Linking environmental and economic modelling for informing policymaking in agriculture

López I Losada, Raül

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LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

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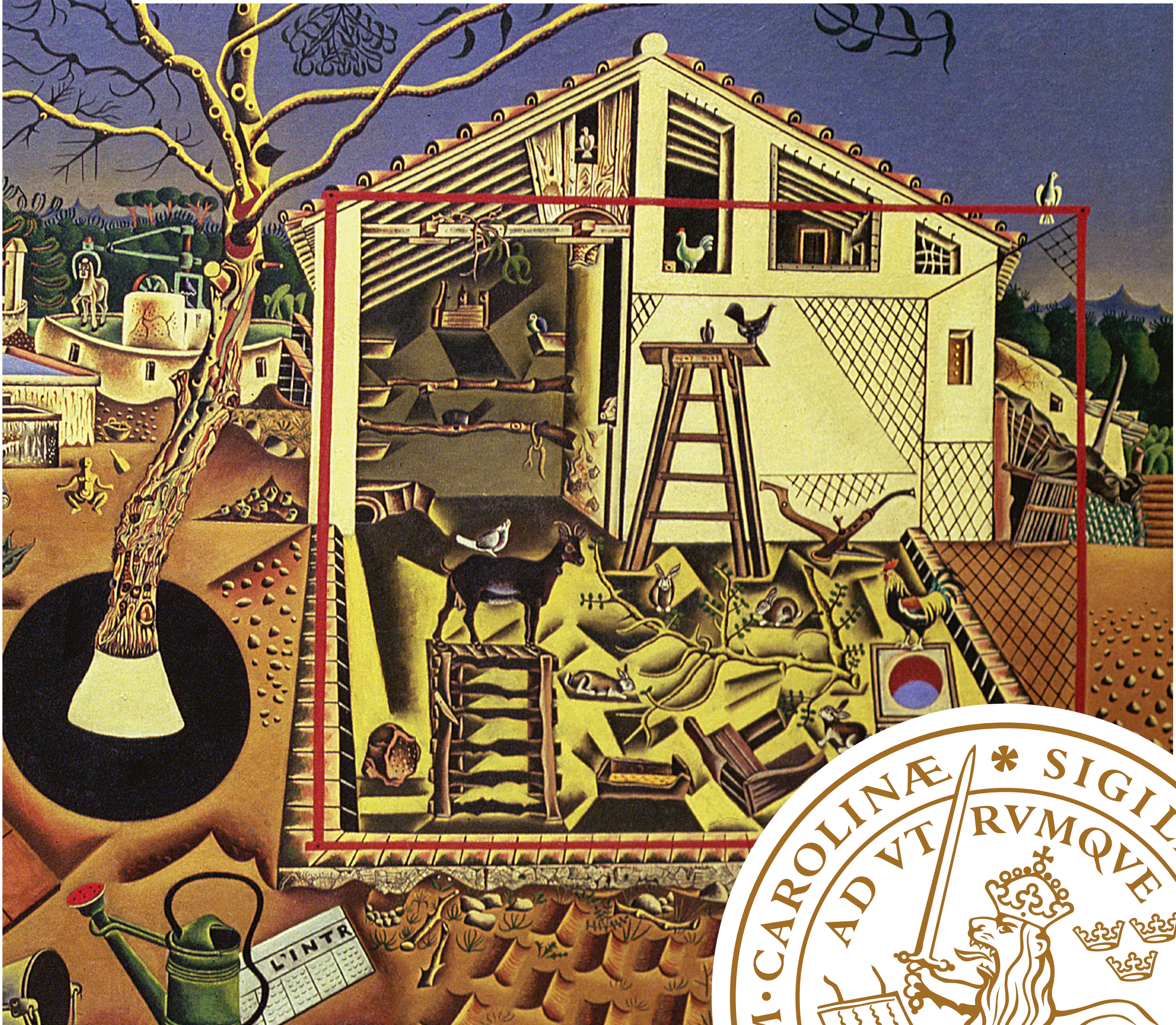
RAÜL LÓPEZ I LOSADA
CENTRE FOR ENVIRONMENTAL AND CLIMATE SCIENCE | LUND UNIVERSITY



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Joan Miró, La Ferme, 1921-1922

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Raül López i Losada

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DOCTORAL DISSERTATION

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Abstract:

The European Green Deal recognises the importance of addressing the environmental challenges posed by agriculture to meet the global biodiversity and climate agendas. Environmental policymaking is needed to drive and speed up sustainability transitions in agriculture because the environmental consequences of agricultural activities are not generally reflected in production costs and lead to market-driven production systems that are not delivering optimal outcomes for society. This thesis contributes scientific analysis for informing policymaking on the benefits and trade-offs of environmental measures concerning arable-land management, bioenergy crops with local soil co-benefits, a price on greenhouse gas emissions, and the removal of coupled income support to cattle.

Chapters 1 and 2 study the societal benefits of improving arable-land management across the EU. This is done with a systematic review and meta-analysis of time series data in long-term field experiments, reported statistics on farm management and economic valuation of C sequestration for climate-change mitigation. Results from chapter 1 show that combining crop rotations, reduced tillage, organic amendments and soil cover can effectively restore soil organic carbon stocks in intensive arable land in climatic regions where wheat can grow. Chapter 2 shows substantial variation in climate-change mitigation benefits from soil management improvements across the EU. This indicates substantial potential to enhance cost-effectiveness of a payment eco-scheme promoting C sequestration through soil management by basing payment levels on expected benefits rather than adoption costs.

Chapters 3 and 4 analyse the environmental implications of policy interventions that advance (at least some) aspects of the European Green Deal for agriculture, namely a subsidy to promote arable grass for bioenergy, a price on greenhouse gas emissions, and removal of the Coupled Income Support to cattle. Both regional and global environmental aspects are captured by linking agent-based modelling of farming regions and territorial Life Cycle Assessment. The environmental implications of policy interventions are strongly influenced by regional structure features, and in particular changes in relative productivity, which can vary widely between intensive and extensive farming regions in the EU. This confirms the importance of adapting environmental policymaking to regional conditions and supports the regional development of the 2023 reform of the Common Agricultural Policy, which also enhances national governance of the payment structure. Agent-based Life Cycle Assessment has thus the potential to speed up sustainability transitions in agriculture by contributing to identify the need or redundance of complementary policy interventions prior to implementation.

Key words:

carbon sequestration, CAP, crop-specialist holding, conservation agriculture, sustainable soil management, territorial LCA, carbon price, soil carbon, biofuel, arable grass rotation

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Raül López i Losada

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A threatened good becomes an explicit
urgent function to pursue.

S.J. Dundon

Table of Contents

Abstract

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Popular science summary

Agriculture increasingly relies on external inputs like pesticides and fertilisers to provide the world with food. This damages nature and in turn reduces its ability to support agriculture with pollination, pest control, and healthy soils. Not all agriculture is equally damaging, and in fact, there are many examples of good agricultural practices that contribute to preserve and restore nature. European policymakers agree that agriculture needs to be transformed to reduce its impact on nature and climate change. To help policymakers in designing policy actions that are good for society, science is needed to understand the costs and benefits of doing agriculture in different ways.

Soils are living ecosystems that are affected by the farming methods used in cropland. Good farming methods contribute to healthy soils, which increase yields and store more carbon. Storing carbon in soils is regarded as an important measure to fight climate change, but it is difficult to know how much more carbon good farming methods store over time. My thesis contributes to fill this gap by looking at many experiments in cropland that have measured carbon in soils over periods longer than 30 years. **Chapter 1** shows that some farming methods in cropland can increase carbon stocks in soils, and by how much. Following up on these results, **chapter 2** estimates how much carbon can be stored in croplands across the EU if all farmers were to implement good farming methods. A relevant finding from this chapter is that the amount of carbon that would be stored varies a lot between regions. This is an important insight for policymakers, because not all land would provide the same benefit to society and hence policy actions should be adjusted to reflect these differences.

