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# Agent-Based Life Cycle Assessment enables joint economic-environmental analysis of policy to support agricultural biomass for biofuels

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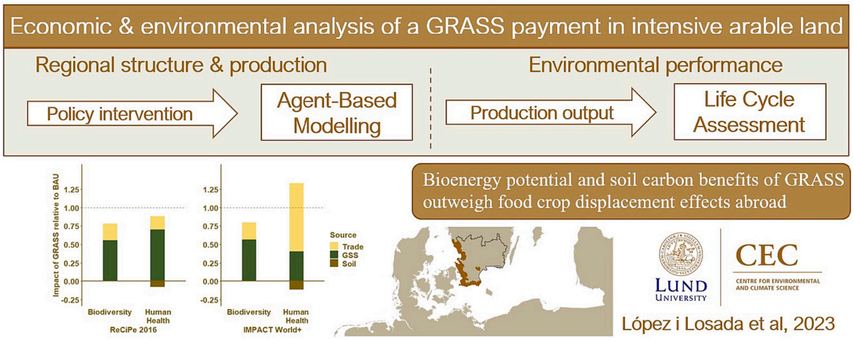
## HIGHLIGHTS

- We develop AB-LCA to analyse regional production and global environmental impacts.
- AB-LCA contributes to the assessment of agricultural biofuels with soil co-benefits.
- A policy payment for grass reduces specialisation without inducing structure change.
- Biofuel potential of grass is key for the environmental performance of the payment.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Production of agricultural biofuels is expected to rise due to increasing climate change mitigation ambitions. Policy interventions promoting targeted bioenergy solutions can be motivated by the large environmental externalities present in agricultural systems and the local context of biomass production co-benefits. Introducing energy crops in crop rotations in arable land with depleted Soil Organic Carbon (SOC) levels offers the potential to increase SOC stocks and future crop yields as a step towards more sustainable agricultural systems. However, the environmental performance of a policy incentive for energy crops with SOC co-benefits is less evident when considering its land-use effects within and outside of the target agricultural system.

We study the potential impacts of a change in agricultural policy on regional agricultural structure and production, and the environment with an Agent-Based Life Cycle Assessment approach. We simulate a policy payment that would achieve adoption of grass leys in crop rotations corresponding to 25 % of the highly productive land in an intensive farming region of southern Sweden. Although enhancing soil health in SOC-depleted farming regions is a desirable environmental objective, its significance is limited within the life-cycle performance of the payment. Instead, crop-displacement impacts and the grass potential as biofuel feedstock are the

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main drivers. The active utilisation of grasses for biofuel purposes is key in reaching a positive environmental evaluation of the policy instrument.

Our environmental evaluation is likely generalisable to other regions with similar technological levels and farming intensity, while our analysis on structural shifts is specific to the policy instrument and agricultural production system under study. Overall, our work provides a method to contrast regional effects and global environmental impacts of policy instruments supporting agricultural biomass for biofuels prior to implementation. This contributes to the environmental assessment of land-based biofuels at a time when their sustainability is highly debated.

## 1. Introduction

Agricultural land currently plays a limited role in global bioenergy supply compared to forestry (World Bioenergy Association, 2021), but its contribution is expected to rise. Agricultural feedstocks are regarded as an attractive option for large-scale deployment of liquid and gas biofuels in terms of potential volumes, technical readiness, and biomass suitability (Marelli et al., 2015; Tsiropoulos et al., 2020; Tsiropoulos et al., 2022). However, agricultural land is a limited resource with many competing uses (Haberl et al., 2011), and trade-offs can easily appear from expanding feedstock production as resultant land use change can impact both food security and the environment (Miyake et al., 2012; Subramaniam et al., 2019; Khan et al., 2021). Still, biofuels are an important component of climate change mitigation strategies for the transport and industry sectors compatible with emission reduction targets established in the Paris Agreement and the European Green Deal (Chiaramonti et al., 2021). A key societal challenge therefore emerges on how to best utilise available land to fulfil food, energy, and environmental needs.

Market-driven expansion of agricultural biofuels is unlikely to result in an optimal outcome for society because environmental externalities of agricultural production systems are generally substantial (Schläpfer, 2020). Furthermore, the impacts (and benefits) of agricultural bioenergy production are often context specific, as they depend on factors such as previous land use, crop (or biomass) choice and regional climatic and soil conditions (Havlík et al., 2011; Smith et al., 2014; Taheripour et al., 2017; Melnikova et al., 2022; Vera et al., 2022; Winberg et al., 2023). Arguably, promoting the expansion of bioenergy in agriculture through targeted policy would result in large societal gains if appropriate interventions can be identified (Englund et al., 2020).

Introducing grass leys or other energy crops like hemp or miscanthus in crop rotations have become a frequent suggestion to unlock biomass resources while simultaneously improving soil health in intensive agricultural systems (Brady et al., 2019; Zegada-Lizarazu et al., 2022; Englund et al., 2023; Næss et al., 2023). However, the overall environmental performance of a policy incentive for grasses is less evident when considering its land-use effects within and outside of the target agricultural system. Firstly, production of grass in arable land decreases land available for food production, and, moreover, introducing a policy incentive may bring about less-intuitive or indirect farm-structure shifts (Brady et al., 2017). Secondly, grass feedstock suitability for biofuels is hindered by its ligno-cellulosic composition, which can lead to lower energy returns per unit of land than would be achievable with e.g., food crops (Khan et al., 2021). Thirdly, most of the global agricultural land dedicated to satisfy the European demand for bioenergy and biomaterials is located abroad, suggesting that competitive advantages – real or contrived – for biomass production, such as more suitable growing conditions or less stringent environmental regulations, are unevenly distributed around the globe (Bruckner et al., 2019). This, in turn, raises additional concerns that increasingly ambitious bioenergy targets in the EU may continue to enhance environmental degradation problems outside its borders (Fuchs et al., 2020). Arguably, the range of impacts and benefits that can be attributed to policy promoting the deployment of grasses is qualitatively broad.

To support policymaking, a need therefore arises to evaluate the performance of policy instruments in a framework that can capture the regional dynamics of structural production shifts and attendant environmental changes. Structural production shifts resulting from policy interventions can be modelled using Agent-Based Models (ABM), while environmental consequences of such shifts can be evaluated using Life Cycle Assessment (LCA). Both can be integrated into Agent-Based Life Cycle Assessment (AB-LCA), a methodology whose application in agricultural systems has developed in recent years (Vázquez-Rowe et al., 2014; Marvuglia et al., 2017; Lan and Yao, 2019; Marvuglia et al., 2022). A major strength of AB-LCA is that it overcomes the static nature of LCA in the modelling of dynamic agricultural systems, which involve complex interactions among human actors and the environment (Gutiérrez et al., 2015). Although AB-LCA has a high potential to evaluate the environmental impacts of policy that promotes agricultural feedstock for bioenergy, its methodology is still in its infancy, with conceptual agent-based representations of farming regions that are either theoretical (Miller et al., 2013; Bichraoui-Draper et al., 2015) or not validated (Lan and Yao, 2019; Ding and Achten, 2022; Marvuglia et al., 2022).

