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Advancing sustainability transformations in agriculture: An agent-based life cycle assessment for supporting policymaking

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ABSTRACT

The European Green Deal (EGD) aims for agriculture to contribute positively to climate change mitigation and nature preservation while meeting growing societal needs for food, energy, and biomaterials. Delivering comprehensive policy action efficiently requires decision-support tools to assess the outcomes of interventions across multiple, and potentially conflicting, goals. By means of agent-based (territorial) life cycle assessment, we evaluate the effect of removing coupled cattle support and pricing greenhouse gas emissions of agricultural products in two regions in Southern Sweden as representative cases for intensive and extensive agriculture in the EU. Regional production features influenced policy outcomes by affecting the profitability of possible production activities, and thereby the economic viability of alternatives to cattle. Production changes abroad were critical for the environmental lifecycle performance of the evaluated policy reforms, given the relatively low environmental impacts of Swedish production compared to global averages. Our ex-ante approach offers decision support by discerning the implications of policy interventions on the regional structure of production and subsequent effects on the environment, considering both regional and global aspects of the EGD objectives for agriculture. Ultimately, we hope our analysis can facilitate policymaking to speed the transition of agriculture towards EGD objectives.

1. Introduction

The sustainability transformation of agriculture is a cornerstone of the European Green Deal (EGD) that encompasses ambitious goals to address numerous and diverse environmental concerns. In sum, agriculture is expected to contribute positively to climate change mitigation and nature preservation while meeting growing societal needs for food, energy, and biomaterials. European policymakers promote this transition through an expanding series of policy initiatives, which currently comprises the Farm to Fork (F2F), Biodiversity, and Soil strategies (European Commission, 2020; Council of the European Union, 2021; European Parliament, 2021), and the national strategic plans of the Common Agricultural Policy (CAP) (EU, 2021). As a recent addition, the EU passed a law on nature restoration in June 2024 to restore biodiversity and secure ecosystem services, including climate adaptation and mitigation (EU, 2024). Besides these, the Renewable Energy Directive (RED) (EU, 2018) and the Bioeconomy strategy (European Commission, 2018) are contingent to a large extent on the availability of additional agricultural biomass (Tsiropoulos et al., 2022). This lengthy range of services expected from agriculture, together with the inherent nature of agricultural land as a limited resource (Haberl et al., 2011), stresses the importance for policy concerned with the transformation of agriculture to realise synergies and minimise trade-offs among its different components (Springmann et al., 2018; El Bilali, 2020; Verschuuren, 2022; Boix-Fayos and de Vente, 2023). The challenge to evaluate the performance of agricultural policy instruments across multiple goals is made harder still by the continuous evolution of agricultural production systems (Báldi et al., 2023).

Here we study the effects of policy instruments on regional structure and production dynamics and their implications towards fulfilling the environmental objectives of the EGD for agriculture by coupling modularly an Agent-Based Model (ABM) of regional farm structure, AgriPoliS, and Life Cycle Assessment (LCA). Our environmental analysis

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Nomenclature

Abbreviations

AB-LCA	Agent-based (territorial) life cycle assessment
ABM	Agent-based model
AEI	Agri-environmental indicator
BISS	Basic income support for sustainability
CAP	Common Agricultural Policy
CIS	Coupled income support
EGD	European Green Deal
F2F	Farm to Fork strategy
FU	Functional unit
GHG	Greenhouse gas
Götaland	*Götaland*'s southern plains
Jönköping	*Jönköping* county
LCA	Life cycle assessment
LSU	Livestock unit
RED	Renewable Energy Directive
SOC	Soil organic carbon
UAA	Utilised agricultural area
WFLDB	World Food Lifecycle Database

Symbols

$\mathbf{X}$	vector of production activities
$\mathbf{p}$	vector of market revenue of $\mathbf{X}$
$\mathbf{c}$	vector of variable costs of $\mathbf{X}$
R_{1y}	number of cattle older than one year
τ	tax per kg CO_2 equivalents of soil organic carbon and enteric methane
ΔSOC	annual change in SOC stock
γ_i	annual enteric methane emissions for one ruminant of type i expressed in kg CO_2 equivalents
r_i	number of ruminants of type i

further integrates LCA with a series of Agri-Environmental Indicators (AEI) of regional environmental relevance, which offers complementary perspectives on the environmental effects of policy in agriculture (Bergez et al., 2022). Two policy instruments have been selected for evaluation based on their potential to affect regional food and biomass production levels (Parlasca and Qaim, 2022; Englund et al., 2023) and apparent interlinkages to several EGD goals, such as soil health, sustainable food production, sourcing of biomass for bioenergy, and preservation of high-value agricultural landscapes (Vera et al., 2022; Nilsson et al., 2023): the coupled income support (CIS) to cattle (i.e., income support payments that are linked to the production of specific products, formerly voluntary coupled support) (Jansson et al., 2021), and pricing GHG emissions from agriculture (Charles Leach, 2022). Here, we explore a pricing mechanism consisting of a tax on methane emissions from enteric fermentation in ruminant livestock and a tax (payment) incentive for arable land management that depletes (increases) Soil Organic Carbon (SOC).

The aim of this paper is thus to analyse how discontinuing the coupled income support for cattle and a pricing mechanism on enteric methane emissions and SOC change would influence the transformation of agriculture towards the EGD objectives. To this end, we model the outcomes of these instruments in two case study regions in Southern Sweden as representative cases for intensive and extensive agricultural regions in the EU. Ultimately, we aim to contribute scientific input for policymaking concerned with climate change mitigation and environmental sustainability in agriculture. The following research questions guide this study:

- What are the regional structure and production effects when implementing the instruments?
- What is the environmental lifecycle outcome of the instruments, considering effects in regional structure, production displacement, and regional SOC development?
- What are the regional environmental effects of the instruments, considering land use development, and on-site pollution from agricultural production?

2. Literature review

2.1. Agent-based (territorial) life cycle assessment

To date, multi-objective evaluations of EGD interventions in agriculture rely on optimisation models or participatory processes that overlook the role of regional structure and production dynamics in the outcome of policy interventions (Lambotte et al., 2023). Agent-based models consider changes in agricultural production as phenomena emerging from the decision-making of farmers and their interactions with each other and the environment (Piorr et al., 2009). In combination with a territorial adaptation of LCA that studies environmental impacts from a defined geographic area (Loiseau et al., 2022), Agent-Based (Territorial) Life Cycle Assessment (AB-LCA) enables joint analysis of regional structure and production dynamics and their impacts on the environment (Vázquez-Rowe et al., 2014; Gutiérrez et al., 2015).

While most agricultural ABM representations used in AB-LCA thus far are either theoretical or not validated (Bichraoui-Draper et al., 2015; Marvuglia et al., 2017; Marvuglia et al., 2022), recent coupling of LCA to AgriPoliS, an empirical and dynamic ABM designed for policy analysis (Balmann, 1997; Happe, 2004), enhances the relevance of AB-LCA as a decision-support tool for environmental policymaking in agriculture (López i Losada et al., 2024).

2.2. Coupled support to cattle

Coupled support for cattle has generally been a part of the CAP in one form or another since the 1990s. The motivation behind EU allowing coupled payments in the CAP, despite the general *decoupling* of payments in 2005, was to enable support to sectors of particular national importance that for economic, social, or environmental reasons were facing difficulties (EU, 2013). Sweden, for example, cited worse terms of trade for Swedish dairy and beef farmers due to ambitious domestic animal welfare regulation, and the public good quality of grazing cattle for preserving biodiversity-rich semi-natural grasslands (Government offices of Sweden, 2014). However, economic support coupled to cattle distorts production incentives and leads to increased production in an industry that accounts for a disproportionate share of the land use and GHG emissions from the agricultural sector compared to the value of food it provides in proteins and calories (Poore and Nemecek, 2018). The current version of coupled support to cattle amounts in Sweden to 90 EUR per animal older than one year and was introduced in the 2015 reform of the CAP and continued in the most recent reform.

2.3. Pricing GHG emissions

Despite ambitious reduction goals, GHG emissions from agriculture have been relatively stable in the EU over recent decades (European Environment Agency, 2022). A pricing mechanism internalising the negative societal consequences of agricultural GHG emissions could speed up the net-zero transformation of the agricultural sector in the EU cost-effectively by allowing farms to reduce emissions in the most beneficial manner and order (Baumol and Oates, 1988). However, carbon leakage can decrease the effectiveness of unilateral interventions for reducing GHG emissions globally (Charles Leach, 2022; Jansson et al., 2024). In addition, establishing a uniform tax on all GHG emissions from agriculture is challenging due to uncertainties associated with the monitoring of non-point sources and abatement measures (Svarer et al., 2024). Nevertheless, a tax on GHG emissions from livestock will be imposed in Denmark from 2030, on the grounds that cost-effective abatement requires inclusion of the agricultural sector in the climate tax framework that already applies to the energy and industry sectors (Svarer et al., 2024). While limited in scope to roughly one third of the GHG emissions in Danish agriculture, the intervention constitutes a tangible measure to address GHG emissions in agriculture (Blandford, 2024).