Farming regions are shaped by thousands of individual farmers trying to make a living. Policy actions affect the decisions that farmers take in relation to their farm, e.g., whether to grow cereal crops or grass fodder. So, what will a farming region look like if there is a policy reform, say a price on greenhouse gas emissions, or a subsidy to include grass in crop rotations to promote carbon sequestration? **Chapters 3 and 4** study the effects of policy reforms in contrasting farming regions and implications for nature and climate change by simulating the behaviour of farmers and using life cycle assessment of environmental impacts. This allows to study the environmental impacts and benefits of policy reforms before they are implemented and contributes to faster transformation of agriculture by identifying concerns before they appear in reality. The results show that farming regions can respond very differently to the same policy reform, which supports a regional focus of policy action concerned with the transformation of agriculture.

List of chapters

This thesis consists of the following chapters:

Chapter 1

López i Losada, R., Hedlund, K., Haddaway, N.R., Sahlin, U., Jackson, L.E., Kätterer, T., Lugato, E., Jørgensen, H.B., Isberg, P. 2024. Synergistic effects of multiple "good agricultural practices" for promoting organic carbon in soils: A systematic review of long-term experiments. Submitted to Ambio.

Chapter 2

López i Losada, R., Brady, M.V., Wilhelmsson, F., Hedlund, K. 2024. Carbon sequestration potential from sustainable management of arable land in the EU. Manuscript.

Chapter 3

López i Losada, R., Rosenbaum, R.K., Brady, M.V., Wilhelmsson, F., Hedlund, K. 2024. Agent-Based Life Cycle Assessment enables joint economic-environmental analysis of policy to support agricultural biomass for biofuels. Science of the Total Environment. 916.

Chapter 4

López i Losada, R., Larsson, C., Brady, M.V., Wilhelmsson, F., Hedlund, K. 2024. Advancing sustainability transformations in agriculture: an Agent-Based LCA for supporting policymaking. Manuscript.

Author contributions to chapters

Chapter 1

The manuscript was written by **RLL**, NRH and KH, and all authors assisted in editing and revising the manuscript. NRH and KH conceptualised the study. NRH and HBJ performed the systematic review of data. KH developed the methodology. **RLL** performed the statistical analyses, produced scripts and curated the data supervised by KH and US. US developed the statistics methods.

Chapter 2

All authors conceptualized the study. **RLL** designed the methodology with input from all authors. **RLL** performed the analysis. **RLL** wrote the manuscript, and all authors contributed with editing and revisions.

Chapter 3

RLL and RKR conceptualised the study. **RLL** designed the methodology with input from MVB, FW, and KH. **RLL** performed the analysis with input from MVB for the agent-based modelling. **RLL** wrote the manuscript and curated the data. All authors contributed with editing and revisions.

Chapter 4

RLL and CL conceptualised the study with input from all authors. **RLL** and CL designed the methodology. **RLL** performed the environmental modelling and CL the economic modelling. **RLL** performed the analysis with input from CL. **RLL** and CL wrote the manuscript, and all authors contributed with editing and revisions.

Abbreviations

ABM	Agent-based modelling
CAP	Common Agricultural Policy
CR	Crop rotation
OA	Organic amendments
RT	Reduced tillage
SC	Soil cover
LCA	Life Cycle Assessment
GHG	Greenhouse gas
SOC	Soil organic carbon
CIS	Coupled income support
ILUC	Indirect land use change
JKP	Jönköping
GSS	Götaland's southern plains
WFDLB	World Food LCA Database

Introduction

Land is a limited resource with many competing interests. Croplands and managed pastures occupy roughly half of the non-barren and ice-free land surface of the world, making agriculture the largest economic sector by land use (Poore and Nemecek 2018). Beyond provisioning commodities, agriculture has shaped landscapes and ecosystems hosting biodiversity and providing ecosystem services that are valuable to society (Buttel 2003). Growing societal needs for food, fuels, and fibres from agriculture have been met over the last half century through management intensification (e.g., increased use of fertiliser and pesticide inputs, and irrigation) as well as clearing of land, predominantly high-biodiversity value forestland in the tropics (Fuchs et al. 2020). Agriculture is in consequence recognised as the main driver of terrestrial biodiversity loss globally (Dudley and Alexander 2017). The subsequent loss of ecosystem services, such as pollination, soil fertility, and pest control, further exacerbates the dependency of agriculture on external inputs. In addition, agriculture is the largest anthropogenic source of methane (CH_4) and nitrous oxide (N_2O) emissions, which mainly result from livestock rumination and manure, cropland fertilisation, and rice cultivation (Poore and Nemecek 2018). In a global context of climate emergency, CH_4 and N_2O emissions make prime abatement candidates due to their disproportionate effect on near-future radiative forcing (Ripple et al. 2024).

Large variability in resource use intensities and environmental impacts of agricultural commodities across regions and production systems suggests there is wide potential for improving the environmental performance of agriculture globally (Poore and Nemecek 2018). This indicates that better environmental outcomes are feasible in agriculture when paying attention to resource use intensities and natural capital. For instance, preserving soil health (defined by Lehmann et al. (2020) as *the capacity of the soil to function as a vital living ecosystem*) increases agricultural productivity while oftentimes at odds with conventional management intensification practices (Lal 2016). Preserving and restoring the natural capital that supports agriculture offers thus substantial potential to stabilise and enhance yields while reducing input dependencies and demand for additional agricultural land (Dudley and Alexander 2017, Báldi et al. 2023). Environmental transitions in agriculture are needed to ensure the preservation and restoration of the natural capital that supports it while also addressing other environmental concerns, e.g., the contribution of the agricultural sector to global GHG emissions and biogenic carbon storage (Duru et al. 2015, Poore and Nemecek 2018).

Informing policymaking that advances sustainability transitions in agriculture

The overarching aim of this thesis is to contribute scientific analysis to advance sustainability transitions in agriculture. The European Green Deal recognises the importance of addressing the environmental challenges posed by agriculture to meet the global biodiversity and climate agendas (Boix-Fayos and de Vente 2023). Market-driven agricultural production systems are not delivering optimal outcomes for society because their environmental consequences are not generally reflected in production costs (Schläpfer 2020). Environmental policymaking is thus needed to drive and speed up sustainability transitions in agriculture to fulfil societal ambitions for biodiversity and climate.

Environmental externalities of agriculture are substantial compared to the economic value of commodities provided (Chang et al. 2016, García de Jalón et al. 2018, Kay et al. 2019, Schläpfer 2020).This indicates that policy interventions devised to advance sustainability transitions in agriculture can have wide-ranging implications for farming regions and the environment. In addition, environmental measures in agriculture often show context-specific outcomes and come with trade-offs for society, such as increased production costs, or reduced outputs that can off-shore environmental pressures elsewhere (Fuchs et al. 2020, Renner et al. 2020). This leads to opportunities for mitigation of environmental damage that are highly variable across regions and require local solutions that are targeted according to the benefits and trade-offs that they generate (Bartkowski et al. 2021, Winberg et al. 2023). The inherent nature of arable and pasture land as a limited resource together with the many commodities and services that it is expected to deliver stress the importance to realise synergies and minimise trade-offs in agriculture (Haberl et al. 2011, Boix-Fayos and de Vente 2023). Identifying sustainability transition pathways that maximise societal welfare raises the challenge to assess environmental policy reforms with methods that can capture their benefits and trade-offs in connection with the environmental objectives of the European Green Deal (Alonso-Adame et al. 2024).