To expand the environmental assessment of agricultural biofuels at a time when their overall sustainability is highly debated, the aim of this paper is to evaluate the environmental life-cycle performance of a payment to farmers for incorporating grass leys in their arable crop rotations. This is a timely instrument to evaluate because an annual grass payment of 43 EUR/ha (500 SEK/ha) was recently removed in a Swedish farming region within the geographical domain of a dynamic and empirical ABM of farmer behaviour, AgriPoliS (Balmann, 1997; Happe et al., 2006). The arguments behind the decision to remove the payment in Sweden were that it largely compensated farmers for leys that would have been there regardless, while it failed to expand their presence in intensive arable land where SOC is depleted (Swedish Board of Agriculture, 2021). The previously existing payment signals a recognition that more grass is a desired objective to the policymakers, while its removal is related to the failure of the incentive to deliver expansion of grass leys into highly productive arable land, rather than a change in political priorities. Furthermore, had the incentive achieved its goal, its overall environmental performance would still be an open question, as land use pressure from displaced food crops risks translating into environmental impacts elsewhere. To guide this study, we formulate the following two research questions:

- How will a payment for grass leys in arable crop rotations change the farm structure and production of food crops in a region with ongoing SOC depletion caused by intensive farming practices?
- What will be the overall environmental life-cycle performance of the incentive when considering the soil health benefits, biofuel potential and crop displacement effects of grass leys?

## 2. Materials and methods

To address these questions, we develop an integrated Agent-Based Life Cycle Assessment (AB-LCA) approach that couples modularly AgriPoliS and LCA. First, we model Götalands Södra Slättbygder (GSS), an intensive farming region in the south of Sweden, in AgriPoliS in the presence and in the absence of a payment adjusted to achieve approximately 25 % coverage of grass leys in arable land. Then, we compare the two scenarios from a LCA perspective, which allows to contrast the trade-offs in production and environmental impacts. Our approach considers structural effects of the policy change at the regional level while providing a global account of environmental impacts, including those associated with displaced food crops.

### *2.1. Agent-based modelling*

AgriPoliS is a tool designed for simulating policy scenarios with outputs of agricultural land-use changes emerging from farm agents' optimizing behaviour (Kellermann et al., 2008). As a non-spatially explicit ABM, it simulates the response of a representative population of individual farms in a particular study region to an economic policy change, which it does by simulating the behaviour of and interactions among relevant economic agents (i.e., farms), given the economic, technological, and environmental context in which they operate. Evaluation of AgriPoliS results shows correct trends and <10 % deviations from observed structural statistics such as numbers of different livestock and types of farms (Hristov et al., 2020). This provides a key advantage in contrast to existing AB-LCA studies, as AgriPoliS is able to predict effects of incentives on land uses, livestock holdings and structural change over time in a real region. Furthermore, it produces a set of quantitative outcomes, including Soil Organic Carbon (SOC) as a key indicator of soil health (Kumar et al., 2022), and economic optimal N fertilisation rates that influence yields, which evolve over time based on the economic decision-making of the farm agents (Brady et al., 2019). This feature is particularly relevant in the evaluation of agricultural biofuel production that should promote soil health benefits as a means to outweigh the environmental challenges traditionally associated with the water-food-land nexus of biofuels (Rulli et al., 2016; Næss et al., 2023).

GSS is the southernmost naturally defined agricultural region of Sweden, characterised by intensive arable farming and high yields, and an integral modelling entity in AgriPoliS. Wheat, barley, rapeseed and sugarbeet production is carried out on the most productive land, whereas a higher prevalence of grass ley is associated with less productive land in mixed forestry-agriculture landscapes, a greater presence of livestock, and lower farming intensity overall. Within GSS, wheat, barley, rapeseed, and sugarbeet are grown on 95 % of the highly productive arable land. In contrast, livestock farms are concentrated in the least productive land parcels, a large portion of which they allocate to animal fodder (primarily grass fodder and some feed grain). Most agricultural land in GSS is arable and there is low presence of grasses, unlike in the surrounding regions (Fig. 1). Observed SOC changes in long-term field experiments in the region for common farming practices suggest depleted SOC levels in highly productive arable land only (Brady et al., 2015; Zhou et al., 2019). Consequently, we formulate our policy intervention as a payment to grass leys in highly productive land, although low productivity fields still operate in the ABM to keep the structural integrity of the farming region. Our definition of grass ley refers to a mix of grass and clover common in Sweden, as described in AgriWise (2020), a farm planning tool based on expert knowledge that is maintained by the Board of Agriculture and the Swedish University of Agricultural Sciences to support farmers.

This study takes the perspective of a policymaker who needs to decide whether to implement a hectare-based payment to grass leys destined for biofuel production in GSS. Our two policy scenarios in AgriPoliS reflect the policymaker perspective, and are therefore

