Integrated Land Use Modelling for Assessing the Socio-Ecological Impacts of Regional Agricultural Land Use Change

DISSERTATION

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submitted by

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Contents

I. Abbreviations

AES	agri-environmental schemes
AEP	agri-environmental payments
BEFM	bio-economic farm model
CS	case study
EU	European Union
GM	gross margin

HVM	habitat value model
ILUM	integrated land use modelling
LUS	land use system
MGGM	market-generated gross margin
MODAM	multiobjective decision support tool for agroecosystem management
RCP	representative concentration pathway
SALCA-BD	an expert system for evaluating the impact of agriculture on biodiversity in Switzerland
SBL	Schwarzbubenland (a cast study area in Switzerland)
SNGL	semi-natural grasslands
SSP	shared socioeconomic pathway

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1. General introduction

1.1 Context: Challenges created by regional land use changes

The regional changes in agricultural land use are highly uncertain in today's fast-paced world (Sundstrom et al., 2023). Changes in temperature and precipitation and the occurrence of extreme weather events are common in many parts of the world (Arnell et al., 2019). Such changes affect crop yields, suitability, and growing seasons and increase the prevalence of pests and diseases (Nelson et al., 2014; Arora et al., 2020; Cradock-Henry et al., 2020). The global population has exceeded eight billion and continues to grow (United Nations, 2022). The increased need for food production has induced greater pressure on agricultural land, leading to the ongoing intensification of agricultural practices (Kopittke et al., 2019). In contrast, the abandonment of land poses a concern in certain depopulated rural areas (Osawa et al., 2016; van Vliet et al., 2015). Market instability, which causes price volatility, income uncertainty, and financial stress for land managers, makes the long-term planning of agricultural production challenging (Fróna, et al., 2019). Furthermore, the speed of technological development, such as recent remarkable progress in the application of digital technologies to agriculture using sensors and drones, is accelerating (Lezoche et al., 2020). Scientific and technological developments may fundamentally change the nature of agriculture. In some cases, such technological development can have negative impacts on agricultural profitability and the livelihoods of farmers (Chavas & Nauges, 2020). The effects of changes in climate, demography, economy, and technology on a global scale inevitably manifest themselves at local scales (Koomen et al., 2005; Fronzek et al., 2019; Arnalte-Mur et al., 2020), compelling local farmers to continuously adapt to the evolving environment. Further complicating matters are the effects of climate and socioeconomic changes, which vary across regions. This reflects different regional sensitivities to such changes in agricultural land use (Henseler et al., 2009; Kiminami & Kiminami, 2017; Fronzek et al., 2019).

Concurrently, the societal demand for sustainable agricultural land use is rapidly increasing. This trend corresponds to increased awareness of the undesirable effects of agricultural land use on the environment (Kirschke et al., 2021). In particular, the loss of terrestrial biodiversity has attracted increased attention within the scientific community (Jones et al., 2017; Reidsma et al., 2018). Agricultural production is the primary cause of biodiversity loss, accounting for 70% of the total biodiversity loss (TEEB 2018; Benton et al., 2021). Certain species have evolved to become dependent on particular environments to survive (Brüggeshemke et al., 2022; Prangel et al., 2023). However, continuing trends in agricultural practices, such as the growing use of synthetic inputs, the loss of crop diversity, and the simplification of landscapes through land consolidation and removal of landscape elements, have put numerous species at risk of becoming extinct (Outhwaite et al., 2022). In response to the increasing conservation needs for biodiversity and the environment, the European Union (EU) set manifold targets in its "EU Biodiversity Strategy for 2030", such as reducing chemical fertiliser use by at least 20%, achieving zero pollution of air, water, and soil, and introducing regulations for invasive alien species (European Commission, 2020). The effects of such ambitious policies are likely to reverberate widely beyond ecological systems: not only the income and livelihood of farmers but also employment opportunities, the competitiveness of the agricultural industry, and rural development will be affected.

Land use is at the foundation of various sustainable development goals (Stehfest et al., 2019). Considering the issue of regional heterogeneity and the multiple impacts of changing agricultural land use, we need to focus on regionally tailored policy-making that can reconcile the socioeconomic and ecological development of sustainable agricultural land use (Lambin et al., 2000; Buysse et al., 2007; Jerrentrup et al., 2017). This PhD study proposes a site-specific interdisciplinary land use assessment framework that views land use as an integral part of a broader system. This assessment framework, embedded within a systems approach, allows for systematically examining the interactions and trade-offs in the underlying systems linked to land use. By applying this framework to rural areas in Europe (Schwarzbubenland (SBL) in Switzerland and Lääne County in Estonia), this PhD study addresses regionally specific issues associated with current agricultural land use. Three case studies included in this PhD thesis provide tangible socio-ecological policy implications targeting agricultural land use.

The subsequent sections of the general introduction are structured as follows. In Section 1.2 Overarching paradigm: A systems approach to land use assessment, the conceptual framework of the systematic approach is introduced, which serves as the overarching paradigm for the whole PhD study. Section 1.3 Methodology: Modelling of the land use system provides an overview of the methodology proposed for this PhD study, which embodies the systematic approach and was applied to all case studies. Finally, Section 1.4 Overview of the thesis presents the overall objectives of this PhD study and introduces the case studies.

1.2 Overarching paradigm: A systems approach to land use assessment

To establish a land use assessment framework for this study that captures land use as a part of a broader system in the context of agriculture, the land use system (LUS) adapted by Verburg (2006) and Schönhart (2010) was selected. Unless otherwise stated, the defined land use is limited to the farm and regional scales of agricultural land use in the European context.

Furthermore, as the LUS is defined within the agricultural context, other types of land use, such as unmanaged land that is not eligible for agriculture, woods, and settlements, are excluded from consideration in this PhD study. In general, a system is referred to as an assembly of interrelated components perceived as having unity. The LUS defined in this PhD study consists of four different components (Figure 1): land use drivers, land use decisions, land use and land use change, and land use impacts.

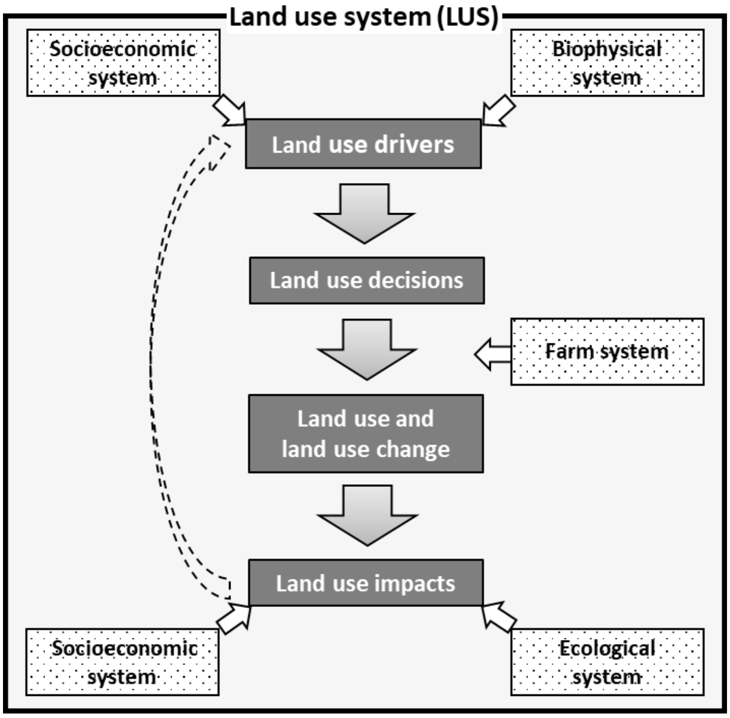

Figure 1 Schematic representation of the land use system (LUS) adapted by Verburg (2006) and Schönhart (2010)

The sequence of the components starts with land use drivers. They are typically conditions that influence the land-use decision-making process. These conditions are derived from socioeconomic and biophysical systems, and different combinations of underlying drivers result in land use changes (Plieninger et al., 2016). The socioeconomic drivers in the LUS are broad, but they can be largely divided into four categories: population and urbanisation, economy, policies, and technology (van Vliet et al., 2015). The underlying biophysical drivers in the LUS are, for example, natural resources and geographical or topographical conditions such as climate, soil quality, and field and landscape characteristics (Kristensen et al., 2016; Peltonen-Sainio et al., 2018). Both drivers spatially span global, national, and local scales. Temporal scales are also important to consider. It is crucial to focus on the underlying scales of these drivers, which shape local opportunities and can result in various challenges (Hazell & Wood, 2008).

Land use decisions are, in most cases, made by land managers (farmers or landowners). As the impacts of land use drivers are mediated by farm-level decisions, an assessment of agricultural land use change needs to account for the goals and constraints that affect land managers' management decisions (Rounsevell et al., 2003; van Vliet et al., 2015). The common goal on which land use decisions are based is to maximise profit (Rounsevell et al., 2003; Kanellopoulos et al., 2014), although in some cases in which individuals have diverse goals, this single goal is not applied (Kelley et al., 2013; Matthews et al., 2007). In such cases, other factors, such as land managers' attitudes towards risk and uncertainty and different views on future price and profitability, could be relevant (Rounsevell et al., 2003; Reidsma et al., 2018). Therefore, the goal of a land manager is to serve as a critical intermediary between land use drivers and the manifestation of land use changes (van Vliet et al., 2015).

Land use and land use change are determined by the decisions of land managers. Land use encompasses a set of different agricultural activities; they include not only field work, such as grazing or cultivating crops but also livestock husbandry. Therefore, various types of farming and cropping practices, including livestock systems, influence land use schemes. Most practices are accompanied by specific types of farm management options with a certain degree of agricultural intensity, for example, tillage or no tillage, with or without synthetic inputs, or caged or free-range livestock.

The way that land is used influences socioeconomic and ecological systems. The socioeconomic factors influenced by land use are, for example, the livelihood of land managers, employment, food supply, prices, the aesthetic value of landscapes, and tourism opportunities, while the ecological factors include soil quality, groundwater quality, air quality, climate, and biodiversity, among others. Depending on the degree and extent of these impacts, land use drivers can be influenced by feedback mechanisms. The effects of these feedback mechanisms between land use impacts and land use drivers can occur at different temporal and spatial scales (Verburg, 2006).

1.3 Methodology: Modelling of the land use system

The above-defined systems approach served as the foundation of the overall methodology of this PhD study. The proposed agricultural land use impact assessment framework for integrated land use modelling (ILUM) is presented in Figure 2. This modelling framework is used to quantitatively assess the socio-ecological impacts of land use changes driven by land use drivers through land managers' decisions at the farm and regional levels. The model consists of four stages, which correspond to each component of the LUS and include feedback loops. The core model in the ILUM framework is a bio-economic farm model (BEFM), which economically optimises farming and cropping practices given certain farm systems and external constraints, following the land managers' goal of profit maximisation. To consider the underlying subsystems in the LUS, a scenario approach and several models across disciplines were combined with the BEFM. Although there are some differences across the three case studies (see 1.4.2 Methodological overview of the case studies for details), the overall modelling approach is identical. The approach of the ILUM developed for this PhD study originated with the multiobjective decision support tool for agroecosystem management (MODAM), which was initially developed by Zander & Kächele (1999) and further developed and applied by Uthes et al. (2010) and Schuler et al. (2013). MODAM supports interdisciplinary model coupling, which allows for an economic and ecological analysis of the farm production process considering land managers' decision-making. There are other whole-farm optimisation-based BEFMs based on integrated modelling, such as FSSIM (van Ittersum et al., 2008; Louhichi et al., 2010), which was developed as a part of the SEAMLESS integrated framework, FAMOS [space] (Schönhart et al., 2011), the FarmDESIGN model (Groot et al., 2012), and, more recently, FARMDYN (Britz, et al., 2014). The application of such integrated farm models embedded with land managers' decision-making processes has been increasing, as this approach can provide information to policymakers to support their decisions regarding agri-environmental policies that reflect diverse agricultural impacts (Kragt et al., 2016). Nonetheless, these models are rarely reused because they were developed for project-oriented, specific case studies and are too data demanding (Britz et al., 2021). Because MODAM has not been applied beyond the German context, a new case study-specific BEFM was established for this PhD study. The following subsections outline how each component of the LUS is represented within the ILUM framework. A detailed explanation of each case study was provided in the literature, so only the key elements of the proposed framework and the detailed work of this PhD study are presented.

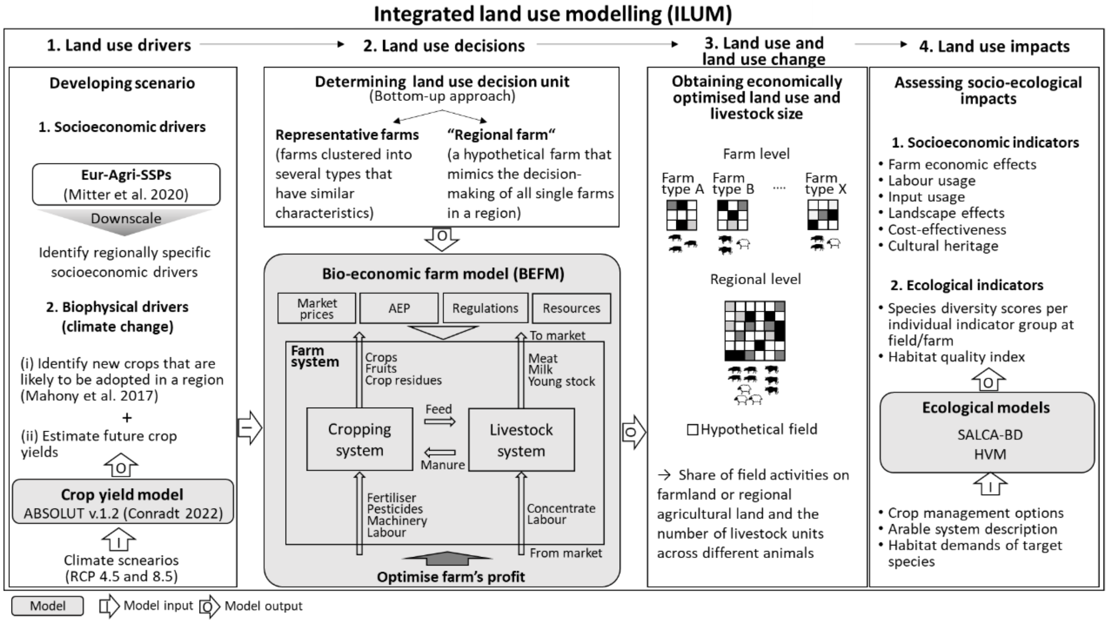

Figure 2 Conceptual representation of the proposed agricultural land use impact assessment framework, integrated land use modelling (ILUM), for this PhD study. SSP: shared socioeconomic pathway, AEP: agri-environmental payments, SALCA-BD: an expert system for evaluating the impact of agriculture on biodiversity in Switzerland, HVM: habitat value model

1.3.1 Land use drivers

The main task here was to develop regionally specific scenarios that provide the BEFM with the framework conditions of land use drivers. Focusing on the agricultural land uses in the study areas that are subject to conservation, land use drivers were selected that were likely to influence the agricultural landscapes in the study areas. Therefore, scenarios were developed based on an understanding of the unique characteristics of the agricultural land use and landscape in each study area. The site-specific information was obtained from publicly available sources and from scientists with expertise in agriculture in the study areas. Based on this information, regionally relevant land use drivers were specified and quantified as model inputs. This scenario development scheme provides a systematic approach for assessing future scenario development based on a model that has already been applied in various studies in the context of land use change (Bukovsky et al., 2021; Doelman et al., 2018; Stehfest et al., 2019). Feedback mechanisms in the LUS were implicitly captured through future scenario development. In the process of scenario development, the following aspects of the scenarios were considered for the second case study (CS 2): consistency and comprehensiveness.

1. Consistency: To determine key socioeconomic land use drivers for future regional land use changes, a well-established scenario framework called shared socioeconomic pathways (SSPs), which was originally developed at a global scale (O'Neill et al., 2014, 2017), was used for developing site-specific future scenarios. The global-scale SSPs comprise five contrasting narratives of how socioeconomic conditions (demographics, economic growth, education, urbanisation, and technological development) could change over the next century. To consistently downscale the socioeconomic changes defined at the global scale to the study areas and translate them into the context of agricultural land use in each study area, the Eur-Agri-SSPs (Mitter et al. 2020) were used as a reference; notably, these SSPs were previously downscaled from the global scale and contextualised to European agricultural and food systems. Figure 3 illustrates the general process of scenario development to capture regionally specific changes driven by socioeconomic factors in 2050. First, three pathways (Eur-Agri-SSP1—agriculture on sustainable paths; Eur-Agri-SSP2—agriculture on established paths; and Eur-Agri-SSP5—agriculture on fossil fuel-based high-tech paths) were selected from the five pathways defined in the Eur-Agri-SSPs. Using the socioeconomic changes associated with these selected pathways as boundary conditions, three different site-specific narratives were illustrated; they were interpretations of the selected pathways in the context of agricultural land use in the study area. Various assumptions related to farm-level decision-making were made to represent land use drivers, such as farm structure, farm management, farm labour availability, labour requirements (demand), livestock capacity, the livestock system, and field size. The developed scenarios with these regionally tailored land use drivers can be largely

classified based on the degree of stringency of agricultural policies and the orientation of agricultural production.

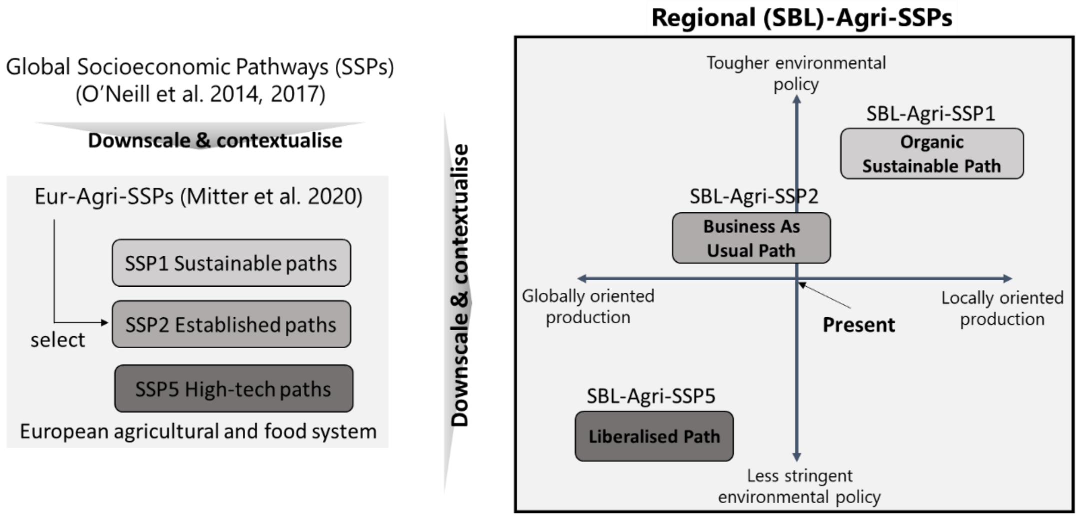

Figure 3 Overview of scenario development to capture regionally specific changes driven by socioeconomic factors in 2050 in CS 2. SBL: Schwarzbubenland

2. Comprehensiveness: The conditions that influence land use are derived not only from human activities but also from biophysical factors. The advantage of using the SSP framework is that it allows for consistent combinations with climate scenarios. The representative concentration pathways (RCPs), which provide a set of scenarios for different concentrations of greenhouse gas emissions, are frequently combined with SSP scenarios (e.g., Kebede et al. (2018), Liu et al. (2021), Fan (2022), or Hoch et al. (2021)). Figure 4 illustrates the methodology applied for CS 2 to capture climate change impacts in the regional-level scenarios. After selecting two climate scenarios from the original RCPs (RCP4.5—an intermediate concentration path and RCP8.5—the highest concentration path), a statistical-based model, ABSOLUT v1.2[1] (Conradt et al. 2022), was used to predict future crop yields for these two climate scenarios. The crop yields predicted in RCP4.5 were combined with the regional

[1] *"Assessing Best-predictive Sets fOr multiple Linear regressions throUgh exhaustive Testing"*

scenarios based on SBL-Agri-SSP1 and 2, whereas the crop yields predicted in RCP8.5 were combined with the scenario based on SBL-Agri-SSP5. Additionally, as land managers often adapt to climate change by adjusting crops, rotations, and production practices (Malcolm et al., 2012), the new crops in the study area that have not yet been cultivated but are likely to be adopted in the future due to climate change were identified by following the methodology used by Mahony et al. (2017) and added to the SBL-Agri-SSPs as model inputs.

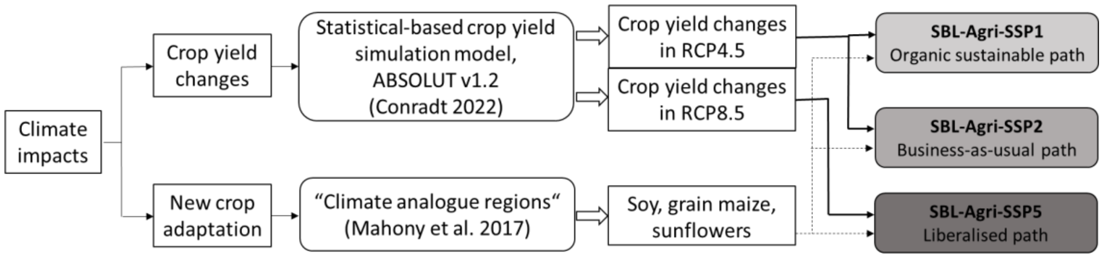

Figure 4 Methodology applied to incorporate climate impacts into scenarios in CS 2. SSP: shared socioeconomic pathway, RCP: representative concentration pathway

1.3.2 Land use decisions

Modelling the effects of land managers' decision-making on agricultural land use constitutes the core of the ILUM. This part of the modelling process started with determining the land use decision-making unit and then setting up the BEFM considering local conditions.

