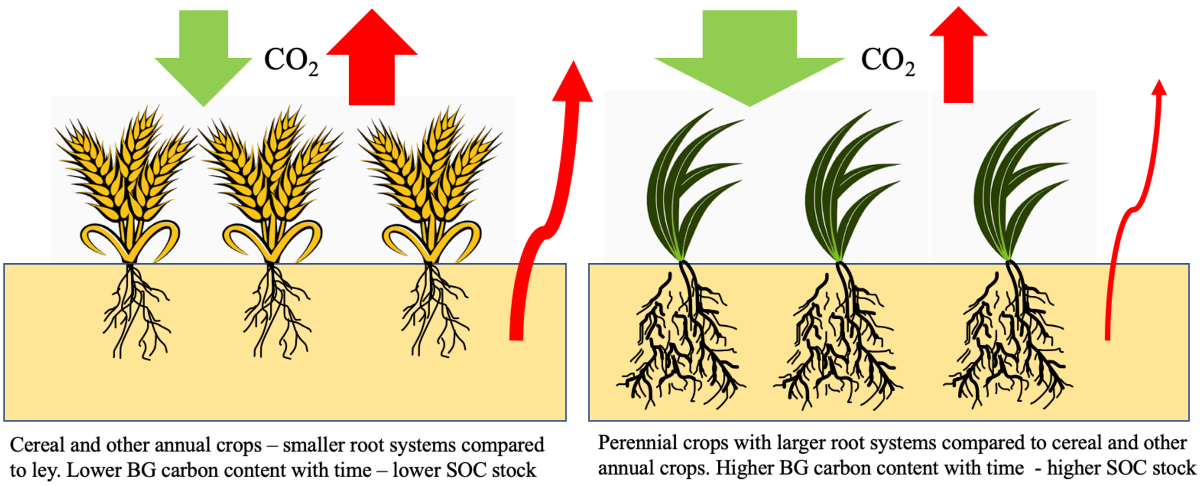

Figure 2. Schematic illustration of two cases of agricultural fields - single cereal cropping system and perennial ley, showing that perennial ley has larger root systems which generates a higher amount of carbon in the soil.

Supported by a collection of results from long-term field experiments in Sweden and other countries with similar soil and weather conditions, perennial ley within arable cropping systems has been shown to capture about 0.52 Mg C ha^{-1} in topsoils compared to crop rotations solely with annual crops (Kätterer et al., 2013). To this, there are secondary benefits possible with introducing a higher share of perennial ley and grasses in cereal-dominated crop rotations. For instance, increased profits as crop yields increase while the use of fertilizers and pesticides decrease (Tidåker *et al*., 2016), and the potential of generating new innovative production options through green biorefineries that can produce high-quality protein and biobased fuels and materials (Yilmaz Balaman *et al*., 2023).

Besides the implementation of perennial leys in crop rotation, other measures have been found to have a significant impact on soil carbon storage. The efficacy of cover crops in sequestering carbon is observed to be approximately half that of ley cultivation, translating to around 0.3 tons of carbon ha $^{-1}$ year $^{-1}$. This finding has been corroborated by both Swedish experiments (Poeplau *et al*., 2015) and international trials (Bolinder *et al*., 2020).

A management strategy that has been discussed in the discourse of agriculture and climate mitigation is "no – tilling". However, this is not further included in this thesis as an extensive body of long-term experimental evidence indicates that, on average, there are no differences in the total carbon reserves between parcels that have been subjected to plowing and those that remain unplowed (Meurer *et al*., 2018). The importance of nitrogen in increasing carbon stocks must not be forgotten. Nitrogen has the potential to aid SOC stock increase with 1-2 kg of carbon for every kg of nitrogen applied in fertilizers (Kätterer et a., 2012). In terms of sequestration rate, nitrogen fertilization treatments have shown carbon stock increase in the range of 197 to 480 k C ha^{-1} year^{-1} (Bolinder *et al*., 2020).

In this thesis, nitrogen fertilization is not included as a climate mitigation measure. While nitrogen can be introduced via manure and mineral fertilizers, it's worth noting that fertilization is already a prevalent practice in many arable fields and is possibly hard to increase. Therefore, the application of nitrogen is not deemed an uncommon approach (Bolinder *et al*., 2020) and, thus, is not viewed as a measure to be implemented since it's an established technology.

Biochar has become more studied in the past years as a valid amendment to agricultural fields as well as a climate mitigation measure. Biochar is a carbon-dense byproduct obtained through the heating process of biomass, including materials like wood, manure, and plant residues in a confined environment where air availability is minimized or nearly absent (Lehmann & Joseph, 2009). The production method, called pyrolysis, is vital to the quality of the biochar. Higher temperature pyrolysis increases carbon content, while lower temperatures enhance porosity and adsorption capacity (Sun *et al*., 2017). The incorporation of biochar into agricultural soils enhances carbon sequestration by introducing organic matter that exhibits high resistance to microbial degradation (Paul *et al*., 2023). Biochar added to soils contributes to soil carbon sequestration due to its high carbon content and high recalcitrance, offering a long-term sink of carbon in the soil (Sykes *et al*., 2020). Given that biochar can be synthesized from basically any carbon-based organic material such as agricultural by-products (Das *et al*., 2021), it easily integrates into agricultural systems as a soil amendment.

Beyond its inherent capability as a durable carbon sink, biochar presents potential for comprehensive improvements when applied to agricultural land. These improvements include but are not limited to, strengthening water retention capacities, improving soil structure and stability, and reducing the reliance on synthetic fertilizers (Allohverdi *et al*., 2021). This highlights the dual capacity of biochar as a highly stable carbon sink and as a soil amendment with additional soil structure quality benefits. There is still an existing knowledge gap in the exact long-term climate effects of biochar due to the unknowns about its persistence in agroecosystems (Nepal *et al*., 2023). The impacts of biochar, beyond its capacity as a carbon sink, should be understood as site-specific. They can vary based on regional factors such as climate and soil type. These variations can significantly influence the positive benefits of biochar when used as a soil amendment (Tsolis & Barouchas, 2023). Further research is essential to quantify the potential of biochar specifically for Nordic countries.

Farmer participation –insights for realistic implementation

While prior research examines soil carbon measures and stability, it often neglects realistic scenarios that account for farmer and stakeholder implementation potential and willingness. As mentioned earlier – SCS and increasing SOC stocks are not a one-time effort with permanent carbon sequestration results, it requires on-going management. Climate mitigation measures to increase SOC stock needs to be upheld for a long time, thus requiring a sustainable transition. This highlights the importance to include farmers and stakeholders in the process of decision-making for suggested measures. Land use decisions are influenced by a wide collection of complex factors, including considerations about farmers´ private economy, the food market, crop decisions and social considerations (Paustian *et al*., 2019a; Paul *et al*., 2023). To mitigate climate change through changing land management, a comprehensive understanding and consideration of the cultural, political, and socioeconomic contexts is essential (Paustian *et al*., 2016). Therefore, to suggest measures and mitigation strategies that are long-term sustainable, deployed strategies need to account for many aspects of the area – one being the farmers themselves and their willingness to participate in a change.

According to a recent study in Norway, the motivation behind implementing climate mitigation measures on farms is mainly driven by factors such as farm economy, time, and the prospect of farm continuation, rather than climate awareness. The study also found that climate mitigation measures are recognized and appreciated for offering additional benefits to the farm besides climate change mitigation (Farstad *et al*., 2022). In a Finnish study, results showed that farmers were likely to choose agricultural methods and measures that have co-benefits besides carbon sequestration, especially enhancement of soil structure (Mattila *et al*., 2022). In Sweden, a study by Henryson *et al*. (2022) revealed that farms associated with dairy production have more significant increase in SOC stock compared to those focused on arable, pig, or beef farming. This suggests that the potential for SCR varies depending on agricultural production system and accordingly, a farm's primary agricultural focus must be considered when finding the most effective measures for that particular setting. This highlights the importance of including farmers' opinions regarding what measures they see fit in their farming system. Possibly the best choice of measurements could align with a farm's operational direction to have a higher success of being implemented. Simply put, to be effective and long-term sustainable, deployed strategies need to account for farmers' decision-making processes and SOC dynamics. If a climate mitigation strategy shows high sequestration potential but is not deployed, it is not a good strategy.

Databases utilized in this study

Swedish Agricultural Soil Inventory (SASI)

SASI was initiated in 1988 with the primary aim of monitoring soil conditions across Sweden. Designed to ensure a comprehensive understanding of the nation's soil health, SASI periodically collects topsoil samples from a broad selection of agricultural fields (Figure 3). The emphasis is on achieving a representative sampling, especially from areas with a high concentration of arable land. While the program has seen three campaigns, the two campaigns from 2001-2007 and 2011-2017 are notable and especially useful in GIS-based investigation for providing exact geographical data, and subsequently enabling rigorous geospatial analyses.

The SASI database encompasses a variety of soil metrics, from soil fractions and pH to micro-element content. Specifically for researchers, it offers a broad view of the nation's soil health. Currently, the fourth sampling campaign is underway, and the complete sampling dataset will be finished in 2027, thus enabling an even longer time series that can be used to quantify SOC changes and other soil metrics. See https://miljodata.slu.se/mvm/aker for data availability. This is an open-source database with freely available information.

Integrated Administrative and Control System (IACS) Database

As a cornerstone of the EU's Common Agricultural Policy (CAP) (Eurostat, 2015), the IACS database is instrumental in streamlining agricultural practices across the European Union. It provides granular spatial data regarding the specific crops cultivated across member states. Each entry in the database may pertain to an individual or multiple land parcels. The underlying objective of IACS is to standardize agricultural subsidy distribution across the EU. To maintain transparency and accountability, farmers are mandated to report their annual cultivation practices. Additionally, random audits ensure adherence to the guidelines. While access protocols for the IACS database might differ across EU nations, in Sweden, national institution-affiliated researchers can readily access it. The broad applications of the database range from land-use categorization to satellite-assisted crop type identification.