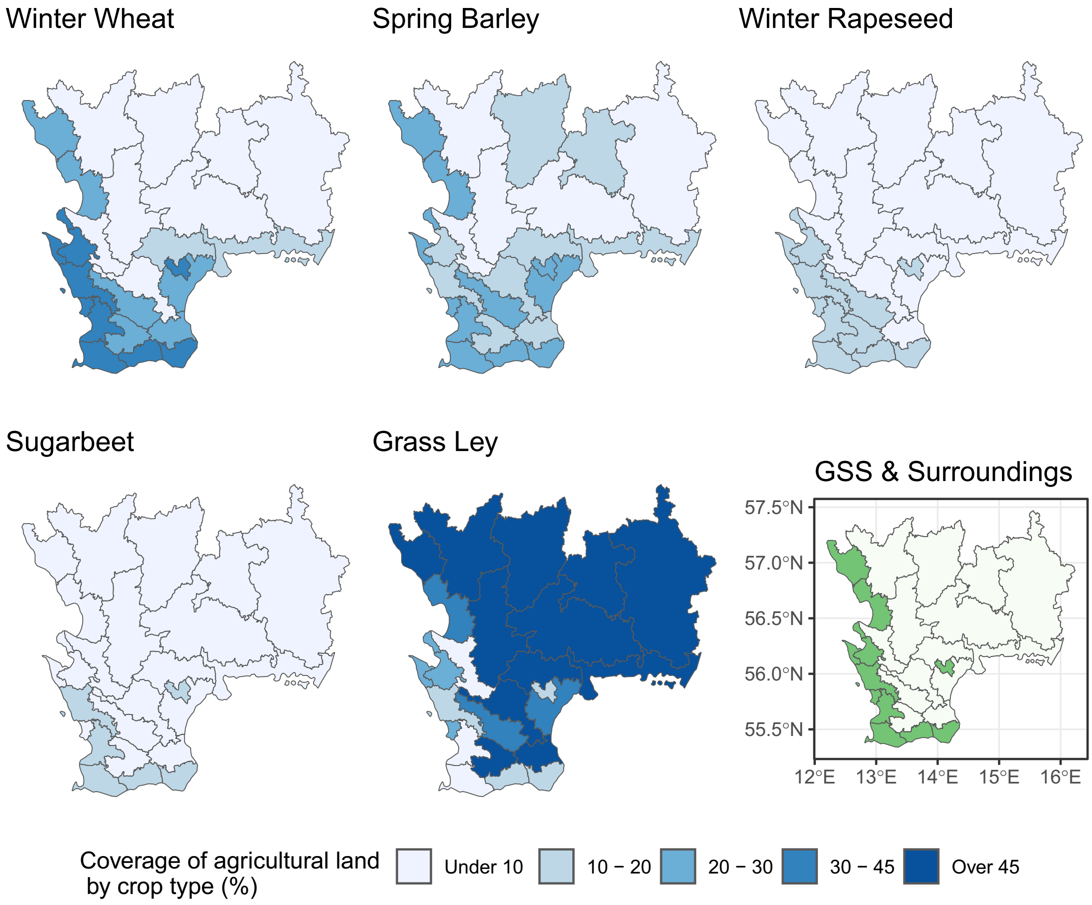

**Fig. 1.** Distribution of crop types in Yield Survey Districts as percentage cover of the total arable area in each district, for GSS and surrounding regions. Map in the bottom right corner shows GSS (dark green) and surrounding regions (light green).

characterised by the presence (GRASS) or absence (BAU) of an incentive designed for that purpose:

- BAU (Business as usual) scenario: in the absence of a policy incentive, the region produces no additional grass feedstock, while SOC levels continue to decline over time.
- GRASS scenario: an annual payment is introduced for 2-year grass leys in land that is defined as highly productive based on observed crop rotation patterns. The payment level, which is kept constant over the years in AgriPoliS, is the result from iterative simulation runs to achieve a ~25 % coverage of grass leys in the high productive land. This level is considered desirable to ensure substantial SOC gains without changing the main purpose of the land from food production based on a sensitivity analysis of grass ley coverage in GSS by Brady et al. (2019). In the simulation, farmers are assumed to grow the same grasses for biofuel production and animal feed. This is reflected in the price at which farmers sell their grass for biofuels in AgriPoliS, which is the estimated market value of feed ley in the region (0.11 EUR/kg). The price level determines optimal N fertilisation levels and yields, and describes an illustrative, standard ley in the region, while inferring the optimal choice of energy grasses is outside the aim of this paper. In addition, the active use of grass for biofuel production is beyond the modelling scope of the ABM, which presupposes the existence of a regional biofuel market that is not currently in place.

### 2.2. LCA modelling

The main goal of our LCA modelling is to support the policymaking process with an evaluation of the environmental performance of the payment, which is assessed as the difference in life-cycle impacts in the presence and absence of the payment. To focus on the impacts related to the agricultural production of the region, this study applies attributional modelling and follows a cradle-to-farm-gate approach. The harvested product with the highest economic return for the farmers in any given field bears all production impacts associated with it, as our ABM does not explicitly model the fate of by-products with low economic relevance such as straw residue (although it is assumed to remain on the farm for internal use, which is the norm in GSS).

The Functional Unit (FU), a quantified description of the performance requirements of the system under study (Arzoumanidis et al., 2020), is essential to ensure alignment with the goal of the LCA and objective comparison between scenarios. The geographical focus of this paper is GSS but crop displacement effects outside of the region are considered as part of the concerns of the policymaker. Similarly to other AB-LCA studies of agricultural regions (Vázquez-Rowe et al., 2014), our FU follows a fixed-consumption approach, i.e. it covers the entire agricultural production of GSS, and trade evens out the differences for each agricultural product between scenarios, which are assumed to come from a global average production pool. This means that system boundaries include impacts of production elsewhere to compensate the within-region food output reductions for each food crop. We justify this assumption in that changes in a small country like Sweden are not expected to result in observable effects on world market prices. However, system boundaries exclude low productivity fields in GSS on the grounds that they are not targeted by the payment, and that their presence is relatively minor. Lastly, the system is annualised, so that one year of regional production is considered in the assessment, and the temporal scope is set at year 20 of the simulation to allow for considerable SOC benefits from the payment. In sum, our FU is defined as:

> “Maintaining total provision in GSS of arable crops in kg wheat, barley, rapeseed, and sugarbeet in year 20 relative to year 1 of the projection via local production and imports, adding the biofuel potential in MJ as a function of grass production in year 20.”

The additional grass ley in the GRASS scenario is assumed to replace imported biofuels, thus replacing a mix of crops purposefully grown for biofuels abroad in BAU. This mix of crops consists of rapeseed (77.7 %), corn (12.3 %), sugarbeet (6.0 %), wheat (2.8 %), and barley (1.2 %) with percentage share in volume for each crop in brackets. This mix of weights is chosen to reflect consumption levels of the main agricultural biofuels in Sweden for 2020 and considers a 1 % cut-off threshold below which crops are disregarded (Fig. 2). Contribution from crops, excluding residues, is heterogeneous across energy carriers, and accounts for 25–37 % of the national consumption of gas and liquid biofuels other than black liquor from the pulp industry. The precise share depends on the undisclosed fraction of bio-oils that is derived from crops. As no predominant technology path is set, replacement of the crop mix by grass happens on maximum energy yields reported by crop in Prade et al. (2017). Consequently, by-products are cut-off, as they are generally technology dependent.

Under these assumptions, the LCA results evaluate the environmental performance of a policy instrument promoting crops for biofuels within a defined region while accounting for crop-displacement effects in terms of land use pressure elsewhere. Modelling of Swedish crop production is based on German analogue data in the ecoinvent database (v3.8), as southern Sweden and northern Germany share similar agricultural and climatic conditions. Modifications of the original German processes in the ecoinvent database account for the changes in yields and fertiliser use simulated by AgriPoliS, as well as production data from AgriWise (2020). A list of these modifications can be found in the Supplementary Material (Table A.1). The results section focuses on damage indicators aggregated by areas of protection *Human health* and *Biodiversity* (i.e., environmental variables of direct concern aggregated by classes with intrinsic value for society). To test the sensitivity of the results to the choice of Life Cycle Impact Assessment (LCIA) methodology, two different methods have been applied: ReCiPe 2016 and IMPACT World+. Both provide midpoint (i.e., defined somewhere along the impact pathway before the damage) and damage indicators (de Haes et al., 1999). The Supplementary Material details impact results for each scenario in all impact categories for midpoint and damage indicators (Tables A.3 and A.4).

