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Redesigning agricultural payments for economic and environmental sustainability

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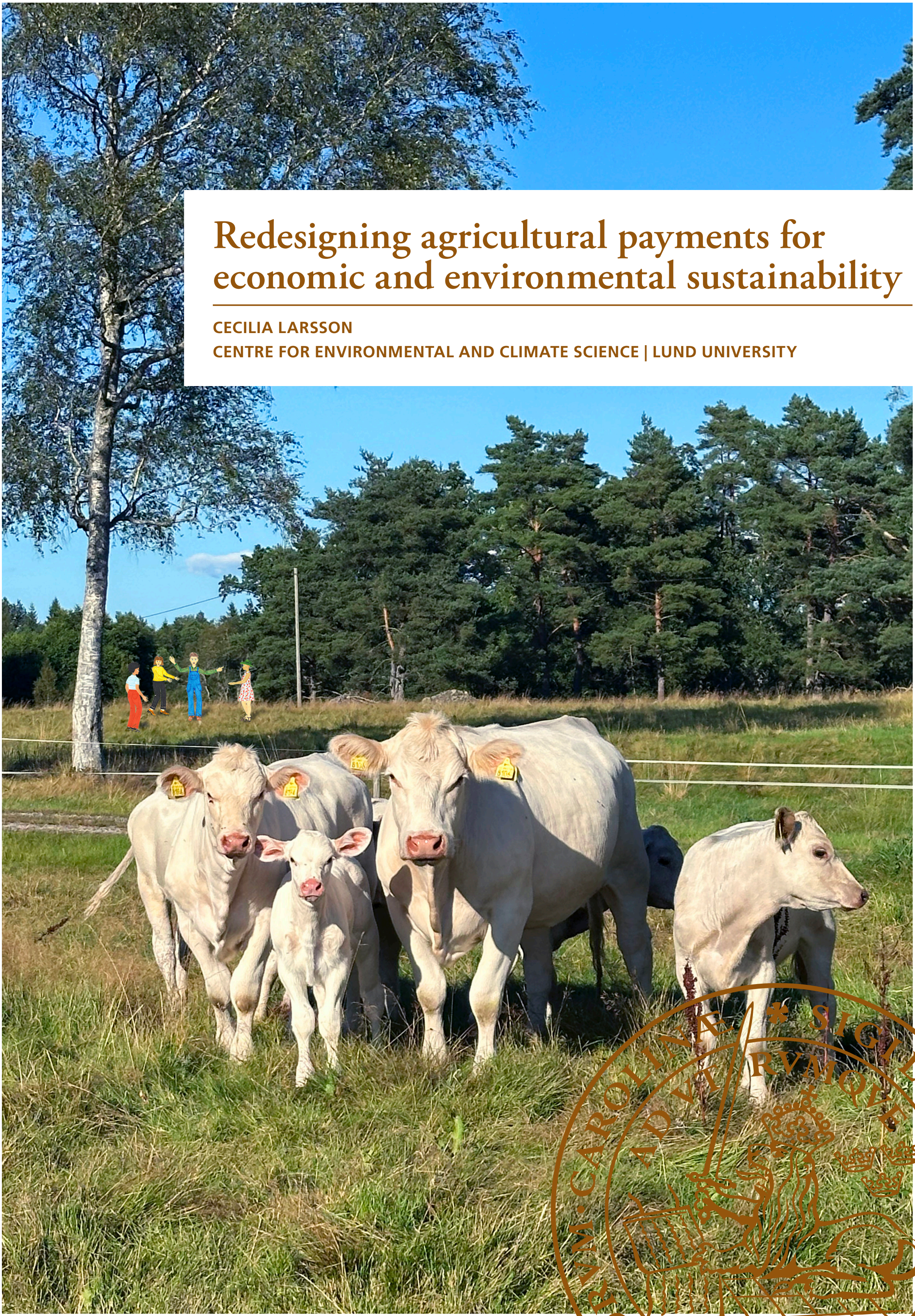

Redesigning agricultural payments for economic and environmental sustainability

Cecilia Larsson

DOCTORAL DISSERTATION

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Using an interdisciplinary modelling framework combining agent-based modelling (ABM) and life cycle assessment (LCA), four studies evaluate policy instruments aimed at biomass energy supply, climate change mitigation, and soil health. The analyses account for spatial heterogeneity, market dynamics, and structural change to assess their influence on policy outcomes. Results show that: (i) coarse spatial targeting reduces cost-effectiveness, as variation in land, soil, farm structure, and market conditions strongly shapes outcomes; (ii) failing to account for jointness in the provision of public goods, climate change mitigation and food security, leads to underfinancing and soil health policy; (iii) instruments unresponsive to market dynamics lose effectiveness when prices change; (iv) policy-induced structural changes can cause indirect environmental effects, including international leakage; and (v) integration of environmental objectives into the CAP remains limited, with some eco-schemes delivering weak environmental gains.

The thesis demonstrates the benefits of integrating economics and environmental science in policy analysis. Because of the overlap and interconnectedness between economic and environmental dimensions, agriculture cannot be economically sustainable unless it is also environmentally so. The findings suggest that advancing agricultural sustainability requires more precise spatial targeting, recognition of ecosystem service interlinkages, mechanisms that adapt to market conditions, and systematic consideration of structural change. Integrating environmental objectives directly into the CAP's incentive structure would promote the sustainable development of agriculture and the food system.

Key words: Agri-environmental policy; Public goods; Cost-effectiveness; Spatial heterogeneity; Agent-Based Modelling; Common Agricultural Policy; Soil carbon sequestration; Climate change mitigation; Structural change

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Abstract

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The thesis demonstrates the benefits of integrating economics and environmental science in policy analysis. Because of the overlap and interconnectedness between economic and environmental dimensions, agriculture cannot be economically sustainable unless it is also environmentally so. The findings suggest that advancing agricultural sustainability requires more precise spatial targeting, recognition of ecosystem service interlinkages, mechanisms that adapt to market conditions, and systematic consideration of structural change. Integrating environmental objectives directly into the CAP's incentive structure would promote the sustainable development of agriculture and the food system.

Popular science summary

Agriculture provides society with food and other vital ecosystem services, making it one of the most important sectors for societal function. It is highly relevant today—and for the future—that agriculture is conducted sustainably, as food security must also be ensured for future generations. Sustainable agriculture means that current methods and resource management do not diminish future food production potential. Ideally, these methods should improve future prospects, especially since agriculture has been conducted unsustainably for decades, leading to depletion of essential natural resources, particularly soils. In the 1960s, agricultural productivity increased significantly, driven by crop breeding, synthetic fertilisers, and chemical pesticides, improving food supply across much of the world. However, these changes have also brought negative consequences, which only became widely recognized later—primarily the degradation of the natural ecosystems that support agriculture and the contribution of intensified farming to climate change. In the long term, this could reduce productivity and weaken food security. It is therefore necessary to adapt agricultural methods and natural resource management not only to meet today's needs but also those of the future.

The EU's Common Agricultural Policy (CAP) is the most important and comprehensive tool available to Sweden and other EU member states to influence how farming is conducted in the union. CAP consists of overarching goals, an accompanying fund with a substantial budget, and a set of policy instruments used to allocate these funds to achieve the goals. However, it is far from clear which mix of instruments yields the greatest benefit for the available resources. My dissertation investigates how policy instruments should be designed to best promote agricultural sustainability. It contains four academic papers that analyse selected instruments based on economic efficiency principles from welfare economics. The analyses use simulations from an agricultural economic model of Swedish farming regions. The model builds on assumptions about how farms respond to changes in economic conditions. The simulation results show how the agricultural sector is likely to evolve in response to policy changes, without needing to test these policies in real life. In two of the articles, the model is linked to life cycle assessment (LCA), providing insights into environmental effects beyond the Swedish agricultural sector itself.

From an economic perspective, agriculture can be seen as the production of a bundle of goods and services. Some generate market revenue for the producing farm—generally commodities such as grain or milk (private goods). Other goods (services) are abstract, and their benefits go to society at large—these are referred to as public goods or externalities. These can be positive (e.g. food security, carbon sequestration, or landscape amenities) or negative (e.g. carbon emissions, nutrient runoff, or soil degradation). The problem is that farms typically only get paid for private goods that can be sold on the market, and do not pay when they cause

negative externalities. As a result, too few desirable public goods are provided, while too many negative externalities are generated in the process. Policy instruments can be used to encourage changes in production practices that increase the overall societal benefit from both private and public goods—for example, by compensating farms that provide environmental services such as carbon sequestration. Although today's EU agricultural policy states environmental sustainability as a goal, in practice, it largely prioritizes income support to farmers. To meet future challenges, both the policy and its instruments need reform.

Currently, CAP funding is primarily distributed through a flat-rate area payment—the Basic Income Support for Sustainability (BISS)—granted for every hectare of agricultural land, as long as it meets minimal eligibility requirements. There are other forms of payments too, such as support coupled to particular industries (cattle in Sweden) and payments for environmental measures. The articles in this dissertation analyse how different modifications or additions to these support schemes affect the achievement of CAP's goals, and whether this happens in a socially efficient way, that is, in terms of this thesis, whether the instruments are cost-effective relative to their objectives.

The first article examines support for cultivating energy crops—grass and woody biomass grown on farmland for bioenergy. The study shows that a flat per-hectare payment can be much more costly to society than a scheme tied to the energy content of the harvested biomass, especially when energy crop markets are volatile. A common concern is that energy crops could compete with food production and threaten food security. However, this study finds that such crops can help sustain agriculture in less productive regions by offering an alternative income source.

A frequent criticism of CAP is that its environmental measures do little to improve environmental outcomes and instead amount to "greenwashing." The second article investigates whether reallocating part of the basic income support to payments for cover crops results in actual improvement. Cover crops are grown between main crops to reduce bare soil exposure in autumn and winter. They help retain carbon in soils, benefiting both climate and soil health. The study shows that such reallocation leads to more societally beneficial use of funds society, compared to maintaining the current scheme. However, the measure is insufficient to turn cropland into a carbon sink, let alone offset all greenhouse gas emissions from farming.

The third article explores how ecological properties of arable soils are relevant to consider for efficient policy design. Arable land is a critical resource for food security—a public good. For a long time, more has been extracted from soils than returned, slowly degrading soil ecosystems and fertility. To improve the situation, attempts have been made using policy instruments that compensate farmers for maintaining soil health. This study examines voluntary support for grass ley cultivation, but uptake by farmers is hindered by high costs—particularly the lost income from not producing cash crops on all land. The results show that the proposed ley payment was too low to lead to additional ley production. The simulated support tended to go to livestock farms already growing ley, thereby also leading to increased cattle production. Thus, the proposed instrument design was not only ineffective for improving soil health—it also raised emissions. For the payment to be effective, all public benefits from improved soil health must be considered when setting the payment level. Ensuring accurate spatial targeting and adding complementary instruments was also shown to enhance policy effectiveness.

The fourth article uses an innovative method to assess synergies and conflicts between the EU's agricultural policy and the European Green Deal. Agent-based modelling was combined with life cycle assessment (LCA) to evaluate two potential policies aimed at accelerating sustainability transitions in European agriculture: removing support for dairy and beef production and introducing a greenhouse gas tax combined with carbon sequestration payments. The results show that policy effects vary regionally depending on economic conditions for farming. Moreover, positive environmental effects in Sweden can lead to negative spillovers abroad if domestic production is replaced by imports with higher environmental impacts. The study highlights the need for carefully balanced instruments that both address sustainability challenges and avoid unintended consequences.

To summarise, this thesis studied how farm payments can be designed to give the best value for money while protecting nature, tackling climate change, and keeping farming viable. The research shows that general payments, i.e., "one-size-fits-all" policies, waste money and miss environmental targets. Payments work best when they are targeted to the right places, account for how different environmental benefits are linked, and adapt when market prices change. Farm subsidies also reshape the farming sector, which can be good or bad depending on whether they actually increase public benefits. At EU level, environmental goals are still not fully built into the CAP, meaning many payments fail to deliver the outcomes they promise. In short, agricultural policy works best when environmental and economic goals are treated as equally important and designed together—because farming can only be truly sustainable if it is both economically and environmentally sustainable.