Agricultural Yield Statistics

Central to understanding agricultural trends in Sweden, yield statistics offer an annual overview of the nation's agricultural output (Jordbruksverket, 2023). This database provides insights into crop and harvest metrics on an annual basis covering all arable land in Sweden. The available harvest data are given at national and regional levels, often using eight production regions in Sweden (Figure 3). The evolution of data collection has seen the inclusion of online submissions since 2005, offering a more streamlined approach to gathering data. At its core, the database aids in calculating farm-level yields and provides detailed regional data that can be instrumental in agricultural strategy formulation.

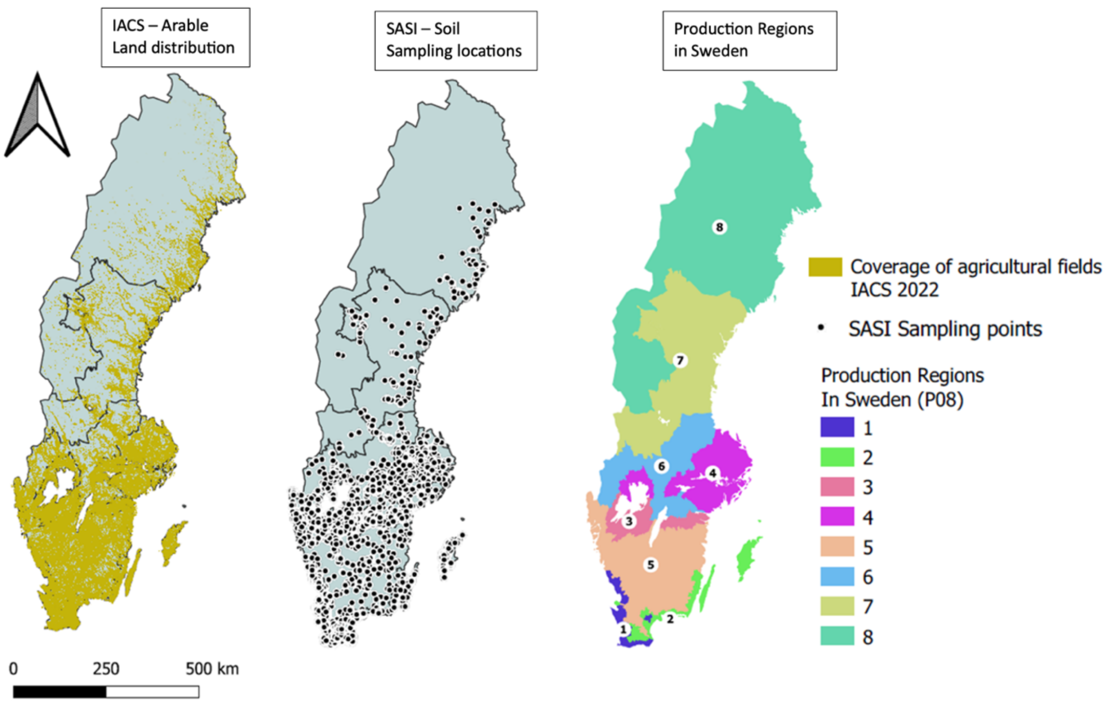

Figure 3. Three illustrations of Sweden including the coverage of the IACS fields, the sampling points included in the SASI sampling program, and the production region's location and size.

CHAPTER 3

Summary and Results from Appended Papers

Paper A - SOC sequestration potential in agriculture

Motivation and aim

Crop rotational diversity and specific soil properties, particularly clay content, play a crucial role in influencing SOC stocks, as highlighted in studies by Hedlund *et al*., (2021) and Wiesmeier *et al*. (2019). The capacity for SOC storage is intrinsically linked to these soil properties. The content of fine soil fractions, especially clay, is known to be a reliable indicator of SOC storage capacity. This is due to the interaction between organic matter and mineral surfaces, which serves as a primary mechanism for carbon stabilization (Wiesmeier *et al*., 2019). This study presents a novel approach to studying the relationship between specific crop sequences over years with various degrees of temporary leys, SOC contents, and the SOC/clay ratio as an indicator of soil structural quality within the Swedish context.

To do this, this study integrates data from the Swedish Agricultural Soil Inventory (SASI) with cultivated crop information from the Swedish Integrated Administrative and Control System (IACS) database where the latter consists of land use history of field-specific crop cultivation spanning 18 years. It includes insights into the usage of ley crops in rotations and the associated variations in SOC, SOC stock, and soil structural quality for individual agricultural plots across Sweden. This method combines geospatial data on soil properties with agricultural land use history. By employing soil sample data from SASI and crop rotation information from the IACS database, the study examines the correlation between specific crop sequences over the years, varying extents of temporary leys, SOC concentrations, and the SOC/clay ratio as a measure of soil structural integrity.

The objective of Paper A is to advance knowledge about changing SOC storage and to offer insights into how SOC/Clay ratio can be used as a relevant soil quality indicator, beneficial in choosing location and type of climate mitigation practices. The study presents a new method for using continuously updated geospatial datasets on soil properties and agricultural land. It investigates how the frequency of temporary grass-clover perennial ley crops in rotations with annual crops affects the SOC contents and subsequently the SOC/clay ratio index. By deepening our understanding of the variables that influence SOC storage, this study provides more targeted and effective strategies for sustainable land management. The methodology introduced in this paper offers insights into the influence of land use and its historical frequency of perennial ley crops in rotations, SOC, and soil structural quality and enables recurring studies to monitor the development over time.

Data analysis and spatial operations

We identified the land use history for agricultural fields from the IACS dataset between 2003 and 2020 (18 years of field-specific cultivated crops) by creating a spatial polygon dataset. We combined this dataset with SASI data to associate soil sampling data from two sampling campaigns with corresponding field polygons. The dataset contains a wide range of information about soil fractions, SOC, pH, and total N.

The two sampling campaigns, with a ten-year interval between them, are referred to as S1 and S2, and were limited to include mineral soils below 7% SOC content. This study included 1607 sampling points.

Crops for each year and field polygon were identified and categorized into four larger groups: ley crops, cereals, rapeseed, and other crops, which make up approximately 88% of arable land. Based on the field-specific land use history of crops cultivated, we determined how many times each crop group was cultivated on each field and translated ley cultivation into six "ley frequency" groups. The SASI dataset lacks soil bulk density information, which is crucial for determining SOC stocks. Estimations of soil bulk density were instead based on linear models from central and southern regions of Sweden. The method developed in this paper thus integrates two databases of land use history crops cultivated, and soil analysis into one unified dataset. Regression analysis in combination with Random Forest Feature importance was performed on the increase of SOC content between S1 and S2 concerning Clay, SOC/clay, and Ley frequency.

Main findings

The study found correlations between historical agricultural use and the soil structure quality indicator SOC/ Clay which is used to indicate physical soil structure quality. As shown in Figure NN, production regions known to have more intensive agriculture (PR 1, 3, and 4) have a larger share of soil samples with lower structure quality classes (Degraded) (Figure 4). In these regions, annual crops, are the most commonly grown crops and occupy a significant portion of agricultural land, and in these regions, most of the cereal and oilseed crops are grown in Sweden. On the other hand, the mixed agricultural/forest regions (PR 5-8) are dominated by ley cultivation, which is essential for Swedish milk and beef production.

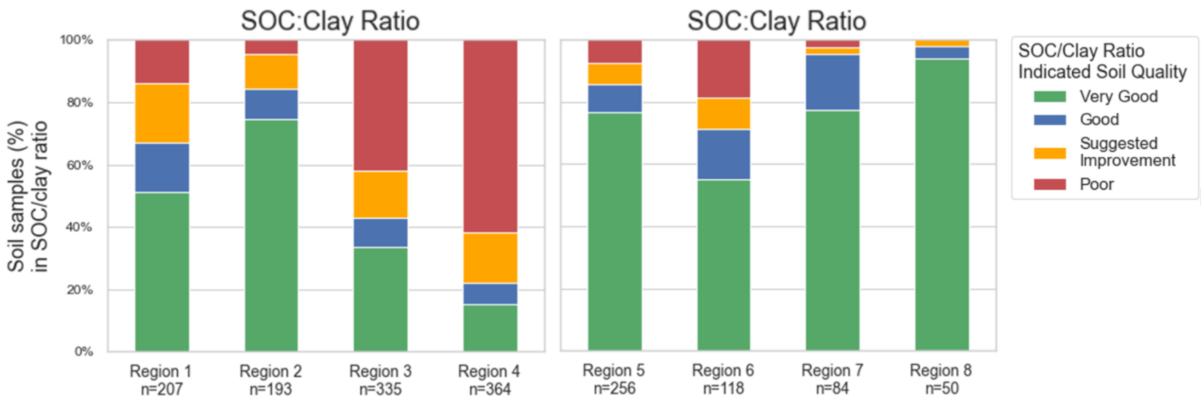

Figure 4. Production regions (PR) in Sweden according to pedoclimatic conditions. Distribution of SOC/Clay ratio in soil samples in the 8 Swedish production regions (n = number of sampled fields in the PR).

The study's results reveal a positive correlation between the frequency of perennial ley crops in rotation and SOC content. The measured SOC contents and calculated SOC stocks across six ley frequency groups showed that the SOC stock difference between the lowest (0%) and the highest (80-100%) ley frequency group was 16.2 Mg C ha-1 in the second sample occasion (S2). Additionally, SOC contents increased in all groups over the 10 years between the two sample occasions (S1 and S2), with the increase being statistically significant in all but the lowest ley frequency group (1-20%) (Table 1).

Table 1. Mean SOC content and SOC stock (0-20 cm) at sampling occasions 1 and 2 (S1 and S2) in the six ley frequency groups and results from statistical non-parametric tests (Wilcoxon). A statistically significant difference in SOC between S1 and S2 is indicated with "s" and non-significance with "n.s". Further details in SI (Table SI 6).