### 2.3. Coupling agent-based modelling and LCA

The coupling of ABM and LCA is a stepwise process. First, AgriPoliS simulates farmers' responses to a policy setting in annual time steps. The simulation runs for 20 years from the time of the policy change, which is an adequate horizon to observe substantial SOC changes while remaining within the temporal domain of the model. AgriPoliS adopts the farm-types proposed by the Swedish Board of Agriculture for calculating agricultural statistics for calibration and validation purposes (Boke Olén et al., 2021), although pig and poultry farms have been aggregated as granivores and further classified into breeding and meat-production types. Given that animal farms are of limited relevance to this study, reporting of modelling results for livestock farm-types has been further simplified into two major archetypes, grain-fed and grass-fed. Calibration and validation to observed structural change in the most recent models for Swedish regions are documented in Hristov et al. (2020) and Hristov et al. (2017). Simulation results for farm-types from AgriPoliS include land use, and input and output quantities. In addition, we use long-term experiments in GSS (Carlgren and Mattsson, 2001) and production functions first parameterised for winter wheat by Brady et al. (2015) to estimate SOC development in arable land under BAU and GRASS scenarios and subsequent effects of SOC changes on yields and optimal N fertilisation. Production functions for spring barley, winter rapeseed and sugarbeet are reported by Brady et al. (2019) (Table S2). Only biogenic carbon related to SOC changes from agricultural management in GSS is included in the LCA results. Secondly, the AgriPoliS results feed into the Life Cycle Inventory (LCI) phase of the LCA. One particularity of this study is that the LCA is neither a classic product/service nor an organisational LCA, but rather falls into the realm of

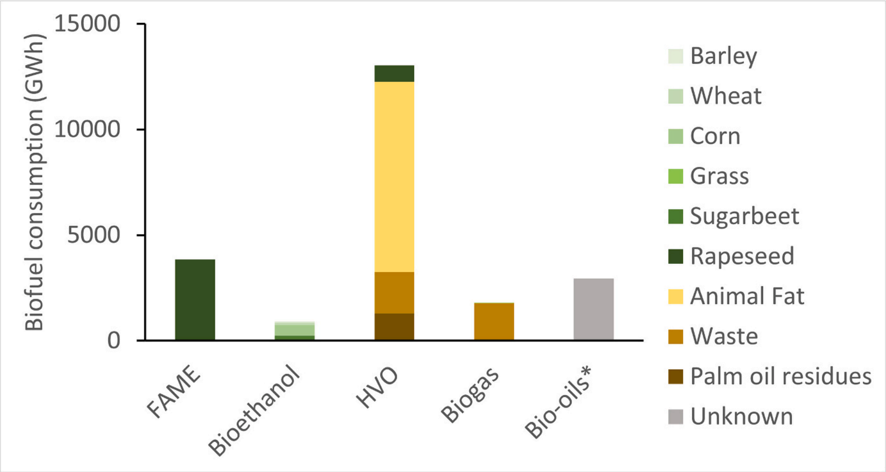

**Fig. 2.** Swedish consumption of biofuels with contributions from arable land by biomass source, 2020. Source: Swedish Energy Agency (2021).
*Bio-oils are defined as an unspecified mix of forestry and agricultural residues, agricultural crops, and urban waste.

territorial LCA with focus on crop production in a given region (GSS) for the purpose of modelling potential consequences of policy changes (Loiseau et al., 2018).

A common issue when integrating an ABM of an agricultural system with LCA concerns whether and how to infer production changes outside the regional boundaries of the ABM. Production changes in GSS are too small to translate into perceptible effects on global trade and prices from global modelling exercises, similarly to previous AB-LCA attempts (Vázquez-Rowe et al., 2014). Our economic modelling is hence limited to the consequences of the policy intervention within the regional limits of the ABM, and the LCA compares the share of the global environmental burden allocatable to GSS in the presence and in the absence of the policy change if the rest of the world remained as it is today (Ekvall, 2019). This allows us to focus on the predictive potential of AgriPoliS within GSS, while considering environmental impacts out of the region as well. In addition, the modelling of regional SOC levels indicates the soil health benefits of including grasses in intensive crop rotations. A sensitivity analysis described in Section 2.4 tests the impacts of a few selected methodological choices, including the use of average market data and assumptions on geographical origin of trade. Altogether, our assessment contributes to improving the scientific basis of policymaking in the task of shaping environmentally-sound instruments to source agricultural biomass for biofuels.

### 2.4. Sensitivity analysis of LCA results

With a sensitivity analysis we evaluate the influence of selected variables on the LCA results, namely origin of imports (*EU imports*), reference year (*Year five*), share of grass converted to biofuels (*Grass loss*), and marginal market data for products outside of GSS (*Marginal*). *EU imports* and *Marginal* relate to the limitations of the ABM, as a regional tool, to predict trade patterns and crop-displacement effects elsewhere. Both sensitivity scenarios also allow to partially test the influence of choosing an attributional life cycle inventory model instead of a consequential one, which could be justified if changes in global production of crops in response to a policy change in GSS were at the core of the present study. The relevance of *Grass loss* lies on the fact that the ABM boundaries of the agricultural system assume a potential grass market for biofuels. *Year five* weighs the relative importance of the regional SOC benefits on the overall performance of the payment.

- *EU imports* assumes that trade occurs predominantly within the EU. Production changes in GSS are unlikely to translate into cascading crop-displacement effects outside of the EU because of the intensification potential in existing land within its borders and EU legislation and use of certification schemes increasingly avoiding land use change outside the EU.
- In *Grass loss*, only 50 % of the optimal grass yield is used for biofuel production. Several reasons, and any combination of them, could be behind a lower-than-expected amount of biofuel production, including, but not limited to, harvest losses, a nascent biofuel industry incapable of assimilating all grass production, and imperfect monitoring of payment requisites.
- In *Marginal*, the ecoinvent attributional life cycle inventories are replaced by their consequential analogues, which link an activity expected to change to the marginal provider on the market rather than to the market average. No further modifications are considered given that the ABM already models the economic consequences of the policy intervention within the region, and changes to trade patterns from a region of the size of GSS are negligible.
- In *Year five*, the impacts are calculated according to AgriPoliS output for the fifth year of the simulation. Major structural changes caused by the implementation of the grass payment have already taken place, but SOC effects on yields are still limited.

## 3. Results

### 3.1. Agent-based modelling: change in agricultural structure and crop production over 20 years

The ABM simulations show that both land distribution across farm-types and total number of operating entities remains mostly unchanged between GRASS and BAU over a 20-year time window, with the greatest differences occurring within land distributions across the farm-types with lowest presence in GSS (Table 1). The model also captures the dynamics of changing farm structure that is reducing the number of operating enterprises over time and shifting land between farm-types. Arable farms and dairy farms increase in area over time in BAU, which indicates that they are the most competitive enterprises, while small holdings and livestock farms for meat recede. At the same time, the total number of farms decreases across most farm-types, as smaller estates go out of business. Overall, a yearly payment of 258 EUR/ha in GRASS was found to achieve a 25 % coverage of grass leys in highly productive land without substantially affecting business-as-usual development of regional agricultural structure.