Determining the land use decision-making unit: Prior to modelling land use decisions, a decision-making unit—a unit (or an agent) whose decisions influence land use—was first identified. This approach is a bottom-up modelling approach that simulates land use change at the level of decision-makers or land (Verburg, 2006). The unit is usually characterised by the degree of aggregation, such as field, individual farm, farm type, or region (Kantelhardt, 2003). The aggregated effects of different types of decision units must be carefully considered, as the degree of bias can change depending on the choice of scale of a unit (Kantelhardt, 2003). For example, if a decision unit is an individual farm, aggregation and system bias can be low, while they can be greater in the case of a typical farm or regional model. In the first case study (CS 1) and CS 2, five representative farm types in the Swiss study area were used as decision units. The rationale behind this approach was that the farms in the study area have diverse characteristics and different farm systems. To reduce the bias inherent to the identification of representative farm types, a quantitative method, *k*-means clustering, was used to computationally classify the farms in the study area into several groups that had similar farm system characteristics. Therefore, the regional land use change in CS 1 and CS 2 is understood as the aggregated land use change across the representative farm types. In contrast, a "regional farm" was used as a single decision unit to simulate regional land use change in the third case study (CS 3). The "regional farm" was created by pooling all the agricultural fields owned by the land managers in the study area. Only a single decision unit was considered for CS 3 because publicly available data were significantly limited. This type of decision unit has the highest risk for aggregation and system bias, according to Kantelhardt (2003). To minimise this bias, it was ensured that the deviation in the land use pattern produced with the baseline simulation from the observed land use pattern was minimised. A more detailed explanation can be found in the documentation for CS 3.

Setting up the BEFM: Land managers' land use decisions, based on land use decision-making units, were modelled by applying the underlying assumption of neoclassical economics to the context of agriculture: land managers employ utility-maximising behaviour. For this PhD study, the total gross margin (GM) of a farm or region was defined as the single maximised utility of land managers. This optimisation of the total GM was performed via comparative-static linear programming. The BEFM developed for this PhD study captures the detailed interactions between cropping activities and livestock activities, as well as the linkages between these activities and existing agri-environmental schemes (AES). The following four prerequisites are met for linear programming: 1. proportionality (the contributions of the respective activities in the objective function are proportional to their values); 2. additivity (the total value of the objective function is the sum of the individual contributions of the respective activities); 3. divisibility (any real numerical value within a predetermined range can be assigned to the decision variables); and 4. certainty (all parameters are known in terms of the decision-making units).

The primary problem was mathematically formulated as a linear programming problem with a normal structure, and it was solved with the simplex method as follows:

maximise $Z = \sum_{j=1}^{n} c_j x_j$ (1)

subject to $\sum_{j=1}^{n} a_{ij} x_j \leq b_i$ for all $i = 1, 2, \ldots, m$ (2)

and $x_j \geq 0$ for all $j = 1, 2, \ldots, n$ (3)

Z is the total GM of the regional farm, x represent the decision variables for farm activities, c denotes the GM or cost per unit of activity, a are the technical coefficients, and b represent the resource availability (land and labour) and are constrained by the upper/lower limits of activities.

The mathematical formula consists of three major components: an objective function, decision variables, and constraints. The targeted GM in the objective function is maximised based on the level of one year of production. This means that costs that accumulate over time, such as investments, are not considered. In the case of calculating costs involving orchard trees for CS 1 and CS 2, such costs were converted into annual equivalent costs with a discount rate and inflation rate. Fixed costs were excluded from this optimisation, as the main focus of this PhD study was on short-term adaptive decision-making by land managers in response to changing land use drivers, which was assumed to be constrained only by factors such as the existing infrastructure and resources. Long-term strategic decisions regarding farms involving fixed costs were therefore beyond the scope of this PhD study. The decision variables are farming and cropping practices, available management options, and livestock systems. The coefficients of the decision variables reflected the revenues or costs of individual farming and cropping practices. The amount of the payments from the AESs was added to the coefficient as needed. Therefore, the total GM was defined as total revenue minus total variable costs plus agri-environmental payments (AEP). As the duality condition of the linear programming problem is valid, the production cost is simultaneously minimised through optimisation. The constraint functions are divided into four modules: input, resource, livestock, and policy modules. In cases where multiple land use decision-making units were considered, this optimisation process was iterated with a loop structure: the total GM was obtained based on the sequential optimisation of each land use decision-making unit.

1.3.3 Land use and land use change

The land use simulated with the BEFM is described as the manifestation of land managers' decision-making for economically optimal land use, i.e., the land use maximising the total GM while minimising the total variable costs. The optimal livestock system (herd size, the ratio of feed ingredients, and the feed system—whether grass-based or not) was simultaneously determined, which influenced the optimal land use. The spatial scale addressed in this PhD study is at the district level and encompasses several municipalities. In the case of typical farm types, the optimal land use patterns across farm types were aggregated to form the regional land use with the weighted share of farm types. In this BEFM, each farm practice is not linked to fields; i.e., the simulated land use is not spatially explicit but rather indicates the contribution of each practice to the total GM in a share. In CS 1, however, the simulated land uses are allocated across the fields in the study area by linking the location of each farm type and the biophysical characteristics of the fields.

1.3.4 Land use impacts

Another highlight of the ILUM framework was that the *ex ante* land use impact assessment was extended to investigate the impacts of land use changes on both socioeconomic and ecological systems. While socioeconomic indicators can be directly derived from the resulting land use simulated with the BEFM, the evaluation of impacts on biodiversity and farmland requires an elaborate approach, considering its complex nature (Souza et al., 2015). Since Janssen & van Ittersum (2007) noted the lack of biodiversity assessments in farm-level models, numerous indicators have been developed and applied (Reidsma et al., 2018). Surrogated biodiversity indicators, such as mowing frequency, Shannon diversity, the Simpson index, and patch size and number, are frequently used (Schönhart et al., 2011; Brown & Castellazzi, 2014; Tasser et al., 2019). The advantage of this approach is that surrogate indicators can be relatively simply obtained from farm-level models. However, such indicators are criticised for their limited capacity to explain farmland biodiversity (Clergue et al., 2005). For this PhD study, farmland biodiversity assessment models (SALCA-BD[2] and HVM[3]) were coupled within the ILUM framework to directly estimate habitat suitability and species richness for selected taxonomic groups as a proxy for biodiversity at the field level. These models consider the detailed farming processes, including crop management options, arable systems, and the habitat demands of target species. These factors evaluated in the ecological models were

[2] An expert system for evaluating the impact of agriculture on biodiversity in Switzerland from Jeanneret et al. (2014)
[3] Habitat Value Model, first developed by Brandt & Glemnitz (2014) then applied regionally by Glemnitz et al. (2015)

consistent with the descriptions of farm activities modelled in the BEFM. Since the biodiversity scores estimated by these models were the scores per hectare per crop or farm activity, these scores were aggregated with a weighted average over a farm.

1.4 Overview of the thesis

1.4.1 Overall objectives and research questions

The overall objective of this work is to identify prominent regionally relevant land use drivers and assess their socio-ecological impacts on regional agricultural land use considering land managers' decision-making. This particular effort to consider land managers' decision-making is intended to facilitate the development of regionally tailored policies for sustainable agricultural land use. Across the case studies, the focus of the ecological assessment is on the impacts of land use changes on farmland biodiversity. Based on the overall objectives and the focus of this PhD study, the following specific questions are explored:

RQ1: To what extent do socioeconomic factors influence regional agricultural land use compared to the impacts of climate change?

RQ2: What farm type characteristics influence land managers' decision-making in response to underlying land use drivers?

RQ3: What trade-offs can be expected due to the promotion of biodiversity-rich land use?

RQ4: What role do agri-environmental payments play in supporting practices that enhance farmland biodiversity?

1.4.2 Methodological overview of the case studies

To explore the above research questions, three case studies were conducted in two European rural areas. Table 1 compares the differences in modelling components of the LUS in the ILUM framework across case studies.

The primary methodological objective of CS 1 was to develop a site-specific BEFM with the identified representative farms as a decision-making agent. This modelling approach was combined with an ecological model (SALCA-BD) to assess the impacts of changing payment levels of AESs on their cost-effectiveness in terms of governmental budgets and farmland biodiversity.

Building upon the methodology of CS 1, CS 2 extends the research in the same study area. For CS 2, the scenario approach explained in Section 1.3.1 Land use drivers was added to the modelling framework in CS 1 to assess a wide range of future land use drivers, particularly those contributing to agricultural diversification. The characteristics of the representative farms identified in CS 1 were modified according to the framework conditions in the Eur-Agri-SSPs and incorporated into the regional scenarios as key land use drivers.

CS 3 was used to demonstrate the transferability of the methodology developed in CS1 in a rural area in Europe with varying agricultural landscapes (Lääne County, Estonia). While an identical modelling approach to CS 1 was employed, it was contextualised to capture the unique agricultural activities and land use in the study area. The novelty of CS 3 lies in the inclusion of the management of semi-natural grasslands (SNGLs) in the BEFM to explore the role of SNGLs in sustainable rural development.

Table 1 Overview of the three case studies explored in this PhD study and the methodological differences. SBL: Schwarzbubenland, SSP: shared socioeconomic pathway, RCP: representative concentration pathway, GM: gross margin, SALCA-BD: an expert system for evaluating the impact of agriculture on biodiversity in Switzerland, HVM: habitat value model

LUS components	Subcategories	Case Study 1 (SBL, Switzerland)	Case Study 2 (SBL, Switzerland)	Case Study 3 (Lääne County, Estonia)
Land use drivers	Socioeconomic factor	Changing payment levels for agri-environmental schemes	Various socioeconomic conditions according to the SSPs framework	Various economic incentive schemes
	Biophysical factor	Slope	Slope Climate change (RCPs)	Not applied
Land use decisions	Decision-making unit	Representative farms	Representative farms	Regional farm
	Model type	Linear programming	Linear programming	Linear programming
	Objective function	Farm GM maximisation	Farm GM maximisation	Regional GM maximisation
Land use and land use change	Spatial scale	Farm and regional	Farm and regional	Regional
	Temporal scale	Present (2020)	Future (2050)	Present (2022)
	Spatially explicit	Yes (partially)	No	No
Land use impacts	Assessment objective	Cost-effectiveness of AES	Agricultural diversification	Sustainable rural development
	Biodiversity assessment	SALCA-BD	SALCA-BD	HVM

1.4.3 Author contributions to each case study

The author's main contribution to this PhD study lies in the development of BEFMs and the integration of other disciplinary models and scenarios to develop an agricultural land use impact assessment framework. Four research institutes participated in this PhD study: Agroscope (Zurich, Switzerland) for CS 1 and 2, Potsdam Institute for Climate Impact Research (Potsdam, Germany) for CS 2, and Leibniz Centre for Agricultural Landscape Research (Müncheberg, Germany) and Estonian University of Life Sciences (Taru, Estonia) for CS 3. The author's contribution to each CS conducted for this PhD work is explained below.

CS 1, titled *"Ecological-Economic Modelling of Traditional Agroforestry to Promote Farmland Biodiversity with Cost-Effective Payments"*, published by *Sustainability* in MDPI, was conducted for a small hilly region in Switzerland. The aim of this study was to examine the effects of incentive-based AES on farmers' decisions regarding forest and farmland biodiversity. The author's contribution to this study was its conceptualisation, which included processing the field data provided by Agroscope, classifying farm types, collecting socioeconomic data for the BEFM, calculating the GMs of farm activities, including orchard activities, setting up the BEFM, integrating the ecological results provided by Agroscope into the BEFM, running the model, visualising and analysing the results, and writing the original manuscript.

CS 2, titled *"Towards diverse agricultural land uses: Socio-ecological implications of European agricultural pathways for a Swiss orchard region",* published by *Regional Environmental Change,* Springer, extended the modelling framework developed for CS 1 to examine the impacts of wide-ranging land use drivers on future land use in the same study region as CS 1. This study aimed to obtain a better understanding of the regionally specific socio-ecological implications for diversified agricultural land use in the long term. The author contributed to designing the study, processing the simulated crop yield data from the Potsdam Institute for Climate Impact Research, collecting socioeconomic data obtained for scenario development, calculating the GMs of farm activities according to each scenario, performing model simulations, visualising and analysing the results, and writing the original manuscript.

In CS 3, with the title *"Assessing Agricultural Scenarios to Reverse Abandoned Semi-Natural Grassland in Estonia"*, submitted to *Environment Management*, Springer, the established modelling approach in CS 1 and 2 was transferred to another study region in Europe that features completely different agricultural landscapes (Lääne County, Estonia). The objective of this study was to explore how the abandonment of SNGLs can be reversed based on agricultural scenarios that describe alternative economic conditions for expanding grassland use. The author contributed to this study by designing the study, processing the field data provided by the Estonian University of Life Sciences, collecting socioeconomic data for the

BEFM, setting up the BEFM, calculating the GMs of farm activities, integrating the ecological results provided by the ZALF into the BEFM, running the model, visualising and analysing the results, and writing the manuscript.

2. Case Study 1

Ecological-Economic Modeling of Traditional Agroforestry to Promote Farmland Biodiversity with Cost-Effective Payments

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Article

Ecological–Economic Modelling of Traditional Agroforestry to Promote Farmland Biodiversity with Cost-Effective Payments

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Abstract: Orchard meadows, a traditional agroforestry system in Switzerland combining the dual use fruit and fodder production, are declining, even though the farmland managed under agri-environmental schemes (AES) has been expanding. Despite increasing interest in agroforestry research for developing sustainable agriculture, it is poorly understood how subsidies contribute to the maintenance of trees on agricultural land and the promotion of farmland biodiversity. Therefore, the objective of the present study is to examine the effects of incentive-based AES on both farmers' decisions regarding trees and biodiversity by developing an ecological–economic assessment model. To explore cost-effective AES, we explicitly consider the heterogeneity of farm types. We apply this integrated model to the farms in Schwarzbubenland, a small hilly region in Northern Switzerland. Results show that the adoption of AES and the compliance costs of participating in AES considerably vary among farm types, and the current AES do not provide farmers with sufficient payments to maintain any type of orchard meadows, despite the ecological benefits of orchard meadows. The integrating modeling developed in this study enables us to better understand the relationship between subsidies and biodiversity through farmers' decisions on land use and facilitates the design of cost-effective payments for the maintenance of agroforestry.

Keywords: agroforestry; biodiversity; agri-environmental schemes; integrated ecological–economic modeling; cost effectiveness

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1. Introduction

Given the increasing awareness of biodiversity degradation in Switzerland [1,2], Swiss agricultural policies have developed agri-environmental schemes (AES) to promote biodiversity on farmland, including orchards, vineyards, vegetables, etc. [3]. AES are voluntary programs that provide financial incentives for farmers. In the case of Switzerland, AES are a part of direct payments. Considering the high share of direct payments to the total farm income in Switzerland (around 50% on average in 2018–2020 [4]), land-use decisions can be assumed to be highly dependent on public payments. One of the requirements for receiving direct payments is that at least 7% of a farm's production area needs to be managed under AES. These areas are referred to as ecological focus areas (EFA) [5], similar to EFA in the European Union, but related to different conditions, and focus on the provision of farmland biodiversity.

The majority of EFA are implemented on grassland and high-stem orchards, regarded as a traditional agroforestry system in Switzerland [6], combining the dual use for fruit and fodder production. Particularly, orchard meadows are likely to play a key role in biodiversity promotion as agrobiodiversity hotspots under AES [7,8]. Due to their diverse structure, they supply habitats for various species, including small mammals, reptiles and several insect groups [9]. Along with biological diversity, orchard meadows provide socio-cultural features, such as landscape aesthetics, recreation and regional identity [10,11]. However, maintaining orchard meadows has become increasingly challenging, due to higher production costs, mechanized farming, increasing quality requirements and the infestation of invasive fruit flies [12,13]. The decline in orchards may trigger the loss of not only the traditional characteristics of the regional landscape, but also the habitats for various species. Therefore, the recent decline in orchard meadows in Switzerland [14,15] is of great concern. It is vital to investigate to what extent AES have an impact on the maintenance of orchards and farmland biodiversity, given a certain level of AES payments. The cost of adopting AES is a critical factor in farmers' decisions of whether to participate [16]. Additionally, the different effects of AES across specific farm types should be considered, as varied adoption costs are expected due to the differences in farm management.

There is accumulating evidence that farm types influence the effects of AES differently [17,18]. Bamière et al. [19] argued that a detailed representation of farm management can provide us with valuable insights into designing agri-environmental policies and AES. Indeed, Mack et al. [5] revealed that the implementation of action-based AES was strongly influenced by farm types. Therefore, simplified AES can lead to less ecologically beneficial effects, failing their conservation potential [20], although they may be readily implemented by farmers [18]. However, more research is needed about the direct relationship between heterogeneous farm types and their consequences on the cost-effectiveness of AES. Fewer than 15% of studies evaluate cost-effectiveness when assessing AES [21]. Investigating the cost-effectiveness of payment programs can be a key to providing relevant implications for optimizing AES and ensuring the sustainability of agricultural policy [22]. Additionally, unless such programs prove to be cost effective, some legitimacy concerns may arise: governmental bodies, taxpayers and users of ecosystem services may be reluctant to pay [23].

To address this science-policy gap, we developed an ecological–economic assessment model by integrating the results of the expert system for farmland biodiversity assessment, SALCA-BD (Swiss Agricultural Life Cycle Assessment—Biodiversity), into an optimization-based bio-economic farm model (BEFM). The objective of this study is to provide policymakers with insight into the design of cost-effective AES, taking into account different farm types, for maintaining orchard meadows and promoting farmland biodiversity. To that end, we investigated the feedback mechanisms between AES and their subsequent ecological and economic effects per farm type, via farmers' decisions on land use. Our study can be distinguished from studies published to date in that we evaluated the cost-effectiveness of agri-environmental schemes while taking into account the impacts of both agroforestry and heterogeneous farms. We addressed the following research questions:

1. What role do AES play in land use and sustaining orchard meadows?
2. Which types of farms are more likely to implement AES and which measures?
3. How does the cost effectiveness of AES differ between farm types?
4. How would AES change the regional land use and affect the diversity of individual species?

2. Materials and Methods

Figure 1 illustrates our methodological approach for this study, in which we integrated the SALCA-BD and the BEFM, and describes the flow of model inputs and outputs. The following subsections explain each of these methodologies in depth.

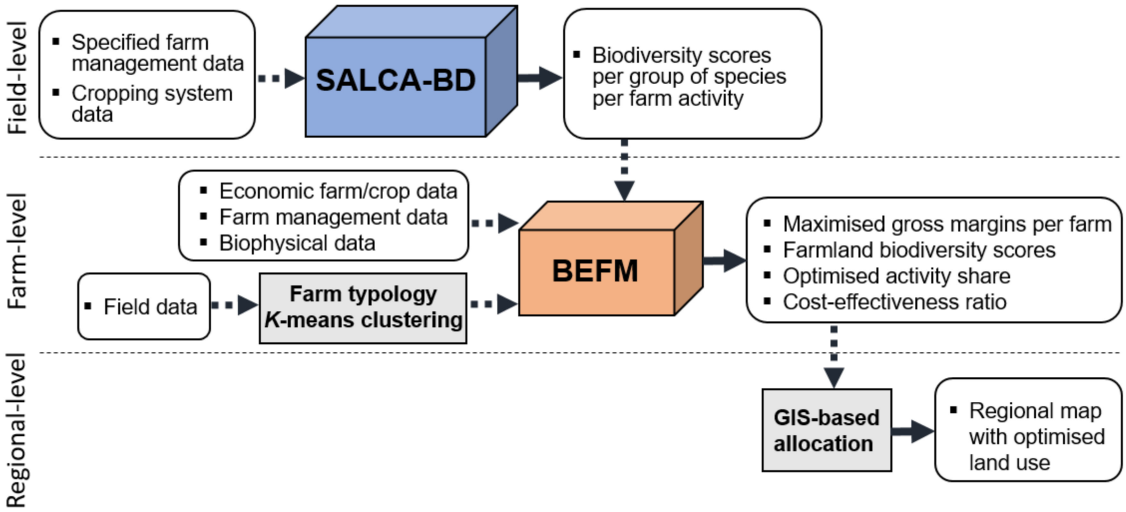

Figure 1. Structure of the ecological–economic model with the flow of inputs and outputs, integrated the results of each activity from the expert system for farmland biodiversity assessment (SALCA-BD) into the optimization-based bio-economic farm model (BEFM).

2.1. Case Study Region and Data

The study region, Schwarzbubenland (Figure 2), is located in Canton Solothurn, characterized by gently rolling hills (elevation 430 to 670 m). The average temperature is between 7.7 °C and 9.1 °C with annual precipitation of 800 to 1000 mm. Forestry (44%) and farmland (43%) are the main land uses. The area size is approximately 50 km^2, of which 1783 hectares are used as farmland, consisting of 32% arable land, 20% grassland and 48% orchard meadows. The study region is characterized by traditional high-stem cherry orchards combined with permanent grasslands. They have been established for subsistence and commercial fruit production, and the permanent grasslands are grazed by cattle and occasionally mown. Orchard meadows are recognized as agro-biodiversity hotspots. However, the decline of orchard trees can also be observed in this region [14].

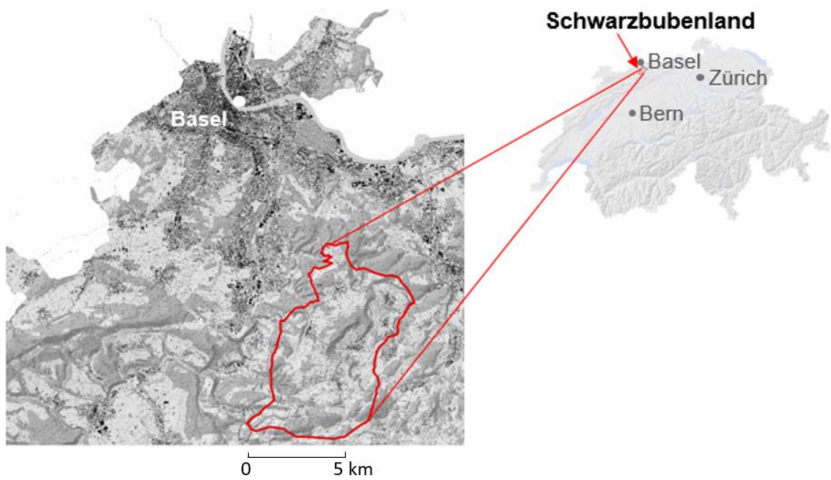

Figure 2. The study region: Schwarzbubenland (Switzerland) (Source: SwissImage ©Swisstopo).

Canton Solothurn provided 4698 spatially explicit field data spots in 2020 on the type of livestock, crops, management, the number of trees, area size, and the average slope degree [24]. Of the recorded 74 farms, over half of the farming enterprises are mixed farms, with combinations of arable crops, animal husbandry (mostly cattle for milk and meat production) and some fruit production. The average farm size is 24.1 ha, slightly larger than the average Swiss farm (21 ha, [25]), with approximately 0.77 livestock units per hectare.