Intensively managed arable soils hold substantial potential for carbon sequestration (Bolinder et al., 2010; Brady et al., 2015; Lal et al., 2021), as the long-term negative effects of intensive farming practices on SOC stocks are well documented (López i Losada et al., 2025). Improved management of arable soils could also bring benefits for the farmerś economy in the form of higher yields and lower variability in the future, although these tend not to be considered, or their discounted value perceived too low(Brady et al., 2019; Dessart et al., 2019). This motivates a tax or payment incentive for arable land management practices that deplete or increase SOC respectively (Bradford et al., 2019; Reisinger et al., 2021).

Here we model a uniform tax on changes in SOC in arable land and enteric methane emissions. Thus, the instrument will provide cost-effective reduction of GHG emissions within this scope, but cost-effectiveness would increase if more emissions sources were included. The resulting level of the tax per unit of revenue is higher for livestock than for arable crops, reflecting evidence that livestock is responsible for a disproportionate share of GHG emissions from the agricultural sector compared to arable crops (Poore and Nemecek, 2018; Chai et al., 2019; European Environment Agency, 2022). Specific policy design beyond this aspect – such as perceived fairness to farmers, distributional effects, and practical implementation (Gren et al., 2021; Moberg et al., 2021) – is not the object of this study.

3. Materials and methods

To address our research questions, we run policy-scenario simulations in the agent-based model AgriPoliS to analyse the effects of the instruments on the agricultural sector in two farming regions contrasting in production structure, agricultural conditions, and landscape features. We then use the simulation results as input for a comparative environmental LCA of the interventions. Furthermore, we develop a set of indicators that link the economic and environmental output of our AB-LCA approach and a comprehensive synthesis of the objectives of the EGD for agriculture. This study defines the environmental performance of a policy instrument as equivalent to the differences in the environmental performance of the regions in the presence and in the absence of the instrument. From this point, we refer to the study regions, i.e., *Götaland*'s southern plains and the county of *Jönköping* (Fig. 1, left), respectively as *Götaland* and *Jönköping*.

3.1. AgriPoliS

AgriPoliS (Agricultural Policy Simulator) is a dynamic agent-based mathematical programming model of the agricultural sector in a specified region (Balmann, 1997; Happe et al., 2006; Kellermann et al., 2008). It was developed to study the effects of policy interventions on structural change and concomitant impacts on agricultural land use and production, farm incomes, and, more recently, environmental impacts (Sahrbacher et al., 2017; Hristov et al., 2020).

Each individual farm agent maximises farm household income by optimising production decisions with respect to expected income, considering the profitability of alternative production activities

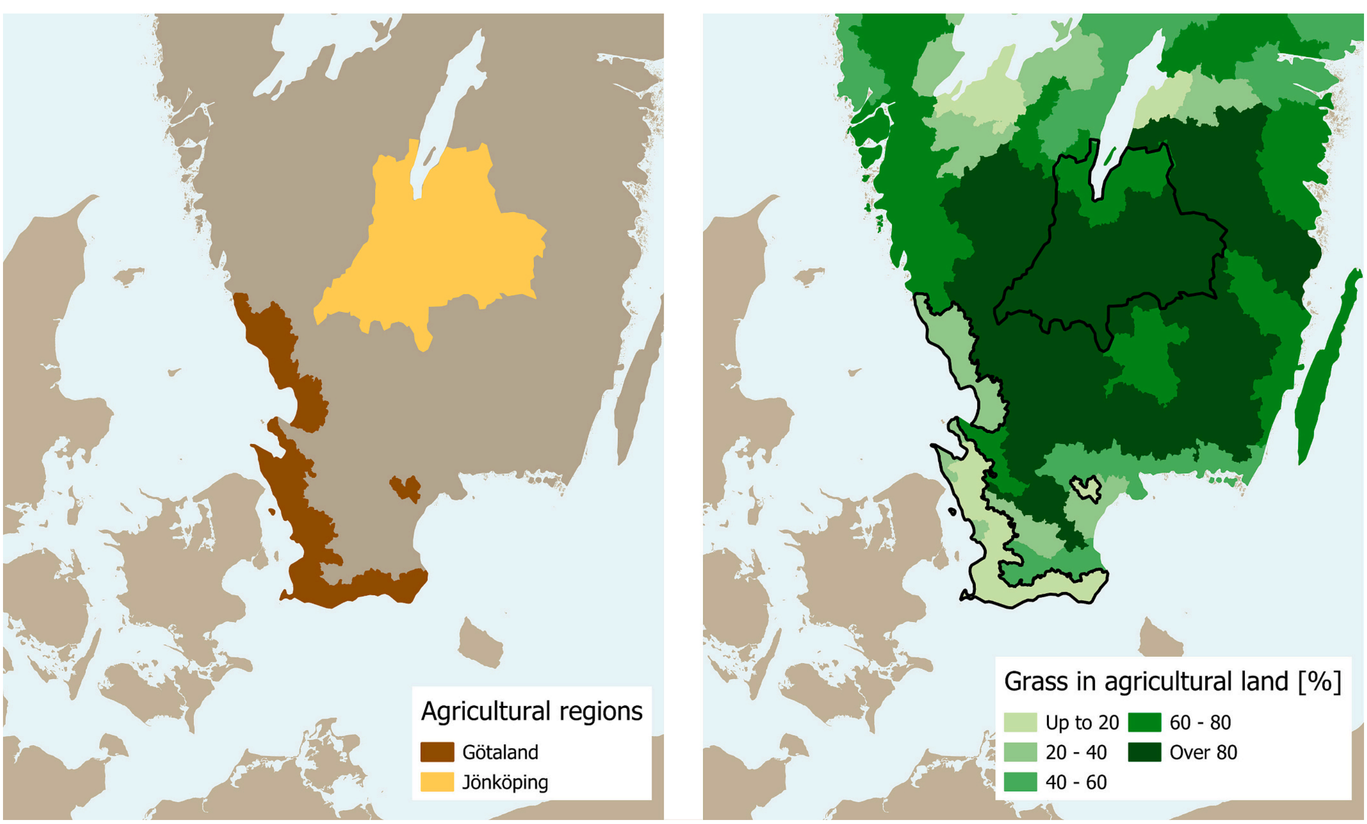

Fig. 1. The agricultural regions of Götaland and Jönköping in southern Sweden (left). Grass coverage of total agricultural land in the yield regions of southern Sweden (right).

(alternative crops and livestock), the opportunity cost of own labour and capital endowments (based on their potential use outside agriculture), the vintage of fixed assets, and the policy framework within which they operate. A farm agent will close the farm if continuing would not cover the opportunity costs of factor endowments, if they are bankrupt, or if the farmer reaches retirement age (65) without a successor. More details and the full mathematical expression of the farm agents' income maximisation problem can be found in Kellermann et al. (2008). A simplified objective function that illustrates the impact of the policy scenarios studied here on the farmer's decision problem is however provided in Eq. 1.1 below.

AgriPoliS simulates development of agriculture in a study region dynamically (in this study over 15 years) in response to changes in the policy framework implemented via policy scenarios (described below). Output comprises full accounting data for individual farms, as well as the development of land use, agricultural production including livestock holdings, land rental transactions and investment activities (new stables or machinery), and ultimately changing farm structure as an emergent phenomenon of farm-agents' individual decision-making and interactions among them.

Farm-agent interaction is a central feature of AgriPoliS, occurring foremost in competition for land on the endogenous rental market. A farm can only grow and make new investments to achieve scale economies if it can acquire more land, which is possible when other farms either release land on expiration of rental contracts or close. Bids for land are based on farm-agents' marginal valuation of additional land, with land being allocated by the auctioneer agent to the highest bidder. Additionally, agents interact on regional markets for calves and piglets to maintain balance with breeding stocks. The AgriPoliS landscape is abstractly modelled and calibrated to mirror the statistical characteristics of the real landscape, such as the distribution of land types (two types of arable land and grassland) and field sizes (Brady et al., 2012). Separate land markets exist for the different types of agricultural land.

Finally, AgriPoliS is a deterministic model, meaning it produces identical outcomes for a given set of inputs (policy scenario), with the only stochastic feature being the initialisation of the landscape. The initialization uses probability distributions to randomly allocate farm centres and fields within the two-dimensional landscape grid, vintage of stables and machinery, farmer age, and managerial ability, increasing the heterogeneity of the farm population further. Replications of the initialisation using different seeds for the random allocations has been tested in Sahrbacher et al. (2017), and is shown not to significantly impact model output. Therefore, a single random initialisation based on identical seed values for stochastic parameters is used for generating a calibrated regional model (described below) that forms the basis of all subsequent simulations.

3.2. Case regions: Götaland and Jönköping

Götaland is the southern-most naturally defined agricultural region of Sweden, characterised by specialized crop production on large, contiguous arable fields with high productivity. Land-use in *Götaland* is distributed 79/5/16 between arable land, pastures, and forest (Statistics Sweden, 2020). Winter wheat, spring barley, rapeseed, and sugar beet account for 95 % of the arable land on crop specialist farms in *Götaland*, comprising about 75 % of the total utilised agricultural area (UAA) in the region (Table 1). The dominance of intensive, annual cropping in *Götaland* results in SOC loss from highly productive arable land (Brady et al., 2015). Specialised pig and poultry are important industries in *Götaland* and modelled in AgriPoliS, but excluded from our environmental analysis because of their lack of connection to the development of land use. Cattle and sheep are less economically important but included in the environmental analysis because of the stronger link with land use and hence relevance for evaluation of the policy instruments in scope.