The focus of the analyses in the thesis concerns environmental impacts and benefits from policy measures that address relevant aspects of the sustainability transformation of agriculture in Sweden and the EU under the European Green Deal, namely: arable-land management improvements, arable grass for bioenergy, a price on GHG emissions, and removal of Coupled Income Support (CIS) to cattle. In particular, I estimate the effects of arable-land management practices on Soil

Organic Carbon (SOC) stocks in soils, which are an indicator of soil health and contribute C sequestration to climate-change mitigation, and I develop an ex-ante approach based on Agent-Based Modelling (ABM) and Life Cycle Assessment (LCA) to evaluate policy interventions in farming regions on their regional and global environmental implications.

Large-scale assessments of SOC stocks often fail to replicate observed trends or appreciate any effects induced by changes in soil management and require arbitrary counterfactual benchmarks because they are based on evidence that confounds relative and absolute changes or that is too short to appreciate effects on SOC from management (Sanderman and Baldock 2010, Haddaway et al. 2016, Bellassen et al. 2022, Zhou et al. 2023). Consequently, policy incentives promoting management improvements are most often based on adoption costs rather than (expected) environmental outcomes, which is detrimental to the cost-effectiveness of measures that are not necessarily placed where they would create the largest gain in societal welfare (Wätzold et al. 2016, Amelung et al. 2020, Sidemo-Holm 2022, Keesstra et al. 2024).

Multi-functional energy crops offer a promising source of biomass for bioenergy with local co-benefits that affects the provisioning function of the land replacing food and feed crops, which highlights the need for a careful analysis of the benefits and trade-offs they provide (Searchinger et al. 2022, Zegada-Lizarazu et al. 2022). Bioenergy is an important component of decarbonisation strategies in the EU compatible with the climate mitigation goals established in the Paris Agreement and the European Green Deal (European Commission et al. 2020). Agriculture provides promising biomass source in terms of potential additional volumes, technical readiness, and feedstock suitability to produce liquid and gas biofuels, which are versatile energy carriers essential to decarbonise the transport and industry sectors (Chiaramonti et al. 2021, Tsiropoulos et al. 2022). At the same time, grass and other lignocellulose energy crops can benefit the local environment, for instance by restoring SOC in intensively managed arable land (Brady et al. 2019, Englund et al. 2023). However, trade-offs can easily appear from strategies that rely on additional bioenergy production in agriculture (Miyake et al. 2012, Subramaniam et al. 2019, Khan et al. 2021).

Economic support coupled to cattle distorts production incentives and leads to increased production in an industry that accounts for a disproportionate share of the land use and GHG emissions from the agricultural sector compared to the value of food it provides in proteins and calories (Poore and Nemecek 2018). Conversely, a tax that internalises societal costs of GHG emissions into the profit function of the farm changes production decisions towards a (more) societally optimal resource allocation that could speed up the net-zero transformation of the agricultural sector in the EU cost-effectively. Removing Coupled Income Support (CIS) to cattle and pricing GHG emissions may also be regarded as removing artificial competitive drawbacks of agricultural bioenergy production under the existing policy framework (Gawel et al. 2019).

Soil C sequestration and soil health

Intensive arable cropping results in large losses of SOC from soils globally, thereby affecting the capacity of land to act as a carbon sink in climate change mitigation efforts (Oldfield et al. 2019). Declining SOC trends also indicate deteriorating soil health, which has negatives consequences for soil fertility and agricultural yields (Lal 2016). In the EU, the benefits that soil improvements could bring to societal welfare are contemplated across a wide range of policy goals under the European Green Deal, including C sequestration for climate-change mitigation, food security, water quality, and nature restoration (Boix-Fayos and de Vente 2023). The potential of croplands for SOC gains is considered particularly large due to the substantial losses that arable soils have endured since agriculture was established, with recent estimates suggesting that 50 % to 70 % of the initial SOC stocks have been depleted globally (Zomer et al. 2017).

Improving soil health provides latent synergies between climate change mitigation and the safeguarding of agricultural yields. Long-term agricultural experiments spanning many decades provide evidence that arable-land management affects SOC stocks, and that management interventions (among which, reduced tillage, organic amendments, crop rotations, and soil cover) can mitigate SOC decline, thereby enhancing soil health (Bremer et al. 1995, Droste et al. 2020, Nilsson et al. 2023). While the environmental benefits of management improvements for the soil are qualitatively broad, their potential for preserving and restoring SOC stocks remains challenging to quantify. SOC stocks in arable land display large inherent variability across spatiotemporal scales due to climatic conditions and soil characteristics that make it challenging to infer effects from agricultural practices (Wang et al. 2021). In addition, SOC stock development from a change in land use or management occurs over the span of decades, and many field experiments measure SOC effects as a single point in time compared to a control (Sanderman and Baldock 2010, Haddaway et al. 2016). This confounds relative and absolute change, i.e., a management improvement can show a relative increase in SOC, or avoided SOC loss, compared to a control but still result in net loss of SOC stocks over time.

Net SOC change rates, defined as change in SOC stocks over time (Don et al. 2024), can be obtained from long-term field experiments that record SOC over decades (Sanderman and Baldock 2010, Haddaway et al. 2016, Le Noë et al. 2023). These independent time series allow estimation of effects on SOC stocks over time from management improvements. Basing payments on (expected) environmental outcomes rather than costs of interventions enhances cost-effectiveness of policy incentives in conservation efforts (Bartkowski et al. 2021, Sidemo-Holm 2022).

Spatial targeting of environmental policy instruments

Spatial targeting is an important aspect to guarantee cost-effectiveness of environmental policymaking in agriculture given that environmental outcomes from conservation measures are highly variable depending on their local context. Targeting policy interventions by regions or farm types aligns with the regionalisation objective of the CAP and contributes to preserving societal trust with measures that are based on (expected) environmental outcomes (Pe'Er et al. 2020).

Agent-Based Models (ABMs) of farming regions are increasingly used in the study of sustainability transitions in agriculture due to their ability to capture non-linear change in complex systems with heterogeneous actors in a wide range of spatio-temporal scales (Alonso-Adame et al. 2024). These models operate under the paradigm that changes in agricultural land use and production are phenomena that emerge from the decision-making processes of individual farmers coexisting in large and heterogeneous communities, and interacting over time with each other and the environment (Brown et al. 2021). Under this modelling paradigm, environmental policy interventions in agriculture induce regional change by modifying the decision-making process of individual farmers with either regulatory or economic incentives (Piorr et al. 2009).

ABMs are often coupled with environmental models to enhance their suitability for environmental analysis (Alonso-Adame et al. 2024). Life Cycle Assessment (LCA) is a common methodology for comparing the environmental performance of production systems (Muralikrishna and Manickam 2017), and an adaptation (Territorial LCA) has developed in recent years for analyses that are linked to a defined geography (Loiseau et al. 2018). Coupling ABM and Territorial LCA enables analyses of the environmental implications of policy reforms affecting land use and production of farming regions (Vázquez-Rowe et al. 2014).

A challenge in linking ABM and Territorial LCA for the environmental evaluation of policy reforms concerns market effects of varying agricultural outputs in a global production system with limited land availability, often framed as Indirect Land Use Change (ILUC) (Searchinger et al. 2008). ILUC plays an important role in the environmental evaluation of bioenergy even though agricultural bioenergy represents a minor share of agricultural land in use (Sumfleth et al. 2020). Regional sustainability transitions in agriculture can have substantial effects on land use and production levels of agricultural commodities, and their climate-mitigation benefits cannot be taken for granted if production displacement effects lead to carbon emissions from deforestation and soil losses (Daioglou et al. 2020). ILUC also results in other environmental or socio-economic impacts, such as depletion of water resources, conventional agricultural intensification or rising food prices that mostly impact communities not directly benefiting from these transitions (Vera et al. 2022). Environmental leakage is thus an important aspect in the evaluation of environmental policy reforms that substantially affect land use and production regionally, yet ABMS are tools designed for regional policy analysis that do not model changes in global agricultural production.