	Total Samples	Ley frequency groups					
		0%	1-20 %	21-40%	41-60%	61-80%	81-100%
# samples	1607	435	259	180	200	206	327
Mean SOC % S1	2.57	2.28	2.43	2.34	2.65	2.79	2.98
Mean SOC % S2	2.64	2.34	2.48	2.45	2.77	2.82	3.08
Significance (Non parametrical) *p=0.05*	*s*	*s*	*n.s*	*s*	*s*	*s*	*s*
Variance σ^2 S1	*1.16*	*0.84*	*1.28*	*0.78*	*1.28*	*0.98*	*1.37*
Variance σ^2 S2	1.04	0.80	0.99	0.80	1.09	1.00	1.11
SOC stock MgC ha^{-1} S1	68.7	63.6	64.7	64.0	71.0	73.2	76.9
SOC stock MgC ha^{-1} S2	71.8	65.2	67.7	69.0	74.4	75.4	81.4

The results of Random Forest and regression analysis show a positive and significant correlation between the frequency of perennial leys in crop rotation and SOC content. Additionally, in 27% of the sampled fields where no ley crops had been cultivated between S1 and S2, we also found a small but statistically significant increase in SOC content (Table 1). This increase may be attributed to the cultivation of cover crops, which is a land management activity that is not registered in the IACS database.

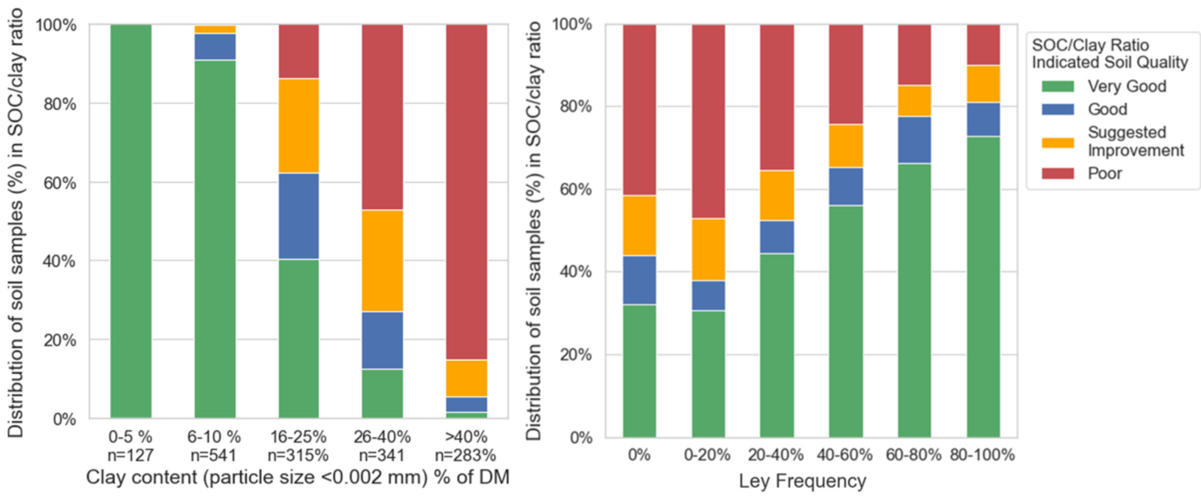

Figure 4. A (left). Distribution of soil samples in SOC/Clay ratio indicating structural soil quality sorted into five classes based on clay content (% of DM). Figure 5 B (right). Distribution of soil samples in SOC/Clay ratio indicating structural soil quality in the six ley frequency groups, calculated as the occurrence of ley in crop rotation between 2003-2020 (share of years with ley cultivation for 18 years).

This finding indicates the potential influence of other agricultural practices on SOC levels. As the SOC content increased with the increased share of ley in cultivation, the study also found a correlation between the SOC/Clay indicator and the Ley Frequency. Built on the classification of the ley frequency groups and the thresholds suggested by Johannes *et al*., (2017) – this study showed that the proportion of fields classified as having a “Very Good soil structure quality” increased with higher ley frequency (Figure 5B). Conversely, the share of fields classified as “Degraded”, or “Poor”, decreased with increased ley frequency. To this, it is also clear that the share of “Very Good soil structure quality” decreases with increasing clay content (Figure 5A).

Discussion and limitations

The results presented here indicate a correlation between low soil structure quality and high clay content in Sweden's arable farming regions by quantifying SOC/Clay ratios. The robustness of this indicator is however challenged in a study on German agricultural soils by Poeplau & Don (2023) and criticized because of its high dependency on clay content. Despite this, SOC/Clay as a soil quality indicator is getting more attention, for instance, in the new proposal directive on soil health monitoring from the European Commission (2023). This underlines the need to further develop and investigate how this indicator and other soil quality indicators can be useful tools for monitoring the effects of land management in agriculture Methodological approaches integrating soil datasets with continually updated land use information render pivotal data for formulating regionalized indicators and establishing baseline thresholds for SOC.

Limitations of the method developed in Paper A are the spatial accuracy of carbon data after the spatial merging between SASI and IACS, and the challenges when simplifying field-specific data of the IACS database itself. Merging the SASI data and the IACS database provides an understanding of SOC conditions in large areas with information about SOC content in relation to crop history. However, the combination of the two datasets and the simplification made in the IACS data should be acknowledged. The method therefore generates limited insights into specific fields of subfields within an agriculture system. Even if the results of this study together with many previous studies by (Bolinder *et al*., 2020; Henryson *et al*., 2022; Wiesmeier *et al*., 2019) suggest that improved agricultural management can sequester carbon in the soil, there are still many challenges related to measurements and verification of these changes.

Including more measurements, that is, increasing the density of sampled fields within a study area, could enhance the understanding and accuracy of SOC stock calculations. However, it is highly expensive and time-consuming to sample individual fields many times – it is simply not a feasible option for larger areas. Soil variability is higher at finer spatial scales which means that when sampling a small area, a high number of samples is required to capture the variability (Conant & Paustian, 2002) while at larger areas, for instance, several thousands of hectares, a smaller amount of sample per unit area will be sufficient to quantify SOC stocks (Paustian *et al*., 2019a). This strengthens the utilization of the SASI soil sampling program as applied and combined with other datasets as in this paper and suggests that the method can be used if the area investigated is large enough, and still provides valuable insights. Field-specific SOC stock estimates could be part of future development of the method by using Random Forest, and in that, assign a SOC content value per field in a study area based on similar soils, climatic, and spatial properties.

The IACS database, while having crop information on most agricultural fields in Sweden has inherent challenges when used for long-term analyses due to changes in land use and sometimes ownership, causing a continuous change in block IDs, and changes in field shapes and boundaries. This presents an important limitation in any study utilizing the IACS databases over a longer time series. As mentioned, and explained in more detail in Paper A, the information on cultivated crops at the field level is simplified and, in the model, fields are associated with only the crop type that covers the largest area, thereby not considering that fields may be divided in smaller parcels and cultivated with several crops. This is however only a problem when trying to understand field-specific information in smaller areas with few numbers of fields. The large volume of IACS data, the number of fields, and their level of spatial data but also the long timeframe of the dataset is quantitatively large and therefore provides a solid basis for analysis.

Paper B - Carbon removal potential in agricultural systems: A model with suggested measures from farmer participation in Sweden

The role of SOC in mitigating climate change is complex yet holds great potential. By implementing improved management practices, the potential for SOC to sequester carbon can increase. These practices not only positively impact carbon sequestration, but also bring environmental co-benefits. Insights and knowledge about soil types, carbon inputs, and management practices can inform sustainable and locally adapted strategies for mitigating and adapting to climate change.

Motivation

In Paper B, a study was conducted to explore how three management practices (cover crops, increased ley cultivation, and biochar production from straw residues) can contribute to atmospheric CO_2 removal to create more soil carbon sinks in agricultural landscapes. The objective of the study was to investigate the contribution of agricultural practices and land management strategies to SOC storage together with farmers by including their choices of measures to construct the model. To bridge the gap between theory and practice, the study introduces a landscape model that represents agricultural land use distributed into different crop rotations. From these, two scenarios were created in which changes could be implemented to enable a quantitative investigation considering the potential for atmospheric CO_2 removal and thus enhanced soil carbon sinks in the landscape. The study acknowledges that implementing SOC strategies in agriculture requires farmers' collaboration and their willingness to implement suggested changes. Therefore, it was natural to take into consideration farmers' perspectives and their decision-making process when it came to land use changes.

By incorporating farmers' preferences regarding the proposed measures, these scenarios provide a more realistic appraisal of climate mitigation measures. By integrating SOC stock data, SCS practices, and carbon allocation metrics to understand the effect of each implemented measure, this paper aims to provide a quantification of atmospheric carbon removal potentials in an arable landscape. Furthermore, the study highlights the importance of understanding SOC dynamics concerning specific agricultural production systems to refine regional and national estimates of SOC stocks.

The research questions focus on understanding how SOC sequestration potential varies across different agricultural systems and scenarios, the overall climate benefit across these landscapes, and how carbon flows can be quantified and linked to land use change. The paper's significance lies in its potential to offer unique insights into the practical application of SOC in agriculture, depending on the production system and feasible climate mitigation measures.