2.2. SALCA-BD (Swiss Agricultural Life Cycle Assessment—Biodiversity)

The expert system SALCA-BD [26] evaluates the habitat suitability and favorable or adverse effects of agricultural activities on terrestrial species diversity at field scale [27]. Farmland biodiversity is represented by a set of indicator species groups (ISGs) that are sensitive to land use and farm management: vascular plants, birds, mammals, amphibians, snails, spiders, carabids, butterflies, wild bees, and grasshoppers. SALCA-BD assessed farm activities on both arable land and grassland as well as EFA. Along with the assessment of habitats' suitability on each ISG, management options, such as fertilizer and plant protection use, soil tillage, sowing, irrigation, the number and timing of mowing, etc., were explored. The SALCA-BD scores are calculated per ISG per farm activity and range between 0 and 50. The evaluation is non-spatially explicit. Results from the model have been validated in Switzerland and neighboring countries [27]. Jeanneret et al. [26] explain the method in more detail. Appendix A presents the biodiversity scores of the farm activities at a field-level evaluated with the model in this study.

For the aggregation of the habitats at a farm-level, we assumed a linear relationship between the biodiversity score of each farm activity and its area. Hence, we calculated the farmland biodiversity (FBD) score as follows:

$$\text{FBD score per farm type} = \sum_{i}^{n}\sum_{j}^{m} \text{BD score}_{ij} * \text{Area}_{ij} / \text{total farm size} \quad (1)$$

where BD score is the biodiversity estimated with SALCA-BD, i is a farm activity, and j is a management option. To obtain the biodiversity score at the regional level, the FBD scores of each farm type are aggregated by applying the weight of aggregation.

2.3. Farm Typology

We used a centroid-based clustering analysis, k-means clustering, to identify typical farm types in the study region. The number of clusters needs to be determined a priori. To determine the optimal number of centroids, we used the elbow method [28], while observing the performance of the cluster method at the same time. Supplementary Material S1 outlines the methods in detail. Based on the expert knowledge and the collected field data, we selected the following six explanatory variables for the identification of representative farms: the number of suckler cows and dairy cows (LSU), area of arable land, grassland, and orchard (ha) and stock intensity (LSU ha^{-1}). We considered the intensity of livestock and the area of extensive farmland habitats in the explanatory variables, as our typology of farms should reflect environmental impacts [29].

2.4. BEFM (the Bio-Economic Farm Model)

2.4.1. General Approach

The BEFM we developed can determine the optimal production pattern and level of land use by maximizing the total gross margin (GM), given the available resources and restrictions [30,31] and the assumption that the farm behaves as a profit maximizer. Therefore, it follows the general form of a linear programming model for n activities and m structural restrictions [32]:

$$\begin{aligned} &\text{maximize } Z = \textstyle\sum_{j=1}^{n} c_j x_j, \\ &\text{subject to}: \textstyle\sum_{j=1}^{n} a_j x_j \leq b_i \\ &\text{and} \quad x_j \geq 0, \end{aligned} \quad (2)$$

where i = 1, 2, . . . , m, j = 1, 2, . . . , n, Z is the total GM at a farm level, x is the farm activities, c is the gross margins or costs per unit of activity, a is the technical coefficients, and b is the resource availability or upper/lower limits of activities. We developed the BEFM for each of the identified typical farm types with the same formula above. The add-in COIN-OR CBC linear solver (OpenSolver 2.9.3) in Excel was used to find the optimal solution in the linear programming model [33].

2.4.2. Farm Activities

The BEFM covers the main activities observed in the farm types that we identified: crop production (cash and fodder production), grassland production (meadows and pasture), livestock production and AES. Some of the activities belong to both fodder production and AES (e.g., less intensive meadows, extensive meadows and orchard meadows). In reality, farmers can choose any measures from the list of AES, but we selected the most relevant measures in our model (Table 1). We also considered different management options for each activity that distinguish the intensity level of inputs. Extensive management must be free of fungicides, plant growth regulators, insecticides, or chemical–synthetic stimulators of natural resistance [34].

Table 1. List of the production activities modeled in the bio-economic farm model.

Grassland (Fodder)		Arable Land (Fodder)		Arable Land (Cash Crops)	
Intensive	Meadow	Intensive	Fodder wheat	Intensive	Spelt wheat
	Pasture		Triticale		Winter Wheat
Less intensive	Meadow [1]		Oats		Spring wheat
Extensive	Meadow [1]		Winter barley		Rye
	Pasture [1]		Ley pasture	Extensive	Spelt wheat
	Orchard-Meadow [1]	Extensive	Fodder wheat		Winter Wheat
			Triticale		Spring wheat
			Oats		Rye
Livestock			Winter barley		Flower strips [1]
	Dairy cow		Ley pasture		
	Suckler cow		White peas		
	Young stock		Silo-green corn		

Less intensive meadow [1], extensive meadow/pasture [1], orchard meadow [1] and flower strips [1] are eligible to receive the payments from AES.

To obtain crop yields across intensity levels, we referred to the yearly, average regional yield data (2003–2020) in Canton Solothurn [35] and the gross margin report of AGRIDEA: "Deckungsbeiträge DBKAT" [36]. For grass yields, we referred to the formula in GRUD [37] and estimated the yields of meadows and pastures at different intensities given the elevation in the study region. Supplementary Materials S2 (Table S2, 1,2) provides all activities modeled in this study, including their yields, variable costs, GMs, etc.

2.4.3. Modules

The BEFM was constructed in a modular way. It is recommended that BEFMs should be modular to enhance the use of evidence in policymaking processes [38,39]. There are four modules exogenously given in the model (Figure 3). Each module is a subset of a larger section of the linear programming and comprises a set of constraints that serve to optimize the farm's gross margin.

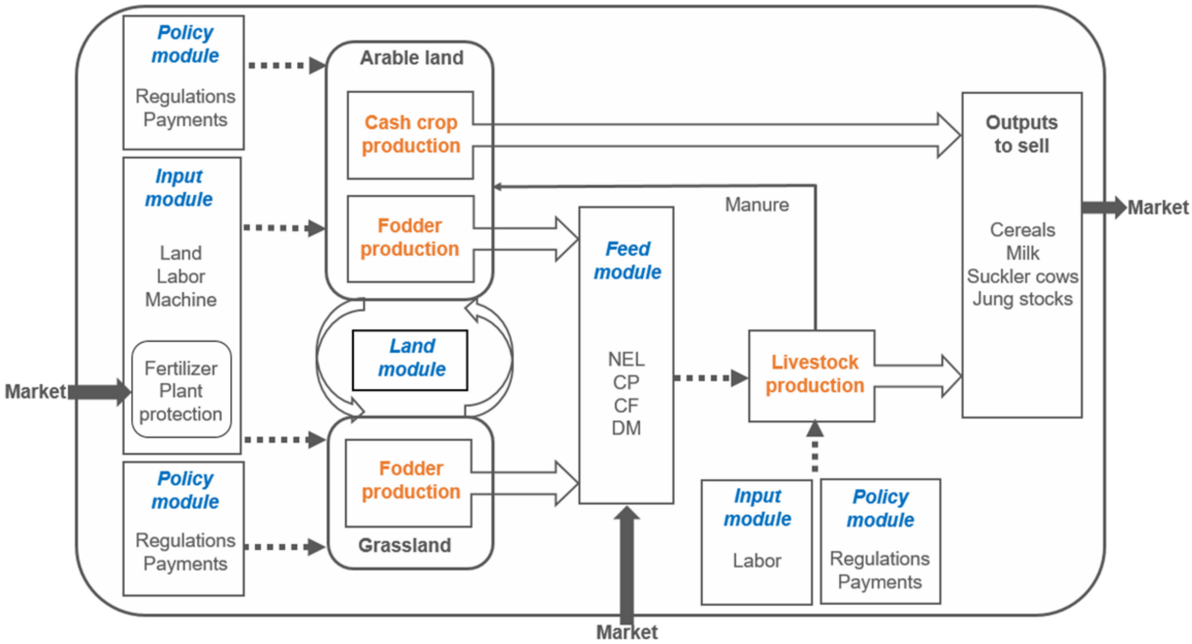

Figure 3. Activity flow inside the BEFM in the case of the dairy farm. NEL is net energy lactation; CP, crude protein; CF, crude fiber; and DM, dry matter.

Land module: We assumed that farmers could convert grassland into arable land depending on the payment level of direct payments as a result of maximizing the GM. Hence, this land module allows the model to convert the initial area of grassland into crop production and determines the optimal ratio of land use (i.e., the share of grassland, orchard and arable land). Under Swiss agri-environmental regulations, this conversion is possible as long as erosion events can be avoided. Nonetheless, we assumed that permanent grassland would remain on steep slopes (>24%), regardless of the payment level.

Input module: This module explicitly specifies the required labor hours and the level of input usage of different fertilizers and plant protection for each activity. For fertilizers, we considered N, P_2O_5, K_2O and Mg, and for plant protection, we included herbicides, fungicides, insecticides, growth regulators and trichogramma treatment. The costs of seeds, machinery and other miscellaneous items were also included [36]. Supplementary Materials S2 (Table S2, 3) details all the categories of variable costs included in this module for each farm activity. Note that we assumed manure to be used only within the farm without any exchanges with other farms.

Feed module: This feed module balances the supply and demand of livestock for feed in a nutritional form. We selected net energy lactation (NEL) in MJ DM-kg^{-1} (DM = dry matter), crude protein in kg DM-kg^{-1} and crude fiber in kg DM-kg^{-1}. We referred to the database of feed nutrition developed in Switzerland [40] to identify the nutritional values of the modeled crops and grasses. Supplement B describes these values per activity. To estimate the demand for livestock nutrition, we assumed the specific weight and performance of an adult milk cow: a 600 kg cow produces 8000 L of milk per year and young stocks (offspring of cows). We referred to the feed requirement tables [41] and determined the minimal requirement of the selected nutritional values as well as the maximum intake of dry matter per day per cow. For young stocks, we aggregated the nutritional requirements over different developmental phases of heifers, calves and bulls. Table 2 shows the results of the calculation for the nutritional constraints in the feed module.

Table 2. Nutritional constraints in the feed module to balance the supply and demand of livestock for nutrition.

	Dairy Cow		Suckler Cow	
	Adult Cow	**Youngstock**	**Adult Cow**	**Youngstock**
Maximum DM intake per day (kg)	16.8	12.5	14.0	7.8
Minimum NEL per day (MJ)	105.0	47.1	80.0	36.1
Minimum crude-protein per day (kg)	2.3	1.2	1.9	0.9
Minimum crude-fiber per day (kg)	3.4	2.4	2.8	1.4

Note that the unit kg is referred to the weight of dry matter (DM). NEL is net energy lactation.

Agricultural policy module: This module captures the role of direct payments, including the AES payments in farmers' land-use decisions by incorporating the obligatory measures and payments. We selected 14 different payment types [3]. Supplementary Materials S2 (Table S2, 4) details the total amount of direct payments that each activity receives and the breakdown of the sum. Table 3 lists all the restrictions that were implemented in the BEFM.

Table 3. List of the modeling restrictions.

Type of Restrictions	Explanation
Restrictions to qualify for direct payments	Crop rotation cereals (without corn and oats < 66% of AL), crop ration wheat, spelt and triticale (<50% of AL), crop rotation oats (<25% of AL), crop rotation corn (<40% of AL), crop rotation white peas (<15% of AL), flower strips (<50% of AL), biodiversity measure (>7% of total farmland), minimal livestock intensity, grassland-based milk and meat program [1]
Restrictions based on expert knowledge	Pasture limitation (less than 50% of grassland), nutritional balance (upper limit of DM intake, minimum NEL, crude protein and crude fiber), permanent GL (slope degree ≥ 24%), crop rotation limit cereals (<80% of AL)
Restrictions based on statistics	Total farm size, area of permanent GL, GL and AL, area of flexible land, labor hour, youngstock balance (share of offspring to adult cows), stable capacity

GL/AL are grassland and arable land. DM/NEL mean dry matter and net energy lactation. [1] The participation of the grassland-based milk and meat program was assumed to be subjected to only the large dairy farm and the suckler farm.

Table 4 shows the current payment level for EFA. While quality measures QI is an action-based measure rewarding farmers for adopting designated EFA, quality measures QII is a result-based measure for fulfilling specific goals [5]. For this study, we only considered the payment level of QI. This is because not all fields are eligible for QII, as they require specific site and biophysical conditions. Yet, for high-stem fruit trees, we considered both payments of QI and QII. This is because the payments for trees are primarily determined by the age of a tree (QI for 0 to 10 years and QII after 11 years) and additional measures (nesting boxes for birds, extensive grasslands, etc.). Thus, the extra costs to qualify for QII can be assumed to be negligible. Therefore, given an assumed tree's life of 60 years [42], we averaged the payments over 60 years per year and calculated the annual payment. In this study, we selected two types of orchard meadows, as explained in the next section.

Table 4. The current payments of AES in Switzerland and the payment level calculated for the model of this study.

Biodiversity Measures (EFA)	Quality Measure I	Quality Measure II	Modeled Payment
Extensive meadow (CHF ha^{-1})	860	1840	860
Less intensive meadow (CHF ha^{-1})	450	1200	450
Extensive pasture (CHF ha^{-1})	450	700	450
High-stem fruit trees (CHF $tree^{-1}$)	13.5	31.5	39.8
Orchard meadow Type A (CHF ha^{-1}) (CHF/ha)	-	-	1642
Orchard meadow Type B (CHF/ha^{-1})	-	-	2052
Flower strips (CHF ha^{-1})	2500	-	2500

Only high-stem fruits trees consider both QI and QII payments. Orchard meadows receive payments for the corresponding meadow production as well as payments for trees (assumed 30 trees ha^{-1}). Orchard meadow Types A and B are explained in the next subsection.

2.4.4. Orchard Meadows

The orchards in the study region are mainly high-stem cherry trees (Kay et al., 2018). To model orchard meadows in the BEFM, we made several assumptions. First, we assumed two types of orchard meadows available in the model: orchard meadows with and without commercial cherry production. For orchard meadows with commercial cherry production (orchard meadow Type A), we assumed that they were managed on less intensive meadows. The gross margin of Type A is based on three price levels (low, medium, and high). For orchard meadows without commercial cherry production (orchard meadow Type B), we assumed that farmers did not harvest cherries, but kept the trees only to receive subsidies. We also assumed that orchard meadow Type B is managed on extensive meadows. Based on our available data, we assumed that 30 trees were planted per hectare for both types of orchard meadows. In the model, both types of orchard meadows are available for all farm types. Table 5 describes the detailed gross margin calculation for the modeled orchard meadows. Supplementary Materials S2 (Table S2, 5) contains comprehensive gross margin calculations of orchard meadows with further disaggregated items.

Table 5. GM calculation for the modeled orchard meadows.

	Orchard Meadow Type A	Orchard Meadow Type B	Source
Description	Commercial cherry production	No cherry production (maintaining trees for AES)	
Trees	30 trees ha^{-1}	30 trees ha^{-1}	Own source
Cherry yield	30 kg $tree^{-1}$	-	Giannitsopoulos 2020
Cherry price	1.5/1.2/0.7 CHF kg^{-1}	-	Giannitsopoulos 2020
Meadow management	Less intensive (2 cuts $year^{-1}$)	Extensive (1 cut $year^{-1}$, no fertilizer)	
Forage yield loss	−15% less (yield: 54 dt ha^{-1})	−10% less (yield: 23 dt ha^{-1})	According to a local expert
Annual replanting	0.5 tree ha^{-1}	0.5 tree ha^{-1}	Schönhart 2011a
Establishment cost	140 CHF $tree^{-1}$	140 CHF $tree^{-1}$	Giannitsopoulos 2020
Maintenance cost [2]	6585 CHF ha^{-1}	630 CHF ha^{-1}	Giannitsopoulos 2020
Clearing cost [1]	60 CHF $tree^{-1}$	60 CHF $tree^{-1}$	Giannitsopoulos 2020
Labor	44 h ha^{-1}	27 h ha^{-1}	Giannitsopoulos 2020
Subsidy for trees	39.8 CHF $tree^{-1}$	39.8 CHF $tree^{-1}$	Bundesrat 2016
Total subsidy	2393 CHF ha^{-1}	2803 CHF ha^{-1}	Bundesrat 2016
Total revenues	3743 CHF ha^{-1} (1.5 CHF kg^{-1}) 3473 CHF ha^{-1} (1.2 CHF kg^{-1}) 3050 CHF ha^{-1} (0.7 CHF kg^{-1})	2803 CHF ha^{-1}	
Total costs [1]	6837 CHF ha^{-1}	882 CHF ha^{-1}	
GM with subsidy	−3094 CHF ha^{-1} (1.5 CHF/kg) −3364 CHF ha^{-1} (1.2 CHF/kg) −3787 CHF ha^{-1} (0.7 CHF/kg)	1921 CHF ha^{-1}	

Establishing cost [1], clearing cost [1] and total costs [1] are converted into annual equivalent costs based on a discount rate of 4% [42] and the average inflation rate over the last 30 years in Switzerland (0.9%). Maintenance cost [2] includes input use, harvesting and machinery for orchard meadow Type A and machinery and miscellaneous costs for orchard meadow Type B.

2.5. Policy Scenarios

Figure 4 illustrates how we ran the model with the baseline scenario and the policy scenarios. We first ran the model to retrieve the optimal baseline solution given the current payment level and the fixed land assumption. Next, we ran the model, while increasing the payment level from the current level to 200% by 10% increments. For this policy scenario, we applied the flexible land assumption. Therefore, the model can determine the optimal share of grassland and arable land at each level of payments of AES and corresponding cropping patterns.

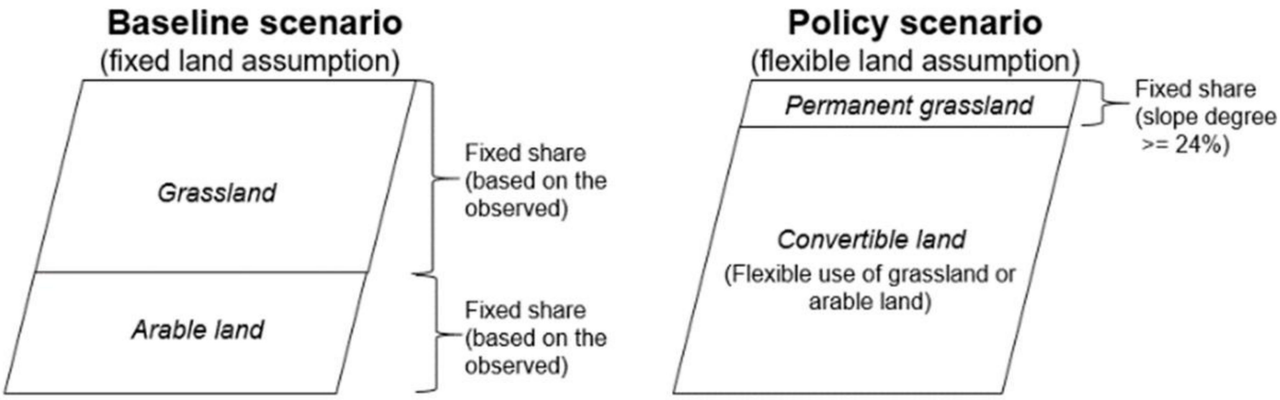

Figure 4. Land use determined under the land module with the baseline and policy scenarios. Note that both grassland and permanent grassland can be also used as orchard meadows in the model.

2.6. Evaluation of Cost Effectiveness

We measured the cost effectiveness of AES using the following two indicators: the cost-effectiveness ratio (CER) [43] and the producer rent. The CER represents the maximum FBD (farmland biodiversity) score that each farm can obtain per CHF 1000 of AES payments. To compare the CERs among farm types, the amount of payments paid out from AES is divided by EFA. Thus, the CER (unit: FBD score/CHF 1000) is computed per hectare as follows:

$$\text{CER} = (\text{FBD score}/(\text{payout from AES}/\text{EFA})) * 1000. \quad (3)$$

The producer rent quantifies how much the implementation of AES forgoes the income of farms [44]. It indicates the opportunity costs associated with impending AES. The producer rent (unit: CHF ha^{-1}) is calculated as follows:

$$\text{producer rent} = (\text{GM with AES} - \text{GM without AES})/\text{total farm size}. \quad (4)$$

Both CER and the producer rent were calculated per farm type and were also aggregated for the regional scale with the weights.

2.7. Map Regional Change of Orchard Meadows

To map the farm-level modeling results to each of the fields, we first identified which farm type was located in which field. Then, we assigned either of the land-use options in shares obtained with the model (grassland, orchard meadows or arable land) per farm type to each of the fields. Second, to determine which fields were most likely to belong to which land-use option, we assumed that fields with lower slope degrees would be covered by arable land for lower production costs, while on fields with higher slope degrees, trees would be planted on meadows to prevent erosion. This is consistent with a finding by Huber et al. [16] that fields with steeper slopes are more likely to enter the agglomeration scheme, which is a part of Swiss AES. The remaining fields were assigned as grassland.

3. Results

3.1. Farm Typology

We identified the following five representative farm types in the study region with the k-means clustering and the elbow methods in R (Version 1.2.1335) (Figure 5): 1. orchard farm without livestock (high-value trees and commercial cherry production, mainly cherries); 2. small-scale dairy farm; 3. large-scale dairy farm; 4. suckler farm; and 5. small-scale farms without livestock. Table 6 outlines the characteristics of these five farm types and their management. Given the number of farms and their farm size, large dairy and suckler farms are found to be the most prevalent farm types in the region. However, their management is contrastingly different. Large dairy farms tend to adopt intensive farming, as they own more arable land and less extensive grassland, whereas suckler farms utilize more extensive grassland. These results were confirmed by regional stakeholders.