Thesis aim

This thesis aims to provide scientific analysis to advance sustainability transitions in agriculture under the European Green Deal. All chapters in this thesis aim to support policymaking by evaluating the environmental benefits and impacts of policy measures, though they vary in methods, spatial scale of the analysis and environmental aspects considered (Figure 1).

Chapters 1 and 2 concern the management of arable-land for **SOC restoration,** whereas **chapters 3 and 4** are focused on the ex-ante analysis of policy instruments to promote European Green Deal goals. These include a payment for arable grass for bioenergy with co-benefits for soil health in **chapter 3** and a price to GHG emissions and the removal of coupled support to cattle in **chapter 4.**

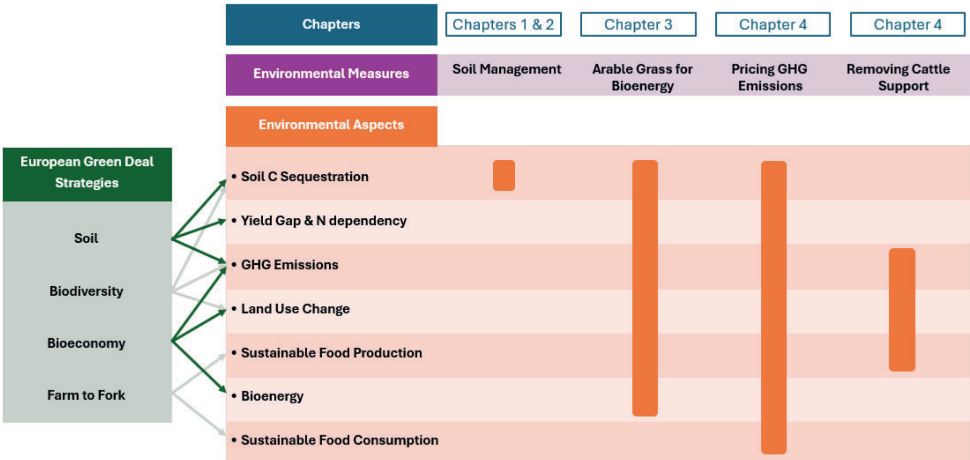

Figure 1. Overview of chapters in the thesis and their linkages with the European Green Deal

These policy measures were selected based on their potential to affect regional land use and production development, and their interlinkages to relevant aspects of the sustainability transformation of agriculture in Sweden and the EU. Bioenergy, soil health and GHG emissions are all relevant components of different strategies comprised within the European Green Deal that relate to the agricultural sector. In addition, the relevance to policymakers of the measures in focus is also inferred from similar interventions being discussed in Sweden and the EU. A payment for grass leys was recently removed in Sweden (Swedish Board of Agriculture 2021), Denmark has reached a political agreement to price GHG emissions in agriculture (Svarer et al. 2024), and the European Commission (2024) has relaxed soil conditionality requirements for Basic Income Support for Sustainability (BISS), and also cited coupled support to cattle and the lack of counterbalance measures to reduce GHG emissions from livestock as a reason to request Sweden to enhance its climate mitigation ambitions in the livestock sector (European Commission 2022).

Soil management for C restoration

Chapter 1: *What is the effect of arable-land management on soil organic carbon stock development over time?*

Chapter 1 performed a systematic review of time series of SOC measurements in long-term field experiments spanning over 30 years and estimated the effects of arable-land management suites on SOC stocks with a meta-analysis. The aim of this chapter was to identify management suites that effectively increase SOC stocks to mitigate climate change and safeguard yields.

Chapter 2: *What is the potential for improvements in arable-land management to enhance soil organic carbon across arable land in the EU?*

Chapter 2 analysed the societal benefits of C sequestration in arable-land from management improvements across the EU with evidence from the long-term experiments in chapter 1 and regional farm statistics. This chapter aimed at supporting the spatial targeting of EU-wide environmental policy interventions promoting arable-land management improvements for C sequestration in soils.

Chapters 1 and 2 predominantly support the Soil and Biodiversity strategies of the European Green Deal (Council of the European Union 2021, European Parliament 2021).

Ex-ante analysis of policy instruments to promote European Green Deal goals

Chapter 3: *Is a subsidy promoting grass leys in intensive arable land beneficial for the environment when considering regional soil health, bioenergy potential and crop displacement effects?*

Chapter 3 analysed the environmental lifecycle implications of a payment to grass leys in intensive arable land in Sweden considering regional land use change and soil benefits, additional biomass for bioenergy, and crop displacement effects. The aim of this chapter was to contribute to the environmental assessment of agricultural bioenergy covering both regional and global aspects of sustainability.

Chapter 4: *What are the environmental implications of pricing greenhouse gas emissions and removing cattle support towards achieving the objectives of the European Green Deal for agriculture?*

Chapter 4 modelled regional land use and production changes resulting from pricing GHG emissions and removing coupled income support to cattle and analysed them in connection to the environmental objectives of the European Green Deal for agriculture. The aim of this chapter was to analyse how these measures would affect the transformation of agriculture towards the European Green Deal objectives and the influence of regional agricultural structure on policy outcomes.

Chapters 3 and 4 present connections to all major environmental strategies of the European Green Deal that are relevant for agriculture, name the Soil, Biodiversity, Bioeconomy and Farm to Fork strategies (European Commission 2018, European Commission 2020, Council of the European Union 2021, European Parliament 2021).

Method

Effects of management on SOC stocks

This section provides a summary of methods used in **chapters 1 and 2**:

- **Chapter 1**: "*Synergistic effects of multiple "good agricultural practices" for promoting organic carbon in soils: A systematic review of long-term experiments*"
- **Chapter 2**: "*Carbon sequestration potential from sustainable management of arable land in the EU*"

In **chapters 1 and 2** of this thesis, I estimated the potential for C sequestration from improved management on intensive arable land in the EU with evidence from time series data from long-term field experiments. **Chapter 1** conducted a systematic review of long-term field experiments and meta-analysis of management effects on SOC in alignment with a published protocol (Haddaway et al. 2016). Building on **chapter 1**, **chapter 2** combined meta-analysis results on the effects from management suites on SOC stocks with farm management statistics from 2016 provided by Eurostat (2024) to estimate recent SOC stock trends and value potential SOC gains from management improvements across intensively-farmed arable land in the EU.

The systematic review in **chapter 1** searched for arable field experiments with at least 3 temporal replicates of SOC stocks or concentrations spanning not less than 30 years to be able to appreciate management effects on SOC stocks beyond exogenous variability. The search was limited to field experiments established in climatic conditions favourable to grow wheat, i.e. warm temperate climate zones (including bordering semi-arid zones), and the snow climate zone according to the Köppen-Geiger climate classification (Beck et al. 2018).

Estimates of the net SOC change rate for individual time data series were obtained from a log-linear model function:

$$\ln(y) = a * t + b$$

where y is SOC level (as a stock or concentration), t is time (years from 0, i.e. the time of the first measurement), b is the intercept parameter for initial SOC level at t=0, a is the parameter for the yearly net rate of change.

The meta-analysis was performed with the *rma.mv* function within the *metaphor* package in R (Viechtbauer 2010) It used a mixed-effect model to estimate the average effect of different types of interventions on the net rate of SOC change with categorical factors (Table 1). A unique study ID assigned to individual experiments based on their experimental facility was included as a random effect to account for exogenous variability from, e.g., climatic conditions, soil characteristics, or experimental bias.