Method

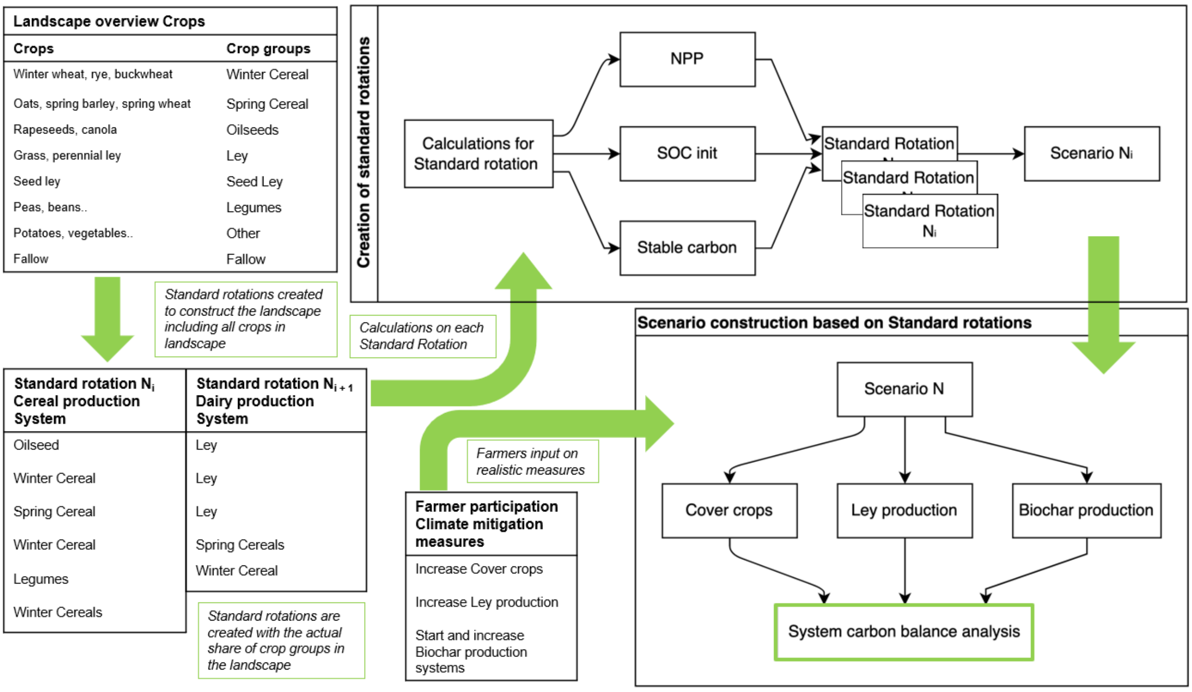

Figure 5. Graphical abstract of the developed method and the mindset behind the methodology of the produced model.

In the method section of Paper B, five archetypical cropping systems were devised to reflect common land use practices in a region in Sweden (Graphical Method in Figure 6). These cropping systems were created to mimic the real agricultural production of the region. The data used to determine these figures is derived from several factors such as the percentage of cultivated crops in the area, the quantity of livestock produced, and the established agronomic practices in crop cultivation. Sources of information regarding crop rotations in arable farming systems were obtained from Tidåker *et al* (2016), while those for dairy farming systems were sourced from Einarsson *et al* (2018). The rotation used in dairy farming was further developed to include a grass-clover ley, which is more in line with typical cattle farming systems and is also suitable for horse fodder production. To create the most realistic rotations possible, data and statistics were gathered at the production region level and included information on cultivation practices such as preceding crops for winter and spring cereals, the composition of grass and clover in the leys, the distribution of temporary ley area by age, and the management of fallow land (SCB, 2017).

Information about farmers' preferences was gathered through stakeholder meetings and surveys. During stakeholder meetings, CDR effects of measures were discussed together with farmers' possibility and ambition to implement and change their current agricultural practices. Surveys were constructed based on climate mitigation measures with known high carbon mitigation effects based on literature reviews and meta-studies on international and Swedish cases (Wiesmeier et al., 2019; Kätterer & Bolinder, 2023; Naturvårdsverket, 2022).

These included perennial ley cultivation, cover crops, re-wetting organogenic soils, agroforestry, cultivating perennial energy crops or short-rotation coppice, forest plantation on arable land, and biochar production. Two scenarios were developed to better understand the effects of SOC sequestration of included measures and the landscape total CDR potential: 1) The Theoretical Max Scenario where three suggested measures were introduced to the landscape – Perennial ley in crop rotation and cultivation of cover crops is included at an agronomically possible maximum, and 2), a No-Ley Scenario where cover crops still were retained, but the inclusion of perennial ley is excluded to investigate the effect of this measure.

A carbon flow model was developed to quantify the amount of stable carbon that could be attributed to each crop, and subsequently, each standard rotation that was developed. This crop-specific carbon allocation starts in the NPP (Figure 6) of each crop, based on the amount of harvest. Harvest data for the region was sourced from the Swedish Board of Agriculture's open-source database, with a three-year mean value calculated from 2020 to 2022 to represent the harvest of each crop.

Crop statistics were compared at the regional, and landscape levels to provide a representative depiction of the landscape´s current land use to create a reference scenario. Each of the standard rotation groups is also assigned an initial SOC stock [Mg C ha^{-1}], based on findings in Paper A, and the proportion of ley (SOC init, Figure 6). The different initial SOC stocks, specified for each of these rotations are an important contribution from Paper A to Paper B, as it is crucial for the carbon stock modeling performed.

Carbon allometric and Data analysis

The livestock population in the landscape is mainly composed of pigs, which are raised for pork production, and cattle, which are raised for beef and dairy production. The amount of manure available for use as fertilizer is influenced by the number and variety of animals in the landscape. To calculate the amount of manure, this study used a nutrient management advisory tool (https://adm.greppa.nu/vera.html), which considers factors such as the type and number of animals, feed consumption, and manure management techniques. The study also calculated the biochar amendment, focusing on biomass from agricultural residues not utilized elsewhere. The carbon content within the produced biochar was calculated using an equation derived from an empirical study of over 60 biomass input types, assuming a pyrolysis temperature of 400 °C (Lehmann & Joseph, 2009: Neves *et al*., 2011).

The estimation of available above ground (AG) residues involves three steps which together work out how much biomass is available to harvest, and subsequently produce biochar. The harvest index (HI) calculates yields as a fraction of the total harvest biomass in dry weight, as described in a study by Bolinder *et al*. in 2007. Data on how much AG residues can be collected is obtained from a study on major Swedish crops (Nilsson, 2009). The amount of AG residues that are not harvested and left to be plowed down in the arable fields, is based on Production regions (PRs) (Figure 3) statistics (SCB, 2013). These datasets were used to quantify the amount of AG residues that can potentially be used in biochar production.

With this, every crop group within each of the standardized rotation schemes was assigned specific carbon flow pathways originating from. To assess the potential for CDR in different crop rotations, we utilized the "Bolinder equations" introduced by Bolinder *et al* (2007). These equations allocate carbon into four categories: Harvested Products, Above-Ground Residues, Roots, and Rhizodeposition. All biomass was assumed to have a standard carbon content of 45% (Kätterer *et al*., 2011).

The Bolinder Equations quantifies how much carbon is available in above-ground (AG) and below-ground (BG) residues for each crop and subsequently the amount of carbon available for SCS within each standard rotation. The carbon contribution attributed to cover crops in the region was set to a constant value (0.32 Mg C /ha/y) as found by Swedish long-term field trials (Poeplau *et al*., (2015). This method generates the opportunity to have multiple changeable factors in the model in which every scenario can be specified and moderated. It is possible to change the pathway of carbon within the crop groups i.e., the amount of carbon allocated for each crop group to manure, biogas, biochar, etc., and change the combination of crop groups within each standard Rotation as well as changing the initial SOC stock within each agricultural system.

Main findings

Table 2 shows the five archetypical crop rotations (SR1-SR5) constructed, where SR1 is based on typical arable farming systems (Tidåker *et al*., 2016) in Sweden. SR2 includes legumes to reduce the risk of root rot pathogens (Källin *et al*., 2022).R3 includes seed ley which has an especially high presence in this region of Sweden. SR4 is based on the typical land use patterns in dairy production systems (Einarsson *et al*., 2018). SR5 is a modification of SR4, considering that around one-third of the ley area in PR3 is four years or older (SCB, 2020). Previous research has shown that farming systems that include perennial ley in crop rotations have a higher SOC stock than farming systems that only grow annual crops (Rehn *et al*., 2023). However, in this study, the model represents 88% accuracy only for the arable landscape, as it excluded 'Fallow' and 'Others' for simplicity.

Table 1. Standard rotations (SRs) with included crop crops in specific order to mimic five different archetypical agricultural directions of production. Based on the share or Cereals and Ley – each SR is assigned an initial SOC stock [Mg C/ha] based on calculations on Rehn et al., 2023.

Year	SR1	SR2	SR3	SR4	SR5
	Crop Group	Crop Group	Crop Group	Crop Group	Crop Group
1	W Cereal	Rapeseed	Legumes	Ley	Ley
2	S Cereal	W Cereal	W Cereal	Ley	Ley
3	W Cereal	S Cereal	S Cereal	Ley	Ley
4	S Cereal	Legumes	Seed Ley	S Cereal	Ley
5	S Cereal	W Cereal	Seed Ley	S Cereal	W Cereal
6	Rapeseed	S Cereal	W Cereal	*Ley round 2*	S Cereal
7	*W Cereal round 2*	W Cereal	S Cereal	*Ley round 2*	S Cereal
8	*S Cereal round 2*	S Cereal	S Cereal	*Ley round 2*	*Ley round 2*
Agricultural Direction	Cereal production	Cereal production	Cereal production	Dairy production	Beef and Horse fodder production
Initial SOC stock [Mg C/ ha]	67.7[a]	67.7[a]	69.0[b]	75.4[c]	75.4[c]
Share of crop land in region [ha]	**18 % (6924)**	**17% (6920)**	**21%(8320)**	**20 % (7990)**	**24% (9408)**

a = SOC stock based on fields with no perennial ley (Rehn et al (2023)
b = SOC stock based on fields with 20-40% perennial ley (Rehn et al (2023)
c = SOC stock based on fields with >60 % perennial ley (Rehn et al (2023)

The main findings of Paper B underscore the potential of specific agricultural strategies to enhance carbon sequestration significantly. By integrating a higher proportion of perennial ley crops, expanding the use of cover crops, and implementing biochar production based on unutilized straw residues otherwise plowed into the ground, a substantial increase in carbon sequestration across diverse rotational systems was observed. In Scenario 1, where the implementation of perennial ley, cover crops, and production of biochar was set to a Theoretical Max, the total increase in SOC stock together with the biochar after three decades resulted in a CDR of 7.1 Mg C/ha (Figure 7A) as a mean value for the whole landscape. Total CDR after 30 years in Scenario 2, in which the perennial ley was not included, was 6.6 Mg C/ha (Figure 7B)