The SOC levels in BAU continue to decline yearly at a regional average rate of −0.29 % while they show an upwards trend of 0.08 % when a 2-year grass ley is included in the rotation to cover ~25 % of the

**Table 1**
Current and year 20 total number of farms, and use of total agricultural land and highly productive arable land across farm-types for BAU and GRASS simulations in AgriPoliS. Results for GRASS are expressed as difference from BAU (positive meaning greater than in BAU).

| Farm-type | Total number of farms | | | Total agricultural land distribution | | | Arable land distribution | | |
|---|---|---|---|---|---|---|---|---|---|
| | Year 0 | Year 20 | | Year 0 | Year 20 | | Year 0 | Year 20 | |
| | | BAU | GRASS (Δ) | | BAU | GRASS (Δ) | | BAU | GRASS (Δ) |
| | – | – | – | $10^3$ ha | $10^3$ ha | $10^3$ ha (%) | $10^3$ ha | $10^3$ ha | $10^3$ ha (%) |
| Food crops | 1905 | 1235 | −5 | 237.5 | 259.6 | −0.1 (0) | 203.4 | 214.4 | 2.9 (1) |
| Mixed crop/livestock | 370 | 285 | 10 | 31.9 | 20.6 | 1.8 (9) | 17.2 | 11.2 | −0.2 (−2) |
| Dairy | 140 | 115 | 0 | 28.3 | 35.9 | −1.1 (−3) | 9.3 | 10.5 | −1.6 (−15) |
| Livestock, grain-fed | 115 | 105 | −5 | 22.0 | 16.3 | −0.5 (−3) | 17.9 | 10.9 | 0.1 (1) |
| Livestock, grass-fed | 275 | 65 | −5 | 15.6 | 7.8 | −0.1 (−1) | 1.6 | 1.7 | −0.5 (−29) |
| Small holdings | 855 | 855 | 0 | 5.1 | 2.6 | 0 | 0 | 0 | 0 |
| All farm-types | 3660 | 2660 | −5 | | | | | | |

land, which is supported by long-term experiments on representative farming conditions in GSS (HS, 2017). Noticeably, total N application in GSS remains higher throughout the simulation in GRASS, since the optimal N rate for mixed clover-grass leys, according to AgriWise (2020), is higher than that for the replaced crop, spring barley. However, the economic optimal N application per ha for food crops increases over time in BAU to compensate for the effects of decreasing SOC levels on yields, while it remains roughly unchanged in GRASS. This causes the difference in total N application between scenarios to be more than halved over the 20-year simulation period, from roughly 2000 t (5 % of the total N application in GRASS) to <1000 t.

The payment promotes the introduction of grass leys in crop rotations in highly productive arable land without substantially modifying the regional agricultural structure. However, some important changes in the production of food crops take place. Production volumes in GSS are affected both by crop substitution effects when the payment is introduced, and dynamic SOC levels influenced by the new crop rotation (Table 2). In the presence of a grass payment, farmers choose primarily to grow grass instead of spring barley, which is the least profitable of the main crops in the region, and to some extent also winter wheat. Rapeseed remains virtually unaffected in terms of land cover, while sugarbeet is farmed on contract with the regional sugar industry and its production volume is fixed in AgriPoliS. The yield response to increased SOC levels is highest for winter rapeseed, followed by winter wheat, sugarbeet and spring barley. The combined effect of land use shifts and dynamic SOC levels on regional production volumes of food crops is mixed. With the grass ley incentive mainly barley production is lost, winter wheat yield gains compensate to a great extent for losses in crop area, and rapeseed production grows over 10 %. Despite yield gains from SOC restoration, the total volume of food production in GSS declines compared to BAU, while at the same time additional feedstock for biofuels becomes available.

**Table 2**
Production Volume (1000 T), Crop Land (1000 ha) and Yield (kg/ha) for each main crop at year 20 of the simulation in BAU and GRASS. Results for GRASS are expressed as the difference from BAU (positive meaning greater than in BAU).

| Crop | Production volume | | Crop land | | Yield | |
|---|---|---|---|---|---|---|
| | BAU | GRASS (Δ) | BAU | GRASS (Δ) | BAU | GRASS (Δ) |
| | $10^3$ T | $10^3$ T | $10^3$ ha | $10^3$ ha | kg/ha | kg/ha |
| Winter Wheat | 868.6 | −36.8 | 109.9 | −7.5 | 7,904 | 218 |
| Spring Barley | 433.9 | −432.8 | 70.4 | −70.2 | 6,167 | 64 |
| Winter Rapeseed | 129.8 | 14.3 | 39.5 | 0.0 | 3,284 | 361 |
| Sugarbeet | 2,129.3 | 4.2 | 29.7 | 0.0 | 71,765 | 177 |
| Grass Ley | 0.0 | 510.8 | 0.0 | 77.6 | 6,580 | 0 |

### 3.2. *Life cycle assessment: environmental impacts with and without a payment for grass leys*

After 20 years of payments for leys, annualised life-cycle impacts are lower in GRASS than in the BAU scenario (i.e., below the dashed black line) for most impact categories and areas of protection considered, and across both impact assessment methodologies (Fig. 3). Impacts are further classified into GSS, Trade and Soil categories. GSS impacts are directly attributed to farming activities within the region, whereas Trade impacts account for production displacement effects elsewhere. In addition, Soil captures the carbon sequestration benefits of SOC restoration, interpreted as the absolute difference in SOC between GRASS and BAU scenarios as a negative emission of $CO_2$, and attributed entirely as a benefit in GRASS. Trade impacts are considerable, and account for over 10 % of the total impact in all categories. Carbon sequestration benefits are much smaller than trade impacts across all impact categories and assessment methodologies considered. The main difference between the impact assessment methodologies relates to the trade-induced impact of water resource depletion on human health. While both methodologies show this impact as the main trade-off of GRASS compared to BAU, the water impact model by Boulay et al. (2011, 2018) used in IMPACT World+ suggests that the performance of GRASS may be overall worse than in BAU for human health due to water resource depletion. These results should be interpreted carefully, as discrepancies still exists on the LCA modelling of water-related impacts (Gerbens-Leenes et al., 2021), and in particular with regard to the impact model implemented in IMPACT World+ (Hélias, 2020). The Supplementary Material details damage impacts at impact category level (Table A.4). The environmental performance of the policy instrument is greatly influenced by the impact of Swedish crops compared to the global average. The differences in water use damage between GRASS and BAU are pronounced due to relatively little irrigation-based agriculture and water scarcity in Sweden, compared to many countries contributing to the global average production of the traded crops.