Jönköping is an inland region in Southern Sweden dominated by forest and mixed farm-forest agriculture where forest and agricultural land represent 71 and 12 % of total land area, respectively. Land-use distribution on farms in *Jönköping* is 27/12/61 between arable, pastures, and forests. Roughly 80 % of its arable land is used for pastures and grass silage production, due to the prevalence of livestock-oriented farms. Crop rotations in Jönköping include cereal crops, mainly barley and oats, as break crops for multi-year grass leys. Thanks to the dominance of ruminant livestock production and associated generation of organic manure and large area of grass leys, loss of SOC from arable land is not considered a problem in the region.

Overall, a higher presence of grass is associated with less productive land, lower farming intensity and higher livestock density in *Jönköping*, thus providing a markedly different farming structure compared to *Götaland* (Fig. 1, right). In particular, the loss of SOC from arable land in *Götaland* and high methane emissions from livestock in *Jönköping* make an interesting contrast for the aims of this paper.

Accordingly, SOC modelling in AgriPoliS is restricted to *Götaland*. AgriPoliS simulates SOC trends based on experimental evidence of the long-term effects of agricultural management and subsequent economic optimal nitrogen fertiliser inputs and yields (Brady et al., 2019). Initial content of soil carbon in the upper 30 cm layer is assumed to be 1.71 % (corresponding to stocks of 75 t per hectare) for all high-productive arable land in *Götaland*. This is a mean estimate for the region determined by Brady et al. (2019) based on extensive field sampling. From long-term experiments representative of the farming conditions in *Götaland*, we assume a yearly SOC content change rate of 1.035 % for multiannual and perennial crops and of −0.290 % for annual crops[1] (Carlgren and Mattsson, 2001). Using these parameters, we calculate yearly changes in SOC stocks of 776.7 kg C ha^{-1} and -217.6 kg C ha^{-1}, associated with multi-annual and annual crops respectively. These values assume linear SOC change, which is reasonable given the relatively short time horizon of our simulations (10 years). We consider that this assumption fits a global agenda with ambitious targets for emission reductions by 2050 and earlier (Verschuuren, 2022). However, SOC equilibrium could be reached within the span of several decades to a century, thereby decreasing the effects of agricultural management in the long-term (Lal, 2016; Joensuu et al., 2021).

Incremental increases of arable grass leys are hence unlikely to provide positive soil health externalities unless they result in arable land being turned into permanent grasslands, which we do not consider an improvement of arable-land management. The incentive excludes low-productive arable and non-arable grasslands, as evidence from long-term experiments on SOC development in the region supports potential for SOC gains in highly productive arable land only (Brady et al., 2019).

3.3. Calibration of AgriPoliS to study regions and uncertainty

To calibrate AgriPoliS to the study regions, we first identified representative farm types using cluster analysis of empirical data on land use areas and livestock holdings (Boke Olén et al., 2021), ensuring they reflect the diversity and structure of farms in the study regions of Götaland (23 farms) and Jönköping (20 farms). These typical farms were then scaled up to represent the regional population based on agricultural statistics. For each representative farm, a mixed-integer programming (MIP) model was developed to capture region-specific production possibilities, based on production statistics and expert data (Agriwise, 2024), following standard practices in agricultural economic modelling (Hristov et al., 2017). All input data needed for representing the region in Agripolis are then fed into AgriPoliS using a set of predefined text files. Finally, the regional AgriPoliS model is calibrated to observed

[1] SOC-enriching activities are perennial and multiannual production of grass ley, willow, or reed canary grass. SOC-depleting activities are annual production of winter wheat, other cereal, rape, and sugar beet.

Table 1
Number of farms, total agricultural land, and ruminant livestock in Livestock Units (LSU) across farm types in 2022 for Götaland and Jönköping.

	Götaland			Jönköping		
Farm Type	Number of farms	Total agricultural land	Ruminant livestock	Number of farms	Total agricultural land	Ruminant livestock
	–	10^3 ha	10^3 LSU	–	10^3 ha	10^3 LSU
Dairy	125	29.0	30.9	375	46.6	42.8
Crop specialist	1860	241.8	6.1	315	7.9	0.4
Livestock, granivores	110	19.5	1.0	0	0.0	0.0
Livestock, grassfed	265	17.1	13.5	1175	56.5	35.6
Mixed	335	29.4	7.0	280	7.6	2.6
Small holdings	960	5.2	0.0	1130	8.5	0.0
Total	3655	342.0	58.5	3275	127.1	81.4

structural trends in farms, land use, and livestock numbers according to statistics for 2010–22 compiled by the Swedish Board of Agriculture (2025). This was done by adjusting a residual variable cost parameter for relevant farm production activities to reflect unobservable or aggregated costs (e.g. family labor, management burden, or risk) that influence farm decision-making (Buysse et al., 2007), while parameters that are observable such as yields and input/output prices were based directly on empirical data and remain fixed. As a result, the model reproduces observed land-use patterns without imposing artificial constraints on farm agents, thus preserving their capacity to adapt to policy changes. In summary, both ex ante input validation and descriptive output validation of AgriPoliS have been carried out (Bianchi et al., 2007), ensuring the model provides an adequate representation of the real system for its intended purpose.

Coupling ABM and LCA can entail a risk of propagating uncertainty across modelling stages (Baustert et al., 2025). Being a deterministic model, AgriPoliS contains no stochastic elements beyond those applied in the initialization phase. To ensure full comparability across scenarios, the same random seed values are used for all simulations, which guarantees identical initialization. Consequently, the uncertainty from stochastic initialization does not propagate into differences between scenarios or into the LCA results. Potential modelling errors are mitigated through validation and calibration against empirical data as described above. Remaining uncertainties are further minimized using scenario comparisons: because identical assumptions are applied across scenarios, systematic modelling errors can be expected to cancel out when results are interpreted as differences between scenarios, thereby isolating the effect of the policy change, all else equal.

3.4. Policy scenarios

We run a reference scenario and two policy scenarios in AgriPoliS over a ten-year period taking 2022 as the starting year for policy changes:

- BAU: the reference scenario simulates a continuation of the 2015–22 CAP until 2032. The major policy components are the Basic Income Support for Sustainability (BISS, formerly Basic Payment Scheme) (190 EUR ha^{-1}), the CIS to cattle (90 EUR $head^{-1}$), and environmental payments under the rural development program, e.g. for management of semi-natural pastures (130 EUR ha^{-1}).
- -CIS: coupled support to cattle is abolished. The subsidy is phased out over four years until 2025 to avoid sudden liquidity problems that can lead otherwise profitable farms to bankruptcy in the short term. N.B.: phasing in changes is normal when implementing real agricultural policy reform for similar reasons.
- -CIS + TAX: In addition to abolishing the CIS, a tax on enteric methane emissions from livestock and a payment/tax on changes in SOC are introduced. The tax on enteric methane applies in both *Götaland* and *Jönköping*, whereas the SOC incentive applies in *Götaland* only because SOC loss is only a problem in this region (see section 3.2).

The ten-year simulation period was chosen to reflect a time horizon that is relevant for policy aspects, while also being sufficient to capture the dynamic adjustments and structural effects of the policy interventions. A longer horizon would increase uncertainty regarding policy, market, and technological conditions, reducing the robustness of the results.

The tax on SOC is modelled as a permit market where production of SOC-depleting activities requires emission permits corresponding to the annual depleted quantity. Emission permits can be purchased or awarded to the farm for production of SOC-restoring activities. The incentive excludes low-productive arable and non-arable agricultural land, as evidence from long-term experiments on SOC development in the region supports potential for SOC gains from introducing bioenergy crops in highly productive arable land only (Brady et al., 2019). Based on the current carbon tax in Sweden on petrol of 0.27 EUR $litre^{-1}$ and based on an estimate of 2.66 kg CO_2 litre $^{-1}$ emissions from combustion in a car (Swedish Energy Agency, 2023), our incentive corresponds to a tax of 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. An overview of methane emissions, SOC change, and subsequent payment/tax levels for specific production activities is provided in the Appendix (Table S2).

The policy interventions analysed in this study are economic instruments that impact decision making by changing the farm income maximisation function of farms, which considers economic factors only. Farmers' maximisation of utility would yield different results to the extent that they have preferences beyond economic factors, e.g. derive utility from promoting biodiversity, or are risk averse. Here we assume that a preference for higher income over lower income drives the utility function for each individual farmer. The objective function below shows the impact of both instruments in a simplified representation of the AgriPoliS farms' income maximisation problem (1.1). See Kellermann et al. (2008) for a complete representation of the decision problem for the farm-agents.

$$\max_{X} \ Y = (\boldsymbol{p} - \boldsymbol{c})\boldsymbol{X} + R_{1y}CIS + \tau\Delta SOC(\boldsymbol{X}) - \tau\sum_{i=1}^{R}\gamma_i r_i + M \tag{1.1}$$

s.t. $\boldsymbol{b}'\boldsymbol{X} \leq \boldsymbol{k}$ and $\boldsymbol{X} \geq 0$.