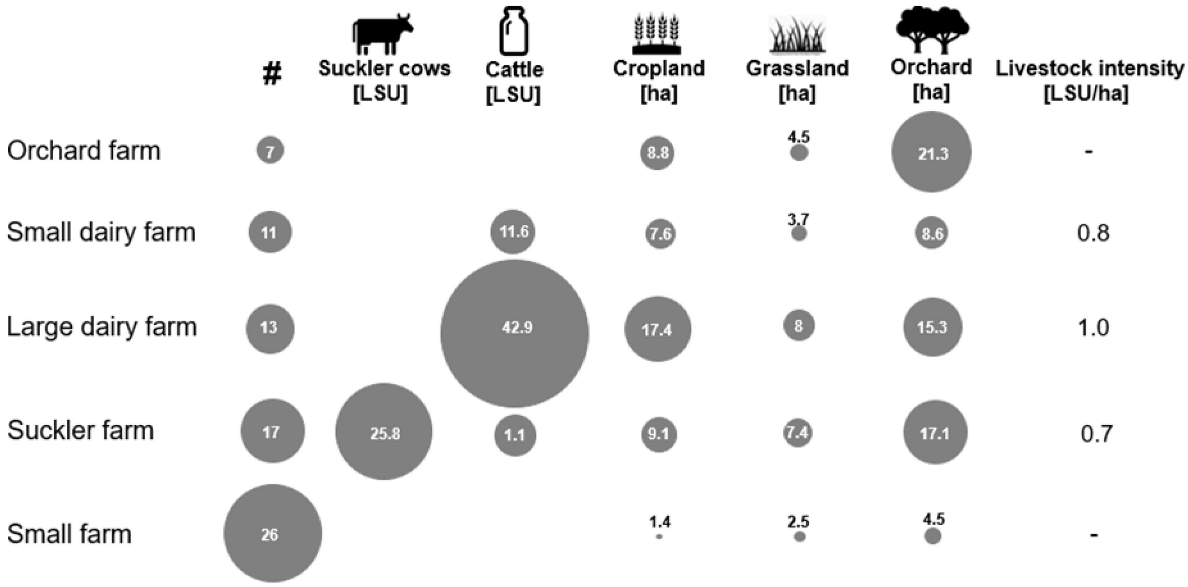

Figure 5. Identified representative farm types (left column) with k-means clustering in the study region and the average value of each explanatory variable. LSU: Livestock units. # indicates the number of farms found in each farm type.

Table 6. Modelled farm types and their characteristics.

	Orchard	Small Dairy	Large Dairy	Suckler Farm	Small Farm
Farm size (ha)	34.8	19.9	40.7	33.6	8.5
Weight for aggregation	14%	12%	30%	32%	12%
Initial grassland share	72%	60%	56%	70%	81%
Of which extensive grassland	41%	29%	19%	31%	46%
Permanent grassland	9.4%	10.5%	8.1%	5.9%	24.8%
Livestock	no	yes	yes	yes	No
Livestock intensity (LSU ha^{-1})	-	0.6	1.1	0.8	-
Capacity of livestock (LSU)	-	12	43	26	-
Labor availability in AWU	0.5	1.34	1.9	1.34	0.2
Grassland-based milk and meat program [1]	-	no	yes	yes	-

AWU stands for the annual working unit (1 AWU = 1800 h). We assumed that the orchard and small farms were part-time farms due to the small-scale farming. Grassland-based milk and meat program [1] provides farmers with an extra subsidy if they keep more than 75% of the share of fodder produced from grassland and less than 10% of the share of concentration (in weight of dry matter).

3.2. Orchard Meadows with the Baseline Scenario

Under this baseline scenario, the EFA of all farm types exceeds the obligatory level (7% of the total farmland) (Table 7). All farm types, except for the large dairy farm, chose orchard meadows for more than 50% of the total farmland. In particular, farm types without livestock (orchard and small farms) resulted in a higher share of orchard meadows. This led to a higher share of subsidy to the GM, which was more than 100%. By contrast, the large dairy farm resulted in the lowest share of orchard meadows. Regarding the FBD scores, orchard and small farms obtained higher values than the other farm types because of a relatively large share of orchard meadows and a lower share of arable land. Accordingly, their CERs were relatively high.

Table 7. Optimal baseline results per farm type with the current payments given the assumption that the area of grassland cannot be converted into arable land.

	GM	Subsidy to GM	EFA (%)	Trees	FBD Score	CER	Producer-Rent	Grass Land	Orchard	Arable Land
Orchard	73,322	113%	72%	755	12.2	6.0	541	0%	72%	28%
Small dairy	83,414	51%	52%	313	10.6	5.2	589	8%	52%	40%
Large dairy	236,446	31%	29%	350	9.4	4.6	256	28%	29%	44%
Suckler farm	101,440	77%	65%	659	11.8	5.8	702	5%	65%	30%
Small farm	17,048	122%	81%	206	13.2	6.4	605	0%	81%	19%

GM is gross margin and subsidy to GM indicates the share of the total amount of subsidies to the GM. EFA/FBD/CER indicate, ecological focused areas, farmland biodiversity (score), and cost-effectiveness ratio.

3.3. Policy Scenario

3.3.1. Role of AES in Land-Use and Sustaining Orchard Meadows

Regional land-use result: The regional result revealed that the share of grassland and orchard meadows at the current payment level was just under 20%, while arable land covered 80% of the land (Figure 6). Given the flexible land assumption, the arable land expanded considerably for all farm types at the current premium level, compared to the baseline result. As a result, the share of EFA dropped to 14%. However, as the payment level increased, the share of arable land decreased to 20% at 150% of the current AES premium, while EFA increased. This increase in EFA is mostly attributed to the expansion of the area of orchard meadow Type B.

Land-use differences across farm types: The EFA of the small and large dairy farms dropped just to the obligatory level, whereas the EFA of the suckler and small farms remained relatively high. Nonetheless, for all farm types, the arable land expanded considerably. Given the flexible land assumption, the difference in how much the arable land expands depends on the share of the permanent grassland. At the current payment level, all farm types except for large dairy farms expanded the arable land to the maximum possible area. Therefore, the share of land use at the current level would not change, even if the payment level was lowered from the current level.

Change in orchard meadows: The regional change in the number of trees is shown in Figure 7. The number of trees at the baseline is shown by a dot at 100%. In the policy scenario, the number of trees fell to 7627 from 29,847 at the current premium level. In the baseline scenario, where the conversion of land was not permitted, there was enough incentive to maintain orchards as shown in Table 7. However, if allowed, the arable land took over a large area of orchard meadows as they became less profitable. Increasing the payment level to 150%, however, restored the profitability of orchard meadows enough, allowing them to expand the area comparable to the baseline. The payment for orchard meadows at this level is around 1000 CHF ha^{-1}, higher than the current AES payments.

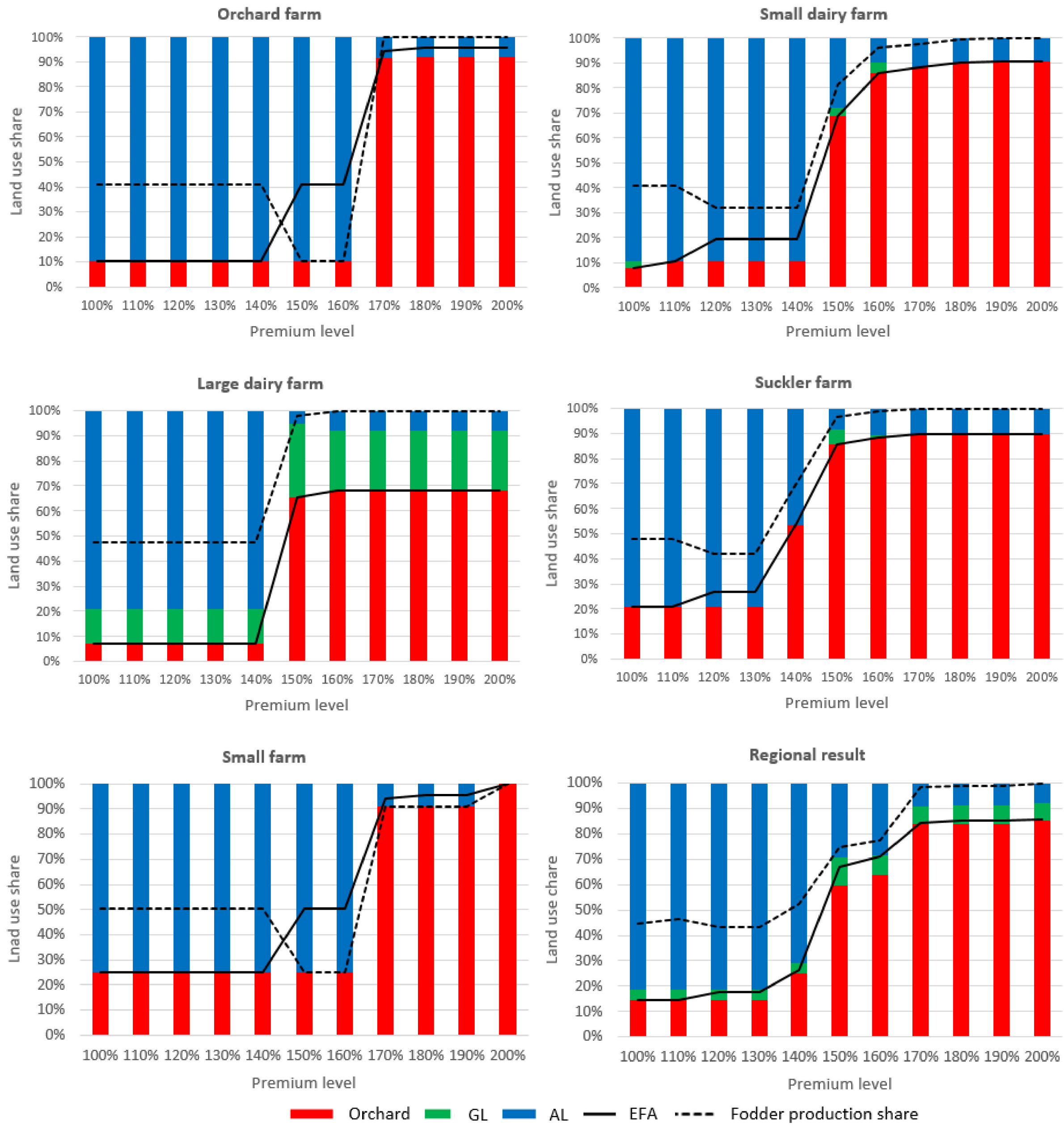

Figure 6. Policy scenario results with the increments of the payments from the current level up to 200%. The X-axis indicates the payment level compared to the current level. The Y-axis indicates land-use share. GL/AL/EFA designate grassland, arable land and ecologically focused area.

3.3.2. Difference in the Adoption of AES and the CER among Farm Types

The difference in the producer rents over farm types indicates the difference in the adoption costs of AES (Figure 8). The producer rent of large dairy farms stayed negative at lower payment levels, unlike other farm types. This reveals that for large dairy farms, the current AES payments cannot compensate for the cost of the mandatory implementation of the AES. The opportunity cost of adopting AES is the highest among all farm types due to the larger number of profitable dairy cows. Contrary to this result, all the other farm types had a positive producer rent with the current payment level. Among these farm types, the producer rent of the suckler farms was the highest: the opportunity cost of the suckler farm was the lowest. Nonetheless, the producer rents in the policy scenario are much less than the baseline producer rents.

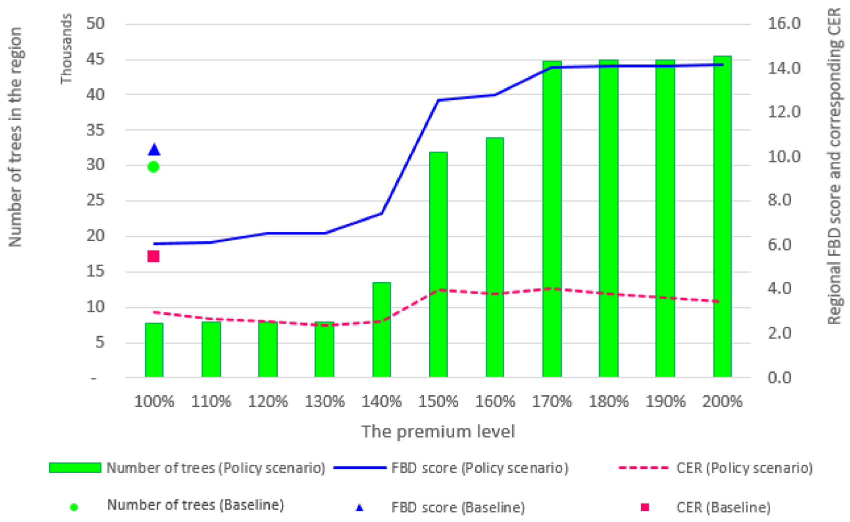

Figure 7. The regional change in the number of trees, regional farmland biodiversity score and the CER depending on the payment level (100% = the current level). FBD is farmland biodiversity.

All FBD scores at the initial level were approximately halved, despite the same level of payment, compared to the baseline scenario. The FBD scores of the orchard, large dairy and small farms remained the same until 140% of the current level. At a premium level of 150% premium, FBD scores increased sharply, as the area of orchard meadows tended to expand considerably.

The change of CER showed a similar trend. Up to a level of 140% premium, CERs tended to slightly decrease as the FBD score remained the same. However, due to the sharp increase in FBD scores above the 140% premium, CERs increased accordingly. For the regional level, it reached a maximum at 150% premium. Yet, they decreased eventually because there was little improvement in the FBD scores at higher payment levels. The highest CER in the policy scenario was even lower than the baseline CER.

3.3.3. Change in the Regional Land Use and Individual Species Suitability with AES

On the map of the case study region (Figure 9) with the baseline result, orchard meadows appeared more in the east and south, where the suckler, orchard and small farms tend to be located. On the other hand, more arable land and grassland appeared in the north and east, where the small and large dairy farms are more prevalent. The grassland mapped here is mostly with intensive pasture. The fields in the north and east area are relatively large and the slopes are flatter than the other areas. Thus, these fields are more suited to crop production and intensive grass production.

In the policy scenario at 100% premium (current level), most of the fields covered by orchard meadows disappeared, as Figure 7 shows that the number of trees is about one-quarter of the baseline number. When the premium was increased to 150%, the fields with orchard meadows appeared almost evenly on the map. However, 150% of the premium level is insufficient to sustain orchard meadows for orchard and small farms. Therefore, the fields belonging to these farm types remained as arable land, despite the increase in the payments. Figure 10 presents the variations in species suitability as a result of these regional-level results. Birds, butterflies, wild bees and grasshoppers are projected to be the most harmed by the expansion of arable land. All of these species groups are strongly linked to extensive grasslands.

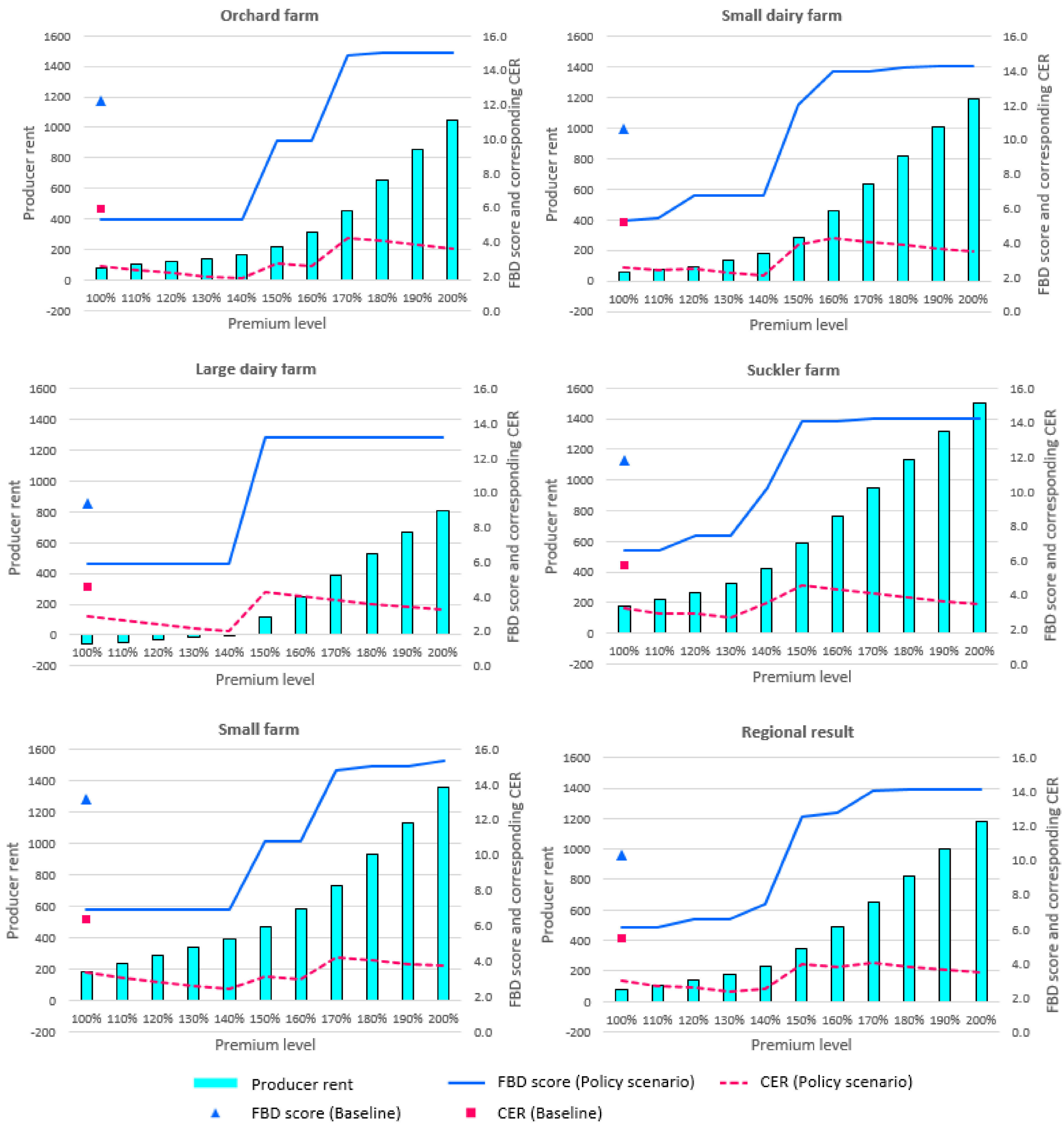

Figure 8. Policy scenario results with the increments of the payments from the current level up to 200%. The $X-$axis indicates the payment level compared to the current level. The $Y-$axis indicates producer rent in CHF per hectare. The $Z-$axis indicates the FBD (farmland biodiversity) scores and the CER (cost-effectiveness ratio). The triangle symbol in the graph indicates the level of FBD scores at the baseline, while the square symbol indicates the corresponding CER at the baseline.

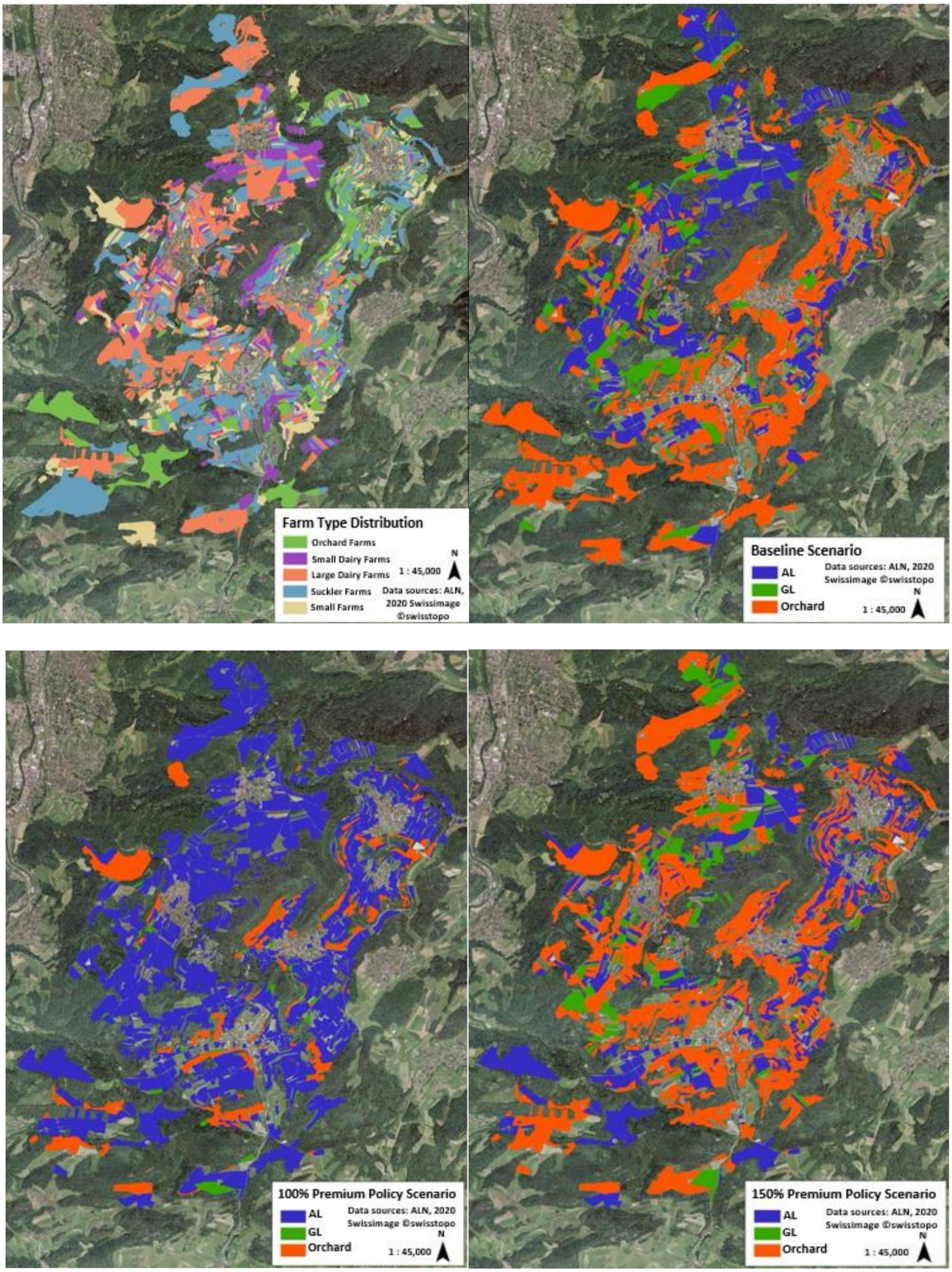

Figure 9. Maps of farm type distribution (above left) and the regional land use under the baseline scenario (above right) and policy scenarios—100% and 150% of the current premium level (bottom). AL/GL designate arable land and grassland.

	Flora of crops	Flora of grasslands	Birds	Small mammals	Amphibia	Molluscs
Baseline	4.2	9.1	17.3	12.5	5.0	4.9
100%	10.5	3.0	10.6	6.4	2.6	3.0
150%	5.3	9.0	18.5	13.5	5.1	5.1

	Spiders	Carabids	Butterflies	Wild bees	Grasshoppers
Baseline	16.0	15.1	13.3	16.2	13.6
100%	9.2	10.5	4.3	8.1	4.4
150%	17.5	16.5	14.6	17.4	14.4

Figure 10. Biodiversity scores of each species indicator group in the regional level with the baseline scenario and the policy scenario (100% and 150% premium levels).