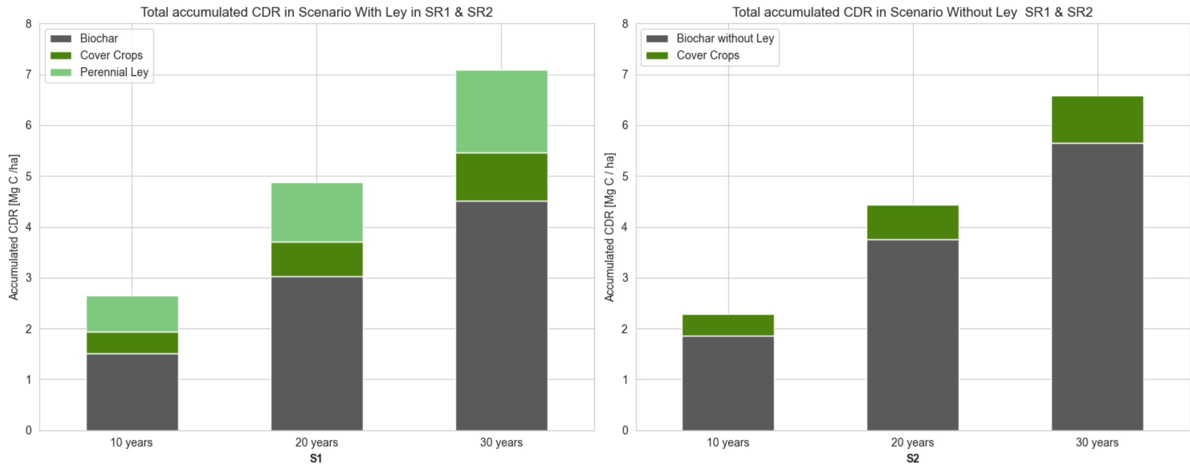

Figure 7. Accumulated carbon dioxide removal (CDR) from the atmosphere in 10-year steps. Each column depicts the contribution of CDR per included measure. Figure 7A (Left) illustrates CDR when Ley is implemented, and Figure 7B (Right) when Ley is not implemented. CDR effects are normalized against the Baseline, meaning that data only represent CDR due to the added measures.

The contribution of biochar to enhancing carbon sequestration emerged as a pivotal discovery in this study. When producing biochar of above-ground (AG) residues, biochar's effect on total carbon sequestration was significant. For Scenario 1, the annual average carbon sink effect of producing was between 75 kg and 135 kg, ranging between the rotations. For Scenario 2, when perennial ley was excluded, biochar sequestered as much as 180 kg C/ha/year (Figure 8).

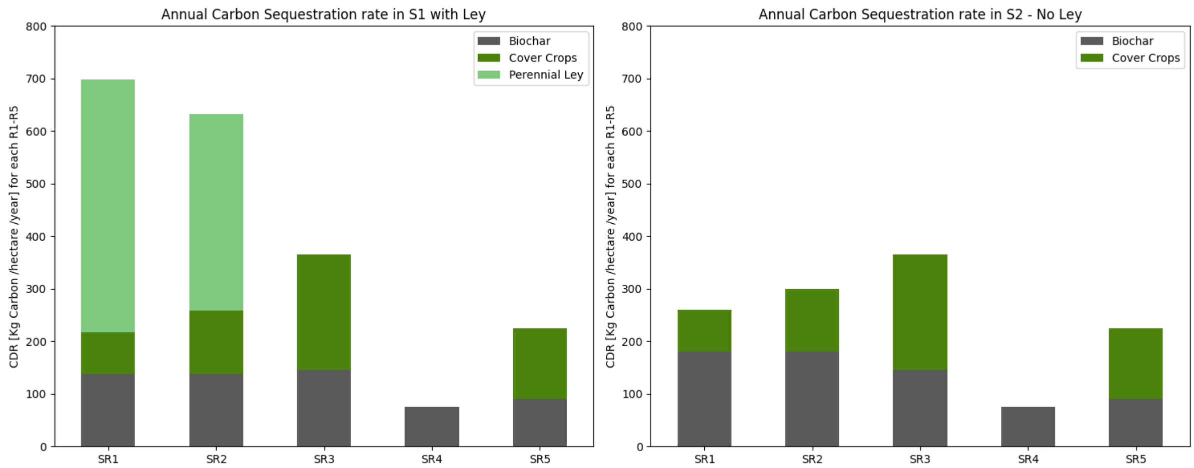

Figure 8. Carbon removal attributed to each included measure in the S1 and S2 scenario - divided up between the five standard rotations (SR) making up the arable landscape. Expressed in Annual CDR contribution within each standard rotation.

The results indicate an interesting trade-off between the inclusion of perennial ley in S1, and biochar production in S2. In scenario 1, the integration of cover crops and perennial ley into crop rotations can enhance atmospheric carbon sequestration into the SOC pool by 1.64 and 0.94 Mg C/ha, respectively, over three decades. When biochar is introduced, the total CDR effect of scenario 1 is 7.1 Mg C/ha. For S2, the total accumulated CDR, when not including perennial ley is 6.6 Mg C/ha after 30 years.

Discussion and limitations

Based on the survey results, there was a strong consensus among the farmers regarding potential measures for implementation in the landscape. Besides that, it is important to note that the participating farmers not only responded to the survey but also attended multiple stakeholder meetings. Even though the motivations behind adopting certain measures in their landscape may vary, the multifaceted reasoning farmers employ in their agricultural decision-making is inherently integrated into their choices of measures, and subsequently the measures in this model.

Through the survey and interactions at meetings, the unique knowledge and experience of the farmers were documented. Their extensive expertise offers a comprehensive view of feasible agricultural practices in the landscape. Despite the study's constraints, the deep involvement with farmers during these meetings lends credibility to their insights. If farmers' opinion about what measures to include in this study was not acknowledged, the results of CDR potentials are at risk of generating an overestimation. The options included in the survey, but not in the study were energy crops or short-rotation coppice, agroforestry, and plant forest. These are measures with, besides SOC enhancement effects, rather high average carbon sink potentials due to large biomass volumes above and below ground (Grelle et al., 2007: Lorenz & Lal, 2014). In this case – the inclusion of any of these measures would probably generate a higher CDR effect per hectare, but this would be a theoretical potential, not a feasible potential for the arable landscape.

One important limitation of this model is in spatial modeling and any estimations made in SOC stock modeling are influenced by the lack and/or granularity of data. The study in Paper B uses three large databases and spatially joins these to understand the landscape as an agricultural system. The decision to associate each agricultural standard rotation that we created with an initial carbon content is based on the calculations of Paper A. This has its uncertainties because the estimation of bulk density is substantial. Nevertheless, Paper A concludes that carbon stocks are higher in agricultural directions and have a higher proportion of ley in their crop rotations compared with those with no or low proportion of ley. Establishing initial SOC contents and stock is crucial when modeling future SOC changes and this could be achieved through the combination of soil and land use databases in Paper A. To utilize that information is fundamental to the SOC stock modeling performed in Paper B. Even though data from SASI in Paper A is based on a short time period of studying SOC changes in temperate regions, the results show that arable with a higher proportion of perennial ley in crop rotation, as on cattle and dairy farms, have a higher initial SOC storage (Rehn *et al.*, 2023, Henryson *et al.*, 2022).

Paper B presents results that underscore the utility of our modeling approach to SOC stocks over time. While there are acknowledged limitations, especially concerning uncertainties in bulk density measurements, the approach remains instrumental as a decision-making tool, particularly for landscapes characterized by diverse agricultural methodologies and strategic orientations. The introduction of a range of sustainable farming practices could play a pivotal role in addressing climate change challenges, making it crucial for policymakers and stakeholders to consider these results in future decision-making. The methodologies and outcomes detailed in Paper B offer a step towards quantifying CDR effects, both on an annual scale and per hectare.

This indicates that the results of this paper could be benchmarked against farm-specific and landscape-specific GHG emissions, so farmers and stakeholders can understand the significance of implemented measures in their practice measures — both in terms of absolute carbon sequestration and its relative significance to overall GHG emissions.

In essence, this provides a better understanding of the role of each measure as a climate mitigation strategy can be evaluated. These findings highlight the potential benefits of implementing these specific agricultural practices. Given the pressing challenges of climate change, any increase in carbon sequestration could be an essential step towards more sustainable agriculture, and making the increase easily quantifiable- this enables understanding of climate mitigation actions possible to implement for farmers and stakeholders based on specific measures.

CHAPTER 4

Conclusion

This thesis and its included articles show that the combination of existing continuously updated databases can generate new insights into the possibilities of agricultural land management to sequester atmospheric carbon as a climate mitigation strategy. The two papers provide insights into possibilities for SCR in agricultural soils and CDR potentials for measures that farmers find interesting and feasible. Increasing SOC stocks while at the same time improving soil structure quality can increase agricultural resilience which benefits both farmers and society as a whole.

The contributions of Paper A create the foundation on which this thesis stands. The paper provides a new method that demonstrates and discusses the combination of continuously updated geospatial soil data with geospatial information on land use history. The method has revealed a positive correlation between ley frequency in crop rotations and increased SOC content, which also contributes to improved soil structure quality. Additionally, clay content in the soil is closely related to its carbon content. Paper A contributes new insights into how the physical soil structure quality indicator SOC/clay ratio can be utilized.

This information is particularly helpful for farmers who want to keep track of how healthy their arable lands are in terms of soil structure. It can also help them to identify which fields that need attention for measures to improve the soil structure. As an example – the results indicate that cereal farmers could increase the total CDR effect with the implementation of cover crops and perennial ley in favor of cereal crops. For a dairy – or cattle farmer, perhaps the most CDR interesting measure would be to initiate biochar production, as there are limited possibilities for increasing perennial ley cultivation. The model presented in the study can help identify explicit measures that have synergy effects, which is beneficial to farmers as well as policymakers at both national and EU levels. The study also highlights the potential for farmers to increase soil organic carbon and remove atmospheric carbon dioxide while simultaneously improving soil structure quality and maintaining yield levels.

Paper B presents a methodology that involves collaboration between farmers and geospatial modeling to gain new insights into the potential for SCR in an agricultural landscape. The method developed in Paper B considers the current situation within an agriculture district based on the current agricultural production systems and crop rotations, and the interest and willingness of farmers to adopt new principles during their transition to more sustainable agriculture, with climatic benefits as well as synergies for their practices. By integrating the pragmatic inputs of farmers, our landscape-level model provides a realistic assessment of CDR efficacy, bridging the gap between theoretical strategies and practical applications within diverse agricultural landscapes. The study quantitatively demonstrates the CDR potential of adopting measures such as cover crops, perennial ley, and biochar, with the latter showing a significant increase in carbon sequestration potential when paired with the availability of above-ground residues from cereal crops.