Populärvetenskaplig sammanfattning

Jordbruket förser samhället med livsmedel och andra viktiga ekosystemtjänster, och är därmed en av de mest betydelsefulla samhällsbärande sektorerna. Det är relevant både idag och för framtiden att jordbruket bedrivs hållbart. Ett hållbart jordbruk innebär att metoder och förvaltning av resurser idag inte minskar möjligheten till livsmedelsförsörjning i framtiden. Metoder och förvaltning bör förbättra möjligheterna till framtida livsmedelsförsörjning, eftersom jordbruket under många decennier bedrivits ohållbart och viktiga naturresurser har utarmats. Under 1960-talet ökade produktiviteten i jordbruket kraftigt, bland annat genom växtförädling, konstgödsel och kemiska bekämpningsmedel, vilket medförde ökad livsmedelstillgång över stora delar av världen. Men det fick även negativa konsekvenser, som uppmärksammats först senare, huvudsakligen att de naturliga ekosystem som är en förutsättning för jordbruket har tagit skada och att ett intensifierat jordbruk bidrar till klimatförändringen. Detta kan på sikt minska produktivitet och livsmedelstrygghet. Därför måste metoder och förvaltning av naturresurser anpassas så att jordbruket inte bara uppfyller dagens behov utan också framtidens.

EU:s gemensamma jordbrukspolitik (CAP) är det viktigaste och mest omfattande verktyget Sverige och övriga medlemsländer i EU har för att påverka hur jordbruket bedrivs. CAP består av ett antal övergripande mål, budgetmedel, samt politiska styrmedel som fördelar medlen med syfte att uppnå målen. Det är långt ifrån självklart vilka styrmedel som maximerar nyttan av budgetmedlen. Min avhandling handlar om hur styrmedlen bör utformas för största möjliga förbättring av jordbrukets hållbarhet. Avhandlingen innehåller fyra vetenskapliga artiklar där för- och nackdelar av utvalda styrmedel analyseras utifrån nationalekonomiska principer för samhällsekonomisk effektivitet. Analyserna i sin tur bygger på simuleringar i en ekonomisk jordbruksmodell av svenska jordbruksregioner. Modellen bygger på antaganden om hur jordbruksföretag agerar när ekonomiska omständigheter förändras. Simuleringsresultaten visar hur jordbrukssektorn i en region kan komma att påverkas av förändringar i politiken, utan att dessa behöver testas i praktiken. I två artiklar kombineras modellen med livscykelanalys, vilket ger information om miljöeffekter även utanför jordbrukssektorn.

Ur ett nationalekonomiskt perspektiv kan jordbruk ses som produktion av en samling varor, där vissa ger marknadsintäkter för det producerande jordbruksföretaget—det kan exempelvis handa om spannmål eller mjölk (privata varor). Andra varor är abstrakta och nyttan av dem tillfaller samhället—detta är så kallade kollektiva varor eller externa effekter. De senare kan vara både positiva som till exempel livsmedelstrygghet, inlagring av koldioxid och ett vackert landskap, och negativa, till exempel utsläpp av koldioxid, övergödning av vattendrag och utarmning av jordbruksmarken. Problemet är att jordbruksföretag i regel endast får betalt för de privata varor som säljs på marknaden. Detta tenderar att leda till att för lite positiva kollektiva varor tillhandahålls, samtidigt som för mycket negativa externa effekter uppstår i samband med jordbruksproduktionen. Styrmedel kan användas för att stimulera ändringar i jordbruksproduktionen så att den samlade nyttan av de privata och externa effekterna/kollektiva varorna blir så stor som möjligt, exempelvis genom att ersätta jordbruksföretag som bidrar med positiva kollektiva varor. Dagens europeiska jordbrukspolitik har som mål att verka för ett miljömässigt hållbart jordbruk, men är i praktiken mer inriktad på att gynna jordbrukssektorn ekonomiskt. För att möta framtida behov och utmaningar bör politiken och styrmedlen reformeras.

Idag är grunden för fördelningen av budgetmedlen inom CAP att alla jordbrukare i EU får en fast summa pengar för varje hektar jordbruksmark de innehar, det så kallade gårdsstödet. Det betalas ut oavsett hur marken används, så länge den fortfarande kan klassas som jordbruksmark. Ytterligare stöd finns för bland annat nötkreaturhållning och miljöåtgärder. Artiklarna i avhandlingen analyserar hur olika förändringar i, eller tillägg till, dessa olika stödformer påverkar måluppfyllelsen i CAP, samt om det sker på ett samhällsekonomiskt fördelaktigt sätt, det vill säga att styrmedlen är effektiva i förhållande till jordbrukspolitikens uppsatta mål.

Den första artikeln handlar om ekonomiskt stöd till odling av energigrödor, det vill säga gräs- och träbiomassa som odlas på åkermark för att användas i bioenergi-produktion. Studien visar att ett stöd som betalas ut per hektar kan bli betydligt mindre effektivt för samhället än om stödet i stället kopplas till mängden energi i den skördade biomassan, särskilt om marknaden för energigrödor är instabil. Ett orosmoment som ofta lyfts kring energigrödor är att de ska konkurrera med livsmedelsproduktionen och därmed hota livsmedelstryggheten. Den här studien visar dock att energigrödor kan bidra till att jordbruk i mindre produktiva regioner lever kvar, genom att produktionen ger en ny inkomstkälla.

En kritik som ofta lyfts mot CAP är att miljörelaterade styrmedel inte leder till mer miljövänligt jordbruk, utan snarare utgör en verkningslös ”grönmålning” av politiken. Den andra artikeln analyserar huruvida en omfördelning av en del av gårdsstödet till odling av täckgrödor medför en samhällsekonomisk förbättring eller inte. Täckgrödor är grödor som odlas under en period mellan två huvudgrödor för att undvika att åkermark ligger bar under höst- och vinterhalvåret. Täckgrödor kan bidra till att bevara mer kol i marken vilket är bra för klimatet och gynnar viktiga marklevande organismer. Resultaten visar att omfördelningen av stöd bidrar till en mer fördelaktig användning av budgetmedel, jämfört med att låta pengarna vara kvar i gårdsstödet. Åtgärden är dock otillräcklig för att helt göra åkermarken till en kolsänka, än mindre för att väga upp för alla jordbrukets utsläpp av växthusgaser.

Den tredje artikeln handlar om hur åkermarkens ekologiska egenskaper behöver beaktas för att effektiva styrmedel för markhälsa ska kunna utformas. Åkermarken utgör en mycket viktig resurs för samhällets livsmedelstrygghet—en kollektiv nyttighet. Under lång tid har mer resurser tagits från marken än vad som återförts, vilket långsamt utarmar markens ekosystem och gradvis försämrar bördigheten. För att motverka utvecklingen finns styrmedel som ska ersätta jordbrukare för underhållet av markens hälsa. I den här studien analyseras ett frivilligt stöd till vallodling, som på grund av höga kostnader, framför allt för utebliven skörd, gör att jordbrukare inte ansluter sig. Därmed kan de konventionella växtföljderna inte påverkas med planerade stödnivåer i Sverige. Studien visar att stöd för vallodling ofta är lägre än det samhällsekonomiska värdet av nyttan de skapar i intensiv växtodling, eftersom man bara tar hänsyn till ett fåtal nyttor. Stödet betalas i stället ut till djurgårdar som redan odlar vall och leder till ökar nötkreaturproduktion. Därmed är styrmedlet inte bara ineffektivt för förbättrad markhälsa, utan leder också till ökade växthusgasutsläpp. För att stödet ska vara effektivt måste alla kollektiva nyttor som förbättrad markhälsa skapar beaktas när betalningsnivån fastställs. Politikens effektivitet kan också förbättras genom att flera olika styrmedel kombineras

I den fjärde artikeln används en innovativ metod för att belysa synergier och konflikter mellan EU:s jordbrukspolitik och målen i den så kallade Europeiska Gröna Given (EGD) (*The European Green Deal*). Agent-baserad modellering länkades samman med livscykelanalys i en analys av två tänkbara styrmedel för att påskynda utvecklingen mot ett hållbart europeiskt jordbruk: att slopa stöd till mjölk- och nötkötts-produktion och att införa en skatt på växthusgasutsläpp i kombination med en betalning för kolinlagring Resultaten visar att effekten av styrmedlen varierar regionalt beroende på de ekonomiska förutsättningarna för jordbruk, samt att positiva miljöeffekter i Sverige indirekt kan leda till negativa miljöeffekter i andra länder. Detta genom att svenskproducerade varor ersätts med importerade varor, som generellt har större miljöbelastning. Studien understryker behovet av en välavvägd kombination av styrmedel som både adresserar de hållbarhetsproblem som finns i jordbruket, och de oönskade konsekvenser som kan uppstå när sådana styrmedel införs.

Sammanfattningsvis har denna avhandling undersökt hur gårdsstöd kan utformas för att ge bästa möjliga värde för pengarna samtidigt som naturen skyddas, klimatförändringarna bekämpas och jordbrukets livskraft bevaras. Forskningen visar att generella stöd, alltså ”one-size-fits-all”-politik, leder till slöseri med resurser och missade miljömål. Stöd fungerar bäst när de riktas till rätt platser, tar hänsyn till hur olika miljönyttor hänger samman och kan anpassas när marknadspriser förändras. Jordbruksstöd förändrar också jordbrukssektorns struktur, vilket kan vara positivt eller negativt beroende på om det ökar nyttan för samhället. På EU-nivå är miljömålen fortfarande inte fullt integrerade i den gemensamma jordbrukspolitiken (CAP), vilket innebär att många stöd inte levererar de resultat de utlovar. Kort sagt fungerar jordbrukspolitiken bäst när miljömässiga och ekonomiska mål behandlas som lika viktiga och utformas tillsammans—eftersom jordbruket bara kan vara verkligt hållbart om det är både ekonomiskt och miljömässigt hållbart.

List of papers

Paper I

Larsson, C., K. Hedlund, F. Wilhelmsson, and M. V. Brady. Mobilising agricultural bioenergy under variable market conditions: Policy design matters. Manuscript.

Paper II

Larsson, C., R. López i Losada, F. Wilhelmsson, K. Hedlund, and M. V. Brady. Intermediate crop subsidies in a CAP Strategic Plan: A successful repurposing of agricultural payments? Manuscript.

Paper III

Larsson, C., F. Wilhelmsson, K. Hedlund, and M. V. Brady. Healthy soils: Are we paying enough for public goods? Manuscript.

Paper IV

López i Losada, R., **C. Larsson**, M. V. Brady, F. Wilhelmsson, and K. Hedlund. Advancing sustainability transformations in agriculture: an Agent-Based LCA for supporting policymaking. Accepted for publication in *Sustainable Production and Consumption*.

Author contributions

Paper I

CL conceived and designed the analysis with input from MB. **CL** performed the agent-based modelling and computer simulations with support from MB. **CL** performed the analysis with input from all co-authors. **CL** drafted the manuscript and MB, KH, and FW contributed to editing and revisions.

Paper II

CL conceived and designed the analysis with input from RLL and MB. **CL** performed the agent-based modelling and computer simulations, and RLL performed the life-cycle emissions modelling. **CL** performed the analysis. **CL** drafted the manuscript, with the exception section 2.3., which was written by RLL. RLL, MB, KH, and FW contributed to editing and revisions.

Paper III

CL conceived and designed the analysis with input from MB, FW, and KH. **CL** performed the economic sustainability assessment and agent-based modelling and computer simulations. **CL** performed the analysis. **CL** drafted the manuscript, and MB, FW and KH contributed to editing and revisions.

Paper IV

RLL and **CL** conceptualised the study with input from all authors. RLL and **CL** designed the methodology. RLL performed the life-cycle environmental modelling and **CL** the agent-based economic modelling and model simulations. RLL and **CL** performed the analysis. RLL and **CL** drafted the manuscript, and all authors contributed to editing and revisions.

Abbreviations

AB-LCA	Agent-based life cycle assessment
ABM	Agent-based modelling
AECM	Agri-environmental and climate-related measures
ANC	Area with natural or other area-specific constraints
BISS	Basic Income Support for Sustainability
CAP	Common Agricultural Policy
CIS	Coupled Income Support
EAFRD	European Agricultural Fund for Rural Development
EAGF	European Agricultural Guarantee Fund
EGD	European Green Deal
EU ETS	European Union Emissions Trading System
GAEC	Good Agricultural and Economic Conditions
GHG	Greenhouse gas
GSS	Götaland's southern plains (*Götalands södra slättbygder*)
IACS	Integrated Administration and Control System
LCA	Life cycle assessment
MIP	Mixed-integer programming
NMP	Normative mathematical programming
SBA	Swedish Board of Agriculture (*Jordbruksverket*)
SDG	Sustainable Development Goal
SMR	Statutory Management Requirements
SOC	Soil organic carbon
UAA	Utilised agricultural area
WFLDB	World Food Lifecycle Database

Introduction

Agriculture is not only fundamental for producing food but also a key provider of essential public goods in the EU—such as food security, climate regulation, soil health, biodiversity, and culturally valued landscapes (Cooper et al., 2009). It is also a source of significant negative externalities, including greenhouse gas emissions, nutrient runoff, and the depletion of natural resources (Campbell et al., 2017). Ensuring that agriculture contributes positively to societal welfare requires policy frameworks that support the efficient provision of public goods while mitigating adverse environmental impacts. Although the Green Revolution and subsequent intensification of agricultural production have led to substantial increases in food availability, these gains have often come at the expense of long-term sustainability (Matson et al., 1997). Practices reliant on synthetic inputs and simplified cropping systems have degraded the ecosystems underpinning agricultural productivity (Stoate et al., 2009), with long-term consequences for both environmental and economic resilience (Tilman et al., 2002; Foley et al., 2005). Moving forward, it is essential to adapt agricultural policies and practices to better internalise external costs and incentivise the delivery of public goods, thereby aligning agricultural development with broader societal and environmental objectives (Pe'er et al., 2019).