The term $(\boldsymbol{p} - \boldsymbol{c})$ is the vector of net returns (i.e., market revenue minus variable cost) per unit of each production activity, and $\mathbf{X}$ is the choice vector of production activity levels. The second term $R_{1y}CIS$ reflects coupled support to cattle: the annual subsidy amount (CIS) is multiplied by the number of cattle older than one year in the year y, denoted R_{1y}, where $R \subseteq \mathbf{X}$. The third term $\tau\Delta\mathrm{SOC}(\mathbf{X})$ is the carbon tax or payment, where τ is the carbon price and $\Delta\mathrm{SOC}(\mathbf{X})$ is the annual change in SOC stock as a function of farm production. If $\Delta\mathrm{SOC}(\boldsymbol{x}) < 0$ the term represents a tax; if $\Delta\mathrm{SOC}(\mathbf{X}) > 0$ it constitutes a payment. The fourth term, $\tau\sum_{i=1}^{R}\gamma_i r_i$, captures the tax on enteric methane emissions, where γ_i is the emissions coefficient for ruminant type i, and r_i is the number of ruminants of that type. The final term M includes other positive and negative components of farm income, such as off-farm labour income, non-coupled CAP payments, overhead costs, and depreciation. The maximisation problem is subject to the resource constraint $\boldsymbol{b}'\mathbf{X} > \boldsymbol{k}$, where $\boldsymbol{b}$ is the matrix of resource use coefficients and $\boldsymbol{k}$ is the vector of resource capacities, notably land and family labour.

Abolishing the CIS to cattle reduces the contribution of cattle to farm income, and thus changes its profitability relative to other production activities. In future instances of decision-making, the income maximising setup of a given farm will contain the same or fewer heads of cattle accordingly and total cattle production declines. The full effect of removing the subsidy will not occur immediately, but over a period during which cattle-related investments depreciate. Besides this direct effect of removing the CIS to cattle, an indirect counteracting effect from market price changes is possible if the total change in cattle production is large enough to induce an increase in market prices, which is more likely if the policy reform applies to the entire EU than to Sweden only. We investigate the impacts of an increase in market prices as part of a sensitivity analysis (section 3.2.1).

The SOC incentive is a two-part instrument designed to both prevent deterioration and incentivise improvements in the carbon store. The payment (tax) for activities that enrich (deplete) SOC is based on the area of crop production on arable land with high productivity. The farm income function shows that when the SOC incentive is active ($\tau > 0$) farmers can influence income by changing ΔC_store through soil management. This changes the profitability of crops that influence SOC and may result in a new income-maximising combination of production activities. The price of soil carbon, i.e. the value of τ, is of major importance for the outcome of the instrument: an effect on land use and SOC will only result if the price is sufficiently high. Because of large differences in profitability between annual and perennial crops, a tax on, e.g., winter wheat below a certain level will not change decision making; winter wheat is still more profitable than a grass ley. Such a tax has no effect on SOC but creates a transfer of societal welfare by reducing farmers' income.

Finally, the tax on enteric methane emissions from ruminants internalises the societal cost of methane emissions to the farms' objective function. For the purposes of our study, we treat the SOC and methane instruments as one tax on GHG emissions from agriculture (TAX). Although there are of course numerous carbon sources and sinks in agriculture that should be considered to ensure cost-effective reduction of GHG emissions, we are content with this subset because livestock and carbon sequestration in soils are key drivers of climate change mitigation in agriculture with high importance across Green Deal goals.

3.5. LCA modelling and coupling to AgriPoliS

This study performs an environmental LCA of policy interventions in *Götaland* and *Jönköping* in observance of ISO standards 14040 and 14044.

3.5.1. Goal and scope definition

Our LCA intends to contribute scientific analysis for environmental policymaking concerned with the sustainability transformation of agriculture in the EU. Following an attributional cradle-to-farmgate approach as established in López i Losada et al. (2024), we model *the share of the global environmental burden allocatable to a farming region in the presence and in the absence of the policy instrument if the rest of the world remained as it is today*.

The definition of a Functional Unit (FU) quantifying service requirements across scenarios enables objective comparison under LCA principles (Arzoumanidis et al., 2020). In this work, we analyse the environmental performance of policy interventions comparatively to the BAU development of *Götaland* and *Jönköping*. For this purpose, our FU is defined for either the region of *Götaland* or *Jönköping*:

Maintaining global provision levels in the region for all agricultural commodities produced in the region in year 10 of the simulation via local production and imports.

Our lifecycle modelling comprises farm production processes for crops and livestock, including the necessary inputs in terms of machine operations, fertilisers, irrigation, seeds, and housing requirement. AgriPoliS output in year 10 (i.e., regional production of crops and livestock for the entire year under each policy scenario) informs the Life Cycle Inventory stage of the LCA.

Under a fixed-consumption assumption, products from a global market mix based on BAU provision levels even out regional production differences across scenarios, which allows us to include displacement effects in our environmental analysis. We refer to the fraction of environmental impacts attributed to displaced production as leakage. As AgriPoliS does not explicitly model a regional bioenergy market, lignocellulosic feedstock from *Götaland* and *Jönköping* is assumed to replace a mix of crops that is currently imported into Sweden for biofuels, which is dominated by rapeseed oil (López i Losada et al., 2024). Furthermore, our account of agricultural outputs disregards crop residues because of their low economic relevance, as farmers are unlikely to weigh them into their business decisions. In practice, crop residues are often locked into a range of non-marketed functions within the region where they are produced, primarily being returned to the soil or used as livestock bedding. As we do not model the agricultural sector globally, we assume that reductions in beef and milk production in our target regions lead to increased production of beef in suckler farms or milk in dairy farms elsewhere. To account for the production impacts of milk outside our target regions, we use an impact allocation factor between beef and milk production based on protein-content suggested by the WFLDB (Nemecek et al., 2014). In contrast, allocation is redundant for impacts in *Götaland* and *Jönköping* because all animal activities are within the boundaries of the system. Our production displacement assumption is tested as part of a sensitivity scenario addressed in section 3.3.1.

3.5.2. Life cycle inventory

Elementary flows representing the exchanges between relevant agricultural activities (i.e., arable crop and livestock production) and the environment are modelled in SimaPro (v9.5.0.0). As a starting point, we use data from the World Food Lifecycle Database (WFLDB) (Nemecek et al., 2014), which we then modify with expert data on Swedish regions (AgriWise, 2020) to better represent *Götaland* and *Jönköping* conditions. Following a cut-off approach, waste is the producer's responsibility and recycled materials are available burden-free. The WFLDB is based on Ecoinvent (v3.8) attributional analogous data but offers, in contrast, a more intuitive structure that enables easier modification of animal husbandry activities.

3.5.3. Life cycle impact assessment

We consider lifecycle environmental impacts in terms of their damage to human health and biodiversity according to endpoint impact assessment methodology ReCiPe, and in weighted environmental scores from the Environmental Footprint (Huijbregts et al., 2017; European Commission, 2021). In addition, we model ReCiPe midpoint impact category global warming potential (in kg CO_2 equivalent) given the relevance of reducing net anthropogenic GHG emissions as an overarching goal of the EGD.

Life cycle environmental impacts for individual agricultural activities are modelled in SimaPro (v9.5.0.0). Then, output production levels from agricultural activities in AgriPoliS are linked to their respective life cycle environmental impacts using base R (v.4.1.3) and package tidyverse (v1.3.1) (R Development Core Team, 2010; Wickham et al., 2019).

Our account of GHG emissions and their damage to human health and biodiversity includes deviations in SOC storage in soils from observed decline in highly productive arable land in *Götaland* as described in section 3.2. Thus, differences in SOC stocks in scenarios -CIS and -CIS + TAX compared to BAU resulting from changes in the management of arable land are accounted for as GHG emissions. This approach assumes that gains and avoided losses in SOC are stored in the soil over long periods of time (i.e., several decades) to compensate the effects of GHG emissions into the atmosphere (Günther et al., 2024).

Impact category 'Land use' describing land occupation in both ReCiPe and Environmental Footprint is excluded from our analysis, given that regional land use and land use change are instead evaluated as an output from AgriPoliS.

3.5.4. Sensitivity analysis

For sensitivity analysis, we evaluate the influence of selected key parameters on our AB-LCA results. Assumptions regarding displaced production and commodity prices are particularly relevant to test, given that substantial changes in agricultural policy at EU-level will affect agricultural market prices and thus the production and consumption of agricultural commodities. Changes in market prices are not modelled endogenously in AgriPoliS, as a change of production in a small region is not expected to impact global market prices. Assuming fixed prices in AgriPoliS implies that the tax burden falls entirely on producers, as they cannot shift part of it to consumers by increasing their output prices in the model. Our sensitivity analysis of the modelling assumptions applies only to -CIS + TAX given that the contribution of environmental leakage in this scenario is the most substantial. The sensitivity analysis scenarios are therefore:

- *Consumption* assumes that part of the tax burden on livestock products is transferred to consumers through higher market prices, which we model in AgriPoliS as a 50 % reduction of the tax on enteric methane emissions. Profitability of cattle production is thus somewhat regained, thereby affecting farmers decision-making, and national consumption of livestock-related products decreases as consumer prices increase by 50 % of the tax level. This allocation of the tax burden is in alignment with simulation results from a previous study on the effects of introducing a GHG tax in agriculture across the EU using CAPRI, a sectoral economic equilibrium model of agriculture (Jansson et al., 2024). We consequently relax the fixed-consumption assumption in our LCA modelling by modifying its functional unit with a sufficiency premise conceptualised by André (2024). Specifically, 5 % of the reference beef production in BAU and 2 % for dairy in *Götaland* and *Jönköping* are matched by reduced consumption domestically, which reflects price elasticities in Sweden for beef and dairy estimated by Säll and Gren (2015).
- *Biofuels* is an extension of *Consumption* that assumes a future reduction in the real or perceived production costs of bioenergy, thereby enhancing the profitability of biomass production above set aside land but below all arable crops. Set aside land therefore produces grass biomass for bioenergy, which reduces biofuel imports and, by that, environmental leakage. All other land uses remain the same.