Paper B´s methodology involves geospatial data of arable fields within a chosen agricultural landscape with the possibility to change cultivation strategies and agricultural practices over any area. It is in this change that stakeholder participation can have an effect, allowing for proposed strategies to align with the practical feasibility of a farming direction and willingness among the farmers.

The findings from Paper B emphasize the important potential of refining crop rotations and harnessing both cover and ley crops to maximize carbon sequestration in a more climate-smart agriculture. This approach provides insight into which measures are most effective for different agricultural systems. One standout insight from Paper B is the high variance between annual CDR effects observed between standard rotations (SR1-SR5). Given that each rotation corresponds to a realistic crop rotation system, with initial SOC stock values, and reflects implemented change of practices deemed feasible by regional farmers, these results offer valuable insights into how sustainable transition can be implemented in an agricultural society. Implementation of cover crops can increase overall CDR, as can perennial ley in favor of annual crops. Since this thesis suggests a method in which CDR effects are quantified per implemented measure, in exact positions in crop rotations specific to different agricultural directions, it is a potentially valuable tool for farmers working towards a sustainable transition.

Any attempt to quantify the climate impact involves various aspects which should include a long temporal scale is inherently challenging, often hinging on precise measurements and underlying assumptions. However, with the tools introduced here, we can help decision-making processes for landscapes encompassing diverse agricultural practices. While we may not know the exact carbon sequestered from the atmosphere, these tools empower us to make informed choices and advance toward the ultimate objective: a net zero agricultural landscape. This thesis bridges the gap between empirical farmer experiences and extensive database research, paving the way for targeted, site-specific carbon sequestration initiatives in agriculture. This could include offering a basis for decision-making in terms of land use for farmers.

The results from Papers A and B have identified strategies for sustainable agriculture, including farmer collaboration and geospatial modeling. These insights strengthen climate mitigation science and provide actionable strategies for sustainable agriculture. The models and their findings lay the groundwork for location-specific, synergistic strategies that can be harnessed to inform both national and EU-level policy development, fostering a transition to more sustainable agricultural practices. By quantifying the CDR impacts of various agricultural techniques, this research provides a crucial benchmark for greenhouse gas emissions reduction, advocating for informed and strategic approaches to sustainable farming and impactful climate action.

CHAPTER 5

Outlook and Future Studies

This thesis establishes a methodological foundation that could improve future research. A cornerstone of the model development is the construction of archetypal crop rotations, grounded in agronomic expertise and informed by initial SOC stock estimations derived from over 1607 sample sites, as detailed in Paper A. While this research has aimed to address relevant questions and quantify the CDR potential for selected agricultural measures, I acknowledge the potential for further methodological refinement and significant model enhancement.

Starting with more opportunities within the current method and model development, future studies will include an elaboration of the scenarios included in Paper B. For instance, from the results of Paper B, it is evident that the dynamics of perennial ley in crop rotation and biochar production are interesting. Notably, in our model, perennial ley's lack of above-ground residues resulted in higher biochar production in scenarios excluding ley. Future research should further investigate the tradeoffs and effects of introducing perennial ley in crop rotation and biochar production to increase overall CDR. Since the roots of perennial ley have a great contribution over time but are affected by annual carbon loss, and biochar is stable, at least within the time frame in this thesis, it proposes interesting choices regarding mitigation measures. What measure to choose is as discussed, a multifaceted choice, and what factors affect the choice of measure for the farmers could be interesting to develop further.

Future research should further investigate the tradeoffs and effects of introducing perennial ley in crop rotation and biochar production to increase overall CDR. The root systems of perennial leys offer a significant annual carbon addition to the soil but are affected by annual carbon loss. In contrast, biochar presents as a more stable carbon sequestration option, remaining stable as a carbon sink throughout the duration observed in this study. This stability positions biochar as a potentially reliable component in CDR strategies, though its long-term interactions and efficacy require further exploration. The decision to implement either or both of these measures is a multifaceted decision, influenced by many factors including environmental benefits, economic viability, and compatibility with existing agricultural practices. Understanding the determinants that influence farmers' preferences for one measure over the other could be interesting in future research.

By broadening the model to include additional scenarios, we can also expand system boundaries to capture the CDR potential of avoided emissions by the implementation of climate mitigation measures. This expansion would allow for a deeper understanding of the substitution effects of these measures. Furthermore, it would provide an option to explore the integration of biogas production within the agricultural landscape, assessing the use of bio-manure as a soil amendment, and evaluating secondary impacts that reach beyond the immediate system. This could be an important aspect to develop, as it would be interesting to fit the results and necessity of this model within a broader regional, national, and potentially European framework.

Such an integration will highlight how regional CDR potentials stack up against GHG emissions from equivalent spatial domains which could be an interesting perspective in policy and decision-making. One specific future development of how his study could be used is to include Green Biorefineries (GB) into the system of a landscape and further investigate possible CDR outcomes and substitution effects. GB utilizes green biomass – grass, legumes, and immature cereals, to produce a wide range of products, often proteins for animal or direct human consumption (Yilmaz Balaman *et al*., 2023). There is an interesting opportunity to investigate how GBs in an arable landscape system could work while increasing the share of perennial grasses that can be used as feedstock into the GBs.

Another interesting approach could be to include financial support and subsidies in the analysis associated to the CDR results of the model. This integration would directly engage with the discourse on carbon subsidies and climate mitigation incentives, offering a quantitative evaluation of the CDR impact per measure and hectare. With further methodological advancements, the existing model—from this thesis and the accompanying papers—could serve as a tool for estimating the climate benefits at a local arable landscape scale. Such precision in estimates could provide farmers with concrete economic reasons to implement changes in crop rotation that enhance carbon sequestration. This would not only further the adoption of carbon-positive farming practices but also align agricultural profitability with climate action goals, creating a win-win scenario for farmers and the environment. An example of where the future inclusion of financial support and subsidies, and other factors for that matter, could be important is found in the results of Paper B. The result suggests that including perennial ley vs producing biochar of above-ground straw residues has a similar CDR effect with time. What then is important for the farmer's decision-making is no longer solely the CDR potential, but other factors such as economy, knowledge, etc.

Advancing the model's capabilities through Machine Learning (ML) techniques could be a promising direction for future research worth investigating. Particularly, integrating ML algorithms such as Random Forest with the SASI and the IACS datasets could refine our spatial predictions of SOC stocks. Such an application would mean that IACS fields that are not sampled, are given a SOC content value based on statistical similarities of crop history, spatial location, climatic factors, and all other soil sample data in SASI. This could potentially address high variability in soils at finer spatial scales as previously discussed. At smaller special scales, a higher number of soil samples would be required to capture the variability (Conant & Paustian, 2002). An ML application to this, based on the mentioned factors would assign SOC content on each field in any arable region. Although this is a calculated estimation, it could aid local understanding and quantification of SOC stocks. There is an upcoming need in Europe for quantifying SOC content in arable land concerning soil parameters, like clay content. In 2023, the EU Commission released a proposal for a directive on soil monitoring and resilience, in which the dynamics of SOC and Clay content in soils, specifically the SOC/Clay ratios as used in Paper A, is proposed to be used as a criterion for healthy mineral soils.

Abdalla, K., Mutema, M., & Hill, T. (2020). Soil and organic carbon losses from varying land uses: a global meta-analysis. *Geographical Research, 58*(2), 167-185. doi:https://doi.org/10.1111/1745-5871.12389

Allohverdi, T., Mohanty, A. K., Roy, P., & Misra, M. (2021). A Review on Current Status of Biochar Uses in Agriculture. *Molecules, 26*(18), 5584. Retrieved from https://www.mdpi.com/1420-3049/26/18/5584

Angst, G., Mueller, K. E., Nierop, K. G. J., & Simpson, M. J. (2021). Plant- or microbial-derived? A review on the molecular composition of stabilized soil organic matter. *Soil Biology and Biochemistry, 156*, 108189. doi:https://doi.org/10.1016/j.soilbio.2021.108189

Berryman, E., Hatten, J., Page-Dumroese, D. S., Heckman, K. A., D'Amore, D. V., Puttere, J., . . . Domke, G. M. (2020). Soil Carbon. In R. V. Pouyat, D. S. Page-Dumroese, T. Patel-Weynand, & L. H. Geiser (Eds.), *Forest and Rangeland Soils of the United States Under Changing Conditions: A Comprehensive Science Synthesis* (pp. 9-31). Cham: Springer International Publishing.

Bolinder, M. A., Crotty, F., Elsen, A., Frac, M., Kismányoky, T., Lipiec, J., . . . Kätterer, T. (2020). The effect of crop residues, cover crops, manures and nitrogen fertilization on soil organic carbon changes in agroecosystems: a synthesis of reviews. *Mitigation and Adaptation Strategies for Global Change, 25*(6), 929-952. doi:10.1007/s11027-020-09916-3

Bolinder, M. A., Janzen, H. H., Gregorich, E. G., Angers, D. A., & VandenBygaart, A. J. (2007). An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. *Agriculture, Ecosystems & Environment, 118*(1), 29-42. doi:https://doi.org/10.1016/j.agee.2006.05.013

Bossio, D. A., Cook-Patton, S. C., Ellis, P. W., Fargione, J., Sanderman, J., Smith, P., . . . Griscom, B. W. (2020). The role of soil carbon in natural climate solutions. *Nature Sustainability, 3*(5), 391-398. doi:10.1038/s41893-020-0491-z

Büchi, L., Walder, F., Banerjee, S., Colombi, T., van der Heijden, M. G. A., Keller, T., . . . Six, J. (2022). Pedoclimatic factors and management determine soil organic carbon and aggregation in farmer fields at a regional scale. *Geoderma, 409*, 115632. doi:https://doi.org/10.1016/j.geoderma.2021.115632

Carey, J. (2023). Unearthing the origins of agriculture. *Proceedings of the National Academy of Sciences, 120*(15), e2304407120. doi:doi:10.1073/pnas.2304407120

Conant, R. T., & Paustian, K. (2002). Spatial variability of soil organic carbon in grasslands: implications for detecting change at different scales. *Environ Pollut, 116 Suppl 1*, S127-135. doi:10.1016/s0269-7491(01)00265-2

Crowther, T. W., Todd-Brown, K. E. O., Rowe, C. W., Wieder, W. R., Carey, J. C., Machmuller, M. B., . . . Bradford, M. A. (2016). Quantifying global soil carbon losses in response to warming. *Nature, 540*(7631), 104-108. doi:10.1038/nature20150

Das, S., Mohanty, S., Sahu, G., Rana, M., and Pilli, K. . (2021). *"Biochar: A sustainable approach for improving soil health and environment," in Soil erosion - current challenges and future perspectives in a changing world Editors A. Vieira, and S. Carlos Rodrigues (London, UK: IntechOpen). doi:10.5772/intechopen.97136*.