4. Discussion

4.1. Orchard Meadows and Land-Use Change

We discovered that all farm types benefit from existing AES [34], and orchard meadows were well maintained in the baseline. Particularly, orchard and small farms favored orchard meadows to a large extent because the total gross margin for orchard meadows of Type B, including tree payments, was higher than the gross margins of pure meadows, due to the expected low selling price of hay (6 CHF dt^{-1}) [45]. Therefore, orchard and small farms rely on AES for a higher share of their income than the other farm types. This is also the case for suckler farms, which require less intensive meadows or pastures, compared to dairy [5]. Having dairy cows with high livestock intensity brings farms relatively high profits. Therefore, the share of orchard meadows on large dairy farms was the lowest of all farm types, as orchard meadows cannot provide the protein-rich fodder needed for dairy production.

In comparison, orchard meadow Type A was not chosen at any payment level. The sensitivity analysis with increasing cherry prices showed that it becomes only economically viable when the price of cherries exceeds 7 CHF kg^{-1}. The high production costs of cherries are mostly due to the high labor cost for harvesting. In reality, however, some orchard farms continue to produce cherries for profits. The discrepancy between our model's predictions and reality can be explained by traditional, family labor-based cherry production in the region: opportunity costs of labor may be low, and the local marketing of homemade products can be attractive. Nonetheless, the ecological benefits of trees alone justify public financial support.

A validity check of the modeling results with reality shows that the model tends toward orchard meadows, where, in reality, we find intensive meadows for dairy. As our model is a static comparative, it includes investments such as a dairy herd and its related infrastructure or planting of trees only as an annual average gross margin. Switching the production system between trees and cows is almost a once-in-a-lifetime decision, which does not depend on actual gross margins, as in our model. So, farmers, in general, have high resistance against such changes and can overcome smaller periods of lower gross margins in part of their production systems by compensating with income from other parts. Only if it becomes obvious that in the long run, the system will have low or even negative returns, do farmers change their production system. Often, this decision goes along with a generational change of ownership of the farm. Additionally, the timing of orchard-related labor peaks may play a role. Tree pruning can be done in winter, when labor pressure is low and the cherry harvest is in early summer, mostly after the labor peak of first hay making and before the start of crop harvesting. Nevertheless, our model shows this tendency under current circumstances. Should the performance relations between orchard meadows and dairy production remain the same for a longer period, we expect to see production shifts as projected in our model runs.

The policy scenario demonstrated that at the current payment level, regional biodiversity was considerably degraded as grassland and in particular, orchard meadows were often replaced by crop production. This implies that crop production in Switzerland is highly financially attractive if subsidies are considered [42]. Farmers receive a guaranteed payment of 1400 CHF ha^{-1} for crop production in addition to 120 CHF ha^{-1} as price support for supplying cereals [46], while a guaranteed premium for cultivating grassland is 1000 CHF ha^{-1} in the hilly regions [3].

4.2. Cost-Effectiveness and Its Difference over Farm Types

While the baseline maintains the current ratio of grassland and arable land, the policy scenarios allow flexible use of more than 75% of the land. With the current payment levels, this leads to lower biodiversity scores and also lower cost effectiveness. However, with increasing payments, the policy scenarios lead to high biodiversity impacts (see Figure 8). This is only possible as farmers are allowed to convert arable land into grassland, which goes along with decreasing cost effectiveness. This trade-off occurs as a result of higher payments, which reduce the cost effectiveness of AES.

Additionally, our results indicated that the producer rents over different farm types largely varied due to the different compliance costs of AES. Among the livestock farms, livestock intensity and type determine the producer rent. Large dairy farms still need to keep sufficient high-yield grassland to sustain high livestock intensity and fulfil the conditions of the grassland-based milk and meat program, which results in lower implementation rates from AES. In contrast, suckler farms gained relatively high implementation rates of AES. Mack et al. [5] verified these findings: the adoption of action-based EFA, which this study examined, is substantially influenced by farm type. Dairy farms are negatively correlated and suckler farms are positively correlated to the adoption rate. Our study demonstrated that farms with a higher implementation rate of AES tended to gain higher CER.

4.3. Methodological Limitations

We assumed that farmers would maintain or abandon orchard meadows depending on the economic profits in relation to the profitability of the other activities. However, we did not consider their non-market benefits, i.e., externalities, such as reduced soil erosion risk, carbon sequestration or regional identity, in the calculation of the economic profit. Although capturing the real value of orchard meadows is a core challenge in the economic assessment [11], accounting for such non-market benefits of orchard meadows in the decision process will improve the validity of results and help to determine a more appropriate level of financial support [42,47].

Another possible limitation of this study is that the evaluation of farmland biodiversity was neither contingent on the complexity of landscapes, such as the spatial configuration of semi-natural habitats [48], nor connectivity at different scales [49]. AES can be ineffective unless the ecological effects are observable at the landscape scale [50–52]. Spatial planning of biodiversity measures can enhance their benefits and reduce the opportunity cost for food production [53]. Understanding species dynamics and their relationships to landscape complexity, using a broader spatial scale and landscape indicators, could help improve biodiversity conservation in agricultural landscapes [43,54].

4.4. Policy Implications

Under the current situation, where it is possible to convert grassland into arable land, expanding arable land will increase the profitability of farms, especially for competitive farms, such as larger-scale dairy farms. The fact that these farms have a negative product rent at the present premium level implies that they will lose income and have no incentive to adopt AES beyond the obligatory level [55]. In contrast, extensively managed farms, such as suckler farms, are likely to profit from AES due to the lower compliance costs. They have more incentives to adopt biodiversity measures [56,57]. When the adoption rate of AES is high, the cost effectiveness tends to be higher. It can be more cost efficient to provide farm-type-specific payments rather than providing all farm types with the same payment level. This way of payments is in line with the claim of Armsworth et al. [18] that the inefficiency of the simplification of AES derives from their inability to address variation within and between farms in terms of private costs associated with providing biodiversity. Additionally, our study recommends a regulatory framework that incentivizes farmers to preserve the existing area of grassland. Under the current direct payments, crop production is far more financially attractive.

5. Conclusions

The purpose of this study is to provide policymakers with insight into the design of cost-effective AES for maintaining agroforestry systems and promoting farmland biodiversity by considering different farm types, using orchard meadows as an example. Based upon our results, the following can be concluded: 1. Higher AES payments increase orchard meadows and biodiversity scores. However, excessive payments would impede the improvement and lower the cost-effectiveness. 2. Farmers would maintain orchard meadows only with higher payments as compared to the current level, under the assumption that they can convert any grassland to arable land for maximizing their profit. However, if the conversion from grassland into arable land was not permitted, all farm types would maintain current orchard meadows. 3. Compliance costs and the adoption of AES vary considerably among farm types. Suckler farms and farms without livestock largely economically benefit from AES, while large dairy farms lose income under the flexible land-use assumption.

These findings can carry the following policy implications. First, AES can be more cost effective in targeting specific farm types and offer them the payments reflecting the compliance costs rather than paying all farm types with the same payments. Second, whether the current AES can contribute to the maintenance of orchard meadows is contingent on how far the conversion of land can be prevented. Under the current direct payments, crop production is significantly more profitable, which may encourage farmers to expand arable land. Therefore, this study recommends establishing a regulatory framework that incentivizes farmers to preserve existing grassland.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14095615/s1, Supplementary Materials S1: Documentation of the cluster analysis, Supplementary Materials S2: List of the parameters in the modeling.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. SALCA-BD Results

Farm activities	Total score	Flora of crops	Flora of grasslands	Birds	Small mammals	Amphibia
Intensive meadows	10.4	0.0	9.4	13.6	11.9	4.0
Intensive pasture	11.7	0.0	12.6	17.4	11.5	6.3
Less intensive meadow*	11.6	0.0	12.2	14.4	12.4	5.1
Extensive meadows*	13.9	0.0	13.9	18.2	13.0	6.4
Extensive pasture*	11.8	0.0	13.9	17.4	11.5	6.5
Orchard meadows Type A*	13.4	0.0	12.2	18.7	16.3	5.4
Orchard meadows Type B*	15.6	0.0	13.4	22.7	17.8	6.7
Intensive crops	4.7	14.3	0.5	7.9	4.1	1.8
Extensive crops	5.1	14.4	0.5	9.2	4.0	1.9
Flower strips*	19.7	30.0	0.0	40.0	12.0	6.0
Farm activities	**Molluscs**	**Spiders**	**Carabids**	**Butterflies**	**Wild bees**	**Grasshoppers**
Intensive meadows	5.3	11.1	12.7	14.9	16.3	14.8
Intensive pasture	4.9	12.3	10.8	17.4	18.6	17.2
Less intensive meadows*	6.2	13.0	14.6	15.9	17.6	16.5
Extensive meadows*	6.6	15.4	17.8	21.2	19.8	21.2
Extensive pasture*	4.7	11.9	10.8	17.4	18.6	17.2
Orchard meadows Type A*	6.1	19.0	16.8	16.1	20.1	16.8
Orchard meadows Type B*	6.4	22.2	19.7	20.0	22.4	20.4
Intensive crops	2.3	6.4	8.6	0.6	5.1	0.6
Extensive crops	2.4	7.5	9.6	0.5	5.4	0.5
Flower strips*	3.0	36.0	27.0	25.0	23.0	15.0

Figure A1. Biodiversity scores (0–50) of modelled farm activities per hectare estimated with SALCA-BD. The total score is the average of the scores of each ISG. * indicates the biodiversity measures under AES (ecological focused areas). Orchard meadow Type A corresponds to orchard meadows with commercial cherry production on less intensively managed meadows, while orchard meadows Type B orchard meadows without commercial cherry production on extensively managed meadows. The scores of intensive and extensive crops are aggregated over individual crops with the same weight. Online Resource 2 (Table S2, 6) provides the biodiversity scores of all of the modeled farm activities.

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3. Case Study 2

Towards diverse agricultural land uses: socio-ecological implications of European agricultural pathways for a Swiss orchard region

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ORIGINAL ARTICLE

Towards diverse agricultural land uses: socio-ecological implications of European agricultural pathways for a Swiss orchard region

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Abstract

Diverse agricultural land uses are a typical feature of multifunctional landscapes. The uncertain change in the drivers of global land use, such as climate, market and policy technology and demography, challenges the long-term management of agricultural diversification. As these global drivers also affect smaller scales, it is important to capture the traits of regionally specific farm activities to facilitate adaptation to change. By downscaling European shared socioeconomic pathways (SSPs) for agricultural and food systems, combined with representative concentration pathways (RCP) to regionally specific, alternative socioeconomic and climate scenarios, the present study explores the major impacts of the drivers of global land use on regional agriculture by simulating farm-level decisions and identifies the socio-ecological implications for promoting diverse agricultural landscapes in 2050. A hilly orchard region in northern Switzerland was chosen as a case study to represent the multifunctional nature of Swiss agriculture. Results show that the different regionalised pathways lead to contrasting impacts on orchard meadows, production levels and biodiversity. Increased financial support for ecological measures, adequate farm labour supplies for more labour-intensive farming and consumer preferences that favour local farm produce can offset the negative impacts of climate change and commodity prices and contribute to agricultural diversification and farmland biodiversity. However, these conditions also caused a significant decline in farm production levels. This study suggests that considering a broader set of land use drivers beyond direct payments, while acknowledging potential trade-offs and diverse impacts across different farm types, is required to effectively manage and sustain diversified agricultural landscapes in the long run.

Keywords Global land use drivers · Shared socioeconomic pathways (SSPs) · Climate change · Scenario development · Diverse agricultural land uses · Trade-off

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Introduction

Agriculturally diversified land uses are closely linked to multifunctional landscapes (Frei et al. 2020; Hölting et al. 2020). These diverse land uses can contribute to the enhanced delivery of wide-ranging ecosystem services (e.g. biomass, biodiversity, aesthetic values, the quality of soil, air, water) (Albert et al. 2017; Dou et al. 2021). Understanding the drivers of agricultural land use changes (LUCs) and their effects is essential for the successful management of more diversified, heterogeneous agricultural landscapes. However, this task is complex due to the uncertain future pathways of agricultural transformation driven by today's fast-paced world. Agricultural LUCs can be triggered by distinct combinations of land use drivers rather than single key drivers (van Vliet et al. 2015). The global drivers that affect agricultural land use include market and labour conditions (e.g. price volatility, changes in workforce), technology (e.g. digitalisation and mechanisation), demography (e.g. population growth, altered age structure), consumption changes (e.g. less demand for meat), policies (e.g. more restrictive agri-environmental policies) and climate change (e.g. extreme weather events) (Alexander et al. 2015; Pröbstl-Haider et al. 2016; Stehfest et al. 2019). These drivers are likely to continue to change over the next few decades (Bryan et al. 2016; Masson-Delmotte et al. 2019).

The effects of global drivers inevitably manifest themselves at smaller scales, such as the regional and farm level (Fronzek et al. 2019; Arnalte-Mur et al. 2020). The majority of European agricultural regions and systems is highly dependent on the path of global drivers (Debonne et al. 2022), and as a result, farming activities constantly adapt to global drivers (Stürck et al. 2018) to survive in today's competitive, market-oriented agricultural sector (Nybom et al. 2021). Farmers' decisions regarding farm activities and land management intensity are influenced by a variety of factors, some of which are stable (topography, soil characteristics) while others change at various paces across different regions (Fronzek et al. 2019; Levers et al. 2018); these factors include crop profitability, regulations, agri-environmental measures, farm technology, climate, farm labour supply and food consumption patterns. Thus, in the long term, we can expect major changes to evolve in agricultural land use (Valbuena et al. 2010; Popp et al. 2017; Stehfest et al. 2019). As these drivers continue to shape agricultural landscapes, understanding how global drivers influence farmers' decisions becomes crucial (van Vliet et al. 2015). To enhance the diverse benefits provided by agricultural landscapes, however, potential trade-offs must be acknowledged, as various benefits react to changes differently (Beckmann et al. 2019; Botzas-Coluni et al. 2021). Scaling up from the regional level to the national level, the knowledge of farmers' adaptation decisions to future uncertain changes can facilitate the development of food and agri-environmental policies that consider the differences in needs across regional and local levels (Schaldach et al. 2011; Bauer & Steurer 2014). However, there is a lack of studies assessing the impacts of global drivers on European agriculture at the regional level (Debonne et al. 2022).

A comparative scenario approach is a prominent method for addressing future uncertainty in changing drivers (Vervoort et al. 2014; Von Lampe et al. 2014; Riahi et al. 2017) as well as scale issues (i.e. straddling impacts across spatial scales) (O'Neill et al. 2020; Stratigea & Giaoutzi 2012). The shared socioeconomic pathways (SSPs), as described by O'Neill et al. (2014, 2017), offer a consistent set of scenarios based on a globally accepted framework. The SSPs encompass five contrasting narratives that describe how socioeconomic factors could change, including demographics, economic growth, education, urbanisation and the rate of technological development over the next century. Combining different levels of greenhouse gases described in the representative concentration pathways (RCPs) allows us to evaluate the impacts of both climate change and the change in socioeconomic drivers under the same scenario framework (Meinshausen et al. 2011; van Vuuren et al. 2011). In a recent study, Mitter et al. (2020) developed Eur-Agri-SSPs (European-Agricultural-SSPs) by adapting the global scale SSPs to suit the context of the European agriculture and food sector. The narratives of Eur-Agri-SSPs capture the uncertainty of the following five socioeconomic, technological and environmental drivers: (1) population and urbanisation; (2) economy and markets; (3) policies and institutions; (4) technologies and (5) environmental and natural resources. Similarly, Lehtonen et al. (2021) extended SSPs to a national scale and applied them to the agricultural and food sectors in Finland, while Pedde et al. (2021) developed a set of multi-driver SSPs for the UK. Each of these studies integrated local and national knowledge with top-down insights derived from the global SSPs. Mitter et al. (2020) and Pedde et al. (2021) propose further SSP extensions towards smaller scales, while Prost et al. (2023) emphasise the importance of explicitly incorporating the farm level into future-oriented studies to support farm transition.

We chose a rural orchard region in northern Switzerland for this study. This region serves as a representative case, as it is not only a small-scale region but also features a combination of different agricultural land uses and farm types. Traditional fruit orchards, a characteristic element, illustrate the current multifunctional nature of agriculture in the region. This study then aims to explore the major impacts of future global land use drivers on regional agricultural landscapes that are shaped by farm-level decisions to obtain a better understanding of the regionally specific socio-ecological implications for diversified agricultural landscapes in the long term. To achieve this objective, we propose an integrated model-based scenario approach: we downscale the Eur-Agri-SSPs and RCPs to create regionally tailored scenarios. In this process, we consider the actual Swiss policy agendas and initiatives (cf, Finger 2021; Schweizerischer Bundesrat 2022). The scenarios were implemented in the integrated Land Use Change and Impact Assessment model (LUCIA) (Nishizawa et al. 2022) to simulate agricultural LUCs at the farm level. Our modelling approach includes the full set of farming activities across different farm types. This is crucial to consider, as the decisions made on farms vary depending on their characteristics (Huber et al. 2023) and the development of indicators for the assessment of farms' environmental performances is also being driven by the Swiss government (Mann & Kaiser 2023). This approach allows us to investigate how unique regional traits and farm heterogeneity can be included in future LUCs and to identify trade-offs in the socio-ecological system by considering different climate and socioeconomic conditions in different future scenarios. Based on the above considerations, we develop the following research questions:

1. What are the major impacts of global socioeconomic and climate conditions on future regional agricultural land use, given the farming characteristics of the case study region?
2. Based on these outcomes, what trade-offs are observed in the socio-ecological system of agricultural land use?
3. What regionally specific socio-ecological implications can we gain to promote diverse agricultural landscapes in 2050 given the resulting agricultural land use changes?

Methods and materials

Case study region

The study region is located in the eastern part of Schwarzbubenland (SBL), which is a part of the Swiss canton of Solothurn in northern Switzerland (Fig. 1). The region covers an area of 42.2 km^2 and is home to 74 farms, each with an average size of approximately 24 ha. This rural area represents a characteristic multifunctional agricultural landscape, predominantly shaped by traditional agroforestry (ALW 2020). The regional agroforestry consists of *Streuobstwiesen*, high-stem cherry orchards of scattered fruit trees combined with perennial grasslands, which are grazed by cattle and/or mown regularly for fodder production (Herzog 1998). These orchard meadows are associated with agro-biodiversity hotspots (Kay et al. 2018), which have the potential to increase the species richness of habitats in rural agricultural landscapes (Horak et al. 2013). However, due to higher labour costs, recent infestations by invasive fruit flies and limited specific protection measures, many farms tend to drop cherry production from their business portfolio. Given the current situation, the ability of these farms to maintain such traditional multifunctional agricultural landscapes has become increasingly uncertain. Arable land accounts for only 32% of the farmland (ALW 2020).

Overall approach

We developed an integrated model-based scenario approach, which consists of three steps (Fig. 2). First, we derived future scenarios for the regional agriculture and food sector in 2050, called the SBL agricultural socioeconomic pathways (SBL-Agri-SSPs) scenarios, which were downscaled from the Eur-Agri-SSPs (Mitter et al. 2020) capturing the regional trends and traits of socioeconomic and climate conditions for agricultural land use. To account for climate impacts, these scenarios were combined with climate projections that are consistent with RCPs. Second, the relevant components of SBL-Agri-SSPs were parameterised for the LUCIA (Nishizawa et al. 2022) to simulate agricultural LUCs at the farm level. Third, we evaluated their corresponding impacts on the socioeconomic system of agricultural land use. In doing so, we explored the most significant impacts of the SBL-Agri-SSPs, analysed the trade-offs

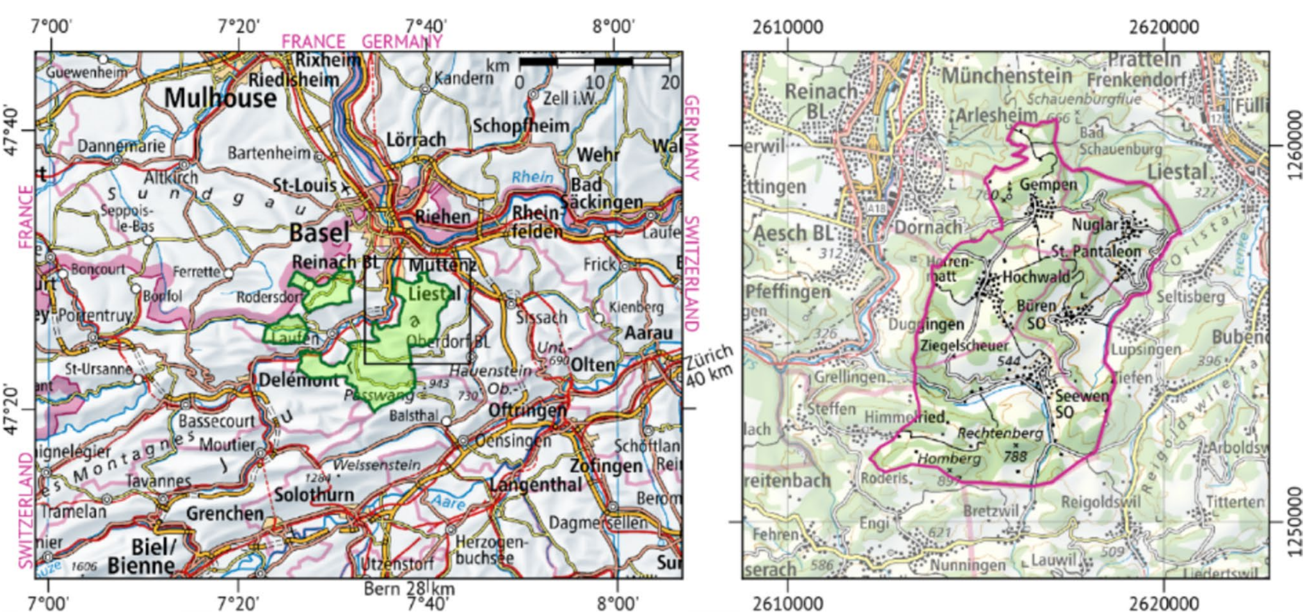

Fig. 1 Location of the Schwarzbubenland (left) and the five municipalities considered in this study (right). The square on the left map highlights the extent of the magnified area shown on the right map. The coordinates and grid lines of the right map refer to the Swiss national grid with a grid line spacing of 10 km. Base maps © 2022 Federal Office of Topography Swisstopo

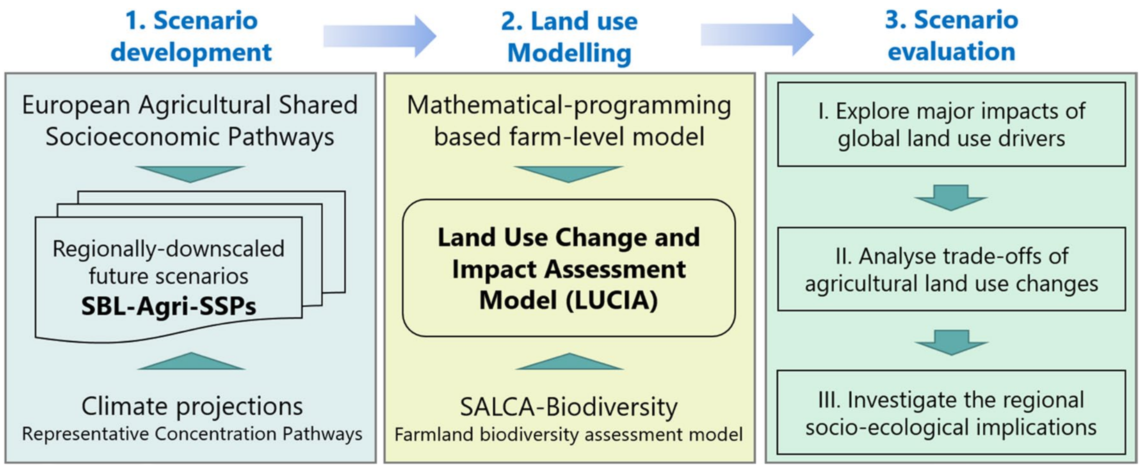

Fig. 2 Framework of an integrated model-based scenario approach for evaluating the impacts of climate change and socioeconomic developments on future agricultural land use at the regional scale (SBL-Agri-SSPs = Schwarzbubenland agricultural shared socioeconomic pathways)

and discussed the implications of the resulting changes in agricultural land use for promoting diverse agricultural landscapes in the future.