The log-linear model of choice explained a considerable part of the variation in the response variable for most data sets, although with large variability across individual data sets, and a minority (23 %) showing an R-square of less than 0.3. Consequently, the meta-analysis approach used in this study weighted individual time data series with the inverse-variance method, assigning more weight to the studies with a lower standard error of the mean.

Management type	Categorical values in meta-analysis	Interventions considered in Eurostat
Tillage	High - Reduced	Reduced tillage - No tillage
Rotation*	Monoculture - Rotation - Improved rotation	Crop rotation
Fallow**	Fallow - Soil Cover	Winter crop - Intermediate crop - Crop residues - Perennial crop
Amendments	None - Organic	Crop residues - Intermediate crop - Livestock presence***
Inorganic fertiliser	Without - With	Not considered

Table 1. Categorical values assigned to the different groups of management practices and Eurostat data categories considered across each type of intervention for sustainable soil management.

*A field is considered as a monoculture if it has the same crop every year, and as a rotation if it has any combination of different crops across the years. Improved rotations contain grasses or legumes.

**Fallow comprises experimental plots where soil is tilled and left bare, either continuously or as a summer fallow.

***Livestock presence is used as a proxy for addition of manure. Further details are provided in the Appendix of **chapter 2**.

Motivated by the results from **chapter 1** that combination of good management practices effectively restores SOC in intensive arable land, **chapter 2** valued the potential benefit to society from improving management in terms of C sequestration for climate-change mitigation. For this, I estimated adoption levels of Crop Rotations (CR), Reduced Tillage (RT), Organic Amendments (OA), and Soil Cover (SC) practices across NUTS2 regions (i.e., territorial units used to report statistics in Eurostat) in the EU by combining farm statistics from Eurostat (Table 1). Since manure data is not recorded in Eurostat, I used livestock statistics and profit-maximising assumptions to estimate manure application rates. This approach is described in the Appendix of **chapter 2**.

Subsequently, I combined regional soil management information into a simple average of the adoption levels of all four types of interventions. This simplification assumes that all practices contribute similarly to SOC, which is motivated by findings in **chapter 1**, where I show that combining an increasing number of interventions is more decisive for SOC enhancement than which types of interventions (Figure 4 in the results section). **Chapter 2** thereafter estimated average net SOC change rates across NUTS2 regions for an increasing number of interventions based on findings from **chapter 1**. Together with spatial information on SOC stocks in arable land from the LUCAS soil dataset (Orgiazzi et al. 2018) and the average price for European Carbon Permits in 2023 (86 EUR per tonne C emitted), I calculated regional SOC development from contemporary soil management, potential for improvement from full implementation of CR, RT, OA, and SC in intensively-farmed arable land, and the economic value to society of changes in SOC stocks for climate-change mitigation in both scenarios.

Coupling ABM and LCA for environmental policy analysis

This section provides a summary of methods used in **chapters 3 and 4**:

- **Chapter 3**: "*Agent-Based Life Cycle Assessment enables joint economic-environmental analysis of policy to support agricultural biomass for biofuels*."
- **Chapter 4**: "*Advancing sustainability transformations in agriculture: an Agent-Based LCA for supporting policymaking*"

Chapters 3 and 4 of this thesis analysed land use and production changes in farming regions resulting from policy interventions in the ABM AgriPoliS and their subsequent environmental implications from a territorial lifecycle perspective, considering regional environmental conditions and production displacement effects (Balmann 1997, Happe et al. 2006, Loiseau et al. 2018). **Chapter 3** evaluated the environmental performance of a policy intervention promoting grass leys in intensive arable land considering the grass potential for bioenergy production, soil co-benefits, and displacement of arable crop production. **Chapter 4** analysed the environmental implications of direct payments to cattle and pricing GHG emissions analogously to **chapter 3** and introduced a set of indicators linking the modelling output to objectives from the European Green Deal for agriculture for a comprehensive evaluation across stated policymaker preferences.

AgriPoliS simulates land use development, agricultural production, and farm structure in a farming region as phenomena emerging from farms´ optimising decision-making and dynamic interactions over time (typically 15-20 year periods).

In AgriPoliS, farmers make decisions over yearly time steps aiming at maximising their profit, which assumes rational economic behaviour. Other behavioural factors (e.g., environmental consciousness or risk aversion) are not directly simulated but assumed to be captured in the empirical calibration of the model with regional farm statistics. AgriPoliS reproduces observed land uses, livestock holdings and structural change over time with realistic trends (i.e., <10% deviations from observed structural statistics such as numbers of different livestock and types of farms). AgriPoliS simulations are limited to the farming region in scope, and cannot possibly account for the development of global production of agricultural commodities. AgriPoliS results should therefore be interpreted as likely representations of the implications of policy interventions on the economic structure of farming regions, all else equal (Brown et al. 2021).

AgriPoliS modelling in this thesis considered two Swedish farming regions, Götaland's southern plains (GSS) and the county of Jönköping (JKP) (Figure 2), which serve as representative cases for intensive and extensive agricultural regions at EU level. GSS is characterised by intensive cropping on large continuous arable fields with high productivity and low presence of arable grasslands and pastures. In contrast, JKP is dominated by extensive livestock production, less productive arable land, and high presence (~75 %) of grass in arable crop rotations. **Chapter 3** includes AgriPoliS modelling of GSS, whereas both GSS and JKP are included in **chapter 4**.

All policy interventions analysed in **chapters 3 and 4** of this thesis are economic instruments that affect regional land use and production of agricultural commodities by changing the income maximisation function of farms (Table 2). The environmental performance of a policy intervention was considered as that of the farming region where it is introduced in comparison to a business-as-usual scenario. Comparing a farming region at a given point in time in the presence and absence of a policy intervention allowed one to differentiate the regional effects from the policy instruments from other regional dynamics.

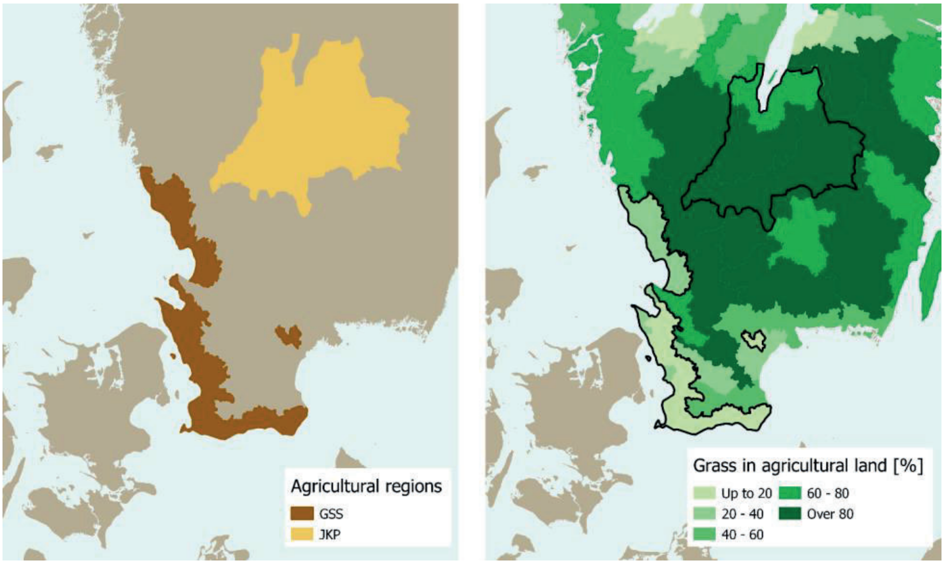

Figure 2. The agricultural regions of GSS and JKP in southern Sweden (left). Grass coverage of total agricultural land in the yield regions of southern Sweden (right).