Unfortunately, agricultural policy has so far to a large extent contributed to the negative externalities and public bads rather than goods (Henderson and Lankoski, 2019). Considerable public support is paid to agriculture: the annual average is over €100 billion in the EU (OECD, 2025), out of which €57.7 billion is from the Common Agricultural Policy (CAP) funds. Such money buys a lot of environmental harm (Scown et al., 2020) and its spending needs to be revised if the environmental objectives of the CAP are to be fulfilled (Pe'er et al., 2019; ECA, 2021), not to mention those of the EU Green Deal (Guyomard et al., 2020) or the Paris Agreement. Science as well as civil society are demanding a change (BirdLife Europe et al., 2024; Pe'er et al., 2020), and several major global institutions are calling for a ‘repurposing’ of agricultural payments (Gautam et al., 2022; FAO et al., 2021; OECD, 2023): reducing producer support that is “*inefficient, unsustainable and/or inequitable*, [and replacing it with policy payments] *that are the opposite*” (FAO et al., 2021, p. 8). The papers in this dissertation analyse a set of policy instruments, asking if and under what circumstances they can contribute toward this ambition.

The role of economics in environmental science

This interdisciplinary work takes an economics perspective on environmental science. Economic analysis is highly relevant to environmental science as a field of research concerned with the interactions between society and nature. The primary cause of anthropogenic environmental degradation is economic activity—people making a living (or a fortune) by using and sometimes abusing nature—such as through food production and other forms of land use, forestry, fishing, construction, etc. (IPBES, 2019). Environmental science is concerned with identifying and quantifying such impacts, while economics is concerned with addressing them in an efficient manner. Neither the natural nor the social sciences are in possession of the complete metaphorical map showing the way towards a sustainable society. Though interdisciplinary research is a challenging venture, society-nature problems cannot be solved by only looking at nature, or only at society, but require integrated approaches—such as those offered by interdisciplinary science. Thus, despite its imperfections, the value of the combined map is greater than the sum of its parts.

Economic policy offers a means to address environmental challenges by realigning the economic incentives that often underlie environmental degradation; harnessing them instead to promote more sustainable outcomes (Western et al., 2024). For economic policy to be effective, it must be grounded in a clear identification of the behaviours driving environmental degradation (i.e., “the problem”), and in the precise design of instruments that directly address those behaviours. Agricultural policy, however, offers numerous examples where insufficient targeting or ambiguous objectives have limited the effectiveness of such instruments (Hristov et al., 2020; Searchinger et al., 2008). Environmental science should make use of economics, a social-science endeavour working to identify and understand economic patterns and behaviour, to translate natural science findings into sharp and cost-effective policy (Dasgupta, 2021; Stern, 2006).

The overarching aim of this thesis is to explore how agricultural policy instruments can be redesigned to more effectively address public goods and mitigate negative externalities. Using integrated economic-environmental modelling, the thesis assesses the effectiveness and trade-offs of various policy instruments, with the goal of improving cost-effectiveness. Particular attention is given to the influence of market dynamics, production jointness, regional and spatial variation, structural change, and the interplay between environmental and economic sustainability, on efficient agricultural policy design. Economic instruments only are considered here.

Before turning to the specific studies comprising this thesis, it is in order to expand on a number of topics relevant for the analysis, not least because of the interdisciplinary nature of this work.

What *is* sustainable agriculture?

Paraphrasing the Brundtland Commission Report (WCED, 1987), sustainable agriculture may be defined as agricultural practices that meet the food needs of the present generation without compromising the ability of future generations to meet theirs. Sustainable development is commonly described as encompassing three dimensions—economic, environmental, and social (UN, 2015). In agriculture, the boundaries between these are far from clear-cut (Goodland, 1995), leading to disagreements or tensions regarding where agriculture should be heading to be 'sustainable' (Shennan et al., 2017). This makes it important to examine how the dimensions interact, and to specify the approach taken in this thesis.

Economic sustainability is primarily concerned with the efficient, i.e., the welfare-maximising, allocation and use of scarce resources across space and time. Pezzey (1992) defines economic sustainability as non-declining utility over time, highlighting the intergenerational nature of agricultural sustainability challenges. This implies that resources should be used so that the productive capacity is maintained or enhanced. In agriculture, many of these resources—such as soil, water, and phosphorus—are natural, meaning that long-term economic viability is inseparable from environmental sustainability. Soil health illustrates this overlap. Defined as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans …" (Lehmann et al., 2020, p. 544), soil health underpins environmental sustainability through ecosystem services such as water regulation and biodiversity, while also safeguarding economic sustainability by preserving arable land as a production factor essential for long-term food security.

Despite these overlaps, the economic and environmental rationales may diverge. From an ecological perspective, conservation is valuable in its own right; from an economic perspective, its justification depends on the balance of costs, benefits, and opportunity costs (Ang and Passel, 2012). A policy that is environmentally sound may not be economically optimal if it imposes costs that outweigh its tangible benefits or ignores opportunity costs.

From the perspective of the CAP, economically sustainable agriculture also encompasses the viability and diversity of farms in the EU (EU, 2021). Ensuring that the sector remains attractive, profitable, and capable of renewal through investment and modernisation is critical for food production. Policies that promote environmental goals must therefore consider how they interact with farm incomes, market conditions, and structural dynamics.

Finally, economic sustainability is not only about efficient allocation but also about scale. Beyond a certain point, agricultural expansion—especially if reliant on finite natural capital—imposes more costs than benefits (Daly, 1996). Recognising this need for balance between production, environmental protection, and long-term welfare motivates the dynamic and spatial modelling approaches applied in this thesis.

Why markets fail in agriculture

Market failure refers to conditions under which the mechanisms of a free market do not lead to an optimal (socially desirable) outcome. Here the focus is on two such conditions: the presence of public goods, i.e., products or services that a member of society can benefit from without reducing its availability to others, and negative externalities, i.e., harmful side-effects of production or consumption on others, that are not considered in production/consumption decisions. Both these are prevalent in agriculture, and policy intervention is required to correct them. This section describes the nature of public goods and negative externalities in agriculture, explains how they lead to market failure, and discusses the rationale for using policy instruments to address them.

Environmental impacts relevant to this thesis

Agriculture is an interesting example of an economic activity that has pervasive negative environmental impacts (Pretty et al., 2000). There is no dispute as to its continuation: despite its environmental impacts, the optimal level of food production is greater than zero. This is arguably not the case with many other consumer products (Durning, 1993). There is though considerable room for improvement in the environmental impact of agriculture with limited or no effect on the level of food production (Willett et al., 2019). This thesis is primarily focused on two central influences of agriculture on society: food security and climate impact.

The aspects of food security in focus here are the *stable*, physical *availability* of food, i.e., the non-declining capacity of the agricultural sector to produce sufficient food indefinitely (FAO et al., 2022). In an EU context, the primary threats to the productive capacity are climate change, environmental degradation, and agricultural system vulnerabilities (Lal, 2010; Antle, 2015; EP, 2024).[1]

Agriculture can contribute positively or negatively to climate change. Agricultural production releases significant amounts of greenhouse gases (GHG) (Nabuurs et al., 2022): i) enteric fermentation in ruminants and manure storage cause significant methane emissions, ii) carbon dioxide emissions are caused by microbial decay of

[1] This thesis is not concerned with the broader requirements for food security regarding, e.g., economic and physical *access* to food or its *utilisation* (FAO et al., 2022). Risks concerning markets and supply chains, and external chocks and crises are not considered (Gullstrand and Jörgensen, 2018).

soil organic matter and combustion of fuels, and iii) nitrous oxide is generated by microbial transformation of nitrogen in soils and manures (Jia et al., 2019). Agriculture can also have negative emissions through sequestering carbon in soils and vegetation (Lal, 2004; Albrecht and Kandji, 2003). It can also contribute indirectly to GHG fluxes: negatively by using inputs that are associated with emissions such burning of natural gas to produce nitrogenous fertilisers, or positively by supplying raw material for e.g. bioenergy (Calvin et al., 2021).

Food security and climate impacts differ in character, which has important implications for their efficient provision and for the design of appropriate policy instruments to target them. In the remainder of this section, the analytical foundation of market failure in economics and some key characteristics of these particular market failures are outlined.

Negative externalities and public goods

In economics, the description of environmental degradation as a phenomenon is that an economic agent imposes damage on society in the form of a negative environmental impact (Baumol and Oates, 1988). This "drives a wedge between humans' demand for the biosphere's goods and services and its ability to supply them without undergoing decline" (Dasgupta, 2021, p. 48). A negative externality such as this occurs when an activity performed by one agent, such as a farmer, appears in the utility function of another member of society, including future people (Arrow et al., 2013), and that member is not compensated for the harm done to them. Because the agent does not bear the cost of the damage they have no economic incentive to limit it, leading to more resources than optimal being spent on production, resulting in over-supply of the harmful good relative to the socially optimal level: a market failure.

A public good is described and analysed analogously but reversed: the activity appearing in others' utility functions is then positive, a benefit, but the provider is not rewarded for its provision, hence the activity tends to be under-supplied.

While environmental science focuses on identifying and quantifying the environmental impacts and contributions of agriculture, economics addresses the complementary challenge of determining the socially optimal level of their provision and the design of efficient policy instruments to guide producer and consumer behaviour to optimality, i.e., the desirable allocation of resources from society's perspective.

As described above, the presence of public goods and negative externalities leads to a failure of the market for agricultural products to allocate the efficient amount of resources to resolving environmental problems. Economic policy instruments can be used to alter producers' and consumers' incentives (Springmann et al., 2016; Moberg et al., 2021). If, for instance, the polluter (producer or consumer) is required to compensate for the damage caused, they have the options to reduce the polluting activity, pay the compensation, or adjust their behaviour somewhere in between, depending on how much they value the activity.

Thus attaching a "price" to pollution corresponding to the damage it causes (Hanley et al., 2012), is a way of internalising the externality into the decision-making framework of the polluter. This compels them to consider not only the cost of the activity in terms of materials, labour, and capital, but its full societal cost, including environmental harm. Provided that the price accurately reflects the damage and is enforceable, this approach can correct the market failure, by allowing supply and demand to adjust toward the societally optimal—the efficient—levels of production and pollution. Compared to using regulation, the economic approach to correcting market failure is more responsive to heterogeneity of consumer preferences and market fluctuations, and, importantly, allows the polluter to find ways of reducing the damage, e.g. through making the production process more environmentally friendly, without necessarily reducing the production level (Sterner and Coria, 2012). However, in some cases regulation will be the efficient approach, such as in the case of banning the use of DDT or other highly dangerous chemicals (but these are not in focus here).

Specific characteristics of food security and climate impacts

Agriculture's contribution to climate change, whether positive or negative, represents a reciprocal externality—those who pollute/mitigate are simultaneously affected by/contribute to the problem (e.g. increasing likelihood of future droughts). This kind of externality underlies the tragedy of the commons (Hardin, 1968; Stavi and Lal, 2013), where the absence of clear property rights over shared environmental resources leads to their overuse or degradation. In contrast, food security is a unidirectional public good: its benefits flow from provider to beneficiary. While the provision of food security can, in principle, be supported through payments to producers, its non-rival and non-excludable nature makes it prone to free-rider problems, where beneficiaries have little incentive to contribute to its production. An important group of beneficiaries that is unable to contribute is future generations (Arrow et al., 2013), whose stakes are arguably at least as high as those of current generations. This often results in inefficient provision of unidirectional public goods. Both characteristics motivate the need for policy intervention.

Why agricultural policy fails on the environment

Agricultural policy in the EU's CAP, and other parts of the world, struggles to meet its environmental performance goals, and commonly contributes to environmental degradation (Reyes-García et al., 2025). There are multiple complexities inherent in this problem, which is really a nexus of problems, that contribute to the failure in aligning CAP with its objectives. This nexus of problems has features that fit well with the definition of a 'wicked problem'.