Climate change impact

Climate change has direct and indirect impacts on agricultural land use and production (Olesen & Bindi 2002; Nelson et al. 2014): First, yields change due to changes in air temperature, precipitation, solar radiation, etc. Second, farmers adapt to climate change by developing new cropping systems with modified shares of common or new crops. To capture the first aspect, we used bias-adjusted EURO-CORDEX (12.5-km grid resolution) climate scenarios for the RCP4.5 and 8.5 emission pathways. Each grid cell has up to 33 parallel realisations of daily meteorological parameters (air temperature, precipitation, solar radiation, wind speed, etc.) for each scenario. These climate scenario data were used in the novel crop yield model ABSOLUT (Conradt 2022). CO^2 fertilisation or changes in management were not represented. While simulated climate change trends in yield levels were clear, trends regarding yield risks (variations) could not be detected between 2020 and 2050 or between RCP4.5 and RCP8.5. Hence, the relative yield changes were included in the LUCIA, but not the yield risks. To capture the adoption of new crops as a climate adaptation strategy, we identified a so-called climate analogue region for the case study region, following Mahony et al. (2017). Utilizing this method, we identified soy, sunflowers and grain maize as potential crops likely to be adopted and cultivated in the study region by 2050. Due to a lack of data, soy was not included in the yield simulation. Therefore, we applied the same relative yield change from sunflower to soy, as they are both oilseed crops (for a more detailed explanation of the methodology and results, please refer to Online Resource 1).

Development of SBL-Agri-SSP scenarios

To cover a wide range of possible agricultural land use scenarios for 2050, we selected three contrasting scenarios from the Eur-Agri-SSPs (Mitter et al. 2020): Eur-Agri-SSP1 (agriculture on sustainable paths), Eur-Agri-SSP2 (agriculture on established paths) and Eur-Agri-SSP5 (agriculture on high-tech paths). Each of these scenarios was individually translated to the study region one by one to construct regionally tailored SBL-Agri-SSP scenarios that capture the regional agricultural traits (biophysical conditions, farm management and structures, and farm heterogeneity), in addition to socioeconomic changes (population and urbanisation, economy and markets, policies and institutions, technologies, and environmental and natural resources) for the region. The narratives of the developed SBL-Agri-SSPs were then parameterised, including the reference scenario that was based on the current data for 2020. To combine SBL-Agri-SSPs with the selected RCPs for this study, we referred to O'Neill et al. (2020) and Hausfather and Peters (2020). The highest forcing pathway, RCP8.5, according to O'Neill et al. (2020), is only likely to occur following the fossil fuel development pathway (the global SSP5). Hausfather and Peters (2020) also argued that the business-as-usual scenario is unlikely to follow RCP8.5. Therefore, we opted for more plausible combinations of the SBL-Agri-SSP1 and SSP2 with RCP4.5. The SBL-Agri-SSP5 was combined with RCP8.5 because we assume that society as a whole will make more mitigation efforts in the SBL-Agri-SSP1 and 2 than in the SBL-Agri-SSP5 (see also O'Neill et al. 2020). Below, we summarise the key outcomes of the scenario development for each SBL-Agri-SSP scenario. Table 1 gives an overview of the SBL-Agri-SSPs, and Table 2 provides the relative change in the key parameters in the LUCIA. More detailed and quantitative descriptions are provided in

Table 1 Summary of the developed future scenarios, the SBL-Agri-SSPs. A more detailed description of the scenarios is given in Online Resource 2

Key characteristics	Reference scenario (Ref)	SBL-Agri-SSP1 (Regional agriculture on the organic sustainable path)	SBL-Agri-SSP2 (Regional agriculture on the BAU scenario path)	SBL-Agri-SSP5 (Regional agriculture on the liberalised path)
Temporal scale	2020	2050	2050	2050
Socioeconomic condition	Current observation	Eur-Agri-SSP1	Eur-Agri-SSP2	Eur-Agri-SSP5
Climate scenario	-	RCP 4.5	RCP 4.5	RCP 8.5
Farm structure	Current status (avg. farm size 24 ha)	More smaller farms with smaller fields (avg. 23 ha)	Lower number of farms (avg. 27 ha)	Almost only large-scale farms with livestock (avg. 60 ha)
Farm types (weight)	Small dairy farm (12 %) Large dairy farm (30 %) Suckler farm (32 %) Orchard farm (14 %) Small farm (12 %)	Small dairy farm (11 %) Large dairy farm (16 %) Suckler farm (35 %) Orchard farm (25 %) Small farm (13 %)	Small dairy farm (10 %) Large dairy farm (28 %) Suckler farm (37 %) Orchard farm (14 %) Small farm (11 %)	Large dairy farm (55 %) Suckler farm (39 %) Orchard farm (6 %)
Crop production	· Both for fodder production and cereals for human consumption	· No synthetic chemical l fertilisers/plant protection products · Only clover allowed for fodder production	· Same as the reference	· Intensive use of mechanisation for larger field size · Eased crop rotation system
New crops	-	·Sunflower, soy, and grain maize (cash crops) ·Clover-grass (fodder)	·Sunflower and grain maize (cash crops) ·Soy (fodder)	·Sunflower and grain maize (cash crops) ·Soy (fodder)
Grassland	· Primarily extensive grass production (meadow/ pasture)	· Intensive management still possible · But only manure allowed	· Same as the reference	· No pasture · Used exclusively for hay production
Orchards	· Orchards combined with extensive grass production · Non-commercial fruit production	· Commercial fruit production sold to regional markets	· Same system as the reference	· Same system as the reference but without subsidies
Livestock production & Fodder system	· Primarily free-range · Low livestock intensity ·Grass-based fodder system * except for large dairy farms	· Smaller scale · Fed exclusively roughage (low milk performance)	· Higher livestock intensity with mechanisation . Same fodder systems as the reference	· Kept in large cattle barns with high livestock intensity · No grazing and no restriction for feed (high milk performance)
Biodiversity measures	· 7% of EFAs on farmland	· 15% of EFAs on farmland · 10% of EFAs on arable land	· 10% of EFAs on farmland · 4% of EFAs on arable land	· No regulation

EFA ecological focused area

*At least 75% of feed must be roughage and the proportion of concentrates (cereals) must be less than 10%

Table 2 Relative change of key parameters under each future scenario in comparison to the current level (100%). The parameter changes except for the ones indicated with an asterisk (*) are our assumptions based on local expert knowledge. Consumer prices reflect the global trend. Please note that the prices of the products sold on direct markets in the SBL-Agri-SSP1 (milk, beef and cherries) are determined independently from the global trend. Labour requirement refers to labour hours required for each farm activity per hectare

Parameter category	Subcategory	Reference	SBL-Agri-SSP1	SBL-Agri-SSP2	SBL-Agri-SSP5	Source
Direct payments	Economic supports	100%	75%	100%	0%	Own assumption
	Ecological supports	100%	125%	110%	0%	Own assumption
Input prices	Hail insurance	100%	150%	150%	150%	Own assumption
	Fuel price	100%	*187%	*187%	100%	L.Felber & SFOE (2021)
Consumer prices	Food commodities	100%	*75%	100%	*88%	Doelman et al. (2018)
Efficiency	Labour requirement	100%	100%	90%	80%	Own assumption

Online Resource 2. Notably, this study does not account for the effects of inflation.

SBL-Agri-SSP1: regional agriculture on the organic sustainable path

Society focuses on sustainable regional development with a high priority on small-scale, environmentally friendly production systems. Farm sizes slightly decrease, while the availability of farm workers increases. The share of large-scale livestock farms also decreases. Farming practices become substantially extensive: the use of mineral fertilisers and any kind of synthetic plant protection products are banned on both grassland and arable land. Cows are fed exclusively fresh grass and hay. The production of fodder, including legumes, on arable land is banned, except for cultivating clover grass to maintain soil nitrogen levels. Therefore, arable crops are cultivated only for human consumption, including soy, sunflower and grain maize, which are feasible due to climate change. Regional direct markets are well established, to the extent that they can offer high prices for locally produced farm products, such as cherries, milk and beef, whose prices are not influenced by the international market. The premium of the subsidies for environmental measures and EFAs (ecological focus areas: the area managed to promote farmland biodiversity) increases, whereas economic measures aimed at supporting agricultural production without considering environmental impacts, such as price support for cereals, are reduced. Furthermore, the conversion of grassland to arable land, currently possible, is banned.

SBL-Agri-SSP2: regional agriculture on the BAU (business-as-usual) path

Farm structures are gradually changing, following the path observed over the past 20 years (Helfenstein et al. 2022). As the average farm size slightly increases, farming efficiency also improves slightly due to increased livestock intensity and larger cattle barns. Larger livestock farms opt for a more efficient fodder system. Labour availability declines due to ongoing urbanisation. Most of the current regulations regarding the use of N fertilisers and synthetic chemical pesticides are maintained. However, as the current trend continues, EFA regulations will become more stringent. Also, a new biodiversity measure is introduced: 4% of arable land should be covered by EFAs. Climate change makes cultivating soy as fodder and sunflower and grain maize for human consumption an option. Livestock farms can intensify with mechanisation. The premium of the subsidies for environmental measures and EFAs increases slightly while remaining the same for economic measures.

SBL-Agri-SSP5: regional agriculture on the liberalised path

Society chooses to focus on economic efficiency, largely neglecting the provision and maintenance of ecosystem services. Thus, rapid structural change is expected. Only large, full-time farms can continue to operate, and part-time farms no longer exist. The field size doubles in comparison to the reference situation. With increasing dependence on fossil energy sources and other fossil-based inputs, the technical efficiency of farming, in terms of labour use, becomes the highest among the scenarios. Highly efficient large-scale livestock farms operate almost exclusively in this region, which contributes to the reduction of farm labour demand. The animals are housed in large cattle barns throughout the year and fed only hay and concentrate; pastures no longer exist. Grassland is used only for hay production. All subsidies, including those for extensively used orchard meadows, are eliminated. Instead, there are fewer limiting regulations. Similar to the SBL-Agri-SSP2, cultivation of soy as fodder, and sunflower and grain maize for human consumption are possible. The existing crop rotation rules, which can be flexible up to certain limits of the crop share on arable land, stay in place, given the assumption that farmers still attempt to maintain soil health. Only the percentage of grain corn acreage becomes less restrictive compared to the current legal restrictions on maximum crop shares.

Integrated Land Use Change and Impact Assessment model

We employed the modelling framework developed by Nishizawa et al. (2022) to evaluate the impacts of the SBL-Agri-SSPs on agricultural land use. This framework had already been applied in the same study region. The present study extended it to capture the impacts of a wide array of agricultural land use drivers, as opposed to the cited study, which was limited to the evaluation of the current direct payment system. The result is "Integrated Land Use Change and Impact Assessment model (LUCIA)," a mathematical (linear) programming-based farm-level model that simulates the changes in agricultural land use for the defined scenarios at the farm level. The underlying assumption is that economically rational crop selections on individual farms lead to optimal land use, which in turn maximises the total gross margin (TGM) at the farm level. While maximizing TGM is only one possible driver for farmers' behaviour, it aligns with the goals of a competitive farm seeking to optimize its chances of long-term financial stability (Hanley et al. 2012). The TGM is calculated by summing total revenues and subsidies, and then subtracting variable costs. This optimisation process was repeated for each of the farm types, typical for the study region (small dairy, large dairy, suckler, orchard and small farms), according to Nishizawa et al. (2022). The land use resulting at the farm level was aggregated across farm types, with weights based on farm size and the number of farms, to form the regional land use.

The farm activities in the farm-level model are constrained by four modules: land, input, feed and agricultural policy. The key assumptions of these modules are (1) no restrictions for converting grassland to arable land or vice versa, except for fields with a slope degree greater than 24%, which were defined as permanent grassland; (2) constant input use and livestock fodder requirements per unit of production; (3) maximum livestock capacity and (4) complete use of manure within a livestock farm. For the present study, new farm activities and management options were added to the existing model to be consistent with the scenario descriptions: new crops, an organic farming system without synthetic inputs, a grass-only fodder system and larger stable systems. We referred to De Ponti et al. (2012) and AGRIDEA (2020) for the yields of organically produced grass, crop and fruit (cherry). Farmers have the following options for the use of orchard meadows across scenarios: (1) turn them into commercial cherry production for regional direct markets (type A, 60 trees per hectare); (2) maintain existing orchards without harvesting cherries, thus only receiving subsidies (type B, 30 trees per hectare); (3) expand orchard meadows without cherry production (type C, 30 trees per hectare); (4) abandon the orchards. All meadows are extensively managed. The descriptions of all farm systems and structures across the developed scenarios can be found in Online Resource 2, along with the modelling parameters defined for each scenario. Online Resource 3 provides a complete list of the gross margins for all crop activities.

For the assessment of socioeconomic changes, we selected the following outputs: TGM (CHF ha^{-1} $year^{-1}$), paid subsidy (CHF ha^{-1}), TGM per labour hour (CHF h^{-1}), N fertiliser use on farmland (kg ha^{-1}), frequency of pesticide applications on arable land (times ha^{-1} $year^{-1}$), livestock intensity on farmland (livestock units ha^{-1}) and cereal, milk, beef and cherry production (kg per farm). The outputs for the ecological assessment are the number of trees, the area of EFAs and the biodiversity scores of individual species groups (ISGs) on farmland. The latter were obtained by coupling SALCA-Biodiversity (BD) (Jeanneret et al. 2014) with the farm model. In this model, each land use for arable land (crops with different intensities and flower strips) and grassland (meadow or pasture with different intensities), including orchards, received scores between 0 and 50 for eleven ISGs (arable land flora, grassland flora, birds, small mammals, amphibians, molluscs, spiders, carabids, butterflies, wild bees and grasshoppers). The scores were determined by the suitability of the land use for each ISG as well as the impacts of the chosen management options on the land. The average score of each land use was calculated based on the food web system on farmland. The biodiversity score at the farm level was calculated by aggregating the average scores of each land use into an area-weighted average. The regional biodiversity score was calculated by aggregating the biodiversity scores of each farm type with the same weights that were used for aggregating the farm-level results into the regional-level results. A detailed description of SALCA-BD can be found in Jeanneret et al. (2014) and Nishizawa et al. (2022).

Data

We obtained the agricultural land use data for 2020 from the canton of Solothurn. These data include spatially explicit information on 4698 fields, containing the type of livestock, crops, management, the number of trees, area size and the average slope degree (ALW 2020). To determine reference grassland yields across intensities, we used a yield equation provided in GRUD (Agroscope 2017). Reference yields of arable crops were derived from regional yield data (2003–2020) for Canton Solothurn (Erdin 2021). We assumed that these yields corresponded to the yield level for extensive management recorded in AGRIDEA because the region's predominant farming system reduces pesticide inputs. We referred to AGRIDEA (2020) for the yield levels for intensive and organic management as well as the gross margins of crops and livestock.

Validation of the scenarios and parametrisation

To validate the SBL-Agri-SSP narratives, we ensured both horizontal and vertical consistency, as suggested by Mitter et al. (2020). The horizontal consistency was checked by assessing the internal consistency across different scenario components within each scenario and across different scenarios, while the vertical consistency was ensured by assessing the consistency across different spatial scales (with the Eur-Agri-SSPs). The initial parametrisation for the reference scenario was validated in the following ways: first, we ran the farm-level model to retrieve the reference land use, which parameters were based on the current data in 2020. Second, we compared the reference land use with the observed land use. In the case of a deviation, we examined the parametrisation of farm activities and constraints and reran the model until the deviation was minimised. This process was repeated for all modelled farm types. Some deviations from the current observation were allowed to realistically model farm activities. For example, the assumption of a specific number of trees per hectare led to a deviation of the total number of trees simulated for the region. This was deemed necessary to maintain a realistic model of orchard meadows as the number of trees within any given field may vary considerably. Furthermore, we verified whether the results simulated by the future scenarios were within plausible ranges by referring to the observation and historical land use data.

Results

Major agricultural land use changes

Figure 3 presents the agricultural land uses, including grassland, orchard meadows with and without commercial cherry production, arable land and flower strips, across the scenarios at the regional and farm levels, simulated with LUCIA given the framework conditions of SBL-Agri-SSPs. Table 3 shows the shares of the regional agricultural land in terms of farming management, fodder production and new crop adoption due to climate change. The reference (Ref) is the modelling result with the input data for 2020. In the SBL-Agri-SSP1, a distinctive change is observed in orchard meadows and flower strips: more than half of the orchard meadows are now used for commercial cherry production, whereas they were previously used exclusively for fodder production, without harvesting cherries. Flower strips as a measure of EFA on arable land, account for around 15% of the arable land. However, for smaller-scale farms (i.e. orchard and small farms), commercial cherry production is still too costly to be an option. The use of grassland increases, but the management intensifies (more cuts per year) due to the roughage-only fodder system, which is demanded under this scenario. In the SBL-Agri-SSP2, the land use share remains similar to the reference scenario. However, more arable land is under extensive management due to higher premiums for ecological measures. Grassland is managed slightly more intensively, similar to the SBL-Agri-SSP1. This is due to the assumed higher livestock capacity on large dairy farms. Consequently, the area of orchard meadows on these farms declines. In the SBL-Agri-SSP2, orchard meadows continue to be used only for conservation purposes: the trees are maintained to receive subsidies. Compared to the regional land use in the reference scenario, a considerable change is observed in the SBL-Agri-SSP5: orchard meadows completely disappear, while grassland is minimised only in the areas with steep slopes and becomes intensively managed. Consequently, most of the farmland is utilised for arable crop cultivation with intensive management. Because of more efficient fodder production, more arable land is allocated for cereal production. The new crops that are likely to be adopted in the case study region are profitable enough to be chosen in LUCIA in all scenarios.

Trade-offs of agricultural land use changes

Table 4 presents the relative changes of the key socioeconomic and ecological indicators across scenarios and farm types in comparison to the reference scenario. The numerical results of all the examined indicators can be found in Online Resource 4 (Table S4.2).

Regional level

In the SBL-Agri-SSP1, despite the largest decline in food prices (Table 2), the total gross margin (TGM) increases the most among all scenarios (+20%). The biodiversity score also increases the most (+12%). However, an increase in subsidy payments is also the highest (+21%), despite the reduction in income support. Against this highest TGM growth, the TGM per required labour hour (hereafter TGM per hour) shows only a modest rise (+4%), compared to that in the SBL-Agri-SSP2 (+13%), indicating more labour-intensive farming in this scenario. In terms of farm production levels in SBL-Agri-SSP1, beef production increases (+21%) due to the assumed increase

Fig. 3 Agricultural land uses across the reference and the SBL-Agri-SSP scenarios at the regional level and farm level. Ref is the reference scenario

Table 3 Shares of the regional agricultural land in terms of farming management, fodder production and the adoption of new crops across the reference and SBL-Agri-SSP scenarios. The grassland with orchards is assumed to be extensively managed. The share of new crops indicates the share of the area utilised for the new crops on the whole arable land in the region. Ref is the reference scenario

Regional land use	Management	Ref	SBL-Agri-SSP1	SBL-Agri-SSP2	SBL-Agri-SSP5
Grassland (100%)	Intensive*	11%	26%	20%	100%
	Extensive	89%	74%	80%	0%
Arable land (100%)	Intensive	70%	0%	44%	86%
	Extensive	30%	0%	52%	14%
	Organic	0%	100%	0%	0%
Fodder production area		72%	69%	70%	40%
Cereal production area		28%	31%	30%	60%
Share of new crops (within arable land)	Soy	-	13%	0%	0%
	Grain maize	-	40%	5%	23%
	Sunflower	-	0%	25%	0%

*Intensity of grassland is determined by the number of cuts

in the number of sucker farms, and the number of trees also substantially increases (+37%) due to the introduction of commercial cherry production. However, both cereal and milk production decline (−29% and −112%). In the SBL-Agri-SSP2, the TGM increases modestly (+10%) and the biodiversity score as well (+7%) paralleling an increase in EFAs (6%). However, the N fertilisers use increases (+16%). In the SBL-Agri-SSP5, both the TGM and the TGM per hour fall considerably (−52% and −100%). This effect was found despite an increase in farm production in all categories except for cherry, as shown by an

Table 4 Relative changes of the resulting key socioeconomic and ecological indicators calculated across the SBL-Agri-SSP scenarios simulated with LUCIA at the regional level and across farm types in comparison to the reference scenario. *TGM* total gross margin, *EFA* ecological focused area. Positive and negative increases are shown in shades of blue and red, respectively

Socioeconomic indicators

Scenario	Farm type	TGM	Subsidy	TGM per hour	N fertiliser	Cereal	Milk	Beef
SBL-Agri-SSP1	Region	20%	21%	4%	-5%	-29%	-112%	21%
	Small dairy farm	35%	17%	2%	11%	-52%	17%	0
	Large dairy farm	17%	27%	16%	6%	-13%	-70%	0
	Suckler farm	37%	12%	11%	35%	-186%	0	4%
	Orchard farm	8%	21%	-14%	-261%	33%	0	0
	Small farm	16%	26%	-10%	-46%	30%	0	0
SBL-Agri-SSP2	Region	10%	10%	13%	16%	-14%	-12%	3%
	Small dairy farm	0%	9%	15%	-1%	18%	-9%	0
	Large dairy farm	0%	2%	6%	24%	82%	17%	0
	Suckler farm	7%	13%	19%	8%	5%	0	-6%
	Orchard farm	0%	12%	12%	-251%	-31%	0	0
	Small farm	-4%	13%	10%	-129%	-610%	0	0
SBL-Agri-SSP5	Region	-52%	0	-100%	54%	60%	24%	55%
	Large dairy farm	-79%	0	5%	35%	84%	42%	0
	Suckler farm	-96%	0	-111%	66%	83%	0	64%
	Orchard farm	-167%	0	-55%	47%	84%	0	0

Ecological indicators

Scenario	Farm type	BD score	EFA	Trees
SBL-Agri-SSP1	Region	12%	11%	37%
	Small dairy farm	10%	9%	50%
	Large dairy farm	11%	10%	42%
	Suckler farm	12%	4%	44%
	Orchard farm	13%	14%	13%
	Small farm	2%	-20%	-114%
SBL-Agri-SSP2	Region	7%	6%	-4%
	Small dairy farm	3%	4%	9%
	Large dairy farm	3%	-21%	-16%
	Suckler farm	4%	3%	4%
	Orchard farm	11%	16%	17%
	Small farm	17%	26%	0%
SBL-Agri-SSP5	Region	-69%	0	0
	Large dairy farm	-67%	0	0
	Suckler farm	-78%	0	0
	Orchard farm	-109%	0	0

Positive change	Negative change	Range
		greater than ±30 %
		±20 % and ±30 %
		±10 % and ±20 %
		±1 % and ±10 %
		within ±1 %

increase in cereals (+60%), milk (+24%) and beef (+55%). These higher production levels were achieved through larger livestock capacities and the specialisation of crops for fodder production, which mainly relies on concentrates. The intensification led to higher use of N fertilisers (+54%) and a decline in the biodiversity score (−69%), followed by the complete abandonment of EFAs and orchard trees.