Paper	Region	Scenario	Policy intervention
B1 & B2	GSS	BAU	Business as usual development of the region
B1	GSS	GRASS	A hectare payment for grass leys in intensive arable land
B2	GSS	-CIS	Removal of Coupled Income Support to cattle
B2	GSS	-CIS+TAX	A price on GHG emissions that considers enteric methane from grassfed livestock and SOC changes in intensive arable land
B2	JKP	BAU	Business as usual development of the region
B2	JKP	-CIS	Removal of Coupled Income Support to cattle
B2	JKP	-CIS+TAX	A price on GHG emissions that considers enteric methane from grassfed livestock only

Table 2. Overview of AgriPoliS scenarios simulated in **chapters 3 and 4**

AgriPoliS was coupled to LCA modularly. Output production and land use from AgriPoliS simulations informed the Life Cycle Inventory stage of a territorial LCA covering the entire agricultural production of the region in scope (Figure 3). To evaluate the environmental performance of policy interventions, I compared regional outcomes in their presence as opposed to business-as-usual. **Both chapters** assumed fixed-consumption, meaning that decreases in production regionally were compensated with increased imports nationally. The Functional Unit for both studies can be roughly defined as:

"Maintaining global provision of agricultural commodities in the last year of the simulation period via local production and imports"

This FU differs from previous AB-LCA studies that consider regional production only (Ding and Achten 2022, Marvuglia et al. 2022). The approach in **chapters 3 and 4** includes production displacement effects resulting from a decrease in production of agricultural commodities in GSS and JKP as part of the concerns of the policymakers.

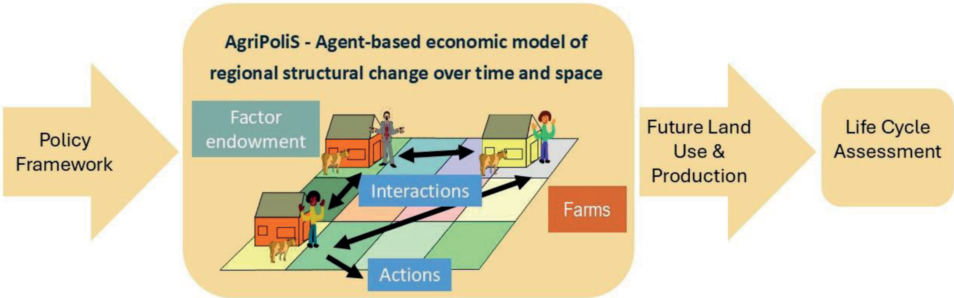

Figure 3. Conceptual coupling of AgriPoliS and LCA. AgriPoliS representation taken from Happe (2004)

Results and discussion

SOC benefits from management improvements

The systematic review in **chapter 1** gathered 209 long-term time data series comprising a wide range of climatic conditions, soil textures, and management suites. The meta-analysis results show relatively weak effect estimates for individual interventions, given that any time data series with one type of intervention also included a broad range of practices under the other management groups. However, when considering pairs of interventions across management groups, reduced tillage (Thapa et al. 2023) , crop rotations (Englund et al. 2023), use of amendments (Bai et al. 2018), and avoiding bare fallow, all showed a significant potential to lower SOC loss in alignment with previous studies (Han et al. 2016, Bolinder et al. 2020, Lessmann et al. 2022). In addition, this study found stronger effects on SOC from the combination of multiple interventions than for specific management suites (Figure 4), and that applying all four interventions simultaneously achieves restoration of SOC stocks over time. This is the basis for estimating potential SOC gains from improved management in **chapter 2**.

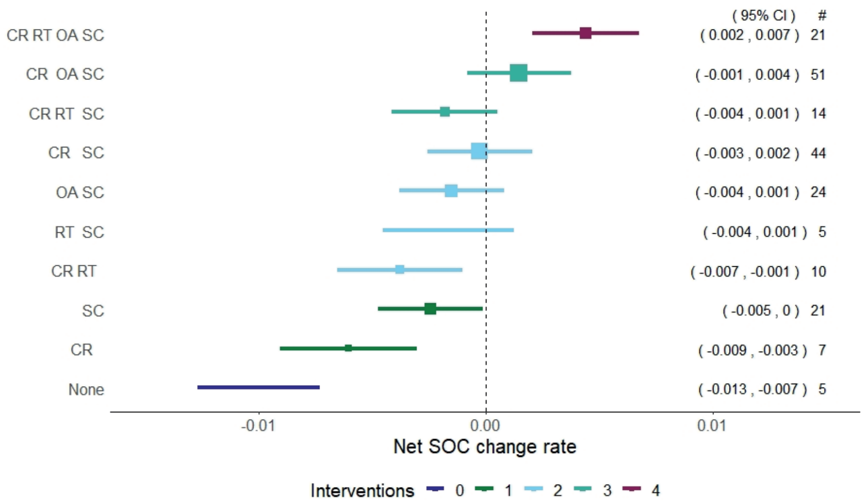

Figure 4. Net SOC change rate estimates for an increasing number of interventions. The size of the squares is proportional to the number of time series represented in each category, which is reported under #. Bars correspond to the 95% confidence interval of the effect, which is reported in ( ).

Focusing on long-term data series with high power evidence enabled the prediction of relatively narrow estimates of management effects on net SOC change rates. This was done with an evidence pool with wide ranging climatic conditions, soil textures and management norms that cover conditions across all arable regions in the EU. Subsequently, **chapter 2** estimates net SOC stock change and potential for improvements in intensively-managed arable land across the EU, in combination with reported statistics on arable land management from Eurostat (2024). This chapter highlights that intensive arable land in crop specialist farms in the EU has recently lost substantial SOC stocks, though losses are concentrated in roughly 40 % of the regions. In addition, the value of sustainable soil management in terms of C sequestration varies substantially (4-fold) across regions in Europe (Figure 5). This implies a large potential to enhance cost-effectiveness of an eco-scheme payment for carbon farming by regionalising payment levels according to expected benefits.

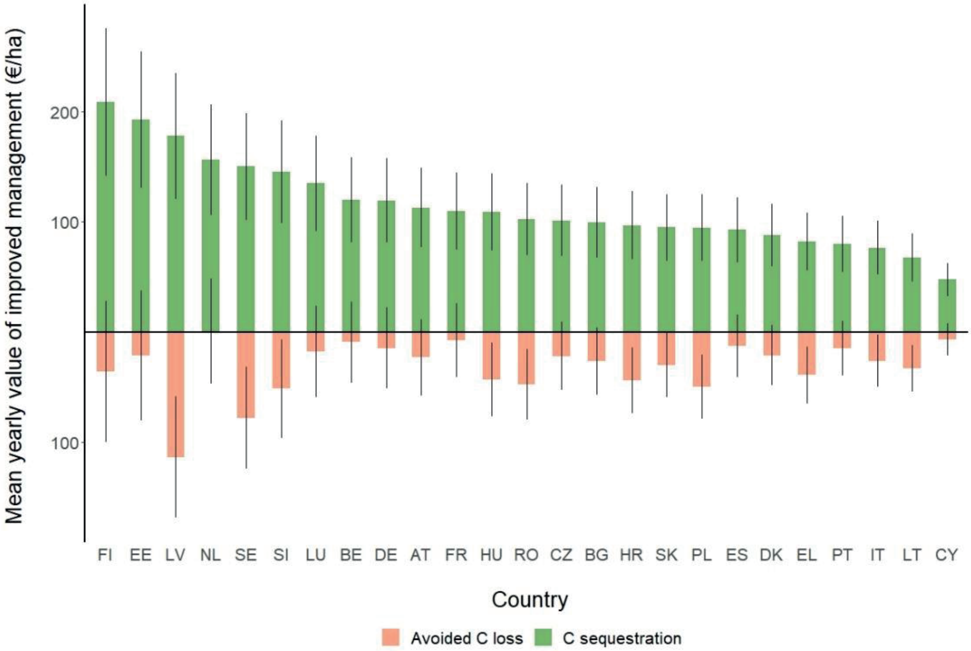

Figure 5. Value of management improvements in 25 EU countries. Malta and Ireland are excluded from our analysis.