Wicked problems go beyond 'complex' problems (DeFries and Nagendra, 2017; Guerry et al., 2015). As expressed by Shortle and Horan (2017), in environmental problems, these features include numerous complex and often imperfectly understood ecological and anthropogenic interactions that contribute to the issue; intricate spatio-temporal dynamics operating across multiple scales (including jurisdictional and bureaucratic borders), which require context-specific strategies over space and time; and economic, political, and institutional complexities that shape the feasibility of potential solutions. Therefore, the problem itself can be resistant to definition, persistent and recurring, characterised by political and stakeholder disagreements, difficult to monitor, and intertwined by other problems (Rittel and Webber, 1973; Head, 2022). Consequently, attempted solutions often expose misunderstood or unrecognised dimensions of the problem and can result in unintended consequences.

This thesis addresses some of these features, as barriers to sustainable agricultural development and policy efficiency, and these are outlines below.

Trade-offs between objectives

Fundamental dilemmas inherent in agri-environmental policy are frequent conflicts and complementarities between agricultural and environmental goals, where the former implies that trade-offs must be made.

The resource conflict

The foundation of many trade-offs in agri-environmental policy is resource scarcity. Had natural capital, such as land, soil health and biodiversity, not been scarce or threatened, sustainability had not been a problem and policy intervention not required. As it is, these resources have multiple potential uses, including conservation, and their optimal allocation is far from clear-cut.

Agriculture-based bioenergy is a topic in three of the papers in this thesis. A main concern with increasing energy crop production are the goal conflicts inherent in the use of arable land and other natural and agricultural resources (Smith et al., 2010; Koh and Ghazoul, 2008; Vera et al., 2022). One such aspect is food security, that could be negatively affected if increased use of agricultural land for energy production leads to replaced food production (Koizumi, 2015; Zilberman et al., 2012). Replaced food production can also mean *displaced* food production, which can cause indirect land-use change with impacts on biodiversity and ecosystem services elsewhere (Núñez-Regueiro et al., 2019; Winberg et al., 2023), and could even negate the climate benefit of renewable energy (Searchinger et al., 2008; Fargione et al., 2008).

Utilising economically marginal agricultural land for energy crop production has been suggested as a way of minimising these risks and simultaneously preventing land degradation and abandonment (Næss et al., 2023). Though this is not a problem-free strategy (Winberg et al., 2024a; Winberg et al., 2024b) it could be risky to rule out energy crops altogether (Xu et al., 2022).

Government funds also represent a finite resource, that has an opportunity cost in the form of other uses that provide benefits to society, such as other environmental improvements or public services like health care or education. In addition, the collection of taxes to fund public spending usually is accompanied by an efficiency loss. Because funds are limited, there is a risk that poorly designed instruments crowd out spending that could lead to greater improvements (Gupta et al., 1995). This is considered in this thesis by analysing policy instruments' budget-effectiveness.

The problem of time horizons

An added layer of complexity is that resources must be allocated efficiently not only across regions but also over time. One of the objectives of the CAP is to support viable farm incomes (EU, 2021). Low incomes have immediate social consequences and can be addressed quickly through direct payments. In contrast, many environmental and economic goals, such as sector resilience, competitiveness, and climate change mitigation, have longer time horizons, both in their impacts and in the policies needed to achieve them. This creates a tension: reallocating payments towards environmental mitigation can reduce farm profitability and competitiveness in the short run. Agricultural diversity—another CAP objective—illustrates this tension well. A more heterogeneous, less specialised farming sector can promote biodiversity and resilience (Egli et al., 2021), hence focusing on short term income support can help sustain a larger and more varied farm population. More specialised farms, on the other hand, are often more competitive and profitable, and more likely to adopt advanced technologies (which can also reduce environmental impacts) and long-term strategies that align with certain economic objectives of the CAP (Appel and Balmann, 2023). There is therefore a temporal trade-off between safeguarding the immediate livelihoods of European farmers and pursuing the longer-term goals of economic and environmental sustainability. This thesis addresses this through dynamic modelling that takes the long-term impacts of farmers' decisions into account.

Inadequate policy instrument design for provisioning of public goods

Poorly designed policy instruments can result in no improvement or even a reduction in efficiency. Effective policy instrument design requires an understanding of the properties of the good or service it is intended to provide, and of the incentives for their private provision (Naeem et al., 2015). Paying too little to induce the societally desired provision level, paying too much and induce over-production that cause other inefficiencies, or paying for practices that would have been adopted anyway thus providing no additionality of the government funds (Ferraro and Pattanayak, 2006; Engel et al., 2008). A common cause of inefficient policy design is the lack of appropriate targeting of policy instruments (Antle et al., 2003; Ekroos et al., 2014; Kleijn et al., 2006). Targeting can be based on benefits, i.e., the actual delivery of public goods, on the severity of threats to the ecosystem, or on cost for provisioning (Engel et al., 2008).

Jointness in production of soil-related ecosystem services

A particular cause of inefficiency addressed in this thesis is under-paying for public goods due to not accounting for bundled soil-related ecosystem services. In ecology, ecosystem service bundles refer to sets of these that co-occur across space or time due to underlying ecological processes and land-use patterns (Figure 1) (Raudsepp-Hearne et al., 2010). These bundles reflect the multifunctionality of ecosystems and the trade-offs or synergies between different services.

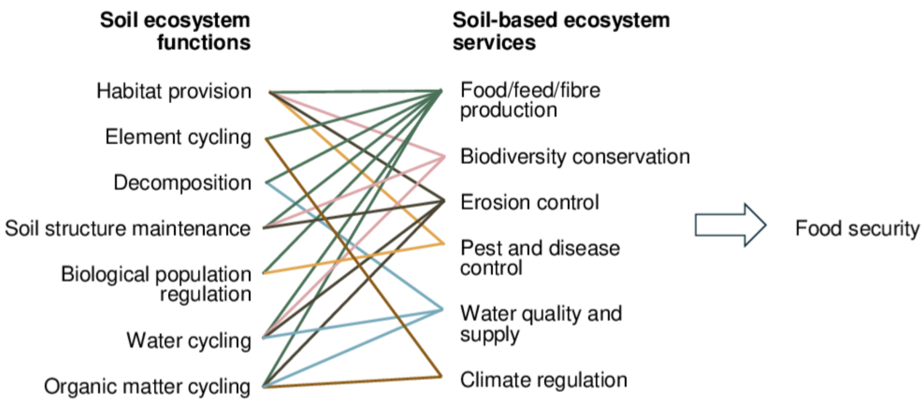

Figure 1 Linkages between soil functions and soil ecosystem services/public goods. Adapted from Bünemann et al. (2018)

In economic terms ecosystem service bundling can be analysed as joint goods, i.e., that the production processes of two or more goods are interlinked (OECD, 2001). Like bundles, joint goods can have different underlying causes and be competitive or complementary. In ecology the notion of ecosystem service bundles is often used to describe and classify the co-occurrence and interdependence of services arising from shared ecological processes (Bennett et al., 2009). In economics, jointness in production is used to analyse the production process itself and the relationships between outputs, with the aim of informing optimal management and policy decisions (Wossink and Swinton, 2007). The implications of jointness in soil-related public goods are explicitly examined in this thesis, both in terms of how it affects the efficiency of payments and how it shapes the balance between different public goods.

Focus on economic analysis of jointness has primarily been on multifunctionality between private and public goods, which, as described above, is an important source of public goods and negative externalities (Vatn, 2002; OECD, 2008). Studies on situations where ecosystem services are jointly produced are few. The third paper of this thesis highlights the potential influence of jointness between public goods. It is argued that maintenance of arable soil health can be analysed as a non-allocable input in the production process of soil ecosystem services. This means that spending on maintaining soil health will supply a bundle of ecosystem services and, consequently, that the possibility of making a partial, targeted investment in soils to extract increased supply of a single ecosystem service is limited, though not zero (Razzaghi et al., 2020). The paper shows that when policymakers attempt to target one service in the bundle, commonly carbon regulation for climate change mitigation and adaptation, this can lead to policy failure (Butler et al., 2009).

Redesigning agricultural policy for sustainability

The tool at hand: the EU Common Agricultural Policy

The Common Agricultural Policy (CAP) is the foremost instrument the EU has at its disposal to change European agriculture. It was launched in 1962, with the purpose of promoting agricultural productivity in the six countries of the EEG, and now in the EU, to ensure fair farmer living standards and reasonable consumer food prices, and stable agricultural markets (Treaty of Rome). European agriculture in 2025 bears little resemblance to that in 1962, yet the original goals persist and new goals have been layered on the old (Daugbjerg and Swinbank, 2015). Today, the sector is highly mechanised and optimised as regards inputs, such that most commercial farm operations resemble industrial production more than the traditional smallholders of the post-war times.

During the modernisation process, the CAP framework has been reformed, moving away from production-based subsidies, towards a stronger focus on preservation of agricultural land and environmental protection. The European Commission intends for the CAP to lead a transition towards more sustainable agriculture (EC, 2017). This is most obvious in the recitals to the CAP regulation, but also conveyed by the legally binding objectives and obligations under the framework.[2] Notably, several CAP objectives are focused on environmental protection and a new article compelling member states to make a greater overall contribution to these than they made in the previous period (the so-called 'no-backsliding' clause (EU, 2021). Since the latest CAP reform in 2023, each EU member state designs their own national CAP Strategic Plan. The plans set out an assessment of needs, intervention strategies to meet CAP objectives, and performance indicators to track results. Member states thus have greater autonomy in (and responsibility for) fulfilling the CAP's objectives than before. This means new opportunities for national and even local adaptation of policies, bringing potential efficiency gains (Wätzold and Schwerdtner, 2005) but also challenges (Röder et al., 2024).

CAP instruments for the climate and the environment

CAP schemes targeting the climate and the environment can be funded as *direct payments* from the European Agricultural Guarantee Fund (EAGF)—previously referred to as the CAP's first pillar—or as *rural development interventions* by the European Agricultural Fund for Rural Development (EAFRD)—formerly the second pillar. The size of the EAGF in 2023 was €41 billion and the EAFRD approximately one-third of that, €13 billion. This thesis is concerned with how direct payment funds are used for agri-environmental policy, which, since the latest CAP reform 2023 have been partially reallocated to *eco-schemes*, i.e., voluntary interventions for the environment and the climate in the form of annual payments (EU, 2021, art. 31).[3] Member states must allocate at least 25 percent of their EAGF funds to eco-schemes and they must cover at least two action areas specified in the regulation, such as climate change mitigation, soil degradation, and biodiversity protection (art. 31(4)). Eco-schemes are different in their design from environmental and climate-related measures (AECM) under the EAFRD. Although AECM's are not explicitly analysed here many of the findings are broadly applicable.

[2] The CAP specific objectives: (a) support viable farm income, resilience of the agricultural sector, long-term food security, agricultural diversity, economic sustainability of agricultural production; (b) enhance market orientation and farm competitiveness; (c) improve the farmers' position in the value chain; (d) contribute to climate change mitigation and adaptation; (e) foster sustainable development and efficient management of natural resources; (f) contribute to halting and reversing biodiversity loss, enhance ecosystem services, preserve habitats and landscapes; (g) attract and sustain young and new farmers, facilitate rural business development; (h) promote employment, growth, gender equality, social inclusion, rural development; (i) improve agriculture's response to societal demands, reduce food waste, improve animal welfare, combat antimicrobial resistance (EU, 2021, Art. 6. Revised for brevity.).

[3] These must go beyond relevant requirements in national and Union law, and the statutory management requirements and the GAEC standards also established in the CAP legislation (Annex III).

A note on methods

This thesis employs the agent-based model (ABM) AgriPoliS (Balmann, 1997; Happe, 2004). ABMs are well suited for ex ante policy evaluation, enabling simulation of structural change and farm-level decision-making in response to policy incentives. A key strength is their capacity to analyse counterfactual scenarios and to capture heterogeneity and interaction among agents, such as competition for land, which gives rise to emergent system-wide outcomes. Additionally, AgriPoliS has the ability to represent spatial variation, which is relevant for multiple ecosystem services, notably soil quality, as well as agricultural profitability, and hence for policy efficiency.

Farmer decision-making in AgriPoliS is based on a mixed-integer programming framework in which autonomous farm agents maximise household income under constraints like land, capital, and market conditions (Kellermann et al., 2008). Farms exit the sector if insufficiently profitable to cover opportunity costs of family labour and capital, bankrupt, or lacking successors. All studies used a consistent model initialisation and compared simulated policy scenarios with counterfactual references. For Papers **II** and **IV**, AgriPoliS was coupled with life cycle assessment (LCA) to capture broader environmental consequences and dynamic interactions between economic and environmental systems.