3.6. Multi-objective analysis across the EGD goals for agriculture

The EGD sets objectives to improve the environmental standards of European farming and reduce its GHG emissions, while minimising environmental leakage outside of the EU (Báldi et al., 2023). The economic and environmental output of our AB-LCA modelling is relevant to a broad range of these environmental goals, which allows for a comprehensive multi-objective analysis of the policy instruments in focus. We study policy effects on nine environmental indicators that integrate LCA and AEI complementary system and regional perspectives (Table 2). LCA aims to comprehensively reflect the impacts of production systems on the environment globally, while it largely lacks information on the receiving environments. In contrast, AEIs are most often defined ad-hoc in a limited geographic context and account for on-site pollution from agricultural systems at landscape, farm, or field level. Our resulting environmental analysis of policy instruments thus encompasses both on-site and global effects on the environment (Bergez et al., 2022). A synthesis by Boix-Fayos and de Vente (2023) provides us with an overview of the EGD goals for agriculture, which we expand to include the biomass resource needs of the RED and the Bioeconomy strategy.

Table 2
Summary of indicators linking environmental EGD goals for agriculture with our AB-LCA modelling output.

#	Indicator	Metric*	Aim	Policy initiative
1	Abatement of global greenhouse gas emissions	kg CO_2 eq.	Climate change mitigation	Green Deal, overarching
2	Abatement of global biodiversity damage	PDF	Avoiding shifts of environmental burdens	Green Deal, overarching
3	Environmental productivity	EUR/PDF	Sustainable farm production	Farm to Fork strategy
4	Reduction of pesticide emissions	CTU	Sustainable farm production	Farm to Fork strategy
5	Reduction of N emissions	kg N	Sustainable farm production	Farm to Fork strategy
6	Additional biomass availability	ha	De-carbonising energy and materials	Renewable Energy Directive & Bioeconomy strategy
7	Preservation of soil organic carbon	ΔC %	Promoting soil health	Soil strategy
8	Preservation of seminatural pastures	ha	Nature preservation	Biodiversity strategy
9	Change in arable land in productive use	ha	Nature preservation	Biodiversity strategy

* PDF: Potentially Disappeared Fraction of species, CTU: Comparative Toxicity Unit.

Indicators 1–3 concern the environmental assessment of policy interventions from a territorial lifecycle perspective. Indicator 1 relates to the overarching aim of the Green Deal to reduce net anthropogenic GHG emissions. Indicator 2 provides an account of lifecycle damage to biodiversity according to ReCiPe endpoint modelling, which is expressed as Potentially Disappeared Fraction (PDF) of species. Indicator 3 focuses on the environmental productivity of the agricultural regions in scope, defined as their capability to produce agricultural commodities and economic returns to farmers with minimal environmental impacts in-region (i.e., without considering leakage).

Indicators 4–9 highlight the links between regional land-use development from AgriPoliS and several environmental goals of the EGD. Potential for N eutrophication and chemical toxicity in agriculture respectively from fertiliser and pesticide applications are a source of environmental concern covered within the sustainable production pillar of the F2F strategy. Indicators 4 and 5 focus respectively on off-field N emissions and pesticide ecotoxicity potentials from changes in the land-use. AgriPoliS models optimal N fertiliser levels as a result from changes in SOC, which are considered in indicator 4. Optimal N fertilisation is then weighed with crop-specific run-off coefficients from regional simulations (Johnsson et al., 2019). In contrast, AgriPoliS does not explicitly model changes in pesticide applications, which we assume to remain unchanged for each crop across scenarios. A crop-specific survey for pesticide application in Swedish agricultural regions in 2021 has been obtained from Statistics Sweden and constitutes the basis of our pesticide inventory for indicator 5. Potential freshwater ecotoxicity impacts from pesticide application are modelled by means of PestLCI and USEtox in Comparative Toxicity Units (CTU) based on Gentil et al. (2020) as in López i Losada (2023).

Indicator 6 accounts for additional biomass grown for bioenergy and the regional bioeconomy, measured in cultivated land area, and including ligno-cellulosic feedstock from short-rotation coppice, energy grass and grass leys grown for bioenergy purposes. In our model, biomass for energy can be supplied exclusively from dedicated energy crops that can only be grown on arable land. We further benchmark our estimate of additional biomass available against a recent estimate of unused and abandoned arable land available for bioenergy across

Swedish counties (Böhlenius et al., 2023). Although *Götaland* is not a county, it contains 75 % of the arable land in the county of Scania and is thus a rough match to the estimate for Scania that we consider sufficient for our analysis.

Indicator 7 measures changes in the average SOC content of arable land in *Götaland* resulting from diverging practices across policy scenarios.

Indicators 8 and 9 focus respectively on semi-natural pastures and arable land in productive use, which are important variables for explaining changes in biodiversity associated with agricultural landscapes. We consider semi-natural pastures to contribute positively to biodiversity both in *Götaland* and *Jönköping*, whereas set-aside arable land is detrimental in *Jönköping* but, if moderate in magnitude, beneficial in *Götaland*. Contrasting biodiversity outcomes from loss of arable land in productive use are expected due to the landscape differences between study regions (Veldman et al., 2015; Hristov et al., 2020).

4. Results

4.1. Structure and production changes over 10 years

Policy interventions in scenarios -CIS + TAX and -CIS are markedly different in their effects on land use (Table 3). *Götaland* and *Jönköping* show similar land development in -CIS in comparison to BAU, whereas substantial reductions of arable land in production and semi-natural pastures occur in -CIS + TAX. In contrast, trends in livestock numbers (given as Livestock Units, or LSU) are similar in both scenarios. In addition, only -CIS + TAX in *Jönköping* shows a marked decrease in the number of operating farms in comparison to BAU. Overall change is larger in -CIS + TAX than in -CIS.

Removing the CIS results in a combined decrease of ~14,000 LSU of cattle that is more pronounced in *Götaland* (−17 %) than in *Jönköping* (−5 %). As beef production declines and semi-natural pastures become available, the sheep industry grows in both regions, although there is less room for the sheep industry to grow in *Jönköping* because cattle production declines less. Overall, ruminant livestock presence decreases (9 %) in *Götaland* and remains roughly stable in *Jönköping*. The effects on land-use are marginal in both regions; some arable land dedicated to grass fodder is converted into arable crops in *Götaland* (~2000 ha) and set aside in *Jönköping* (~1700 ha), i.e., kept out of production but in good agricultural condition to comply with direct payment requirements. The loss of income in cattle production is not sufficient for energy crop production to expand under current market conditions.

In -CIS + TAX, ruminant livestock decreases drastically in both regions, particularly dairy cows, which account for higher enteric methane emissions and therefore incur a higher methane tax (roughly 50 % more than suckler cows). Here, we refer to suckler and dairy cattle as including their calves and replacement heifers. Energy crop deployment is substantial in arable land in *Götaland* (60,800 ha), where they replace food and feed crops. In *Jönköping*, arable land dedicated to bioenergy is very limited in both scenarios despite considerable amounts of land being made available. This is because the profitability of energy crop production in this region is lower than that of setting the land aside and collecting the basic payment, due to lower yields. In addition, the instrument removes the least profitable land from production: a combined 61,000 ha of arable land is set aside between the two regions and 8500 ha of semi-natural pasture is abandoned in *Jönköping* to afforestation. The contrasting fate shown in our results for arable land and semi-natural grasslands when they are removed from active use reflects the physical properties of the land. Arable land can be kept rather inexpensively with machinery in condition to qualify for BISS payments, which is more profitable than forestry, whereas semi-natural grasslands depend on livestock grazing for their maintenance. Accordingly, much more agricultural land is set aside or abandoned in *Jönköping* because of higher presence of economically marginal land in this region.

4.2. Regional lifecycle performance of the policy interventions

This section describes results concerning damage to the natural environment from the ReCiPe impact assessment method at endpoint levels. Environmental impacts to human health from ReCiPe and weighted scores from Environmental Footprint exhibit similar trends and can be found in the supplementary information (File S1 and File S2). Furthermore, we categorise environmental impacts by output, which allows us to disaggregate the environmental effects of production changes across scenarios. This reflects contrasting farm structures between regions, as environmental impacts are dominated by arable crops in *Götaland* and livestock in *Jönköping* (Fig. 2). Overall, in-region damage decreases more for livestock than for arable land-use, and leakage impacts in -CIS + TAX become the most predominant in *Jönköping*.