Environmental analysis of regional policy interventions

Regional farm-structure features, particularly relative profitability of production activities and the presence (or absence) of economically viable alternatives, show substantial influence on the outcome of policies for land use and production. In **chapter 3**, grass leys expand in intensive arable land when the subsidy makes them more profitable than barley. In **chapter 4**, the removal of the CIS shows a larger decrease in cattle in GSS due to the absence of viable alternatives in JKP. A decline in profitability of livestock due to a price on GHG emissions results in decreasing livestock numbers and arable grasslands in both regions. Arable land in active use also decreases in JKP, thus indicating that the agricultural viability of the land is tightly linked to the presence of livestock in this region.

In **chapter 3**, the regional lifecycle benefits from SOC improvements are lower than the impacts from displacing crop production towards less efficient regions. Actively using grass biomass is essential for a positive environmental evaluation of the payment to grass leys, which is largely due to the low impacts of grass compared to other arable crops. This approach assumes production of grass biomass to replace arable crops that are still in use in Sweden for biofuels. Contributions from (mostly imported) crops account for 25 % to 37 % of Swedish consumption of liquid and gas biofuels other than black liquor from the pulp industry (Swedish Energy Agency 2021). While this comparison has a substantial influence on the LCA results, a similar conclusion could be extracted if, e.g., grass biomass was actively used in the production of high-protein feed to replace soy and grain feed (Jørgensen et al. 2022).

Results from **chapters 3 and 4** show that containing the displacement of production abroad becomes critical for the environmental lifecycle performance of interventions causing substantial production changes, given the low environmental impacts of Swedish production compared to global averages (Martin and Brandão 2017, Nordborg et al. 2017). This analysis requires comparison of agricultural production from Swedish farming regions and other areas of the world. Our modelling approach relies on lifecycle inventory data on agricultural activities outside of Sweden from the World Food LCA Database (WFLDB) and Ecoinvent, thereby implicitly including all their modelling assumptions (Frischknecht et al. 2005, Nemecek et al. 2014). Among these, N_2O emissions from fertiliser application and biogenic carbon emissions from ILUC are covered in LCA with a range of modelling paradigms exhibiting large variability (Daioglou et al. 2020, Henryson et al. 2020). Only a few inventory inputs in Swedish activities are modified according to regional statistics to account for differences in yields and use of fertiliser and water resources. Other inventory inputs could have been further refined, e.g., N_2O emissions from liquid slurry manure management systems in cold climates in the WFLDB are too high according to scientific evidence used in the Swedish inventory of GHG emissions (Rodhe et al. 2015, Swedish Environmental Protection Agency 2022). However, the comparative LCA approach used in this thesis limits conflicting modelling assumptions between Swedish and non-Swedish production of agricultural commodities to reduce systematic bias. At large, the environmental impacts of global agricultural commodities from main producing countries according to WFLDB and Ecoinvent highlight documented environmental concerns related to resource use efficiency, productivity and deforestation (Martinelli et al. 2010, Fuchs et al. 2020, Bawa and Seidler 2023).

Chapters 3 and 4 assume fixed-consumption and even out different production levels across scenarios with imports from a global supply of agricultural commodities, the modelling of which is outside the scope of agricultural ABMs like AgriPoliS. Accounting for changes outside the region in scope poses a scale challenge, given magnitude differences between production levels in an ABM of a farming region and what would be meaningful to compute in a global trade model (Vázquez-Rowe et al. 2014). At the same time, AgriPoliS simulates structural change in representative regions, but environmental policy interventions could (and reasonably would) be devised at larger scales and cause global effects (Jansson et al. 2021, Jansson et al. 2024). **Chapter 3** performs a sensitivity analysis on the origin of the consumption of agricultural products, which finds some effect on the LCA results that are largely driven by the effect of replacing intensive crops with grass as a biofuel feedstock. In **Chapter 4**, a sensitivity scenario introducing sufficiency thinking in the definition of the Functional Unit relaxes the fixed-consumption assumption introducing a price increase and market elasticities for livestock products (Säll and Gren 2015, André 2024, Jansson et al. 2024). Avoided consumption of livestock products does not occur at a magnitude that would compensate for an increase in environmental impacts from displaced production in Sweden.

	Change relative to BAU (-)			
Indicator	-CIS		-CIS+TAX	
	GSS	JKP	GSS	JKP
Additional biomass for bioenergy	0.01	0.03	1.55	0.03
Preservation of Soil Organic Carbon	0.00	N.A.	1.04	N.A.
Reduction of N emissions	0.00	0.02	0.29	0.31
Reduction of pesticide emissions	0.00	0.02	0.23	0.31
Environmental productivity	-0.02	-0.05	0.12	0.25
Abatement of global biodiversity damage	-0.02	0.00	0.09	-0.19
Preservation of seminatural pastures	0.00	-0.01	-0.04	-0.22
Abatement of global GHG emissions	-0.03	0.00	-0.03	-0.39
Change in arable land in productive use	0.00	-0.02	0.07	-0.40

Figure 6. Heat map showing positive (green) and negative (red) contributions (above and below zero, respectively) to policy goals in the European Green Deal from structural changes in -CIS and -CIS+TAX relative to BAU, for GSS and JKP regions. Grey cells indicate not assessed.

Chapters 3 and 4 illustrate that sustainability transitions in agriculture can lead to substantial changes in the land use and production structure of farming regions in the EU. These changes can have wide-ranging implications across the environmental goals of the European Green Deal (Figure 6). Yet less intensive land use and decreases in production in farming regions in the EU are not necessarily desired pathways to achieve (at least some of) these objectives (Möhring et al. 2020). In a context of climate and biodiversity crises where many transitions are expected to occur in parallel in agriculture, this opens the question about how European Green Deal objectives are formulated. The approach developed in **chapters 3 and 4** provides a systems method that integrates environmental sciences and economics perspectives to contrast regional and global environmental impacts of policy interventions in farming regions. Hopefully this work improves scientific input for policymakers on how to best utilise available land to fulfil food, energy, and environmental needs under the European Green Deal.

Suggestions for future research

The approach in **chapter 1** can be expanded with data from additional long-term field experiments. Recent measurements of SOC across many field experiments in North America as part of the NAPESHM project could substantially expand the number of long-term data series fulfilling inclusion criteria and reflect relatively novel practices such as cover crops (Peng et al. 2023). The data gathered in **chapter 1** also contributes to cover a need identified in the literature for independent time series to support validation processes in dynamic SOC models (Le Noë et al. 2023). This could be particularly insightful to understand the interactions between arable-land management and climate change.

Shifts in soil management can bring about contrasting short- and long-term effects on yields, fertiliser needs and operational requirements that are substantial (Pittelkow et al. 2015, Oldfield et al. 2019, Nilsson et al. 2023). For instance, **chapter 2** identified the lack of incentives to distribute manure between farms that produce it abundantly and farms that lack it within the same region, transportation distance and subsequent costs and emissions are critical aspects regarding the feasibility and overall climate-change mitigation potential of manure redistribution that are not included in this study (Lötjönen et al. 2020). Life Cycle Assessment (LCA) can build understanding of the relative importance from each of these aspects regarding the climate change mitigation potential of conservation practices, thereby contributing to identifying best performing alternatives and their drivers.