Farm level

The TGM growth for livestock farms is particularly strong in the SBL-Agri-SSP1. However, large dairy farms produce much less milk (−70%) due to the reduced livestock capacity, while small dairy farms produce more (+17%). The revenue loss from the sale of milk is offset by the assumed higher milk price (0.6 CHF kg^{-1} to 0.9 CHF kg^{-1}). In the SBL-Agri-SSP2, while the biodiversity score of large dairy farms increases (+3%), this farm type uses significantly more N fertilisers and reduces the area of EFAs and the number of trees. In the SBL-Agri-SSP5, all farm types experienced an extensive loss of TGM given the assumed larger farm size and the elimination of subsidies, but these declines are more distinct for suckler and orchard farms (−96% and −167%), which rely on subsidies for their income more than large dairy farms do in the reference scenario.

Figure 4 depicts the differences in biodiversity scores across ISGs, indicating the extent to which agricultural land use potentially impacts them. Even though the overall score of the SBL-Agri-SSP5 decreases considerably (−41%), the score for the arable field flora is higher than the reference. This particular score decreases in the SBL-Agri-SSP1, while all other biodiversity scores increase, reflecting the change in the shares of grassland and arable land. These land use changes also translate to the scores of fauna species that particularly depend on (species rich) grassland. The scores of butterflies, wild bees and grasshoppers are reduced by more than 50% in the SBL-Agri-SSP5 as compared to the other scenarios. The scores for carabid beetles, which are also related to arable land, and for farmland, birds were also significantly reduced as both are impacted by the disappearance of fruit orchards in the SBL-Agri-SSP5.

Discussion

Implications for promoting diversified agricultural landscapes

Contrasting land use changes were observed regarding agricultural diversification across the investigated scenarios. In the SBL-Agri-SSP1 (regional agriculture on the organic sustainable path), commercial cherry production became profitable, and the total number of trees increased substantially, reaching 1981 levels (BfS 1983, the last tree census), and a large area of arable land was also converted into flower strips. This result is primarily due to an assumed higher premium for extensive grassland and other ecological measures and a higher cherry price (1.2 CHF kg^{-1} to 3.8 CHF kg^{-1}), driven by consumer preferences, i.e. higher demand for local produce. These assumptions mitigated the negative impact of the decline in food commodities. Our sensitivity analysis on cherry prices showed that 3.7 CHF kg^{-1} is the threshold for commercial cherry production to be sufficiently incentivised. Consequently, the highest level of farmland biodiversity was achieved in this scenario. The SBL-Agri-SSP2 (regional agriculture on the BAU path) maintains the current level of biodiversity, but uses N fertilisers more extensively. This presents a challenge to the core environmental objectives in the Swiss agricultural policy from 2022 and 2050 (Schweizer Bauernverband 2020; Schweizerischer Bundesrat 2022). Without financial support, orchard trees are in danger of abandonment (Mack 2017). The SBL-Agri-SSP5 (regional agriculture on the liberalised path) demonstrates that the potential for multifunctional use of agricultural land comes at the expense of an increased supply of farm products (i.e. specialising in intensive crop production and abandoning orchard meadows). Agricultural land use in crop monocultures could lead to a decline in soil functionality and productivity (Gregorich et al. 2011), and potentially increase the risk of infectious diseases and pest outbreaks (Keesing et al. 2010; Civitello et al. 2015), apart from the degradation of biodiversity (Marques et al. 2019; Raven & Wagner 2021).

In addition to prices and subsidies, various socioeconomically related assumptions such as the choice of fodder systems, livestock intensity and labour supply affected the multifunctional nature of regional agriculture and biodiversity. As shown in the SBL-Agri-SSP2, large dairy farms with the same fodder system as the reference scenario but with higher livestock capacity led to a reduction in the overall EFAs on the farms. The loss of biodiversity on grassland was, however, compensated by the mandatory implementation of EFAs on arable land. Regarding labour supply, in the SBL-Agri-SSP1, securing sufficient farm labour is a prerequisite for the agricultural system assumed in this scenario, which is highly labour-intensive due to the total ban on synthetic inputs, exclusive grass-based fodder systems and commercial cherry production. This scenario assumed a 14% increase in regional farm labour compared to the reference scenario, which could pose a legitimate challenge for this scenario, given a general trend of declining farm populations in advanced countries (Eurostat 2022). In the SBL-Agri-SSP5, higher agricultural efficiency was considered, which reduced the labour demand for field activities by 20% and for managing dairy cows by 30%. Nonetheless, large dairy farms could not reach the maximum livestock capacity due to the lower availability of labour. The sensitivity analysis showed that one additional full-time labour unit (2600 h) is required to generate almost the same TGM as obtained in the reference scenario.

Compared to the impacts of these changed socioeconomic conditions, the long-term impacts of climate change through

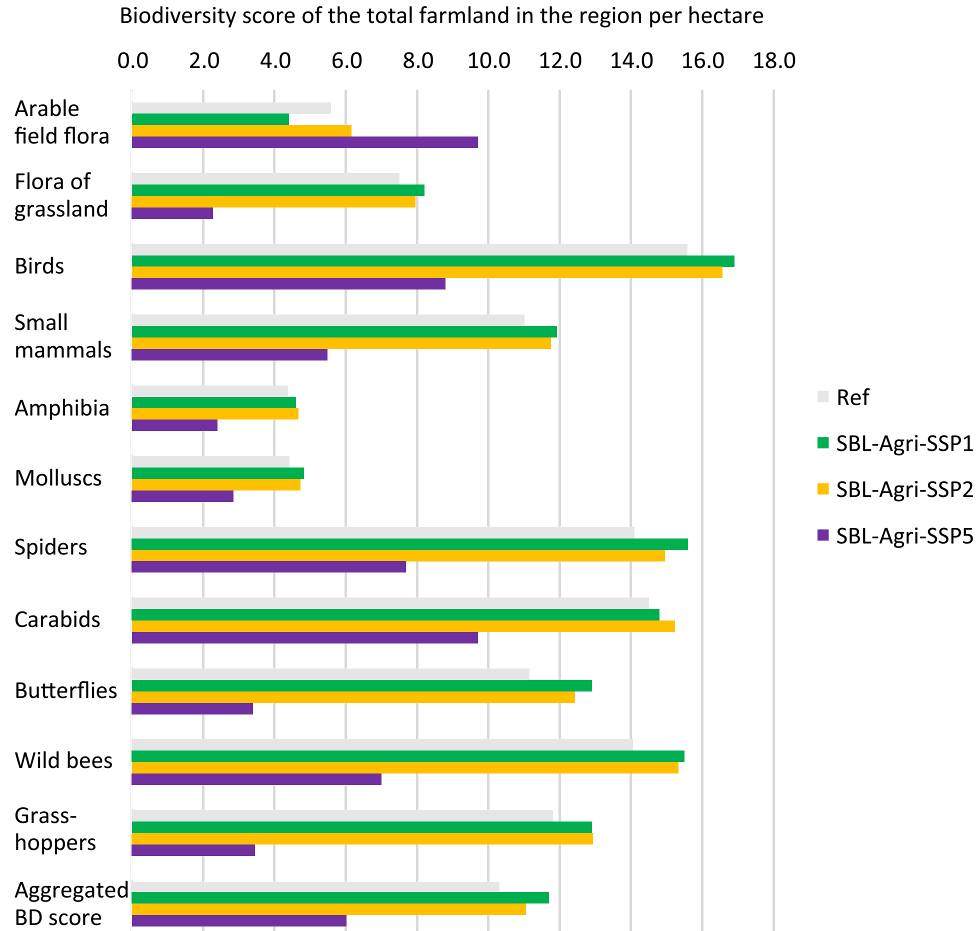

Fig. 4 Absolute change in the biodiversity (BD) scores of individual species groups and the aggregated scores over species groups. The biodiversity scores are area-weighted averages for the whole regional farmland

yield changes were minor in this study (Online Resource 1). This is not only because the estimated yield changes from the baseline remained rather marginal, independent of the chosen climate scenario, but also because agriculture in Switzerland is highly dependent on the subsidy system. This finding supports the claim that agricultural land use in Switzerland is less sensitive to climate change than other drivers (Lehmann et al. 2013; Klein et al. 2014; Fronzek et al. 2019). Instead, in all scenarios, the more noticeable impacts of climate change appeared as the adaptation of new crops, as the farmers' choice of the new crops in the model generated higher incomes.

The characteristics of farms play an important role in influencing changes in agricultural land use (van Vliet et al. 2015) and the effectiveness of agricultural policies (Huber et al. 2023). By accounting for farm heterogeneity, we also demonstrated differences in the sensitivity of farm-level indicators among farm types to specific drivers. Because suckler and orchard farms rely more on subsidies than dairy farms, their TGMs are sensitive to changes in the subsidy scheme. Particularly in cases in which subsidies are eliminated, the economic losses for these farm types could be substantial. Differences were also observed in the adoption of EFAs. There was no incentive for livestock farms to implement EFAs on arable land beyond the minimum required. In the SBL-Agri-SSP2, large dairy farms even reduced EFAs and orchard meadows, despite an increase in the premium for ecological measures. Additionally, our assumption that smaller farms face significant structural changes, e.g. no more small and part-time farms in the SBL-Agri-SSP5 aligns with Arnalte-Mur et al. (2020) who found that small farms are highly impacted by social changes.

This study uncovered several important trade-offs. The increase in subsidy expenditure was unavoidable to promote biodiversity and diverse agricultural landscapes, driven by commercial cherry production and more ecological measures. The increase in the TGM for farms does not necessarily imply a commensurate increment in the rate of TGM per hour. Another trade-off appeared between production level and farmland biodiversity. The extensification of agricultural practices in the SBL-Agri-SSP1 scenario increased the biodiversity level but resulted in a substantial reduction in cereal and milk production. Conversely, the agricultural intensification in the SBL-Agri-SSP5 scenario led to a significant increase in all farm produce, excluding cherries, which came at the expense of biodiversity. This finding confirms many other previous studies that demonstrated the trade-off between intensification and specialisation in agricultural systems and biodiversity (Klasen et al. 2016;

Dudley & Alexander 2017; Beckmann et al. 2019; Zabel et al. 2019), implying that increasingly stringent agri-environmental regulations may be linked to national food security issues. Mann and Kaiser (2023) found that the failure of recent ambitious agri-environmental objectives in Switzerland stems from insufficient measures to maintain a national self-sufficiency rate, while Finger and Möhring (2022) argued that the implementation of synthetic pesticide-free production in Switzerland necessitates a diverse array of policy instruments that extend beyond purely financial incentives. Correspondingly, this study recommends that food and agri-environmental policies should address broader issues that promote diversified agriculture while acknowledging diverse impacts across different farm types and potential challenges and trade-offs. These encompass securing a rural agricultural workforce to mitigate declining farm populations (see Dutta et al. 2017), maintaining national food self-sufficiency, managing food consumption preferences and patterns that potentially contribute to an increase in prices of locally produced products (see Mann & Kaiser 2023) and implementing feed systems and livestock intensities that inhibit the extensive use of arable land.

Limitations of the study

This study's integrated model-based scenario approach addressed scale issues related to investigating the impacts of global future pathways on regional agricultural land use. The approach enables comparative studies in other Swiss and European regions under the common SSP scenario framework, considering the regional variation in the implications of global drivers (Vanbergen et al. 2020; Debonne et al. 2022). This study, however, did not implement an even smaller reference unit (i.e. parcel or field) for decision-making that could connect with real physical entities as opposed to the more abstract entities that were considered. Modelling at a high spatial resolution can generate more refined future projections based on individual farmers' decisions and then facilitate stakeholder engagement in scenario development (Brown & Castellazzi 2014). We also identified three major limitations to our applied farm-level model. First, even though our focus was on comparative analysis across scenarios, the static nature of our farm-level model could not account for the dynamic process of farm management and development over time. For example, substantial investments that require long-term decisions might be needed to realise the structural changes to farms and the improvement of productivity assumed in the scenarios (Neuenfeldt et al. 2019; Giller et al. 2021). Orchard planning also happens on a decade-by-decade basis rather than yearly. Second, in the interviews conducted by Suškevičs et al. (submitted), the stakeholders in the same study region mentioned various agricultural technologies that could potentially be adopted. However, our ability to explicitly consider the impacts of technologies was limited. These impacts were reflected only in the assumed changes in prices and labour requirements. Lastly, even though data on farm labour use and the agricultural workforce are often remarkably inaccurate (Nye 2018), it is crucial to consider a flexible farm labour supply, especially when structural changes in a farm reduce family farm labour, as anticipated in the SBL-Agri-SSP5. The change in agricultural efficiency through investment in agricultural technology is a key determinant of agricultural land use dynamics (Popp et al. 2017; Stehfest et al. 2019). Future studies should explicitly consider the adoption of new agricultural technologies and explore how the associated efficiency changes would impact farm and seasonal labour demand as well as agricultural land use patterns. Eventually, other climate change effects could have a considerable influence on yield patterns. For example, CO_2 fertilisation effects might at least partially compensate for potential reductions in plant growth and net primary production (Leung et al. 2022). Nonetheless, it seems exceedingly optimistic to posit that the effects of increased ambient CO_2 may completely manifest as yield improvements (Long et al. 2004, 2006; Wang et al. 2020). Furthermore, given the anticipated increase in drought frequency and severity in large parts of Europe, including Switzerland (Grillakis 2019; Vicente-Serrano et al. 2022), one should carefully interpret our results concerning climate change within the limitations of the approach we employed for the incorporation of climate change into LUCIA.

Conclusions

This study identified the socioeconomic implications of agricultural LUCs for promoting agriculturally diverse land uses in the long term. By explicitly accounting for farm heterogeneity and regional characteristics of socioeconomic and climatic conditions, we addressed the scale issues that inevitably arise when examining the effects of global drivers on regional agricultural land use impacted by farm-level decisions. To our knowledge, this study is the first to downscale the Eur-Agri-SSPs to a small region representing multifunctional agricultural landscapes in Switzerland and infer regional future scenarios. The results suggest that food and agri-environmental policies need to consider a broader range of land use drivers beyond financial support for farms for future agricultural diversification while acknowledging potential trade-offs and diverse impacts across different farm types. We conclude that our established approach, which simulated agricultural land use changes on a smaller scale with various socioeconomic and climate conditions that reflect regional trends and traits, is easily applicable to other regions in Europe and allows us to envision a wider set of tangible future implications across these regions towards desired pathways.

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Data Availability The datasets analyzed during the current study are available from the corresponding author on request.

Declarations

Informed consent Informed consent to participate in the study was obtained for all participants in this study.

Conflict of interest The authors declare no competing interests.

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Appendix: Correction for Table 4

The corrected Table 4 and the modified corresponding text for the section “Trade-offs of Agricultural Land Use Changes” are provided below. These corrections have no impact on the overall interpretation of the results or the main conclusions of the study.

Corrected: Trade-offs of agricultural land use changes

Table 4 presents the relative changes of the key socioeconomic and ecological indicators across scenarios and farm types in comparison to the reference scenario. The numerical results of all the examined indicators can be found in Online Resource 4 (Table S4.2).

Regional Level: In the SBL-Agri-SSP1, despite the largest decline in food prices (Table 2), the total gross margin (TGM) increases the most among all scenarios (+25 %). The biodiversity score also increases the most (+14 %). However, an increase in subsidy payments is also the highest (+27 %), despite the reduction in income support. Against this highest TGM growth, the TGM per required labour hour (hereafter TGM per hour) shows only a modest rise (+4 %), compared to that in the SBL-Agri-SSP2 (+15 %), indicating more labour-intensive farming in this scenario. In terms of farm production levels in SBL-Agri-SSP1, beef production increases (+26%) due to the assumed increase in the number of suckler farms, and the number of trees also substantially increases (+59%) due to the introduction of commercial cherry production. However, both cereal and milk production decline (−22 % and −53 %). In the SBL-Agri-SSP2, the TGM increase modestly (+11 %), and the biodiversity score as well (+7 %) paralleling an increase in EFAs (+6 %). However, the N fertilisers use increases (+19 %). In the SBL-Agri-SSP5, both the TGM and the TGM per hour fall considerably (−34 % and −50 %). This effect was found, despite an increase in farm production in all categories except for cherry, as shown by an increase in cereals (+147 %), milk (+32 %), and beef (+122 %). These higher production levels were achieved through larger livestock capacities and the specialisation of crops for fodder production, which mainly relies on concentrates. The intensification led to higher use of N fertilisers (+118 %) and a decline in the biodiversity score (−41 %), followed by the complete abandonment of EFAs and orchard trees.

Farm level: The TGM growth for livestock farms is particularly strong in the SBL-Agri-SSP1. However, large dairy farms produce much less milk (−41 %) due to the reduced livestock capacity, while small dairy farms produce more (+20 %). The revenue loss from the sale of milk is offset by the assumed higher milk price (0.6 CHF kg−1 to 0.9 CHF kg−1). In the SBL-Agri-SSP2, while the biodiversity score of large dairy farms increases (+3 %), this farm type uses significantly more N fertilisers (+32 %) and reduces the area of EFAs and the number of trees (−17 % and −14 %). In the SBL-Agri-SSP5, all farm types experienced an extensive loss of TGM given the assumed larger farm size and the elimination of subsidies, but these declines are more distinct for suckler and orchard farms (−49% and −63%), which rely on subsidies for their income more than large dairy farms do in the reference scenario.

Corrected: Table 4 Relative changes of the resulting key socioeconomic and ecological indicators calculated across the SBL-Agri-SSP scenarios simulated with LUCIA at the regional level and across farm types in comparison to the reference scenario. TGM: total gross margin. EFA: ecological focused area. Positive and negative increases are shown in shades of blue and red, respectively

Socioeconomic indicators

Scenario	Farm type	TGM	Subsidy	TGM per hour	N fertiliser	Cereal	Milk	Beef
SBL-Agri-SSP1	Region	25%	27%	4%	-4%	-22%	-53%	26%
	Small dairy farm	54%	21%	2%	13%	-34%	20%	-
	Large dairy farm	21%	36%	19%	6%	-12%	-41%	-
	Suckler farm	58%	14%	13%	53%	-65%	-	4%
	Orchard farm	8%	27%	-12%	-72%	49%	-	-
	Small farm	19%	34%	-9%	-31%	30%	-	-
SBL-Agri-SSP2	Region	11%	12%	15%	19%	-13%	-10%	4%
	Small dairy farm	0%	10%	18%	-1%	23%	-8%	-
	Large dairy farm	0%	3%	6%	32%	2%	20%	-
	Suckler farm	8%	15%	23%	9%	5%	-	-6%
	Orchard farm	0%	14%	14%	-72%	-23%	-	-
	Small farm	-3%	15%	12%	-56%	-86%	-	-
SBL-Agri-SSP5	Region	-34%	-100%	-50%	118%	147%	32%	122%
	Large dairy farm	-44%	-100%	5%	55%	458%	74%	-
	Suckler farm	-49%	-100%	-53%	194%	111%	-	176%
	Orchard farm	-63%	-100%	-35%	88%	518%	-	-

Ecological indicators

Scenario	Farm type	BD score	EFA	Trees
SBL-Agri-SSP1	Region	14%	13%	59%
	Small dairy farm	11%	9%	101%
	Large dairy farm	13%	11%	72%
	Suckler farm	13%	4%	79%
	Orchard farm	14%	16%	15%
	Small farm	2%	-17%	-53%
SBL-Agri-SSP2	Region	7%	6%	-4%
	Small dairy farm	3%	5%	10%
	Large dairy farm	3%	-17%	-14%
	Suckler farm	4%	3%	4%
	Orchard farm	13%	20%	21%
	Small farm	20%	36%	0%
SBL-Agri-SSP5	Region	-41%	-100%	-100%
	Large dairy farm	-40%	-100%	-100%
	Suckler farm	-44%	-100%	-100%
	Orchard farm	-52%	-100%	-100%

Positive change	Negative change	Range
		greater than ±30 %
		±20 % and ±30 %
		±10 % and ±20 %
		±1 % and ±10 %
		within ±1 %

4. Case Study 3

Modelling Alternative Economic Incentive Schemes for Semi-Natural Grassland Conservation in Estonia

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Modelling Alternative Economic Incentive Schemes for Semi-Natural Grassland Conservation in Estonia

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Abstract
Semi-natural grasslands (SNGLs) in Estonia are threatened by abandonment. This threat is leading to concerns about the degradation of biodiversity within grassland communities. Despite the high relevance of economic incentives in this context, how such incentives influence land managers' decision-making regarding the agricultural use of SNGLs has not been investigated. To obtain its socio-ecological implications for policy-making, we developed regionally specific agricultural scenarios (compensation payments, livestock capacity, hey export, and bioenergy production) and an interdisciplinary modelling approach that made it possible to simulate agricultural land use changes through land managers' responses to varied economic conditions. Through this approach, we found that some economic factors hampered the use of SNGLs: the moderate profitability of beef production, labour shortages, and the relatively high profitability of mulching. We observed a positive relationship between SNGLs and habitat suitability for breeding and feeding birds. However, due to the high maintenance costs of SNGLs, the modelling results indicated that increasing the use of SNGLs through public budgets caused crowding-out effects, i.e., the deteriorating market integration of regional agriculture. This study emphasises the need for policy measures aimed at cost-effective, labour-efficient management practices for SNGLs.