Considering production changes, displacement effects, and regional SOC development, the overall lifecycle performance of the regions at the end of the 10-year simulation period in -CIS is similar to BAU. Substitution effects across types of ruminant livestock constitute the main structural change in this scenario, which do not cause large differences in environmental impacts. While a net decrease in LSU also occurs in

Table 3
Agricultural production overview in Götaland and Jönköping in terms of land use and grassfed livestock in year 10 of the simulations. Results for -CIS and CARBON are expressed as difference from BAU in that year. Total arable land in productive use excludes set-aside arable land, which is grass-sown fallow, and seminatural pastures, which are not arable.

	Götaland			Jönköping		
	BAU	Δ -CIS	Δ -CIS + TAX	BAU	Δ -CIS	Δ -CIS + TAX
		(%)	(%)		(%)	(%)
Number of operating farms	3100	−50 (−2)	−50 (−2)	2845	−25 (−1)	−370 (−13)
Distribution of land	10^3 ha	10^3 ha (%)	10^3 ha (%)	10^3 ha	10^3 ha (%)	10^3 ha (%)
Total arable land in productive use	321.7	−0.3 (0)	−23.2 (−7)	71.6	−1.4 (−2)	−28.3 (−40)
Arable food and feed crops	259.9	1.6 (1)	−74.1 (−29)	17.4	0.0 (0)	−7.6 (−44)
Energy crops in arable land	0.0	0.0 (–)	60.8 (–)	0.4	0.0 (0)	0.0 (0)
Arable grass fodder	61.8	−2.1 (−3)	−10.0 (−16)	53.8	−1.4 (−3)	−20.7 (−38)
Arable land set aside	1.4	0.3 (21)	23.2 (1657)	15.9	1.4 (9)	28.3 (178)
Seminatural pastures, non-arable	18.7	0 (0)	−0.8 (−4)	38.7	−0.3 (−1)	−8.5 (−22)
Distribution of livestock	10^3 LSU	10^3 LSU (%)	10^3 LSU (%)	10^3 LSU	10^3 LSU (%)	10^3 LSU (%)
Total ruminant livestock	60.9	−5.5 (−9)	−30.7 (−50)	72.0	−2.0 (−3)	−37,6 (−52)
Dairy cattle	41.1	−3.4 (−8)	−25.1 (−61)	45.6	0.5 (1)	−35.9 (−79)
Suckler catte	18.2	−6.9 (−38)	−4.9 (−27)	25.7	−3.0 (−12)	−1.3 (−5)
Sheep	1.6	4.7 (294)	−0.7 (−44)	0.7	0.4 (57)	−0.4 (−57)

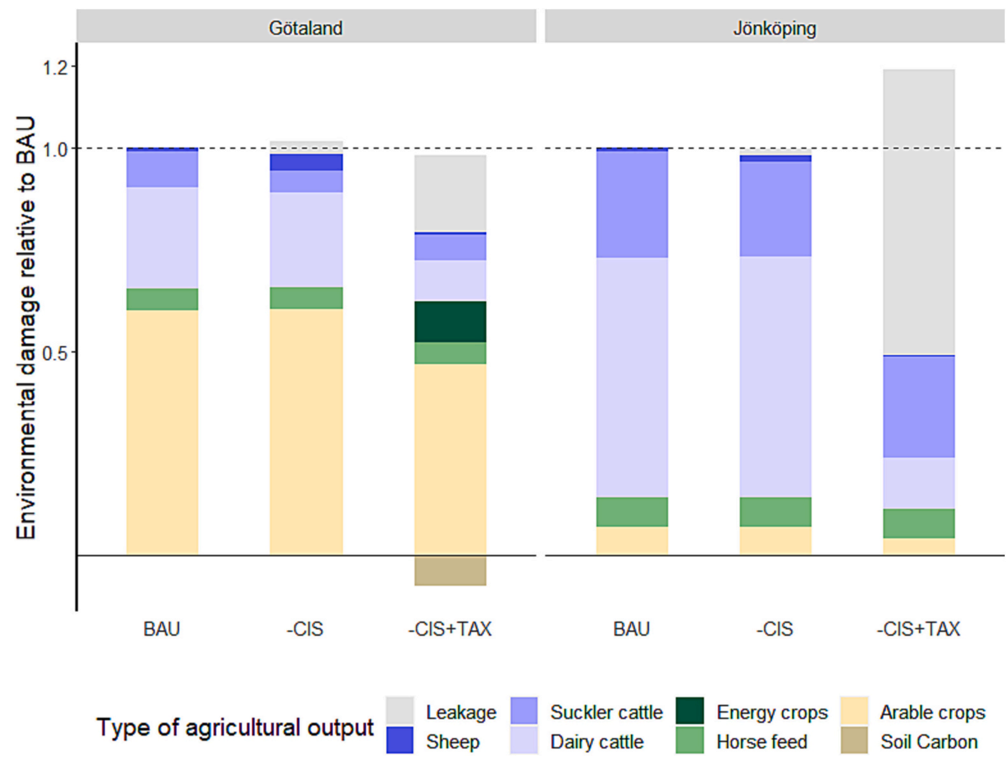

Fig. 2. Environmental damage across scenarios following ReCiPe 2016 relative to BAU. Shares correspond to major categories of agricultural outputs. The dashed black horizontal line represents BAU results normalized to 1.

Götaland, one LSU of sheep (i.e., 10 sheep) causes higher environmental impacts than one LSU of cattle (e.g., one dairy cow), meaning that sheep replacing cattle diminishes in this case reductions in environmental impacts from an overall decrease in LSU. SOC levels in *Götaland* evolve similarly to BAU as there are no major changes in arable land-use.

In contrast, our analysis estimates global damage in -CIS + TAX to be 20 % higher than BAU (i.e., above the black dashed line) for *Jönköping*, and 10 % lower than BAU for *Götaland* (15 % when considering regional

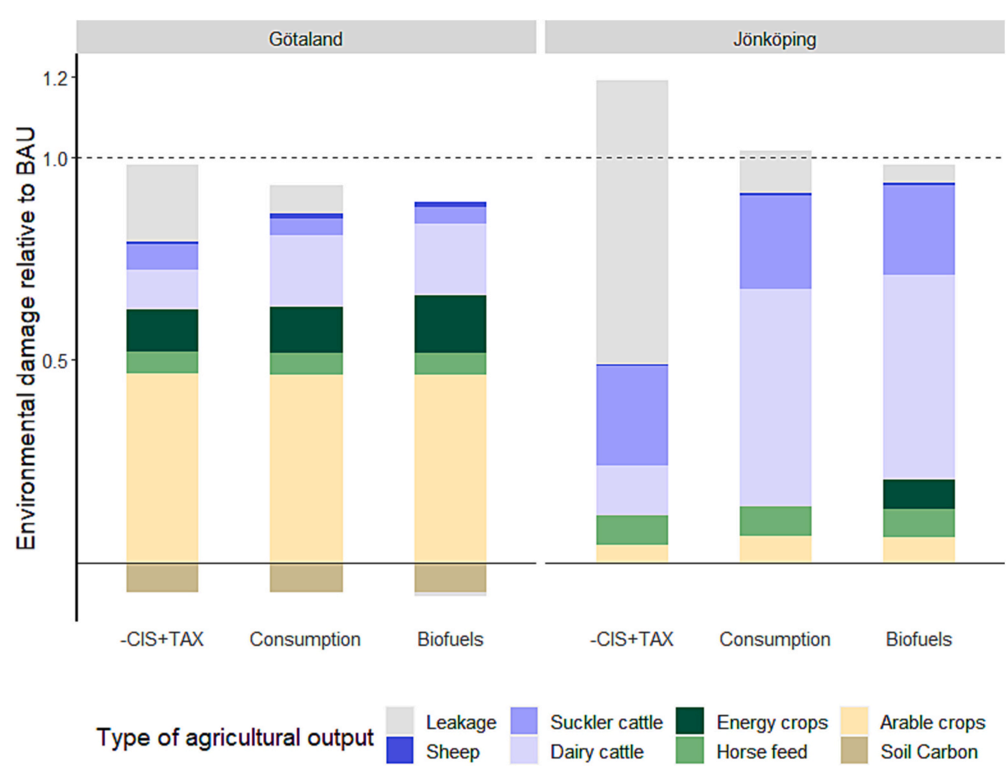

Fig. 3. Damage results for the base and sensitivity scenarios considered for -CIS + TAX following ReCiPe 2016, and normalized to results for BAU. Shares corresponding to major categories of agricultural outputs. Dashed horizontal line represents results for BAU.

SOC benefits). The worse environmental performance attributed to *Jönköping* is due to large decreases in production, particularly dairy. As dairy farms are more productive in Sweden than the global average according to the WFLDB, a large decrease in dairy output results in more damage to the environment overall due to production displacement abroad. In fact, leakage of displaced production becomes the largest contribution to the environmental impacts in *Jönköping*, representing roughly 60 % of the total. While *Götaland* also experiences notable decreases in agricultural outputs in -CIS + TAX, leakage of environmental impacts is minimized by the expansion of energy crops, as we consider their potential to replace arable crops imported to Sweden for bioenergy production. SOC levels in arable land in *Götaland* are stable in -CIS + TAX, which is an environmental improvement compared to the downward trend for SOC in BAU and reduces environmental damage through a reduction in net CO_2 emission. However, this benefit is comparatively small in magnitude and reflects the limited potential for carbon sequestration in soils to affect the lifecycle environmental performance of agricultural production in *Götaland* when considering damage to biodiversity comprehensively. In contrast, carbon sequestration in soils nearly compensates the negative effects of displaced production in *Götaland* when focusing on GHG emissions only (Fig. S1).