The sensitivity analysis showed that the scenario *Grass loss* produces the most distinct outcome in comparison to the base modelling setup, followed by *EU imports*, while *Year five* and *Marginal* do not result in any considerable differences (Fig. 4). The GRASS scenario performs substantially worse in *Grass loss* across impact assessment methods and areas of protection (i.e., above the dashed red line), although it still shows an impact reduction compared to BAU for biodiversity in both impact assessment methods (i.e., below the dashed black line). *EU imports* produces substantially different results only for Human Health in IMPACT World+, which may be traced back partly to differences in the inventory database for water irrigation rates globally and in the EU, and partly to water use impact modelling choices from Boulay et al. (2011) lacking clear consensus within the LCA community. A joint evaluation of *Grass loss* and *Year five* illustrates that the life-cycle performance of the payment is driven by crop-displacement effects and the potential of grasses as feedstock for biofuels, while the significance of SOC benefits

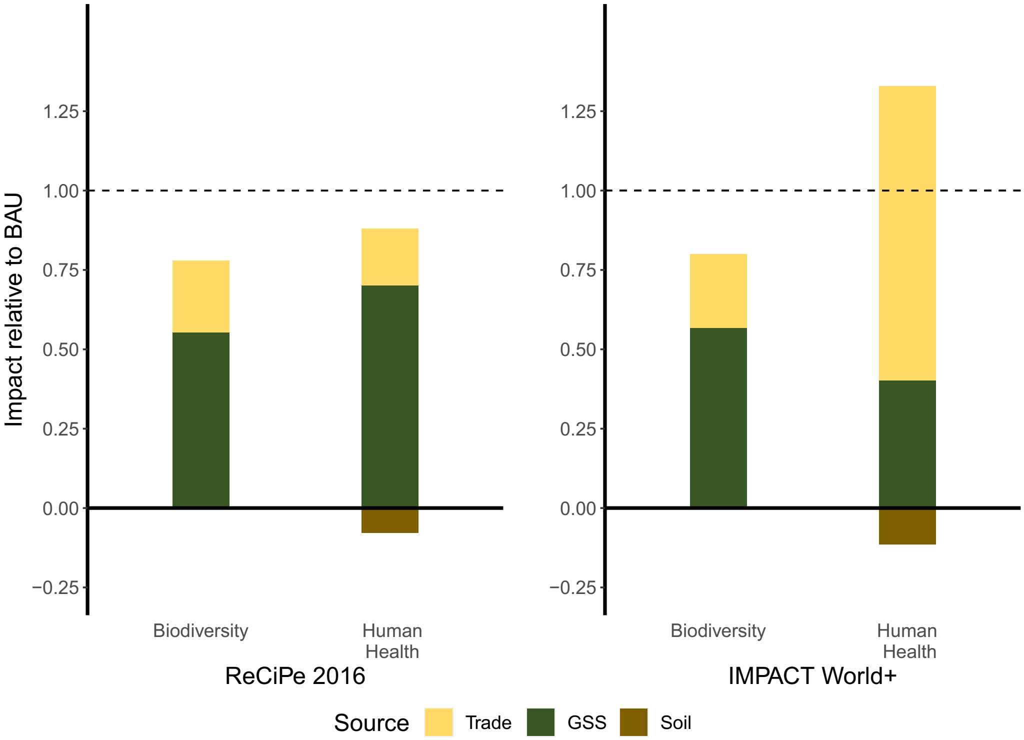

**Fig. 3.** Damage results for GRASS following ReCiPe 2016 (left) and IMPACT World+ (right) methodologies aggregated by area of protection and normalized to BAU results. The dashed black horizontal lines represent BAU results.

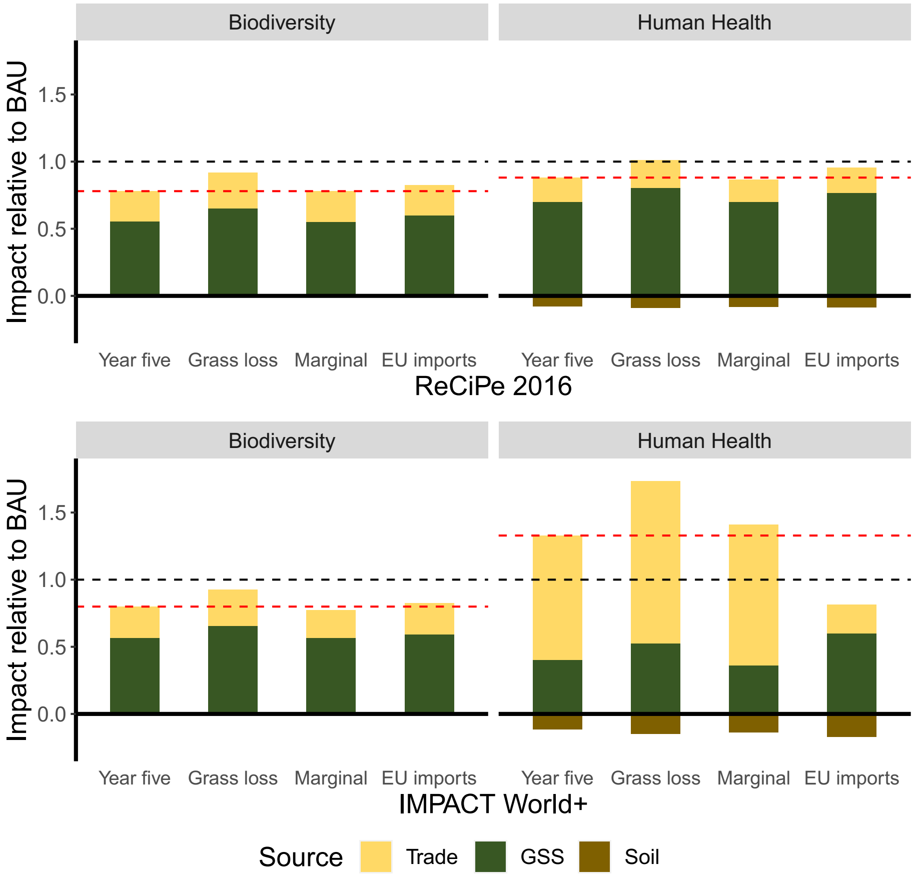

**Fig. 4.** Damage results for the four sensitivity scenarios considered, following a) ReCiPe 2016 (above) and b) IMPACT World+ (below) methodologies aggregated by area of protection and normalized to results for BAU. Dashed horizontal lines represent results for BAU (black) and GRASS (red).

on yields is limited. A comparison between *Year five* and the original modelling setup also shows that the carbon sequestration potential is more significant than the increased yields in GRASS for human health, while their relevance is similar for biodiversity. Overall, the AB-LCA results are robust against assumptions for impacts to biodiversity, although it is important to ensure that grass is utilised in bioenergy production. In contrast, assumptions about import origin and the impact assessment of irrigation are critical for impacts on human health.