While the same model base was used across papers, extensions were made to address specific research questions. These included the introduction of non-food energy crops (Paper **I**), modelling of cover crop strategies (Paper **II**), addition of soil-based agri-environmental measures (Paper **III**), and simulation of policy instruments targeting methane emissions and soil carbon sequestration (Paper **IV**). Together, these studies demonstrate how integrated modelling approaches can support policy design aligned with environmental and structural goals.

Overview

The remainder of this doctoral thesis is structured as follows. I first present the overarching aim and scope of the project, followed by an account of the methods and materials used in the four papers. A synthesis of the main results and a discussion in relation to the overarching aim then follow, before concluding with a summary of key findings and policy recommendations.

The four papers presented share a focus on agricultural policy at the intersection of economic efficiency and environmental sustainability. They all analyse how the design of policy instruments influences outcomes and implications for achieving defined policy targets, using Swedish agricultural regions as empirical cases. Paper

I concentrates on climate change mitigation as a policy objective, Papers **II** and **III** focus on soil carbon sequestration as a way of maintaining soil natural capital, and Paper **IV** examines broader impacts on EU Green Deal objectives.

A cross-cutting theme throughout the papers is the provision of public goods from agriculture, the complementarities and trade-offs with commodity production, structural change, and land use, and how regional characteristics shape policy outcomes. The empirical settings vary: Paper **I** focuses on a livestock-dominated region; Papers **II** and **III** analyse an intensive cropping region; and Paper **IV** compares both types of regions. The studies are complementary in that each addresses a different aspect of the agri-environment: Paper **I** investigates agriculture-based bioenergy feedstocks, Paper **II**, the role of agricultural soils as carbon sinks, Paper **III** is focused on maintenance of soil natural capital, and Paper **IV**, greenhouse gas emissions from livestock and soils.

Aim and scope

This thesis examines the economic efficiency and environmental effectiveness of agricultural policy instruments designed to support the sustainable provision of public goods, with emphasis on balancing food security, agroecosystem management, climate change mitigation, and the long-term viability of the agricultural sector. The analysis adopts an interdisciplinary environmental science perspective, combining theoretical and methodological approaches to evaluate policy performance.

The scope is the EU agricultural sector, with Sweden as a case study. The primary focus is on economic instruments under the Common Agricultural Policy (CAP). Regulatory measures, equity and distributional aspects, and political economy considerations fall outside the scope of this work.

This overarching aim is operationalised through four papers, each addressing a specific policy question within the broader themes of economic efficiency and environmental effectiveness. Paper **I** assesses the cost-effectiveness of alternative subsidy designs for expanding non-food energy crop production, examining their effects on agricultural structure and land use under varying market conditions. Paper **II** evaluates whether reallocating CAP direct-payment funds from basic income support to a cover crop eco-scheme for carbon sequestration can be considered a form of policy repurposing, and whether such reallocation improves efficiency without compromising other CAP objectives. Paper **III** investigates how recognising the joint provision of soil-based public goods influences the efficiency of a soil-health policy instrument, analysing both environmental outcomes and economic or structural implications. Paper **IV** explores how removing coupled income support to cattle and introducing a combined tax/payment incentive targeting methane emissions and soil carbon sequestration could steer agricultural transformation towards European Green Deal objectives, considering structural, environmental, and life-cycle impacts.

Together, these studies provide complementary perspectives on how agricultural policy instruments can be designed or adjusted to better align economic viability with the sustainable provision of public goods.

Methods

The work in this thesis combines two complementary approaches: theoretical analysis grounded in welfare and environmental economics, and agent-based modelling of the agricultural sector. The following sections summarise each method and describe how they were applied in the individual papers.

Economic analysis of policy instruments

The policy instruments analysed in this thesis are all economic instruments and primarily action-based, which is the most common type of CAP instrument (i.e., a hectare payment for a particular activity/measure). This section outlines two central concepts in policymaking: allocative efficiency and cost-effectiveness, which are central to the aim of this thesis and to all four papers, in addition to provisioning of public goods and management of negative externalities in agriculture.

Efficiency and cost-effectiveness

Using the words of Peter Drucker (1977), allocative efficiency is concerned with "doing the right things", while cost-effectiveness is about "doing things right". Economic efficiency is achieved when scarce resources, including environmental resources, are allocated to maximise societal welfare—including welfare of future generations (Arrow et al., 2013). To this end, market failures must be eliminated, which requires policy intervention. To design policy instruments that lead to an efficient resource allocation and maximised societal welfare it is necessary to know the benefits and costs of public goods and externalities. In practice, the benefits and costs of externalities and public goods like food security and climate change mitigation are difficult to quantify and value reliably. The CAP instead comprises a set of objectives that the framework of policy instruments aim towards.

Cost-effectiveness analysis can provide a guide to policymaking for target achievement. Typically, several means of attaining a target are available and differ in cost, and the least costly action (or combination of actions) is not always easily identifiable. A persistent problem of action-based agri-environmental policy is that the marginal cost of achieving a target—such as mitigating climate change, reducing nutrient pollution, improving soil health, or addressing biodiversity loss—varies substantially across space and between alternative measures (Shortle and Horan, 2017; Bamière et al., 2023; Moran et al., 2011). The same target can therefore be achieved at a higher or lower cost, depending on how and where interventions are implemented.[4] In this thesis, societal cost is proxied by loss in value-added in the agricultural sector. Cost-effectiveness analysis is a systematic method for finding the lowest cost means for achieving the policy target (Tietenberg, 2003). This thesis examines how policy instruments can contribute to greater efficiency in terms of cost-effectively addressing the CAP objectives.

Central to cost-effectiveness is the equimarginal cost principle: total costs are minimised when the marginal cost of delivering an additional unit towards a target is equal across sites and methods (Baumol and Oates, 1988). In other words, every incremental unit of improvement should occur where it is cheapest to achieve. Achieving this in practice requires understanding not only the spatial variation in environmental potential, but also how farm-level decisions respond to economic incentives and interact with markets. This thesis addresses these complexities by applying integrated economic–environmental modelling to simulate policy outcomes under diverse spatial, structural, and market conditions. The approach enables ex-ante assessment of cost-effectiveness, identification of trade-offs, and evaluation of where targeted interventions can deliver the greatest benefit at the lowest cost.

Finally, a practical criterion in redesigning agricultural policy for sustainability is budget-effectiveness—the efficient use of limited public funds per unit of target achievement. While cost-effectiveness remains the guiding principle, budget-effectiveness highlights the importance of ensuring that policy goals can be pursued within real-world budgetary constraints.

In this thesis, societal cost is defined as the sum of private costs (direct compliance and opportunity costs to farms) and indirect costs of environmental impacts. Administrative and transaction costs are excluded. In the modelling framework, societal cost is proxied by the change in sector profit excluding CAP payments, while external costs of environmental impacts are not monetised but assessed separately through environmental indicators. This approach is applied across the four papers: the cost of increasing bioenergy feedstock supply (Paper **I**), enhancing SOC (Papers **II** and **III**), and reducing GHG emissions (Paper **IV**) varies spatially and between measures. Cost-effectiveness calculations are explicitly described in

[4] 'Cost' is the societal cost, i.e., the total welfare loss to society from a policy, measured as the sum of private costs (direct compliance costs and opportunity costs to farms) and non-market environmental damages, plus any welfare losses arising from market-mediated effects such as changes in consumer and producer surplus.

e.g. Paper **III**. The measure of fiscal cost used in the papers is total CAP expenditure.

Economic, agricultural, and environmental modelling

The agent-based model AgriPoliS has been used for all the papers comprising this thesis. It has been extended to allow for additional analyses tailored to each study's objectives. In Paper **I**, production activities and markets for non-food energy crops were incorporated to explore land-use shifts under an energy crop subsidy. Paper **II** introduced cover crop activities in the model to assess the enrolment in such a scheme and predict its impact on SOC concentration. For Paper **IV**, a GHG emissions tax was implemented to simulate the effects of a typical climate policy on the environmental impact of agriculture. These targeted extensions reflect a cumulative modelling approach, where AgriPoliS was adapted to address increasingly complex environmental and policy challenges.

Agent-based modelling with AgriPoliS

Agriculture consists of a large number of heterogeneous businesses (farms) that operate under varying natural conditions and compete for a limited production resource—agricultural land. As a result, the sector is characterised by spatial variation in productivity and medium- to long-term decision-making under uncertainty, such as output and input price variability. In addition, agricultural production is subject to an evolving policy landscape. To analyse sector- and landscape-level economic and environmental impacts of agricultural policy instruments, a method was needed that could accommodate this complexity, leading to the adoption of an agent-based modelling (ABM) approach. ABM has been frequently applied in agricultural policy analysis to simulate responses to policy incentives (e.g., Huber et al., 2023; Berger and Troost, 2013; Marvuglia et al., 2022; Hristov et al., 2020; Brady et al., 2015). This method allows for *ex ante* assessment of policy interventions which is of fundamental importance, especially in systems where experimental approaches are unfeasible.

The ABM used here comprises a full population of individually acting farms (agents) that operate in virtual representations of two agricultural regions, following a set of pre-defined behavioural rules based on economic theory. Farm agents interact with each other, often in terms of land exchange (Brady et al., 2012), which dynamically affects farmer decision-making. This allows the ABM to capture emergent phenomena, i.e., that system-wide change emerges from the aggregation of individual decisions, leading to complex, non-linear outcomes through a bottom-up process. A system characterised by path dependence and hysteresis cannot be adequately captured by aggregate models (Bonabeau, 2002). This property makes ABMs suitable for modelling structural change and hence the long-term impacts of policy reform.

ABM has several advantages over other economic modelling approaches. A central one is the capacity to distinguish impacts for different farm types. Farms differ in orientation, size, degree of specialisation and intensity, etc., and therefore, potentially, also in their responses to changes in policy. Assessments of structural and environmental effects are therefore more reliable when this heterogeneity is considered (Reidsma et al., 2018).

The model used in this thesis is AgriPoliS (Agricultural Policy Simulator), a model developed for analysing structural change in regional agricultural sectors and policy analysis (Balmann, 1997; Happe et al., 2006), and described in the ODD protocol[5] by Sahrbacher et al. (2012). Farm-agent's optimising decision-making in AgriPoliS is based on a mathematical programming (MP) approach (Hazell and Norton, 1986). The virtual landscape, endogenous markets, system dynamics, etc. are programmed in the object-orientated programming language C++ (Happe, 2004). The actions and interactions of farm agents thus builds on maximisation of farm household income, subject to constraints like resource endowments, the vintage of fixed assets, market prices, spatial context, and the agricultural policy framework. Optimal production decisions reflect the relative profitability of alternative agricultural activities (crops and livestock), the opportunity costs of labour and capital (i.e., off-farm opportunities), and the institutional environment. A farm agent quits farming if it becomes bankrupt, cannot cover opportunity costs, or the farmer reaches retirement age without a successor (Kellermann et al., 2008).

Model input includes empirical data on individual farm agents, e.g., family labour, machinery, buildings, production facilities, land, liquid assets, and borrowed capital, and regional data on, e.g., number of farms, farm types, total land, technical coefficients, prices, and costs (Hristov et al., 2017). The AgriPoliS landscape is abstractly modelled, calibrated to match the statistical characteristics of the real-world region, including land type distribution and field size variability (Brady et al., 2012). Three land types are modelled: two arable land types and semi-natural pasture. The arable land types are characterised by their productivity and thus usage: high-productivity land is used today in cash-crop rotations and low-productivity land in feed crop rotations. Separate land markets exist for each land type. Land is allocated by an auctioneer agent based on marginal land valuations submitted by competing farms, with the highest bidder winning each parcel. Additional interaction occurs in regional livestock markets for calves and piglets to maintain herd dynamics and breeding stock.

[5] The ODD (Overview, Design concepts, Details) protocol is a set of documentation guidelines designed to describe agent-based models as fully as possible (Grimm et al., 2010).

For Papers **II**, **III**, and **IV** it was necessary to model agriculture's multifunctionality. Challenges to modelling multifunctionality include measuring the non-commodity output and linking it with the commodity output (Buysse et al., 2007). Because AgriPoliS provides a wide range of economic, structural, and environmental outputs it can capture multifunctionality to an adequate extent (Brady et al., 2012). AgriPoliS output compiles aggregate economic data at the sector level and individual farm data on, e.g., land use, farm size, yields, input and output quantities and values, fixed and variable costs, assets and investment expenditure, labour, capital. It also models environmental variables indicators, notably SOC, GHG emissions, and nutrient surplus. Se Paper **II** for more detailed information about the modelling of change in SOC concentration and optimisation of yield and fertiliser application given current SOC.