Increased beef and dairy prices in our sensitivity analysis partially compensate for the income loss associated with cattle production activities caused by the tax on enteric methane, which alleviates the decrease in cattle production in -CIS + TAX to some extent in *Götaland* and substantially in *Jönköping* (Fig. 3). Leakage decreases mostly due to both less displacement of livestock production and increased deployment of energy crops, while the effect of reduced consumption due to the incidence of the tax on consumer prices is limited. As a result of the decrease in leakage, the LCA performance of the policy intervention in *Consumption* and *Biofuels* improves. In fact, environmental damage in *Jönköping* is reduced to BAU levels in both sensitivity scenarios, which contrasts with results in -CIS + TAX being substantially higher. When analysing GHG emissions only, *Consumption* and *Biofuels* show similar emission levels to BAU in *Jönköping*, and a 20 % reduction in *Götaland* when including regional SOC benefits (Fig. S2).

Overall, the sensitivity analysis indicates that the results from the -CIS + TAX scenario are sensitive to the assumed tax incidence on producer prices, which may vary depending on whether the policy instrument is applied at regional, national, or continental level. In the analysis of policy interventions that lead to considerably reduced output levels, displaced production remains a major contributor to environmental damage in policymaking aligned with EGD objectives regardless of tax incidence on consumption.

4.3. *Effects on green Deal goals*

Policy interventions in -CIS and -CIS + TAX lead to markedly different outcomes in terms of their influence on the transformation of agriculture towards fulfilling the EGD objectives (Fig. 4). Positive and negative contributions (above and below zero, respectively) towards the goals during the last simulation year are normalized to regional BAU performance. In the case of arable land dedicated to biomass for bioenergy, present levels are virtually zero, and results are instead benchmarked against a recent estimation of technical potential in Swedish counties (Böhlenius et al., 2023). For SOC, a score of zero indicates same yearly loss of stocks as in BAU, and values above one indicate net growth. -CIS + TAX shows stronger structural effects than -CIS, leading in turn to stronger consequences for the environmental objectives of the EGD. Further, large variations in the indicator scores between *Götaland* and *Jönköping* in -CIS + TAX highlight the influence on the environmental outcome of policy interventions from regional profitability of dominant production activities and the availability (or absence) of alternatives that are economically viable.

Biomass for bioenergy from arable land increases substantially in *Götaland* due to the added incentive of the SOC payment in -CIS + TAX enhancing relative profitability of energy crops. In fact, our simulations predict higher biomass potential in *Götaland* for this scenario than the benchmark estimate of bioenergy potential from unused and abandoned arable land in the region (Böhlenius et al., 2023). However, the increase in set-aside of high-productive land is also considerable, which indicates unrealised potential for bioenergy to expand in otherwise unused arable land. Together, higher presence of set-aside arable land and energy crops achieves preservation of SOC stocks in *Götaland*, and regional emissions of N and pesticides, which are relatively higher for food and feed crops, decrease. *Götaland* and *Jönköping* in -CIS and *Jönköping* in -CIS + TAX show no additional deployment of energy crops in comparison to BAU. Arable land that is released from livestock production in *Jönköping* is instead set aside (recall that the SOC incentive is not applicable in this region). As the least profitable land goes out of production, environmental productivity increases markedly in *Jönköping*, and regional emissions of N and pesticides decrease. However, *Jönköping* also experiences substantial loss of its biodiverse seminatural pastures (−22 %) coupled with a large decrease (−40 %) in arable land in productive use, which, in mixed farm-forest regions like *Jönköping*, is also highly detrimental to biodiversity. Meanwhile, the decrease in seminatural pastures and arable land in productive use is limited in *Götaland*.

Global abatement of damage to biodiversity and GHG emissions is greatly influenced by loss of agricultural production in -CIS + TAX and subsequent environmental leakage abroad. In this scenario, *Jönköping* performs 19 % and 39 % worse than BAU for damage to biodiversity and GHG emissions respectively. In contrast, leakage is minimized in *Götaland* due to the expansion of energy crops, leading to impacts lower than and similar to BAU for biodiversity and climate change. The influence of leakage on the overall lifecycle performance of -CIS + TAX is further reduced in both regions in the sensitivity scenario *Biofuels*.

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

Fig. 4. Heat map showing positive (green) and negative (red) contributions (above and below zero, respectively) to policy goals in the EGD from structural changes in -CIS and -CIS + TAX relative to BAU, for Götaland and Jönköping regions. Indicators are listed from most positive (top) to most negative contribution across regions and scenarios. Grey cells indicate not assessed.

5. Discussion

5.1. Regional structure and production effects of the interventions

Here we analyse the regional structure and production effects of discontinuing the coupled income support for cattle in -CIS and a pricing mechanism on enteric methane emissions and SOC change in -CIS + TAX relative to business-as-usual development of *Götaland* and *Jönköping*.

Our results indicate that the CIS has a larger effect on cattle production in intensive cropping regions than in mixed farm-forest landscapes. At first glance this is a surprising finding given that agriculture in *Jönköping* is less profitable and dominated by beef and dairy production, which ostensibly should be more sensitive to removal of a subsidy to cattle. We explain this outcome by differences in relative profitability of cattle in *Götaland* and *Jönköping*. In *Götaland* there is an abundance of substitutes for cattle production, that become more profitable relative to cattle when the CIS is removed. In contrast, there are few alternatives to cattle production in *Jönköping*, and beef and dairy remain the most profitable options for most farms even after the CIS is abolished. In consequence, profit decline in -CIS compared to BAU is larger in *Jönköping* than in *Götaland*. The coupled cattle payment also holds back expansion of the sheep industry that would otherwise occur, and that could contribute to preserving grazing capacity (recall that preserving grazing was one of the reasons argued by Sweden to motivate the payment (Government offices of Sweden, 2014)). Overall, there is a limited decrease in ruminant livestock, and agricultural land use remains largely unchanged due to removing the CIS.

The compounded effect of the removal of the CIS and the tax/payment in -CIS + TAX leads to large reductions in meat and dairy production levels in both our study regions. However, its implications for land use differ due to regional differences in profitability. In *Götaland*, a high productive region, the increase in set-aside area compared to BAU is limited (5 %). In contrast, half of the arable land in *Jönköping* is set aside compared to ~20 % in BAU, and one quarter of its bio-diverse semi-natural pastures are abandoned to forest development. This indicates that the economic viability of arable crop land in *Jönköping* relies on the continuity of livestock farming and suggests that regions similar to *Jönköping* could experience large reductions in arable land if cattle activities become unprofitable. Importantly, the -CIS + TAX scenario represents farmers' production decisions in a situation where land use and production changes are the only way in which they can reduce their emissions and, by that, their tax duties. This is a limitation of AgriPoliS, as in reality other abatement channels may be available to the farmers presently or in the future, such as feed additives reducing enteric methane emissions (Kelly and Kebreab, 2023), which would allow them to sustain BAU to some extent. Therefore, our modelling results represent an upper estimate of the land use and production changes induced by policy interventions in -CIS + TAX.

The payment for carbon sequestration internalises the positive externalities of multiannual crop production in the farm's profit function, resulting in energy crop production on 20 % of arable land in *Götaland*, compared to virtually none in BAU. Notably, there are complementarities between the SOC payment and the parallel tax on enteric methane emissions and CIS removal. The simultaneous reduction in livestock production leads to a reduction in feed grain production, which frees up arable land for energy production. Without the livestock-related instruments the increase in energy crops and subsequent SOC benefits would have been smaller. The large differences between additional biomass availability in our scenarios and a recent estimate of agricultural land available based on current land uses show that considering constraints on economic profitability can substantially reduce biomass potentials in bioenergy deployment strategies (Böhlenius et al., 2023).

5.2. Environmental evaluation of the interventions

Our LCA results show that reduced output levels lead to substantial leakage of environmental impacts globally, reflecting high yields, efficient use of resources, and generally high environmental standards of Swedish agriculture in comparison to global averages (Martin and Brandão, 2017; Nordborg et al., 2017). When considering market feedbacks of policy instruments in *Consumption*, differences in the environmental performance are largely driven by the lower inference of the tax on producer earnings and its subsequent effect on output levels. In contrast, a reduction in meat and dairy consumption in Sweden in accordance with observed trends from Jansson et al. (2024) and market elasticities for beef and dairy from Säll and Gren (2015) does not considerably reduce leakage compared to our fixed-price scenario, i.e., -CIS + TAX. This reflects that our AB-LCA approach is sensitive to tax burden shifts to consumers when policy interventions are applied at large spatial scales because it will reduce the tax level to the farmers, but not to avoided consumption. The sensitivity analysis modifies the provisioning definition of our FU by including effects of policy on domestic consumption of animal products via changes in prices, which introduces sufficiency thinking in territorial AB-LCA for policy analysis (André, 2024). Reducing meat and dairy consumption does not affect nutritional wellbeing in Sweden and contributes to maintaining global provisioning levels despite a decrease in local production (Sundin et al., 2021; Trolle et al., 2024). Overall, a joint evaluation of -CIS + TAX and *Consumption* shows that displaced production is a larger aspect than avoided consumption governing the lifecycle performance of pricing GHG emissions in agriculture.