## 4. Discussion

### *4.1. Regional analysis of the payment*

AgriPoliS allows us to study policy interventions prior to their implementation and assess the ability to fulfil their goals in terms of farmer behavioural change, although the techno-economic environment of an agricultural region may change in reality over time (e.g., after the 7-year CAP cycle, or because of the spread of new agroecological practices). The hectare-payment has been determined to obtain a ~25 % coverage of grass leys in highly productive arable land, which roughly corresponds to homogenous implementation of 2-year grass leys in an 8-year rotation that is typical in the region according to reported statistics (SCB, 2020). This reverses the decreasing SOC trend without the payment and reduces optimal N fertilisation levels for all crops. However, total N application remains higher throughout the simulation in the GRASS scenario, which is attributable to the higher N application in grass leys compared to the main crop they replace (i.e., barley). Increased fertilisation as a result of crop substitution should not lead to a higher risk of eutrophication in GSS, as modelling results specific to the region suggest that grass leys have lower N emissions off field than barley, in spite of higher fertilisation levels (Johnsson et al., 2019).

Our results show that a payment of 258 EUR/ha (in addition to the assumed market value of harvested grass) would induce farmers to include grass leys in their crop rotation on highly productive land, where they would have the potential to restore SOC levels. Furthermore, the payment would not cause substantial shifts in the land allocation among farm-types, or changes in the number of operating farms, which are good measures to spot major structural change in AgriPoliS (Brady et al., 2012; Boke Olén et al., 2021). This is an important aspect for policy efficiency given that structural change is in principle outside the remit of policy promoting agricultural biomass for biofuels. The payment level that we derive from our simulation to reach the 25 % target for grass ley is substantially higher than the payment of 43 EUR/ha that was recently removed, which indicates that it did not sufficiently compensate farmers for their losses to motivate a switch from profitable crops to grass leys. In this regard, the payment proposed in this study can be seen as a revised version of the removed payment that addresses its low adoption rate in highly productive land, which illustrates the importance of regional dynamics in targeting payments to promote bioenergy feedstock production. The yearly SOC-increase rate for grass leys in arable rotations corresponds to the average of 2-yearly grass leys, which is significantly higher than that of yearly grass leys. The active utilisation of the aboveground biomass does not considerably affect SOC development, which is otherwise largely driven by the non-linear growth of the root system (Kätterer et al., 2011; Dignac et al., 2017). Notably, one year grass leys applied to the same extent would not succeed in reversing the SOC-depleting trend in arable land in GSS.

Although studies reviewing the influence of agricultural management on SOC development and its subsequent effect on yields and optimal N fertilisation levels may show highly variable responses (Bolinder et al., 2020; Vendig et al., 2023), our reference experiments were designed to be representative of the farming practices and diversity of soil and field characteristics in GSS (Carlgren and Mattsson, 2001). They also address the shortcomings often associated with the pool of evidence on SOC development gathered from field experiments, namely that the timespan of measurements is too short, SOC is recorded as a single point in time relative to a control field, or SOC measurements come from ad hoc regional sampling campaigns where dominant exogeneous variables prevent establishing a relationship between management and SOC variation (Sanderman and Baldock, 2010). As an additional effect, Droste et al. (2020) showed that SOC gains in GSS may contribute to stabilising yields in a changing climate with higher frequency of extreme weather events. Our analysis of the benefits of grass leys in intensive arable land is conservative in this regard because AgriPoliS does not consider effects from evolving climate conditions on interannual yield stability and its influence on the farmers ́ decision-making process.

An interesting aspect for regional policymaking that is not covered in this paper concerns policy effectiveness in terms of all potential benefits to society compared to its costs. Particularly in a context where the current structure of agricultural payments in the EU comes under scrutiny for failing to advance social and environmental sustainability goals (Scown et al., 2020). Our study sets the basis for such analysis, as it allows one to calculate the total policy cost if implemented in a particular region, here GSS. Following the ABM simulation for a 258 EUR payment per hectare, the total policy cost would be 19.8 M EUR, which is higher than, but comparable in magnitude to, the total modelled agricultural direct-payments budget for this region, namely 11.8 M EUR.

### *4.2. Overall environmental evaluation*

Although a policy instrument might be set to achieve its goal of introducing grass leys in crop rotations, the overall environmental performance of the intervention is still an open question, as land-use pressure from displaced crops risks translating into intensification elsewhere. Even more so in a region characterised by excellent yields and technological competitiveness such as GSS, where impacts per unit of crop are low in comparison to global averages (Martin and Brandão, 2017). In addition, differences in usage of water resources are even more pronounced than in any other impact category due to relatively little irrigation-based agriculture in Sweden, although seasonal droughts induced by climate change are increasingly becoming an issue of concern in Scandinavia (Grusson et al., 2021).

LCA provides a suitable framework to simultaneously evaluate local soil health benefits, biofuel potential and crop-displacement effects of bioenergy crops. Overall, our LCA results indicate a favourable environmental performance of the policy instrument introduced in GRASS. From a comparative analysis of our main results and changes in *Grass loss* and *Year five*, it follows that the positive performance is first and foremost attributable to the relatively low-input requirements of grass leys as a biofuel source when substituting a mixture of other agricultural feedstocks, of which rapeseed is the largest contributor. While SOC gains ensure the long-term sustainability of the agricultural system, which is a desirable outcome in itself, the effects of SOC on yields, N fertiliser application and carbon sequestration are minor and insufficient on their own to counteract on crop displacement towards less impact-efficient regions. In this regard, the lack in AgriPoliS of a yield-response curve specific to grass leys in the absence of supporting data (even though they may benefit from increasing SOC levels as other crops do) is considered inconsequential to the overall environmental performance of the payment.

For this analysis, the impact category "Land transformation, biodiversity" in Impact World+ has been excluded because the beneficial impact obtained from the grass activity was considered unrealistic and out of proportion in comparison to expected biodiversity improvement from actively farmed grass leys in an intensive region (Tiainen et al., 2020). Furthermore, carbon sequestration benefits in the GRASS scenario should be interpreted carefully, as there is currently no consensus on how to account for SOC changes in LCA (Goglio et al., 2015; Joensuu et al., 2021). The payment in GRASS over 20 years cannot ensure the residence of carbon over longer periods, and short-lived carbon sequestration would be inconsistent with the choice of impact assessment methods, which include a Global Warming Potential impact category with a time horizon of 100 years.