AgriPoliS is an empirically validated ABM that is able to reproduce observed trends in land use and production in farming regions but requires large data gathering and modelling efforts. In a context where substantial environmental policy reforms adapted to farming regions are expected (Pe'er et al. 2019, Pe'Er et al. 2020), a question arises on how ABM modelling efforts can be optimised to cover the regional ambitions of the new CAP and the green deal. Conceptualising paradigms of farming regions in the EU based on farm structure and behaviour can perhaps contribute to identify relevant regions to model in ABMs and to generalise insights. In addition, the nexus between ABM, LCA and global trade models offers promising complementarities for the analysis of policy interventions in agriculture (Beaussier et al. 2019). A challenge of scale remains on how to couple ABMs of farming regions with global trade models.

Conclusions for future policymaking

I would like to conclude with a point summary of what I find to be the most relevant implications for future policymaking from this work:

- Combining crop rotations, reduced tillage, organic amendments and soil cover can effectively restore SOC stocks in intensive arable land in climatic regions where wheat can grow. Any of these practices on its own would prevent some SOC loss, but net gains are only achieved when all are present. Policy promoting good soil practices in intensive arable land can enhance SOC stocks while incurring lower production displacement effects than introducing bioenergy crops.
- Climate change mitigation benefits from soil management improvements vary substantially across the EU due to varying management norms and SOC capital. Larger SOC stocks exacerbate absolute C gains or losses from a given management suite. Basing an eco-scheme payment for carbon farming on expected benefits would therefore substantially enhance its cost-effectiveness.
- The loss of income support by farmers not fulfilling soil management conditionalities is substantially larger than the societal benefit of climate-change mitigation generated by the improvements. This finding supports a reformulation of the conditionalities on soil management so that they only affect a fraction of the income support
- Introducing grass leys in intensive arable land can yield environmental benefits if grass is actively used for biofuel production replacing other feedstock sources. Soil organic carbon benefits do not compensate the negative effects of displaced production of arable crops. Regional bioenergy markets that can absorb grass production are therefore important for the environmental performance of the incentive.
- The environmental implications of policy interventions are strongly influenced by regional structure features, and in particular changes in relative productivity, which can vary widely between intensive and extensive farming regions in the EU. This confirms the importance of adapting environmental policymaking to regional conditions and supports

the regional development of the 2023 CAP reform, which also enhances national governance of the payment structure.

- Agent-Based LCA has the potential to speed up sustainability transitions in agriculture by contributing to the identification of the need or redundance of complementary policy interventions prior to implementation.
- Displacement effects lead to substantial environmental leakage given the low impacts of Swedish production compared to global averages. Flanking bioenergy policy with local soil co-benefits can contribute to mitigate environmental leakage with policy interventions that substantially reduce the output levels of GHG-intense commodities.
- Avoided consumption of animal products from a price increase in Sweden is unlikely to counter environmental impacts from displaced production, based on Swedish market elasticities. Measures to advance sustainability transitions in agriculture under the European Green Deal risk off-shoring regional environmental degradation and result in higher GHG emissions unless parallel transitions occur in consumption.

Beyond the research contributions of my work, this is a final note based on my personal research experience:

My work with AgriPoliS is possible thanks to spatially-explicit data on farm holdings that is collected yearly by the Swedish Board of Agriculture and entrusted to the Centre for Environmental and Climate Science for research purposes. While all EU countries collect similar data as part of the Integrated Administration and Control System (IACS), this data is often not available for research in other EU countries. I hope my work highlights the influence of regional farm structure on policy outcomes, and thereby the relevance of research access to IACS data across the EU in a context where sustainability transitions in agriculture are urgent to fulfil global climate and biodiversity ambitions.

Acknowledgements

I am writing this section as I ride the train over the Öresund bridge to print my thesis. I slept in a bit this morning, and it is already as bright as it gets on a winter morning in Copenhagen – so not that much, really. It is a calm winter day with no trace of fog, which creates a sight of the open sea over the bridge that befits the moment. The beginning of closure to a five-year journey that has brought me through paths that I did not know existed and hundreds of trips over this bridge. I find this to be the right moment to reflect on gratitude, for a doctoral thesis is certainly not an individual project.

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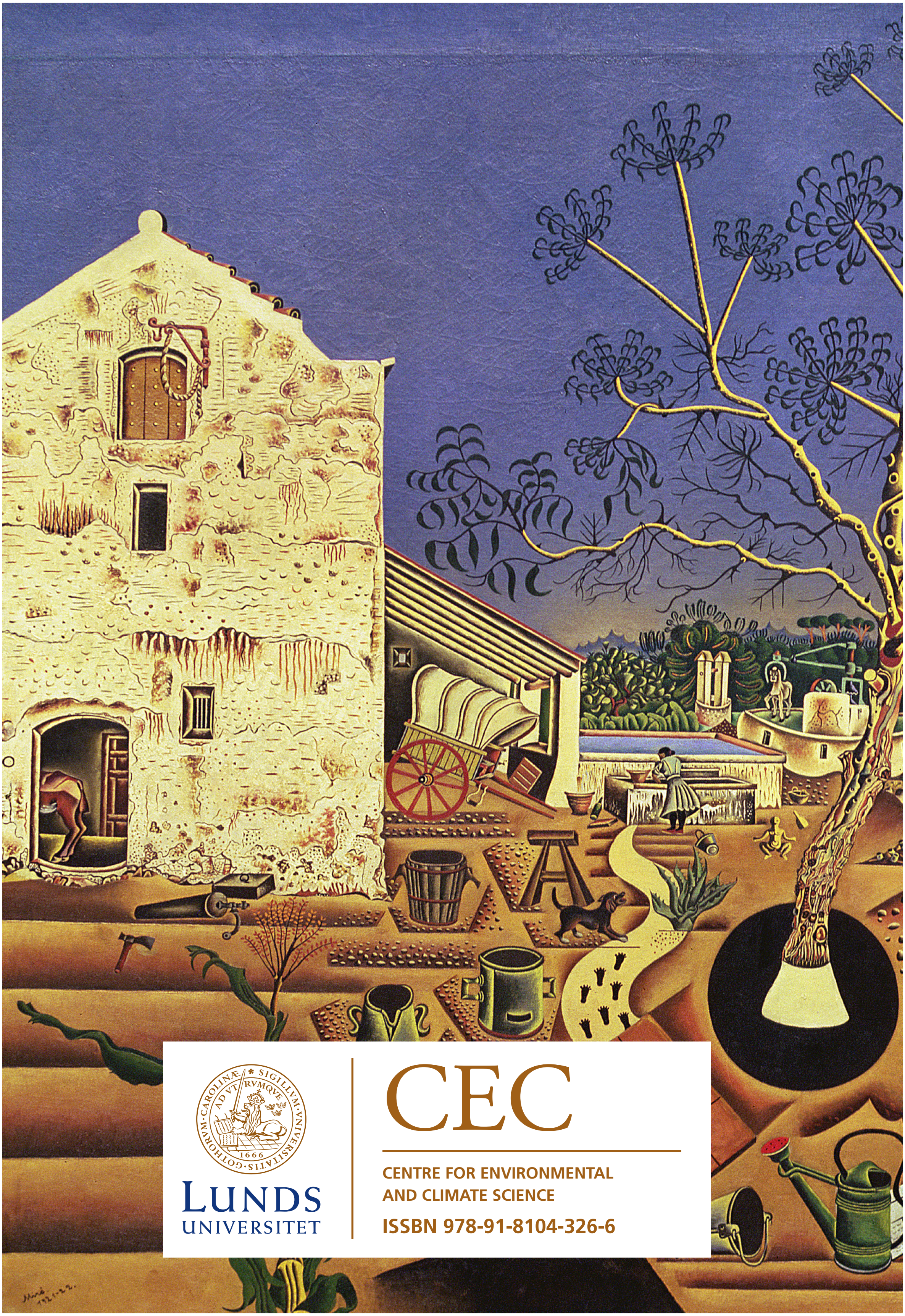

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