Case regions

Two distinct case regions in AgriPoliS were studied in this thesis: Jönköping County (Papers **I** and **IV**) and Götaland's southern plains (*Götalands södra slättbygder*, GSS) (Papers **II**, **III** and **IV**), both located in southern Sweden (Figure 2). These cases are interesting in an EU perspective, as examples that are representative of two common farming regions in the EU. Jönköping County is a typical *area with natural or other area-specific constraints* (ANC), i.e., areas that experience specific conditions that make farming difficult. Of all utilised agricultural area (UAA) in the EU-27 in 2021, 59 % was ANC area (EC, 2021b). GSS is a typical intensive-cropping region and similar to many areas in continental Europe (Rega et al., 2020).

Jönköping County is an inland region dominated by forest interspersed by fragmented agricultural land. Agriculture in Jönköping is livestock based, dominated by dairy and beef, and many farms combine livestock production and forestry. One third of agricultural land is semi-natural pasture (SCB, 2022). Because of the land fragmentation, moraine soils, and uneven terrain, agriculture in Jönköping is characterised by relatively low productivity and profitability. Jönköping is therefore an interesting case for studying the impact of policy on land abandonment and structural change, which has occurred over the past decades (SBA, 2024).

Götaland's southern plains (GSS) is a naturally defined agricultural region located along the south-western coast. It is the most productive agricultural region in Sweden with primarily arable agricultural land (95 %) in large, continuous, and well-connected parcels. Production is characterised by intensive arable cropping, economies of scale, and high yields (normal winter wheat yield is 8 t ha^{-1}) (Statistics Sweden, 2020). Typical cash-crop rotations contain winter wheat, winter rapeseed, sugar beet, and spring barley. Specialised pig and poultry are important industries in GSS, whereas livestock density is low, resulting in low availability of stable manure and low demand for temporary grasses and pastures. Long-term intensive management with limited use of organic soil amendments has been accompanied by a trend in SOC decline in GSS (Brady et al., 2019). The region was therefore a suitable choice for the analyses of soil carbon loss and soil health.

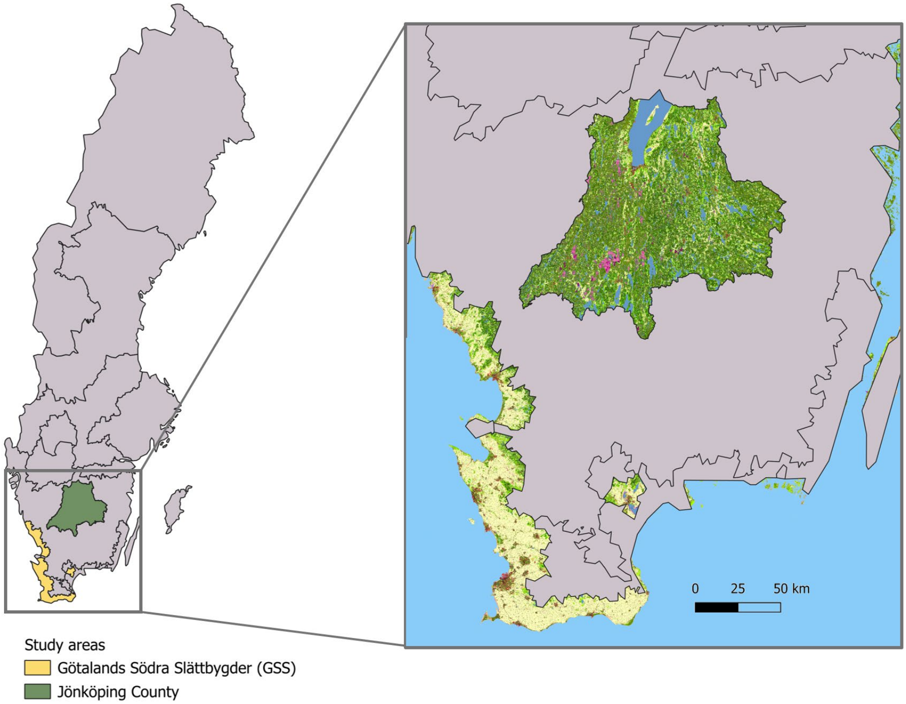

Figure 2 Location of case regions Jönköping County and Götaland's souther plains on a map of Sweden. The map is created using NMD 2023, base layer v2.0: yellow = farmland, green = forest.

Combining AgriPoliS with agent-based life cycle assessment (AB-LCA)

For Papers **II** and **IV** AgriPoliS modelling was combined with life cycle analysis (LCA) in an agent-based LCA (AB-LCA) framework. The methodology has been developed for agricultural systems in recent years (Vázquez-Rowe et al., 2014; Lan and Yao, 2019; Marvuglia et al., 2022). The coupling to AgriPoliS and LCA modelling for these papers was performed by co-author Raül López i Losada (López i Losada et al., 2024).

The integration was modular: output from the final simulation year of AgriPoliS was used as input to the Life Cycle Inventory stage of the LCA. An attributional cradle-to-farmgate approach was applied to model environmental impacts. In Paper **II**, a territorial LCA of greenhouse gas emissions was conducted over a 100-year time horizon using the ReCiPe midpoint hierarchical methodology (Huijbregts et al., 2017). The system boundary encompassed the agricultural sector in GSS.

Paper **IV** employed a more comprehensive LCA, assessing impacts on human health and biodiversity using ReCiPe endpoint methodology, alongside weighted environmental scores from the Environmental Footprint (Huijbregts et al., 2017; EC, 2021a). The system boundary included the agricultural sectors of Jönköping County and GSS. A key assumption was fixed consumption: any reduction in regional production was offset by imports. The functional unit was defined as maintaining global production levels in the final simulation year across scenarios. This assumption allowed for more accurate estimation of environmental impacts resulting from production displacement.

LCA added a layer of environmental consequence analysis, particularly capturing indirect effects of policy beyond the AgriPoliS region. Conversely, AgriPoliS contributed a dynamic dimension to the LCA (Gutiérrez et al., 2015), resulting in synergistic insights.

Study-specific modelling and setup

The same model initialisation was used in every study. The four analyses all build on policy scenario simulations and comparison to a reference scenario.

In Paper **I**, the cost-effectiveness and land-use impacts of an area-based and energy content-based subsidy for promoting expansion of production of non-food energy crops were assessed. Jönköping County was chosen as the study region because of its relatively low opportunity cost for arable land and risk of agricultural land abandonment, making the adoption of non-food energy crops more likely. For this analysis, AgriPoliS was extended to include energy crops. Three non-food energy crops were added to the already published model: reed canary grass, ley grass mix, and SRC willow. Output and input parameters were collected from the Swedish agricultural production database (Agriwise, 2020). The energy crop selection was based on a holistic judgement of their relevance in an expansion of non-food energy crop production (Börjesson, 2021), including natural conditions for cultivation of crops throughout Sweden, economic conditions for a viable market notably transportation costs, and on whether they were cultivated in Sweden at present (Mola-Yudego et al., 2021; Nilsson et al., 2015; Björnsson et al., 2016; Dimitriou and Mola-Yudego, 2017). A difficulty in the modelling and calibration of these activities was that energy-crop production levels are currently very low in Jönköping. This was overcome by applying a consistent method for compiling data and using the same data sources for all the crops in the model (Hristov et al., 2017). The same challenge occurred in the modelling of rotational leys in Paper **III**. We return to the implications for model calibration below.

The aim of Paper **II** was to assess whether reallocation of CAP direct-payment funds to a payment for cover crops was successful as a policy strategy to improve policy efficiency. GSS was used in this analysis because soil health in the region is exhibiting deterioration due to intensive management practices (Brady et al., 2019).

For this analysis two contrasting cover crop strategies were modelled in AgriPoliS. They differed in management cost and intensity, in policy payment, and in associated agronomic benefits. For the high-cost, high-payment, high-benefit option, oilseed radish was modelled, which is a favoured option in southern Sweden for its agronomic benefits. For the low-cost, low-payment, low-benefit cover crop activity barley was modelled. Both activities were parametrised with coefficients for annual SOC carbon sequestration based on Poeplau and Don (2015) and N uptake based on Tonitto et al. (2006). The AgriPoliS results were used to inform a territorial LCA of GHG emissions (see more on LCA below).

In Paper **III**, the impact was analysed of accounting for jointness in the provision of soil-based public goods when designing a soil health payment. A payment for grass leys on arable soils is forthcoming in Sweden (to be introduced in 2026). The instrument is intended to promote carbon sequestration in soils, thus contributing to climate change mitigation and soil fertility. Jointness was represented in the model through the dependence of soil ecosystems on SOC levels. SOC was thus used as a proxy indicator of soil health: changes in SOC are associated with improvements in multiple ecosystem functions, including carbon sequestration, nutrient cycling, water holding capacity, and microbial activity (e.g. Lal, 2004; Creamer et al., 2022). AgriPoliS does not explicitly represent each individual service, hence SOC was used as a central indicator to reflect the non-allocability of soil health maintenance for multiple public goods. Again, the GSS model was used for this analysis because soil health deterioration is a potential problem and because the ley payment that will be introduced in Sweden by 2016 only applies to nitrogen-sensitive regions like GSS.

A modelling choice had to be made regarding the use of the additional biomass resulting from the policy-induced land-use change. It was assumed that livestock production (i.e., feed and pasture) could not expand onto arable land typically used for cash cropping. To test the sensitivity of the results to the presence of a market outlet for the biomass, an alternative set of scenarios was introduced in which a market for biogas feedstock was assumed. The energy crop activities developed in Paper I were therefore extended and adapted to the GSS context, with yield levels and cost parameters adjusted to reflect GSS conditions.

Finally, the aim of Paper **IV** was to analyse how abolishing the coupled income support to cattle and a tax/payment incentive on enteric methane emissions and carbon sequestration in soils would influence the transformation of agriculture towards the EU Green Deal objectives. Both regional models were used in this study to capture differences in effects of regional variation. The tax on SOC was modelled as a permit market where production of SOC-depleting activities required emission permits corresponding to the annual depleted quantity. Emission permits could be purchased or awarded to the farm for production of SOC-restoring activities. The tax was based on the current carbon tax in Sweden and set to 2.74 EUR kg^{-1} CH_4 for enteric methane emissions and a payment/tax of 0.37 EUR kg^{-1} C for sequestering/releasing SOC. Similar to Paper II, ABM was integrated with LCA for this analysis, but in a more extensive analysis that included life cycle environmental impacts in terms of damage to human health and biodiversity. In addition, the results were related to nine agri-environmental indicators defined from EGD goals.

Table 1 provides an overview of central aspects of the papers.

Dealing with uncertainty: model verification, validation, and calibration

AgriPoliS is a deterministic model: for a given set of inputs, it yields exact and repeatable outputs. Consequently, stochastic variation is not present in the model's output. However, the landscape initialisation is based on probability distributions of various variables: location of farm centres, field size, vintage or stables, farmer age, etc. The impact of different random seeds for model initialisation was tested by Sahrbacher et al. (2017), and shown not to significantly influence model outcomes. An initialisation based on an identical random seed forms the basis for all subsequent policy simulations. Because standard errors and statistical significance cannot be computed, uncertainty must be handled differently. The approach taken here includes: (1) rigorous verification, validation, and calibration during model development; and (2) a conditional interpretation of simulation results, focusing on scenario comparisons that control for shared model limitations.

Verification and validation in ABMs are not confined to testing the final model but are integral to the entire development process (Figure 3) (Sargent, 2010). AgriPoliS has undergone substantial validation throughout its development (Happe, 2004; Brady et al., 2012).

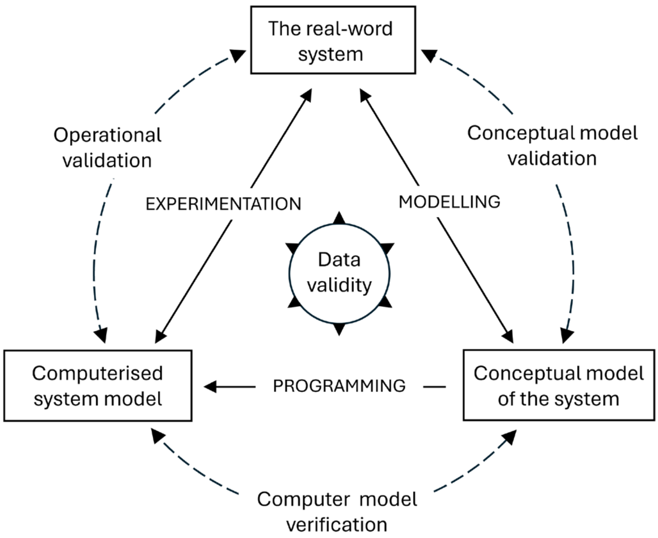

Figure 3 The modeling process. Adapted version from Sargent (2010).