Davidson, D. J., Jones, K. E., & Parkins, J. R. (2016). Food safety risks, disruptive events and alternative beef production: a case study of agricultural transition in Alberta. *Agriculture and Human Values, 33*(2), 359-371. doi:10.1007/s10460-015-9609-8

Davis, K. F., Downs, S., & Gephart, J. A. (2021). Towards food supply chain resilience to environmental shocks. *Nature Food, 2*(1), 54-65. doi:10.1038/s43016-020-00196-3

Dignac, M.-F., Derrien, D., Barré, P., Barot, S., Cécillon, L., Chenu, C., . . . Basile-Doelsch, I. (2017). Increasing soil carbon storage: mechanisms, effects of agricultural practices and proxies. A review. *Agronomy for Sustainable Development, 37*(2), 14. doi:10.1007/s13593-017-0421-2

Droste, N., May, W., Clough, Y., Börjesson, G., Brady, M., & Hedlund, K. (2020). Soil carbon insures arable crop production against increasing adverse weather due to climate change. *Environmental Research Letters, 15*(12), 124034. doi:10.1088/1748-9326/abc5e3

Edlinger, A., Garland, G., Banerjee, S., Degrune, F., García-Palacios, P., Herzog, C., . . . van der Heijden, M. G. A. (2023). The impact of agricultural management on soil aggregation and carbon storage is regulated by climatic thresholds across a 3000 km European gradient. *Global Change Biology, 29*(11), 3177-3192. doi:https://doi.org/10.1111/gcb.16677

Einarsson, R., Cederberg, C., & Kallus, J. (2018). Nitrogen flows on organic and conventional dairy farms: a comparison of three indicators. *Nutrient Cycling in Agroecosystems, 110*(1), 25-38. doi:10.1007/s10705-017-9861-y

European Commission. (2023). Proposal for a Directive of the European Parliament and of the Council on Soil Monitoring and Resilience (Soil Monitoring Law). *Directive of the european Parliament and of the Council on Soil Monitoring and Resilience (Soil Monitoring Law)*.

Eurostat, E., Directorate E; Sectoral and regional statistics. (2015). *Strategy for agricultural statistics for 2020 and beyond*. Retrieved from https://ec.europa.eu/eurostat/web/agriculture/methodology/strategy-beyond-2020:

Farstad, M., Melås, A. M., & Klerkx, L. (2022). Climate considerations aside: What really matters for farmers in their implementation of climate mitigation measures. *Journal of Rural Studies, 96*, 259-269. doi:https://doi.org/10.1016/j.jrurstud.2022.11.003

Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., Bakker, D., C. E., H., J., Le Quéré, C., Peters, G. P., Peters, W., Pongratz, J.,, Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Anthoni,, P., B., N. R., Becker, M., Bellouin, N., … Zeng, J. (2022). Global, carbon budget 2021. Earth System Science Data, 1917–2005., https://doi.org/10.5194/essd-14-, . . . 2022. (2022).

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Gregor, L., Hauck, J., . . . Zheng, B. (2022). Global Carbon Budget 2022. *Earth Syst. Sci. Data, 14*(11), 4811-4900. doi:10.5194/essd-14-4811-2022

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., . . . Minx, J. C. (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters, 13*(6), 063002. doi:10.1088/1748-9326/aabf9f

Ghafoor, A., Poeplau, C., & Kätterer, T. (2017). Fate of straw- and root-derived carbon in a Swedish agricultural soil. *Biology and Fertility of Soils, 53*(2), 257-267. doi:10.1007/s00374-016-1168-7

Grelle, A., Aronsson, P., Weslien, P., Klemedtsson, L., & Lindroth, A. (2007). Large carbon-sink potential by Kyoto forests in Sweden—a case study on willow plantations. *Tellus B: Chemical and Physical Meteorology*. doi:10.1111/j.1600-0889.2007.00299.x

He, W., Grant, B. B., Jing, Q., Lemke, R., St. Luce, M., Jiang, R., . . . Smith, W. N. (2021). Measuring and modeling soil carbon sequestration under diverse cropping systems in the semiarid prairies of western Canada. *Journal of Cleaner Production, 328*, 129614. doi:https://doi.org/10.1016/j.jclepro.2021.129614

Hedlund, K., Kätterer, T., Bracht Jörgensen, H., & Haddaway, N. (2021). *Växtföljders påverkan på inlagring av organiskt kol i jordbruksmark En systematisk översikt och samhällsekonomisk analys*. Retrieved from Forskningsrådet för miljö, areella näringar och samhällsbyggande, Formas. ISBN: 978-91-540-6148-8. Diarienummer: 2019-02296O:

Henryson, K., Meurer, K. H. E., Bolinder, M. A., Kätterer, T., & Tidåker, P. (2022). Higher carbon sequestration on Swedish dairy farms compared with other farm types as revealed by national soil inventories. *Carbon Management, 13*(1), 266-278. doi:10.1080/17583004.2022.2074315

Herrero, M., Thornton, P. K., Mason-D'Croz, D., Palmer, J., Benton, T. G., Bodirsky, B. L., . . . West, P. C. (2020). Innovation can accelerate the transition towards a sustainable food system. *Nature Food, 1*(5), 266-272. doi:10.1038/s43016-020-0074-1

IPCC. (2018). V. P. Summary for Policymakers. In: 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. (2018).

IPCC. (2019). Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.- O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press.

IPCC. (2021). Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. In Press.

Janzen, H. H., van Groenigen, K. J., Powlson, D. S., Schwinghamer, T., & van Groenigen, J. W. (2022). Photosynthetic limits on carbon sequestration in croplands. *Geoderma, 416*, 115810. doi:https://doi.org/10.1016/j.geoderma.2022.115810

Johannes, A., Matter, A., Schulin, R., Weisskopf, P., Baveye, P. C., & Boivin, P. (2017). Optimal organic carbon values for soil structure quality of arable soils. Does clay content matter? *Geoderma, 302*, 14-21. doi:https://doi.org/10.1016/j.geoderma.2017.04.021

Johansson, E. L., Brogaard, S., & Brodin, L. (2022). Envisioning sustainable carbon sequestration in Swedish farmland. *Environmental Science & Policy, 135*, 16-25. doi:https://doi.org/10.1016/j.envsci.2022.04.005

Jordbruksverket. (2018). *Production of cereals, dried pulses, oilseed crops and temporary grasses in 2018. Preliminary statistics for counties and the whole country*.

Jordbruksverket. (2023). Jordbruksverkets statistikdatabas. https://statistik.sjv.se/PXWeb/pxweb/sv/Jordbruksverkets%20statistikdatabas/?rxid=5adf4929-f548-4f27-9bc9-78e127837625 Access June 2023. .

Keel, S. G., Anken, T., Büchi, L., Chervet, A., Fliessbach, A., Flisch, R., . . . Leifeld, J. (2019). Loss of soil organic carbon in Swiss long-term agricultural experiments over a wide range of management practices. *Agriculture, Ecosystems & Environment, 286*, 106654. doi:https://doi.org/10.1016/j.agee.2019.106654

Keel, S. G., Bretscher, D., Leifeld, J., von Ow, A., & Wüst-Galley, C. (2023). Soil carbon sequestration potential bounded by population growth, land availability, food production, and climate change. *Carbon Management, 14*(1), 2244456. doi:10.1080/17583004.2023.2244456

Keel, S. G., Leifeld, J., Mayer, J., Taghizadeh-Toosi, A., & Olesen, J. E. (2017). Large uncertainty in soil carbon modelling related to method of calculation of plant carbon input in agricultural systems. *European Journal of Soil Science, 68*(6), 953-963. doi:https://doi.org/10.1111/ejss.12454

Kätterer, T., & Bolinder, M. A. (2023). Agriculture practices to improve soil carbon storage in upland soil. In C. Rumpel (Ed.), *Understanding and fostering soil carbon sequestration*: Burleigh Dodds Science Publishing, Cambridge, UK.

Kätterer T, B. M., Thorvaldsson G, Kirchmann H. (2013). Influence of ley-arable systems on soil carbon stocks in Northern Europe and Eastern Canada. . *EGF Series 'Grassland Science in Europe' 18:47–56*.

Kätterer, T., Bolinder, M. A., Andrén, O., Kirchmann, H., & Menichetti, L. (2011). Roots contribute more to refractory soil organic matter than above-ground crop residues, as revealed by a long-term field experiment. *Agriculture, Ecosystems & Environment, 141*(1), 184-192. doi:https://doi.org/10.1016/j.agee.2011.02.029

Kätterer, T., Bolinder, M. A., Berglund, K., & Kirchmann, H. (2012). Strategies for carbon sequestration in agricultural soils in northern Europe. *Acta Agriculturae Scandinavica, Section A — Animal Science, 62*(4), 181-198. doi:10.1080/09064702.2013.779316

Lal, R. (2015). Restoring Soil Quality to Mitigate Soil Degradation. *Sustainability, 7*(5), 5875-5895. Retrieved from https://www.mdpi.com/2071-1050/7/5/5875

Lal, R. (2023). Carbon farming by re-carbonization of agroecosystems. *Pedosphere*. doi:https://doi.org/10.1016/j.pedsph.2023.07.024

Lehmann, J., & Joseph, S. (2009). *Biochar for Environmental Management*: Science and Technology (1st ed.).