Notably, transfers of local or regional environmental impacts (e.g. ecotoxicity or eutrophication) can still result in net losses of biodiversity when threatening regions with higher biodiversity value (Fuchs et al., 2020), given that impact assessment methods in LCA generally lack information about the affected environment (Rosenbaum et al., 2018). Increasing energy crop production on set-aside arable land in *Jönköping* (*Biofuels*) creates an interesting synergy effect: minimising the negative environmental consequences of land abandonment while reducing the leakage effects of the intervention, thereby improving its environmental lifecycle performance. Prevented SOC loss in *Götaland* is important to achieve a net reduction in GHG emissions when livestock activities decline in -CIS + TAX. In contrast, the contribution of regional SOC changes to the overall lifecycle performance of the intervention is limited when analysing damage to biodiversity and human health comprehensively with ReCiPe endpoint indicators and EF weighted scores.

Regionally, land use change in *Jönköping* and *Götaland* indicates substantial reductions in indicators for ecotoxicity and eutrophication impacts from pesticide and fertiliser application respectively, which can have a positive effect on regional biodiversity. In a mixed farm-forest landscapes such as *Jönköping* however, losing high-value pastures, arable crops, and grasslands has a stronger impact on biodiversity (Öckinger et al., 2012; Andersson et al., 2022). This indicates that the overall outcome from -CIS + TAX is likely to be negative for regional biodiversity in *Jönköping* despite positive change in some regional AEIs. In contrast, biodiversity in an intensive cropping region like *Götaland* substantially benefits from reductions in N and pesticide emissions, and SOC improvements, and semi-natural grasslands are preserved in the region.

Regarding the CIS to cattle, our LCA shows minor environmental effects from its removal in both *Götaland* and *Jönköping* because increased sheep production keeps in-region lifecycle impacts at similar levels. Regional land use change in -CIS only involves some minor substitution of grass fodder production with low ecological value for arable food crops, while semi-natural grasslands remain unaffected. These land use changes do not cause any substantial differences in regional AEIs related to pesticide and fertiliser use, or SOC loss. Regarding the development of semi-natural grasslands, it is worth noting that an agri-environmental payment already exists to promote their continuity, and that their grazing only requires a fraction of the existing cattle population in Sweden (Larsson et al., 2020). Overall, our environmental evaluation shows little effect from the CIS, both in-region and from a lifecycle perspective. Conversely, its removal could unlock economic resources (490 M SEK in Sweden, or 13 % of the Swedish CAP budget (Swedish Code of Statutes, 2014, Swedish Board of Agriculture, 2020)) to better target environmental and social development goals in agriculture and rural areas (Scown et al., 2020).

5.3. Implications for policymaking aligned with European green deal objectives

Our regional-level approach identifies negative environmental side-effects of policy and, subsequently, the specific need or redundance for flanking policies, i.e., complementary instruments that address the negative effects of interventions without sacrificing the good. In a recent study of consumption trends from taxing GHG emissions of food items in Sweden, Moberg et al. (2021) suggest that harmful effects to biodiversity may arise from a decrease in beef consumption if land abandonment affects semi-natural grasslands. With our modelling, we show that a need for increasing the agri-environmental payment to semi-natural grasslands varies by region. Raising this payment could be motivated as a flanking policy in -CIS + TAX for *Jönköping*, but not for *Götaland* because no decrease in semi-natural grasslands is observed in this region.

Despite contrasting degrees of energy crop deployment, interventions in -CIS and -CIS + TAX may be regarded as removing artificial competitive drawbacks of agricultural bioenergy production under the existing policy framework (Gawel et al., 2019). Particularly in *Jönköping*, energy crop deployment on marginal arable land (*Biofuel)* illustrates potential synergies in policymaking for the EGD that risks being obscured when minimal indirect land use change is a primary criterion for bioenergy policy, as in the Renewable Energy Directive (Springmann et al., 2018; Daioglou et al., 2020). High levels of set-aside land in -CIS + TAX indicate that promoting bioenergy production for biofuels may improve future cost-effectiveness of emissions abatement through renewable energy production in *Jönköping* (dynamic efficiency) and reduce the risk of abandonment and afforestation of arable land (Larsson et al., n.d.).

Agriculture is broadly associated with large (positive and negative) environmental externalities that result in production levels and use of resources that are not optimal for society (Pretty et al., 2001). Therefore, policy interventions to transform agriculture in alignment with EGD objectives potentially pose a much larger influence on future agricultural land-use and the environment than bioenergy development on its own. Our results show that policies to reduce the environmental impacts of Swedish agricultural production can shift environmental burdens outside its borders and do not contribute substantially to reduce the environmental pressures of the Swedish society by motivating consumption change (Fuchs et al., 2020; Moberg et al., 2021). This confirms the importance of addressing displaced production of all agricultural commodities to avoid environmental leakage, which may be achieved through coordinated climate policy at EU level and trade measures such as carbon border adjustments to reduce leakage elsewhere (Fuchs et al., 2020; Mörsdorf, 2022; Jansson et al., 2024). While conceptually challenging, further coupling of AB-LCA with general equilibrium models offers promising complementarity in the environmental analysis of policy interventions in agriculture (Beaussier et al., 2019; Guillaume et al., 2024).

Our analysis illustrates that changes in regional land use and production from environmental policy interventions can have relevant, and sometimes conflicting, effects across EGD goals for agriculture. Arable land in *Jönköping* that is set aside from production is detrimental to regional biodiversity but also contributes to reducing off-field emissions of fertilisers and pesticides (Öckinger et al., 2012; Andersson et al., 2022). Notably, land use change may be considered an unintended, and even undesired, pathway to achieve (at least) some of the EGD goals for agriculture: for instance, the pesticide reduction target arguably aims at technological improvements rather than reduction in food production (Möhring et al., 2020). In addition, our indicator of environmental productivity is not sensitive to the negative implications of displaced production because it only considers the direct use of resources for production activities in a defined region. In consequence, environmental productivity improves substantially in *Jönköping* when internalising the environmental costs of GHG emissions in agricultural products, while global GHG emissions increase due to the leakage effects of displaced production. Overall, our analysis shows relevant implications of regional land use and production change across EGD objectives and markedly different outcomes of similar policy interventions across *Götaland* and *Jönköping*.

6. Conclusions

Our analysis demonstrates the influence of regional agricultural structure, and in particular relative profitability of production activities, on policy outcomes. The CIS to cattle is more economically important in regions dominated by dairy and beef production, but removing it has a more visible effect of decline in the cattle industry in intensive cropping regions due to strong competition for land and other productive resources. In contrast, pricing GHG emissions results in a substantial decrease in livestock production across regions, while agricultural land in productive use declines only in mixed farm-forest landscapes where the economic viability of the land is tightly linked to the presence of livestock.

The lifecycle performance of the instruments is strongly influenced by changes in regional production. Removing the CIS shows little environmental effect from a lifecycle perspective because decreasing cattle production results in an increase in sheep production causing similar environmental burdens. In contrast, displacement effects when pricing GHG emissions leads to substantial environmental leakage, given the low impacts of Swedish production compared to global averages. The magnitude of changes in production depends on how the tax burden is shared between farmers and consumers, which can vary whether the intervention is applied regionally, nationally or at EU level. Avoided domestic consumption of livestock products with large environmental impacts does not counterbalance the negative effects of displaced production in the lifecycle performance of the intervention.

Similar policy interventions show markedly different land-use outcomes across intensive and extensive farming regions in the EU, and this has relevant implications across the objectives of the EGD for agriculture. In this regard, our ex-ante approach offers support for policymaking to speed the transition of agriculture towards EGD objectives in evaluating the need or redundance of flanking policies such as increasing the payment for semi-natural grasslands, bioenergy promotion, or carbon border adjustments. We show that pricing GHG emissions from agriculture should be accompanied by measures for the preservation of semi-natural grasslands to avoid detrimental effects on regional biodiversity in mixed farm-forest landscapes. This aligns with previous findings that addressing environmental impacts effectively requires adapting policy instruments to regional conditions (Wätzold et al., 2016). Furthermore, policy promoting bioenergy deployment can mitigate the decrease of land in active use by providing economically viable alternatives while reducing leakage effects of displaced production. Lastly, containing the displacement of production abroad becomes critical for the environmental lifecycle performance of the intervention (Guillaume et al., 2024). This signals the importance of coordinated climate policy at EU level to avoid leakage effects that thwart the positive effects of environmental policy (Mörsdorf, 2022; Jansson et al., 2024).

We hope that our study highlighted the potential of agent-based life cycle assessment for supporting policymaking to advance sustainability transformations in agriculture by evaluating the environmental implications of policy instruments across regions.

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CRediT authorship contribution statement

Raül López i Losada: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Cecilia Larsson:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Mark V. Brady:** Writing – review & editing, Supervision. **Fredrik Wilhelmsson:** Writing – review & editing, Supervision. **Katarina Hedlund:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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