One validation challenge with ABM is its flexibility and complexity. However, ABM and MIP are natural ways to describe farming systems and resonate with how practitioners think—using activity-based input-output relationships over the crop cycle (Hazell and Norton, 1986; Bonabeau, 2002). This alignment facilitates expert validation, which was carried out through consultation and review (Börjesson, 2021; Segerslätt, 2022; Pålsson, 2024; Andersson, 2025). A critical step was the accurate initialisation of the farm agent population. This was done through a cluster analysis of the IACS database to generate a representative set of regional farm types (Boke Olén et al., 2021). Model extensions developed for this thesis were constructed using a consistent data framework, applying uniform methods and data sources across all crop activities (Hristov et al., 2017).

Calibration was carried out using operational validation via graphical comparisons between simulated and empirical data for the 2010–2022 period (SBA, 2023b; a). It was done by iteratively adjusting a residual variable-cost parameter for selected production activities until they repeated the observed trend. This method accounts for unobservable or aggregated costs that are not captured by standard accounting but influence farm decisions such as use of unpaid family labour, managerial effort, or risk preferences. The goal was to reproduce key structural trends such as farm numbers and livestock types (Hazell and Norton, 1986; Buysse et al., 2007). These steps together resulted in a model that behaves in a theoretically sound and empirically grounded manner when subjected to policy changes, thereby supporting reliable policy analysis and insights into the agricultural sector.

Summary of data sources

The modelling in this study drew on multiple data sources. Regional characteristics on farm structure, normal yields, crop areas and livestock were collected from the IACS database and official statistics from the Swedish Board of Agriculture (SBA, 2025a), while enterprise budgets for different production activities were obtained from Agriwise (2020). Historical production data were used for model calibration (SBA, 2023b; a). Estimates for soil carbon levels came from (Brady et al., 2019).

Environmental impacts in the LCA modelling were assessed using the World Food LCA Database (WFLDB) (Nemecek et al., 2014).

Model limitations

As with any modelling approach, the use of AgriPoliS involves simplifying assumptions that should be borne in mind when interpreting results. Importantly, the farm agents' decision-making behaviour is represented through an income maximisation assumption. While this is consistent with much of the economic modelling literature, it does not capture the full range of motivations and preferences real-world farmers have, such as relating to risk aversion, cultural norms, or environmental stewardship goals. Additionally, the model's landscape representation is abstract, and while it captures certain structural characteristics of the regions it cannot reflect the full spatial complexity. For instance, the representation of arable land is simplified to only two types, whereas real landscapes are differentiated by a broad range of characteristics. Environmental processes are also represented in a simplified form. For example, SOC change is used as a proxy for soil health. While SOC is an important and widely used indicator, it does not encompass the full spectrum of soil physical, chemical, and biological properties that influence ecosystem productivity. As described above, AgriPoliS is deterministic, hence the stochastic variability that characterises real agricultural systems is excluded.

Table 1 Structured overview of papers comprising the thesis.

Dimension	Paper I	Paper II	Paper III	Paper IV
Thematic focus	Cost-effective instrument design for promoting agriculture-based bioenergy production.	Reallocating direct payments as a strategy for improving policy efficiency.	Efficient policy for maintaining soil health in the presense of jointly produced soil public goods.	Impacts of agricultural policy on EU Green Deal objectives.
Research questions	How cost-effective are different subsidies for increasing non-food energy crop production, and what are the structural implications in agriculture?	What is the impact on SOC of reallocating direct payments to a voluntary cover crop payment?	How do different instrument designs of a ley payment affect soil health maintenance, and do they lead to improvements?	What are the regional and global environmental effects of GHG taxes in agriculture?
Objects of analysis	Area- and energy content-based subsidies to energy crops.	Cover crop payment.	Rotational ley payment.	SOC payment/tax, methane tax, cattle subsidy.
Methods	Agent-based modelling, cost-effectiveness analysis. Case region: Jönköping	Agent-based modelling, Life Cycle Assessment. Case region: GSS	Agent-based modelling. Case region: GSS	Agent-based modelling, Life Cycle Assessment. Case regions: Jönköping + GSS
Type of contribution	Modelling-based comparative assessment of policy instruments' cost-effectiveness.	Modelling-based assessment of reform strategy for improved goal alignment.	Modelling-based policy assessment with conceptual contribution.	Empirical and methodological contribution on the life-cycle impacts of GHG pricing OR Modelling-based policy assessment
Main findings	Cost-effectiveness can be the same for an area- and energy content-based subsidies, but not under variable market conditions.	The reallocation improved alignment with environmental goals and constitutes repurposing, but the impact was limited in scale.	Failing to recognise jointness can result in suboptimal or even zero soil health maintenance and public good provision.	Regional differences in agriculture cause differences in policy impact. Risk of leakage of environmental impacts.
Policy relevance	The food-energy land-use dilemma is overly simplistic to be constructive as a policy principle.	The concept of repurposing is more useful when applied to entire policy frameworks, not single instruments.	Broader soil health valuation and spatial targeting are needed to deliver cost-effective outcomes.	Tailored and coordinated policy is needed to avoid unwanted side-effects and leakage of damage.

Synthesis of results and discussion

Main findings

Paper **I** assessed the cost-effectiveness and structural impacts of an area-based and an energy content-based subsidy for promoting expansion of production of non-food energy crops. Under stable market conditions, area-based subsidies and energy-based subsidies performed similarly. When feedstock market prices dropped however, area-based subsidies led to substantially higher societal costs. In contrast, energy content-based subsidies maintained cost-effectiveness by being responsive to changing market conditions. This indicated that failing to align the goal of the farmer with the goal of society can lead to excessive costs for biomass production. Specifically, energy-based payments increased the area-efficiency (MJ ha^{-1}) of energy crop production, while this did not occur for the area-based payment.

The study also highlighted the structural implications of energy crop subsidies, demonstrating that they can reduce agricultural land abandonment, support food security, and maintain landscape heterogeneity in a marginal agricultural region. This challenged the notion that food and energy production are inherently in conflict. In areas at risk of land abandonment, bioenergy crops can serve as transitional crops—maintaining farm income and keeping land in good agricultural condition while supporting the energy transition.

Paper **II** evaluated reallocation of CAP direct-payment funds from basic income support to a cover crop eco-scheme for carbon sequestration in arable soils. The aim was to assess if it constituted repurposing, as a test of the potential for such reallocation as a strategy to improve policy efficiency.

Reallocating a portion of direct payments to cover crops slowed the decline of SOC in high-productivity arable soils, improved nitrogen efficiency, and reduced greenhouse gas emissions. From an economic perspective, farm incomes and sector profitability were only marginally affected, indicating that the reallocation did not jeopardise long-term food security or farm viability. Structurally, it induced (minor) shifts toward fewer and larger farms but did not trigger land abandonment or loss of food production capacity. It was hence concluded that the reallocation constituted a partial repurposing of direct payments: efficiency of the CAP funds for achieving its targets improved.

The SOC gains were, however, relatively small. The improvement was not sufficient to reverse the negative trend in SOC stocks. Nor did it suffice as a climate change mitigation measure for agricultural GHG emissions, particularly as it does not target livestock emissions. Moreover, while the cover crop eco-scheme supported climate change mitigation at a competitive cost (€50 CO_2e^{-1}), both in comparison to carbon prices and findings in other studies, its long-term effectiveness depends on sustained carbon storage and could be reversed if the policy changes or farming practices shift.

Paper **III** focused on the efficiency of a carbon sequestration policy for arable soils when considering jointness in production of soil-related public goods. Jointness limits the possibility of targeting a single soil-related public good/ecosystem service. When farmers were offered a payment for introducing leys in cash-crop rotations corresponding to the climate benefit of the resultant improvement in SOC content, they chose not to enrol in the scheme. Consequently, the instrument resulted in neither climate benefits nor any other public goods associated with improved soil health. Simulations of the forthcoming ley payment in Sweden (to be introduced in 2026)—a lower payment without spatial targeting—resulted in both no additionality and an increase in GHG emissions from livestock.

In summary, the study demonstrated that failing to recognise jointness, and hence under-paying for soil health, can result in suboptimal and even absent soil health maintenance, i.e., inefficient provisioning of both the targeted public good and of other soil-related public goods. An over-simplified policy instruments in this case led to at least one of two policy failures: first, the market failure that the instrument is meant to address remained unsolved and, second, an increase in unintended negative effects (e.g., increasing emissions). The results suggest that both an efficient payment level and precise spatial targeting of policy payments are necessary to consider in the design of action-based policy instruments for soil health.

Finally, Paper **IV** examined the effects of removing coupled cattle support and implementing a tax on soil C and methane emissions, on the environmental performance of agriculture within the European Green Deal framework. The carbon pricing mechanism led to substantial reductions in livestock production, land use changes including abandonment of semi-natural pastures that are crucial for biodiversity conservation, and expansion of bioenergy crops in high-productivity regions. Though the environmental impacts declined regionally, the LCA results showed that damage to natural environments globally was 10-20 % higher than in the reference scenario, because of displaced Swedish production. That is, the leakage of environmental impacts outweighed the domestic emissions reductions. Farming in Jönköping contracted substantially, e.g., ruminant livestock declined by half and arable land use by 40 %. Leakage effects were hence particularly strong in Jönköping, with the most pronounced effects in the dairy industry.

The results also pointed to important effects of regional heterogeneity. Abolishing the coupled cattle support had a stronger effect on cattle production in the intensive cropping region than in the livestock dominated region due to the availability of alternative profitable agricultural activities in the former. Similarly, energy crop deployment was substantial in arable land in Götaland, but limited in Jönköping due to low profitability, which made land set-aside or afforestation more attractive in Jönköping than energy crop cultivation.

Discussion

The findings reveal a number of overarching insights that are not apparent when the papers are considered individually. These are discussed below with reference to the overall aim of this thesis: to evaluate the economic efficiency and environmental effectiveness of agricultural policy instruments for the sustainable provision of public goods, with particular attention to balancing food security, agroecosystem management, climate change mitigation, and the long-term viability of the agricultural sector.

Cost-effective policy instrument design for public goods

The papers in this thesis analysed policy instruments designed to achieve targets for biomass energy supply (Paper **I**), climate change mitigation (Paper **II** and **IV**), and maintaining soil health (Paper **III**). Several insights emerged regarding the design of instruments, particularly the importance for cost-effective policy of spatial heterogeneity, the optimal payment level, and responsiveness to market conditions; these are discussed in the following sections.

Spatial heterogeneity

A clear theme across the papers is that spatial heterogeneity—differences in land and soil characteristics, land-use pressures, farm structure, and market access—strongly shapes both the environmental and economic outcomes of agri-environmental policy. Thus, the same instrument can yield very different effects depending on where (i.e., region) and how it is applied (i.e., general or targeted payments).

Spatial heterogeneity was operationalised in the modelling along two main dimensions: agricultural regions—an intensive cropping region and a livestock-dominated, highly forested region—and three land-use types: high-productivity arable land, low-productivity arable land, and semi-natural pasture, that are further differentiated according to field size and distance from farm centres. The proxy commonly used for distributing agri-environmental payments in Sweden is less specific, distinguishing between regions, arable land, and pasture, which the results show to be an insufficient representation of spatial heterogeneity for allocating agri-environmental payments. For instance, as demonstrated in Paper **III**, ‘arable land in a high-productivity region’ proved to be a poor proxy for SOC deficit, as it varies depending on the combination of soil characteristics and historical management practices, resulting in suboptimal policy outcomes. More granular or function-based targeting may offer more effective means of aligning policy objectives with on-the-ground realities (Bamière et al., 2011; Cong et al., 2014; Brady et al., 2019).

Not considering regional differences can also lead to unexpected policy outcomes. Paper **IV** found that a tax on GHG emissions from soil and livestock over time resulted in production displacement and leakage of environmental damage in a livestock-dominated region but not in an intensive-cropping region. This was related to a difference in economic resilience between the regions, as the tax impacted less profitable livestock farms more strongly. (This discussion closely relates to structural change effects that are further discussed below.) Paper **IV** contributes with important context for interpreting the effects on food production observed in Papers **I** and **III**, the effects of which were only analysed regionally. LCA thus provided valuable insights into the potentially substantial global consequences of domestic policy and magnitude of indirect impacts. The coupling of ABM and LCA was essential for this, as the dynamic effects would not have been visible in a static LCA.

The policy implications of these findings are not clear-cut. The risks of indirect land-use change are commonly pointed to in literature on agriculture-based bioenergy (Daioglou et al., 2020), warning that increased energy crop production can result in negative effects on the environment globally (Searchinger et al., 2008). This has given rise to policy restricting bioenergy use in the EU (2018). However, avoiding all policy that could cause indirect land-use change may be counterproductive, as it risks constraining necessary structural transitions and the development of more sustainable land-use strategies (Xu et al., 2022; Fujimori et al., 2022). Moreover, current land-use patterns may themselves be shaped by inefficient or environmentally counterproductive policies already in place (Bulte et al., 2007).