### 4.3. General applicability and limitations

Our AB-LCA approach considers simultaneously local SOC benefits, crop-displacement effects, and biofuel potential of grasses, when evaluating structural changes in agriculture and subsequent environmental impacts of policy promoting grass leys in arable land with SOC-depleted levels. This advances the environmental assessment of policy alternatives promoting purposefully grown crops for biofuels and contributes to policy support for a transition to a green economy with multiple, and sometimes conflicting, societal goals for agricultural systems (Boix-Fayos and de Vente, 2023). Our study design focuses on the potential amount of total energy obtainable as biofuel from agricultural land, regardless of specific carriers (Prade et al., 2017). This is in alignment with reviewed policy goals, which ultimately are not specific towards any technological pathway. Regarding the LCA modelling, this assumption implies adaptability from the industry and/or the transport sectors, on a mid-term 20-year time horizon, to utilise any biofuel type based on feedstock availability, which seems reasonable given the present transitional context of production and consumption systems (Martínez-Gordón et al., 2022). Overall, our results can be used for further analysis to expand the debate on the desirability of dedicating agricultural land for biofuels by providing a regional example where a policy instrument promoting grass leys yields benefits from an environmental life-cycle perspective.

An important aspect in the coupling of ABM and LCA relates to the geographical boundaries of the system in focus (Vázquez-Rowe et al., 2014; Marvuglia et al., 2017). As LCA aims at providing a global account of the impacts that a given system is responsible for in relation to the targeted decision context, this study extends the environmental accountability of a policymaker to trade-induced impacts caused elsewhere by their decisions in relation to the agricultural production in GSS. This is to capture land-use pressures and related consequences of introducing grasses for biofuels, which are a recurrent source of concern in the literature in relation to any land-based biofuel (Searchinger et al., 2008; Daioglou et al., 2020). However, AgriPoliS does not model land use or any trade activity outside of GSS boundaries, which makes it challenging to incorporate trade-induced impacts in the LCA. To overcome this issue, our study uses global average market processes from the ecoinvent attributional library and tests alternative modelling setups in the sensitivity analysis. In this regard, the similarity in results from *Marginal* and *EU imports* in Fig. 4 in comparison to the main modelling setup presented in Fig. 3 are important to establish the robustness of our results beyond modelling choices that could be otherwise seen as arbitrary.

### 4.4. Policy implications

Our study offers scientific evidence for policymakers in the context of shaping sound instruments for sourcing agricultural biomass for biofuels at different decision-making levels. Regionally, we support policymakers in the task of adapting policy instruments to the regions, in alignment with the regional focus of the 2023 CAP reform, which also enhances national governance of the payment structure (Błażejczyk-Majka, 2022). However, regional CAP strategies devised by individual Member States can lead to apparent inconsistencies across borders. For instance, the removal of the payment for grass leys in Sweden contrasts with the recent adoption of an analogous payment in Denmark, which targets farming regions with comparable production structures facing similar environmental concerns (Danish Board of Agriculture, 2022). This highlights the relevance of ex-ante economic-environmental modelling as a tool to motivate policy interventions with scientific evidence, thereby also contributing to preserve trust from farmers and society for the policymaking process.

A targeted payment to grass for bioenergy would reduce land use specialisation and achieve a more sustainable use of arable land in GSS. This would contribute to better crop rotations for healthy soils, biomass production to advance fossil-free energy systems, and carbon mitigation from SOC restoration, all of which are explicit sustainability goals in the European Green Deal (Mina et al., 2022; Boix-Fayos and de Vente, 2023). However, the regional benefits of the payment are lower than the impacts from displacing crop production towards less efficient regions. The active utilisation of grasses to replace higher impact resources is found to be essential for a joint analysis of the global and regional aspects that influence agricultural bioenergy systems to result in a positive environmental evaluation of the payment.

Given the relevance of grass feedstock in our analysis, it is important to discuss its implications for policy implementation purposes. Although there is little doubt from the literature that demand for biofuels will continue to rise to advance the energy transition in the transport and industry sectors, technological and other societal barriers may still exist, which can hinder the utilisation of grasses for biofuel purposes even if an expansion of grass leys occurred (Nevzorova and Kutcherov, 2019). According to our simulation results, a compensation of 258 EUR/ha would achieve a homogeneous adoption of 25 % coverage of grass leys in the highly productive land in GSS. This level of compensation assumes that farmers are also paid 0.11 EUR/kg of grasses for biofuel production, but a regional biofuel market does not yet exist. If the payment does not set conditions for the active usage of grasses, it can result in a solid net negative performance of the instrument.

Similar SOC-change rates have been found in a recent review on management-induced SOC changes for other intensive farming regions in temperate zones across Europe and the US (Brady et al., 2015).This implies that similar soil health improvements could be achieved when implementing 2-year grass leys in other locations, although successfully reverting SOC depletion may require consideration to all aspects of soil management in a field (Nilsson et al., 2023). Furthermore, similar weight of soil health impacts on the overall LCA of crop activities has been found in other highly productive arable land with SOC-depleted levels in temperate regions with similar yields and levels of technology (Joensuu et al., 2021). However, the feedstock mix that replaces grasses in BAU is dominated by oil crops, which is a characteristic of the EU consumption of agricultural biofuels (Fuchs et al., 2020) that is unlike that of other main biofuel consumers such as the US or Brazil, with a higher prevalence of bioethanol. The relatively high impacts of rapeseed have a strong effect on the overall performance of our payment, which is consistent with literature stressing the variability of LCA studies of bioenergy as a result of methodological choices related to system boundaries and multifunctionality (Martín-Gamboa et al., 2020). Thus, this paper highlights the main variables affecting the LCA of the payment and their relative weights, which constitute a main finding of our environmental evaluation and a key input for policymaking. Lastly, our results concerning structural changes in the region are specific to the policy instrument and agricultural production system in scope.

## 5. Conclusion

This study provides a method to contrast regional effects and global environmental impacts of policy instruments supporting agricultural biomass for biofuels prior to implementation. Similar studies at field and regional level highlight the relevance of grass leys as a biomass source for biofuels with low impact potentials and added value as soil ecosystem services to arable crop rotations (Englund et al., 2023; Nilsson et al., 2023). In contrast, avoiding crop displacement effects from biofuels has been at the core of the successive reforms of the Renewable Energy Directive (Sumfleth et al., 2020). Our results indicate that the environmental benefits of reducing specialisation in highly productive land combined with the reduced impacts of grass ley cultivation in replacement of the current consumption mix of agricultural biofuels outweighs the impacts of displacing some food crop production abroad.

This aligns with studies suggesting a shift from bioenergy strategies towards comprehensive land-use policymaking that stresses the importance of systems approaches in transforming agriculture for a sustainable future (Daioglou et al., 2020; Englund et al., 2020). Our work therefore improves scientific input for policymakers on how to best utilise available land to fulfil food, energy, and environmental needs, at a time when the overall sustainability of land-based biofuels is highly debated.

## CRediT authorship contribution statement

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

## 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.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.170264.

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