Lorenz, K., & Lal, R. (2014). Soil organic carbon sequestration in agroforestry systems. A review. *Agronomy for Sustainable Development, 34*(2), 443-454. doi:10.1007/s13593-014-0212-y

Lynch, J., Cain, M., Frame, D., & Pierrehumbert, R. (2021). Agriculture's Contribution to Climate Change and Role in Mitigation Is Distinct From Predominantly Fossil CO2-Emitting Sectors. *Frontiers in Sustainable Food Systems, 4*. doi:10.3389/fsufs.2020.518039

Mattila, T. J., Hagelberg, E., Söderlund, S., & Joona, J. (2022). How farmers approach soil carbon sequestration? Lessons learned from 105 carbon-farming plans. *Soil and Tillage Research, 215*, 105204. doi:https://doi.org/10.1016/j.still.2021.105204

MEA. (2005). Millennium ecosystem assessment: Ecosystems and human well-being: Synthesis. Island Press, Washington, DC. https://www.millenniumassessment.org/documents/document.356.aspx.pdf.

Meurer, K. H. E., Haddaway, N. R., Bolinder, M. A., & Kätterer, T. (2018). Tillage intensity affects total SOC stocks in boreo-temperate regions only in the topsoil—A systematic review using an ESM approach. *Earth-Science Reviews, 177*, 613-622. doi:https://doi.org/10.1016/j.earscirev.2017.12.015

Moinet, G. Y. K., Hijbeek, R., van Vuuren, D. P., & Giller, K. E. (2023). Carbon for soils, not soils for carbon. *Global Change Biology, 29*(9), 2384-2398. doi:https://doi.org/10.1111/gcb.16570

Mosier, S., Córdova, S. C., & Robertson, G. P. (2021). Restoring Soil Fertility on Degraded Lands to Meet Food, Fuel, and Climate Security Needs via Perennialization. *Frontiers in Sustainable Food Systems, 5*. doi:10.3389/fsufs.2021.706142

Naturvårdsverket. (2022). *Jordbrukssektorns klimatomställning. Underlagsrapport om jordbrukssektorn inom regeringsuppdraget om näringslivets klimatomställning*. Retrieved from https://www.naturvardsverket.se/om-oss/publikationer/7000/978-91-620-7060-1/

Nepal, J., Ahmad, W., Munsif, F., Khan, A., & Zou, Z. (2023). Advances and prospects of biochar in improving soil fertility, biochemical quality, and environmental applications. *Frontiers in Environmental Science, 11*. doi:10.3389/fenvs.2023.1114752

Neves, D., Thunman, H., Matos, A., Tarelho, L., & Gómez-Barea, A. (2011). Characterization and prediction of biomass pyrolysis products. *Progress in Energy and Combustion Science, 37*(5), 611-630. doi:https://doi.org/10.1016/j.pecs.2011.01.001

Nilsson, D. S. B. (2009). *Straw as Fuel Part 1 - Available resources and harvest times*. Retrieved from SLU:

Olson, K., Ebelhar, S. and Lang, J. . (2014). Long-Term Effects of Cover Crops on Crop Yields, Soil Organic Carbon Stocks and Sequestration. Open Journal of Soil Science, 4, 284-292. doi: 10.4236/ojss.2014.48030.

Paul, C., Bartkowski, B., Dönmez, C., Don, A., Mayer, S., Steffens, M., . . . Helming, K. (2023). Carbon farming: Are soil carbon certificates a suitable tool for climate change mitigation? *Journal of Environmental Management, 330*, 117142. doi:https://doi.org/10.1016/j.jenvman.2022.117142

Paustian, K., Collier, S., Baldock, J., Burgess, R., Creque, J., DeLonge, M., . . . Jahn, M. (2019). Quantifying carbon for agricultural soil management: from the current status toward a global soil information system. *Carbon Management, 10*(6), 567-587. doi:10.1080/17583004.2019.1633231

Paustian, K., Collier, S., Baldock, J., Burgess, R., Creque, J., DeLonge, M., . . . Jahn, M. (2019a). Quantifying carbon for agricultural soil management: from the current status toward a global soil information system. *Carbon Management, 10*(6), 567-587. doi:10.1080/17583004.2019.1633231

Paustian, K., Larson, E., Kent, J., Marx, E., & Swan, A. (2019). Soil C Sequestration as a Biological Negative Emission Strategy. *Frontiers in Climate, 1*. Retrieved from https://www.frontiersin.org/articles/10.3389/fclim.2019.00008

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature, 532*(7597), 49-57. doi:10.1038/nature17174

Poeplau, C., Bolinder, M. A., Eriksson, J., Lundblad, M., & Kätterer, T. (2015). Positive trends in organic carbon storage in Swedish agricultural soils due to unexpected socio-economic drivers. *Biogeosciences, 12*(11), 3241-3251. doi:10.5194/bg-12-3241-2015

Poeplau, C., & Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. *Agriculture, Ecosystems & Environment, 200*, 33-41. doi:https://doi.org/10.1016/j.agee.2014.10.024

Power, A. G. (2010). Ecosystem services and agriculture: tradeoffs and synergies. *Philosophical Transactions of the Royal Society B: Biological Sciences, 365*(1554), 2959-2971. doi:10.1098/rstb.2010.0143

Prout, J. M., Shepherd, K. D., McGrath, S. P., Kirk, G. J. D., & Haefele, S. M. (2021). What is a good level of soil organic matter? An index based on organic carbon to clay ratio. *European Journal of Soil Science, 72*(6), 2493-2503. doi:https://doi.org/10.1111/ejss.13012

Rockström, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., . . . Smith, J. (2017). Sustainable intensification of agriculture for human prosperity and global sustainability. *AMBIO, 46*(1), 4-17. doi:10.1007/s13280-016-0793-6

Rumpel, C., Amiraslani, F., Chenu, C., Garcia Cardenas, M., Kaonga, M., Koutika, L.-S., . . . Wollenberg, E. (2020). The 4p1000 initiative: Opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. *AMBIO, 49*(1), 350-360. doi:10.1007/s13280-019-01165-2

SCB. (2013). Odlingsåtgärder i jordbruket (Management practices in agriculture). *Statistiska Meddelande MI30 SM1302. Statistics Sweden.* .

SCB. (2017). Odlingsåtgärder i jordbruket 2016 (Cultivation measures in agriculture 2016). Statistiska Meddelande MI SM 1703.

SCB. (2020). Odlingsåtgärder i jordbruket 2019 (Cultivation measures in agriculture 2019). Statistiska Meddelande MI30 SM2003.

SGU. (2023). SGU - Geological Survey of Sweden. Quaternary geology.

Shah, H., Hellegers, P., & Siderius, C. (2021). Climate risk to agriculture: A synthesis to define different types of critical moments. *Climate Risk Management, 34*, 100378. doi:https://doi.org/10.1016/j.crm.2021.100378

Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., . . . Yongsung, C. (2016). Biophysical and economic limits to negative CO2 emissions. *Nature Climate Change, 6*(1), 42-50. doi:10.1038/nclimate2870

Sposito, G., Chesworth, W., Evans, L. J., & Chesworth, W. (2008). Geology and Soils. In W. Chesworth (Ed.), *Encyclopedia of Soil Science* (pp. 292-298). Dordrecht: Springer Netherlands.

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B. L., Lassaletta, L., . . . Willett, W. (2018). Options for keeping the food system within environmental limits. *Nature, 562*(7728), 519-525. doi:10.1038/s41586-018-0594-0

Sun, J., He, F., Pan, Y., & Zhang, Z. (2017). Effects of pyrolysis temperature and residence time on physicochemical properties of different biochar types. *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, 67*(1), 12-22. doi:10.1080/09064710.2016.1214745

Sykes, A. J., Macleod, M., Eory, V., Rees, R. M., Payen, F., Myrgiotis, V., . . . Smith, P. (2020). Characterising the biophysical, economic and social impacts of soil carbon sequestration as a greenhouse gas removal technology. *Global Change Biology, 26*(3), 1085-1108. doi:https://doi.org/10.1111/gcb.14844

Tao, F., Huang, Y., Hungate, B. A., Manzoni, S., Frey, S. D., Schmidt, M. W. I., . . . Luo, Y. (2023). Microbial carbon use efficiency promotes global soil carbon storage. *Nature, 618*(7967), 981-985. doi:10.1038/s41586-023-06042-3

Tsolis, V., & Barouchas, P. (2023). Biochar as Soil Amendment: The Effect of Biochar on Soil Properties Using VIS-NIR Diffuse Reflectance Spectroscopy, Biochar Aging and Soil Microbiology—A Review. *LAND, 12*(8), 1580. Retrieved from https://www.mdpi.com/2073-445X/12/8/1580

Tubiello, F. N., Karl, K., Flammini, A., Gütschow, J., Obli-Laryea, G., Conchedda, G., . . . Torero, M. (2022). Pre- and post-production processes increasingly dominate greenhouse gas emissions from agri-food systems. *Earth Syst. Sci. Data, 14*(4), 1795-1809. doi:10.5194/essd-14-1795-2022

Vidaller, C., & Dutoit, T. (2022). Ecosystem services in conventional farming systems. A review. *Agronomy for Sustainable Development, 42*(2), 22. doi:10.1007/s13593-021-00740-w

Wiesmeier, M., Urbanski, L., Hobley, E., Lang, B., von Lützow, M., Marin-Spiotta, E., . . . Kögel-Knabner, I. (2019). Soil organic carbon storage as a key function of soils - A review of drivers and indicators at various scales. *Geoderma, 333*, 149-162. doi:https://doi.org/10.1016/j.geoderma.2018.07.026

Zacháry, D., Filep, T., Jakab, G., Ringer, M., Balázs, R., Németh, T., & Szalai, Z. (2023). The effect of mineral composition on soil organic matter turnover in temperate forest soils. *Journal of Soils and Sediments, 23*(3), 1389-1402. doi:10.1007/s11368-022-03393-8