The complexity is underscored by other findings from this thesis. Paper **I** showed that a subsidy for non-food energy crops supported the maintenance of agricultural landscapes by reducing abandonment of arable land (Ustaoglu and Collier, 2018; Kuemmerle et al., 2016). In the analysis of the cattle payment in Paper **IV** it was found that the instrument, which, while constituting a subsidy to an emissions-intense product, alleviated global emissions due to comparatively low emissions intensity in Swedish milk and beef. (It may be added, however, that such subsidies also reduce consumer prices and thereby increase overall consumption (Jansson et al., 2021), potentially offsetting the intended benefits.)

The optimal payment level

The payment levels for agri-environmental schemes are decisive for the instruments' effectiveness and efficiency. As previously outlined, instead of attempting to equate marginal social benefit with cost, which involves determining the societal value of public goods and costs of externalities, the CAP is built on a set of predefined objectives that are to be achieved. In this framework, it is no longer a matter of assessing the value of the outcome in welfare-economic terms, but of minimising the societal costs of reaching the stated target. Target-steering reflects the practical difficulty of valuing public goods, where monetary evaluation is replaced by implicit valuation. Thus, instruments can be cost-effective relative to the stated objective, but this does not guarantee that the objective itself is efficient.

The payment level is a key determinant of farmers' enrolment in agri-environmental schemes (Schaub et al., 2023). As shown in Paper III, high opportunity costs in high-productivity regions can require correspondingly high payments, which in turn may limit total target achievement under a fixed budget. In this case, the rotational ley payment exhibited lower cost-effectiveness for carbon sequestration than a cover crop payment, suggesting that alternative measures can sometimes deliver more at lower cost. However, high compliance costs do not necessarily undermine policy effectiveness when no cheaper alternatives exist; in such situations, a high payment level can still be justified if the instrument achieves the target at a lower cost than other options.

Paper **III** also addressed the particular case of jointness in production of soil-related public goods, as an economic expression of bundled soil ecosystem services (Bennett et al., 2009; OECD, 2001). The analysis showed that a policy instrument that targeted soil carbon sequestration for climate change mitigation—paying farmers for that value at carbon market prices—had no effect. If climate change mitigation had been the only societal benefit created by carbon sequestration this outcome would have been optimal. However, because the benefits of SOC for soil health also contributes to a range of other public goods (Figure 1), the payment level was too low to reflect the value of maintaining soil health (implied by the CAP target *e* regarding natural resources management). This issue is relevant to consider in connection with policy instruments supporting 'carbon farming' or carbon offsets (Saifuddin et al., 2024; Paul et al., 2023; Strauss et al., 2024). These often refer to the positive effects of revitalising soil ecosystems as 'co-benefits' or synergies of climate policy (Barbieri et al., 2024; Verspecht et al., 2012; Bustamante et al., 2014), which understates their importance and risks leading to underfinancing of soil recovery efforts (Karlsson et al., 2020; Ding et al., 2021; Moinet et al., 2022). Since determining the full societal value of soil-related public goods is effectively impossible, predefined policy targets for soil health serve as a pragmatic substitute for efficiency. They allow for cost-effective progress toward specific objectives, but do not guarantee societal optimality; the efficiency of such an approach depends critically on the adequacy of the targets themselves and the instruments chosen to achieve them.

Responsiveness to market dynamics

Policy instruments interact with markets for agricultural inputs and outputs, which can amplify or undermine policy effectiveness depending on how well the instrument design accounts for market dynamics. Paper **I** demonstrated that poor alignment between policy objectives and instrument design created inefficiencies under market volatility; the area-based subsidy failed to maintain cost-effectiveness as energy crop prices fluctuated. Similarly, Paper **III** showed that the effectiveness of a soil health policy varied substantially depending on whether a market for bioenergy feedstock existed. When such a market was present farmers could sell the new ley biomass to biogas facilities, thereby reducing the opportunity cost of implementing the measure and making adoption more attractive.

Together, these findings reinforce a fundamental design principle: instruments that are adaptive to changing market conditions—either by design or through built-in adjustment mechanisms—are more likely to remain cost-effective over time and across diverse contexts.

Structural change

Introducing an agricultural payment, whether or not it targets public goods, can alter the structure of the agricultural sector (Appel et al., 2016). This effect was observed across all papers in the thesis, resulting in indirect environmental effects. By increasing the profitability of certain farms, payments influence relative returns across production activities, triggering changes in resource allocation (e.g., land, capital, labour) and, over time, the composition and number of farms. In Papers **II** and **III**, payments for SOC sequestration shifted land and other resources toward recipient farms; in Paper **II**, toward crop farms adopting cover crops; in Paper **III**, toward livestock farms; and in Paper **IV** the methane tax shifted livestock production outside of Sweden.

From a welfare economics perspective, such reallocations are desirable if they reflect a correction of a market failure, i.e., if the payment internalises an externality or supports the efficient provision of public goods. However, in the case of the proposed ley payment (a low payment level available to all farmers) that failed to increase provisioning of public goods, the policy shifted production away from the mix of goods that consumers preferred (more beef and milk), without providing compensating benefits, thereby reducing overall consumer welfare. (It is unlikely that the initial market-clearing allocation is efficient, but it is possible the resulting allocation is even more inefficient.) Thus, because the structure of the agricultural sector is an indirect representation of consumer preferences, the instrument created welfare loss in addition to what was imposed by increased GHG emissions and its direct budgetary cost.

There are also potential dynamic effects to consider. For example, a policy intervention may accelerate land-use changes that would otherwise occur later. Data from Sweden shows a declining trend in cattle production (SBA, 2025b)—a trend that modelling in this thesis suggests will continue—as well as increasing afforestation of agricultural land in low-profitability areas (Kumm and Hessle, 2020). This indicates that displacement of production may already be occurring 'organically'. In response to this structural development, introducing alternative income sources could help prevent land abandonment, farm closures, and sector homogenisation, thereby supporting food security and agricultural diversity. Dynamic modelling with AgriPoliS made it possible to observe this effect in Paper **I**, where risk of land abandonment was reduced by the introduction of energy crop subsidies. Through their dynamic effects on agriculture in the region they arguably supported rather than threatened food security. This reflects the kind of dynamic effects discussed by Requate (2005), where policy instruments not only influence current behaviour but also shape long-term structural changes by altering incentives for land use, innovation, and adaptation over time.

Ultimately, this suggests that land-use change should not be viewed as inherently beneficial or detrimental, but rather assessed in relation to its policy context, timing, and contribution to long-term sustainability and resilience.

Environmental effectiveness and policy integration

Finally, it was found that policy instruments commonly favoured in the CAP have limited impacts on environmental objectives. In particular, Papers **II** and **III** both analysed instruments that are currently part of Sweden's CAP Strategic Plan, showing that neither have a substantial effect on their intended targets, i.e., soil carbon sequestration and climate change mitigation. Concern was also raised by the European Commission in its assessment of Sweden's proposal (EC, 2022), stating that it might have a predominantly negative impact on the climate compared to the current situation (p. 3). In general, integrating payments for ecosystem services in agricultural policy does not have a good track record (Pe'er et al., 2014; Pattanayak et al., 2010; ECA, 2017)

The design flaws discussed above partly explain the lack of effects, but it is also indicative of a tension between economic/structural and environmental objectives that could severely limit the potential for substantial efficiency improvement: the limitation is not inherent in the CAP framework, but the framework allows it (Röder et al., 2024). The absence of effects suggests that the integration of environmental policy in the framework remains low, i.e., it is not genuinely perceived by the majority of policymakers that the agricultural sector should be a provider of public goods, as opposed to a recipient of economic support (Alons, 2017). The political difficulties associated with removing established subsidies is also echoed by the recent 'repurposing' agenda, which argues for reallocating rather than reducing economic support to the agri-food system (FAO et al., 2021; Gautam et al., 2022; Gill et al., 2024).

Agricultural policy for sustainability

Agricultural sustainability is commonly conceptualised as encompassing environmental, economic, and social dimensions, with emphasis on the intergenerational nature of the challenge (UN, 2015). In agriculture, these are closely interdependent: the maintenance of productive resources such as soil, water, and biodiversity is essential for economic viability, while economic resilience influences the adoption of environmentally beneficial practices. However, the two are not automatically aligned in the short term, as economically attractive strategies may degrade the resource base (Stoate et al., 2009), and environmentally sound measures may impose additional costs on farmers.

The results of this thesis highlight that policy design is central to reconciling these dimensions. Recognising spatial heterogeneity improves the targeting of measures; setting payment levels in line with clearly defined objectives reduces inefficiency; and incorporating responsiveness to market dynamics helps maintain cost-effectiveness over time. Policy instruments also shape the structural trajectory of the sector, with implications for land use, diversity, and resource allocation. The net effect on sustainability depends on whether these changes enhance or diminish the capacity to maintain resources and supply public goods.

These findings illustrate the value of combining economics and environmental science in policymaking, particularly in the design of integrated environmental–economic policy frameworks. Such integration enables the assessment of both environmental outcomes and their economic trade-offs, supports the identification of cost-effective interventions. Advancing agricultural sustainability requires policy frameworks in which environmental performance is a central indicator of sectoral viability. Targeted, cost-effective, and adaptive instruments can align environmental and economic goals, reduce structural distortions, and preserve the resource base needed to meet societal needs over the long term.

Conclusions

The overarching aim of this thesis was to evaluate the economic efficiency and environmental effectiveness of agricultural policy instruments that support the sustainable provision of public goods, with particular attention to balancing food security, agroecosystem management, climate change mitigation, and the long-term viability of the agricultural sector. Five main conclusions emerge from the thesis:

CAP agri-environmental payments need better spatial targeting. Variation in land and soil characteristics, farming intensity/risk of land abandonment, farm structure, and market conditions strongly shaped policy outcomes. An instrument that was based on a poor proxy of its actual aim resulted in a worse outcome than if the instrument had not been implemented at all. Relying on coarse regional categories or broad land-use types led to poor results; more precise criteria—such as soil health status, productivity potential, or ecosystem service capacity—is needed to improve cost-effectiveness of CAP payments for environmental management.

Jointness in provision of public goods should be accounted for in policy. For soil-related public goods, focusing payments narrowly on one service (i.e., carbon sequestration) resulted in underfinancing soil-health interventions and inefficient provision of the broader ecosystem service bundle (i.e., multiple public goods), including services critical for food production. In general this implies that recognising and incorporating the properties of the targeted ecosystem, at the appropriate spatial scale, should be part of the instrument design process.

Policy instruments that are responsive to changing market conditions are more cost-effective. Because farmers decision-making is responsive to market conditions, instruments that were unresponsive lost its effectiveness when market prices declined or increased. To avoid policy instruments that are as unpredictable as the market, mechanisms should be built into the instrument that adjust for market fluctuations. This implies that the efficiency of the current hectare-based design of the CAP Progress Assessment, e.g. impact and result indicators, could be improved by considering instruments that adapt to changing market conditions.

Indirect environmental effects caused by structural change can be substantial. Policy instruments aimed at environmental benefits had dynamic effects on structural change in the sector. Changes in production volumes and composition spread globally through trade and resulted in this case in negative environmental impacts globally, but structural change can also have positive net effects. This thesis does not conclude that structural effects should be avoided, but they may impact the outcome of policy instruments, and should therefore be considered as part of the policymaking process.

Environmental policy integration in the CAP remains limited. The eco-schemes studied delivered relatively weak environmental outcomes, reflecting a persistent framing of agriculture as a recipient of income support rather than a provider of public goods. Achieving genuine integration will require embedding environmental objectives directly into the incentive structure and repurposing funds or redesigning instruments that do not contribute to provisioning of public goods, to take into account the issues identified above.

Collectively, these findings demonstrate that agricultural sustainability cannot be achieved by focusing on either economic or environmental performance in isolation. The thesis contributes by combining economics and environmental science in an interdisciplinary modelling approach, showing how agri-environmental payments can be redesigned to improve both cost-effectiveness and environmental sustainability. It also highlights that the sustainable provision of public goods is a complex, potentially wicked, problem, that demands more nuanced, flexible, and evidence-of-effects-based policy frameworks.

Ultimately, because of the overlap and interconnectedness between economic and environmental dimensions, agriculture cannot be economically sustainable unless it is also environmentally so. A policy framework that fully integrates these objectives will be better positioned to support a resilient agricultural sector, a sustainable food system, and food security.

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