Keywords Semi-natural grasslands · Abandonment · Sustainable rural development · Integrated land-use modelling · Economic viability · Habitat quality

Introduction

Semi-natural grasslands (SNGLs) support a diverse range of species that have evolved to thrive under unique conditions (Brüggeshemke et al., 2022; Prangel et al., 2023). Across Europe, vast rural areas are covered by species-rich semi-natural habitats, including meadows and wooded pastures (Wilson et al., 2012). SNGLs in Estonia have exceptionally high levels of biodiversity, in particular wooded meadows (76 species/m^2; Kukk (2004); Kukk and Kull (1997)), alvars (63 species/m^2; Pärtel et al. (1999)), floodplain meadows (50 species/m^2; Truus and Puusild (2009)), and coastal meadows (34 species/m2; Burnside et al. (2007)), among the most species-rich habitats in Northern Europe (Benstead et al., 1999). The benefits associated with the conservation of SNGLs extend beyond biodiversity; SNGLs are directly linked to various socio-economic factors in rural communities (Perpiña Castillo et al., 2021). For example, conservation efforts provide employment opportunities for agricultural production, contribute to the preservation of cultural heritage and traditional cultural landscapes, and support ecotourism activities (Veidemane, et al. 2019). This is why SNGLs are said to be a part of broader socio-ecological systems, contributing to the sustainable development of rural communities (Burnside et al., 2007; Pärtel & Helm, 2007; Sammul et al., 2008).

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Despite increasing awareness of SNGLs as high nature-value grasslands, SNGLs in Estonia have been continuously declining since the 1950s (Kana et al., 2008). Between 1957 and 1960, 90% of coastal meadows were grazed or mown, whereas between 1992 and 1995 only 35% of coastal meadows remained in use (Kaisel et al., 2004). As of 2020, there were 130,000 hectares of SNGLs in Estonia, but the current area is estimated to be insufficient to secure the survival of the habitats of the protected species associated with these areas (Helm and Toussaint, 2020). Increasing evidence suggests that the abandonment of SNGLs leads to biodiversity loss within grassland communities (Kull & Zobel, 1991; Pärtel et al., 2005; Ward et al., 2013). Agricultural management, particularly, grassland-based extensive beef production through SNGLs, plays a crucial role in maintaining SNGLs (Eriksson, 2022; Directorate-General for Environment, 2023). Reintroducing traditional management practices is a recommended strategy (Valkó, et al., 2018) but it requires support through appropriate policies, such as regulations, subsidies, or innovative measures that aim to increase the demand for grassland products (Waldén and Lindborg, 2018). The economic viability of managing SNGLs is a highly relevant factor in this context (Kikas et al., 2016; Zindler et al., 2023). While there are some studies incorporating economic analysis into the evaluation of grassland conservation policies for their cost-effectiveness (Gerling et al., 2023; Robert et al., 2017; Wätzold et al., 2016), how it influences land managers' decision-making, particularly focusing the agricultural use of SNGLs, has been less studied. Most studies on conservation measures for SNGLs have been concentrated in the agronomic or ecological fields (Waldén and Lindborg, 2018; Johansen et al., 2019; Villoslada Peciña et al., 2019; Herzon et al., 2021).

Therefore, this study aims to explore how the agricultural use of SNGLs can be promoted by examining the effects of various economic incentives for land managers, using a rural Estonian region as a case study. We assess the impacts of resulting land use changes through the land manager's decision-making considering various factors crucial to sustainable rural development. To this end, we develop an interdisciplinary land use impact assessment framework, and integrated land use modelling. Within this modelling framework, agricultural scenarios are developed that describe alternative regionally specific economic incentives. These scenarios reflect the current regional strategies for increasing the demand for grass products. The bio-economic farm model (BEFM), in turn, simulates land use change via land managers' decision-making under the scenario conditions. We estimate habitat quality on agricultural land by combining an ecological model with the BEFM to extend the assessment of land use changes to both ecological and socio-economic dimensions. Given that agriculture is closely tied to rural development, we assess the impacts of the agricultural scenarios based on three aspects: cultural heritage, rural economic profitability, and farmland biodiversity.

With this approach, we address the following research questions:

1. How will different economic conditions influence the agricultural use of SNGLs?
2. How will the change in grassland use affect rural economic profitability and farmland biodiversity?
3. What trade-offs are observed between these three considered aspects of sustainable rural development?

Methodology and Data

Case Study Region

Our case study region is Lääne County (Fig. 1), a western coastal area of Estonia facing the Baltic Sea to the west. It consists of three municipalities: Lääne-Nigula, Haapsalu Town, and Vormsi (a small island in the far west of Lääne County). We excluded Vormsi from this study because the land on the island is rarely used for agriculture. The area is characterised as predominantly flat land. The average annual temperature is between 6.1 °C and 7.8 °C, with precipitation of 500–700 mm.

Based on the map layer of SNGL in the Estonian nature information system (2022) (Estonian Environment Agency/EEA), the map layer of the inventory of SNGLs of the Estonian Semi-Natural Community Conservation Association (2022) (Estonian Semi-Natural Community Conservation Association/ ESCCA) and the Register of Agricultural Support and Agricultural Parcels (2022) (Agricultural Register and Information Board/ARIB), and the map layer of SNGL maintenance support (ARIB, 2022), approximately 43,000 hectares is used for agriculture, 57% of which is arable land, 31% is SNGLs and 12% is more intensively used permanent grassland. In this study, we defined SNGLs as naturally grown grasslands without planting cultivated plant seeds, ploughing, or fertilising at a specific time, while permanent grasslands as grass fields without being interrupted by the cultivation of arable crops for at least 5 consecutive years. Fertilising is possible for permanent grassland. SNGLs fall under permanent grassland but require additional conditions that natural biota have been formed under the influence of long-term human activities (mowing, grazing), which are included in the range of habitats protected at the EU level. Approximately half of all SNGLs are estimated to be abandoned in Lääne County. We counted fields as abandoned that have not received agri-environmental payments (AEPs) or direct payments in the last 2 years. Over time,

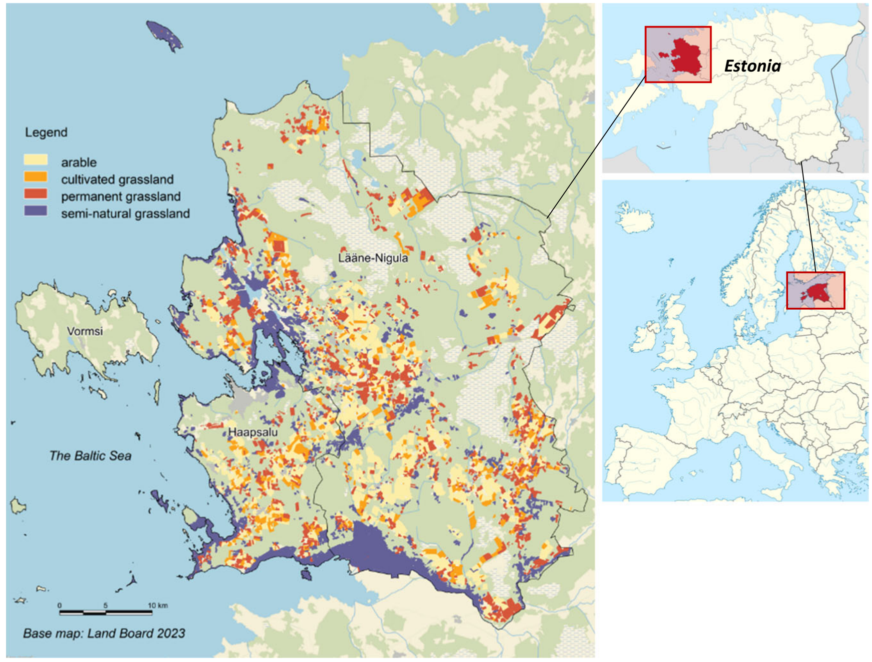

Fig. 1 Land use classes in the case study region, Lääne County (Estonia) on the left (Source: the map layer of SNGL Estonian nature information system (EEA), the inventory of SNGLs of the Estonian Semi-Natural Community Conservation Association (ESCCA), and the Register of Agricultural Support and Agricultural Parcels (ARIB), and the map layer of SNGL maintenance support (ARIB). The maps on the right are distributed under a CC BY-SA 3.0 licence)

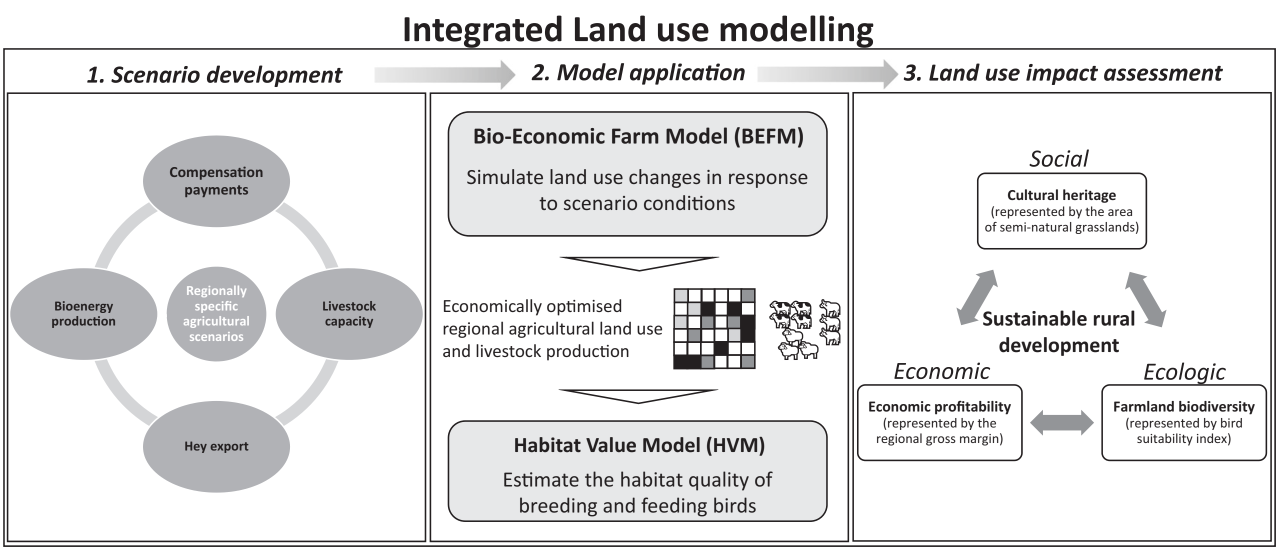

Fig. 2 Framework of integrated land use modelling

abandoned fields are typically covered by shrubs, reed beds, or forests.

The main crops on AL are field grass (referred to as cultivated grasslands in Estonia), winter wheat, spring barley, and winter rapeseed. Based on the map layer of the inventory (ARIB, 2022), the total number of farm holdings that own more than one hectare of land in Lääne County is 476 with an average farm size of 78 hectares. Most farm holdings are mixed farms with combinations of arable crops and animal husbandry (mostly beef cattle for meat production) or focused on crops. The region is suitable as an example because most SNGLs have been preserved in this area; thus, various conservation efforts have been made, including the restoration of abandoned SNGLs and the construction of a biomass heating plant to increase the demand for grass products.

Integrated Land Use Modelling

Figure 2 illustrates the framework of the integrated land use modelling. The first part is the scenario development. The second part represents the integrated modelling application that combines the BEFM with the Habitat Value Model (HVM). The third and final part is the assessment of land use changes resulting from the scenarios, considering three aspects of sustainable rural development: cultural heritage for a social aspect (represented by the area of SNGLs), economic profitability for an economic aspect (represented by the regional gross margin (GM)), and farmland biodiversity for an ecological aspect (represented by bird suitability index). We first explain the applied models and then introduce the scenarios and the indicators for the assessment of sustainable rural development.

Bio-Economic Farm Model (BEFM)

General approach

The aim of developing the BEFM was to simulate the change in agricultural land use in response to varying economic conditions based on the land managers' decision-making. Thus, we consulted earlier work on BEFM, such as the multi-objective decision support tool for agro-ecosystem management (MODAM) by Schuler and Kächele (2003), Schuler et al., (2013, 2020), and Uthes et al. (2010), as well as more recent studies by Nishizawa et al. (2022, 2023).

We first pooled 1-year data on 8689 agriculturally used fields in Lääne-Nigula and Haapsalu Town that were registered in ARIB (2022) to form "the regional farm" in accordance to Rounsevell et al. (2003) and Glemnitz et al. (2015). This regional farm represents the land-use decision-making of all land managers in the targeted areas and disposes of all available farm resources as one aggregated entity, given established farm structures, including total livestock, farmland, and farm labour. ARIB (2022) includes the field size, crop type and land use (permanent grassland or arable) of each field but no information on the grassland type (SNGLs, permanent grassland, or cultivated (field) grassland) or SNGL management practices (grazing, mowing, or abandoned). To obtain these missing data, a GIS-based dataset retrieved from the map layer of SNGL maintenance support (2022), a map layer of SNGLs in the Estonian nature information system (2022) and a map layer of the inventory of SNGLs of the Estonian Semi-natural Community Conservation Association (2022) was used. Cultivated grassland was distinguished by AL.

In the optimisation process, the total GM of the region is maximised, assuming that the regional farm engages in profit-maximising behaviour. Hence, regional agricultural land use is understood as the manifest of their aggregated land-use decisions. The optimisation algorithm follows the general form of linear programming (LP) for n activities and m structural restrictions:

$$\text{maximise} \quad Z = \sum_{j=1}^{n} c_j x_j \tag{1}$$

$$\text{subject to} \quad \sum_{j=1}^{n} a_{ij} x_j \leq b_i \quad \text{for all } i = 1, 2, \ldots, m \tag{2}$$

and

$$x_j \geq 0 \quad \text{for all } j = 1, 2, \ldots, n \tag{3}$$

Z is the total GM of the regional farm, x represents the decision variables for the farm activities, c denotes the GM or cost per unit of activity, a is the technical coefficients, and b represents resource availability (land and labour) or the upper/lower limits of activities.

By maximising the regional GM, the economically optimal combination of crop activities and their area sizes, and, in our case, the optimal livestock numbers can be determined. Fixed costs, such as investments, paid labour, or rented land, were excluded from the optimisation, as the focus of this study was on short-term decision-making by the regional farm in response to changing economic conditions. Therefore, all the costs considered in LP are directly related to a production level (i.e. variable costs). The operation of LP was conducted with mathematical programming software (General Algebraic Modelling System —GAMS, version 31.2.0).

Modelled agricultural activities and constraints

Model activities The following field activities were considered for the different site types (Table 1):

SNGLs: grazing for beef cattle and sheep; mowing (1 cut) for hay and biomass production for generating heat (bioenergy); and mulching. Ploughing and fertilisation are not allowed. Biomass production for bioenergy is harvested only from SNGLs, and its demand is limited by the existing demand for biomass heating. Grass cut through mulching on SNGLs is collected from fields as a recommended practice for the environment to preserve the original soil characteristics (Janssens et al., 1998; Bakker and Berendse, 1999) but is usually disposed of due to its low quality for feed purposes (Lepmets 2015). The remaining fields, which are not used by any of these activities, are counted as abandoned fields. The initial restoration costs associated with restoring abandoned SNGLs were not considered in the BEFM. Given that different grass habitats provide different yields and nutritional values, we assumed that grazing was conducted on coastal meadows and mowing was carried out on alluvial meadows.

Permanent grassland: grazing for all livestock types; mowing for hay production (1–3 cuts); and "mixed" (mowing for hay or silage production and subsequent grazing on the

Table 1 Modelled field activities based on site types and livestock husbandry

SNGLs	Permanent grassland	Arable land	Livestock husbandry
• Grazing • Mowing • Biomass production for bioenergy • Mulching	• Grazing • Mowing (1 cut/year) • Mowing (2 cut/year) • Mowing (3 cut/year) • Mixed (hay-grazing) • Mixed (silage-grazing) • Mulching	• Field grass (hay and silage) • Mechanically tilled fallow • Field beans[a] • Field peas[a] • Green maize[a] • Oats[a] • Rye[a] • Spring barley[a] • Spring and winter wheat[a] • Potatoes • Spring and winter rapeseed • Buckwheat[a]	• Dairy cows • Offspring of adult dairy cows • Beef cattle • Offspring of adult beef cattle • Sheep

SNGLs semi-natural grasslands

[a]arable crops with a possible choice of three different management options (tillage, reduced tillage, and direct seeding). Other crops are managed only through ploughing

same field). These activities must not be interrupted by a crop rotation scheme and managed with fertilisation but without ploughing or pesticides. Unlike mulching on SNGLs, grass cut through mulching on permanent grassland is left on the fields. Producing hay for export (e.g. to Saudi Arabia) is possible, and both SNGLs and permanent grassland can be utilised for that purpose. We assume that the export of hay is carried out on a contractual basis.

Arable land: field grass for baling or silage; mechanically tilled fallow; and twelve different crops (field beans, field peas, green maize, oats, rye, spring barley, spring wheat, winter wheat, potatoes, spring rapeseeds, winter rapeseeds, and buckwheat), which follow a crop rotation scheme (see Table 3). While potatoes and rapeseeds are managed only through ploughing, three different management options are available for the other crops: tillage, reduced tillage, and direct seeding. Buckwheat, potatoes, and winter and spring rapeseeds are modelled solely as cash crops, while the other crops can be used for sale or as feed. Organic farming is not considered because it is not widely practised in the region according to regional experts.

For livestock husbandry, we modelled dairy cows, beef cattle, their offspring, and sheep by referring to Nishizawa et al. (2022). The observed number of sheep was counted as one LU of beef cattle for every six sheep and added to the total number of beef cattle cows to determine the initial livestock capacity.

The GM per unit of activity was calculated as revenue = yield × producer price − variable cost + public payments. Producer prices, variable costs, and public payments were based on the average for the 2019–2021 period taken from the Estonian farm data handbook published by the Agricultural Research Centre in Estonia (ARC, 2021). This source differentiates variable costs over three levels of yields. We selected the yield level that best matched the average yield over the last 5 years (2017–2021) in the study region, as reported by Statistics Estonia (https://www.stat.ee). Different yield levels were not considered in this study as they play no significant role in the regional GM or habitat suitability values (Glemnitz et al., 2015). The variable costs included all costs involved in fieldwork steps, such as input use (seeds, fertilisers, and pesticides), machinery use, and transportation.

As the ARC (2021) provides no activities for SNGLs, we referred to Piirsalu et al. (2019) for yield information; their results are based on an empirical study in Estonia, whereas the variable costs were extrapolated from those of permanent grassland in ARC (2021). As most locations of SNGLs tend to be localised in marginalised areas such as coastal areas (see Fig. 1), we considered additional machinery and fuel costs (130 €/ha) for travel and transport to and from farmsteads to SNGLs based on expert judgements. The GMs of dairy cows and beef cattle assumed a dairy cow with 9000 kg of milk production per year, as reported by Statistics Estonia, and one beef cattle with 650 kg, as this is the standard size recorded in the ARC (2021).

We considered two types of public payments paid per hectare per year (see Table 3): i. AEPs include direct payments such as the SAPs for which all used agricultural fields are eligible, payments for so-called greening measures for maintaining permanent grassland and diversifying crops, and payments for following a crop rotation scheme Table 3; ii. compensation payments are paid additionally for SNGL activities on top of direct payments except for mulching.

Labour supply: The BEFM was also allowed to hire seasonal labour for harvesting up to the observed level (18,000 h) with a wage of 10 €/h (both from Statistics Estonia). As we could not obtain information on the share of

Table 2 Modelled activities for producing grass products

Site type	Activity for grass products	Yield (t/ha)	Price of hay (€/t)	Variable costs (€/ha)	AEPs (€/ha)	Compensation payments (€/ha)	Labour demand (h/ha)
SNGLs	Grazing	1.2	0	70 (+130)	160	150	1.9 (+1.0)
	Mowing[a]	1.9	70	131 (+130)	160	80	2.4 (+1.0)
	Bioenergy production[a]	1.9	70	131 (+130)	160	80	2.4 (+1.0)
	Mulching	0	0	53 (+130)	160	0	0.6 (+1.0)
Permanent	Grazing	3.0	0	161	160	0	2.7
Grassland	Mowing 1 cut/year[a]	3.4	70	188	160	0	2.4
	Mowing 2 cuts/year[a]	6.0	70	335	160	0	5.0
	Mowing 3 cuts/year[a]	9.7	70	539	160	0	6.5
	Mixed (hay-grazing)	5.1	0	254	160	0	3.7
	Mixed (silage-grazing)	6.4	0	222	160	0	4.0
	Mulching	0	0	53	160	0	0.6
Arable land	Field grass (silage)	5.3	0	286	210	0	4.1
	Field grass (silage/bale)	5.3	0	409	210	0	5.9

The price of hay is 70 €/ha only when hay is sold on the market; otherwise, it is 0 €/ha. Additional variable costs and labour for SNGL activities are presented separately with brackets

[a]The hay produced from these activities can be used for feeding livestock and/or for sale

the total agricultural labour units that were actually allocated to field and livestock activities, we derived this information from the observed land use, by multiplying hectares with the labour needed per field and livestock activity.

Labour requirement: Each fieldwork and type of livestock husbandry requires specific labour hours per hectare or LU. Due to a lack of data in Estonia, we referred to MLUK (2021), an agricultural handbook of Brandenburg in Germany, as it shares comparable conditions with its rich grassland region. To account for the specific conditions of the study area, we added 1.0 h/ha (based on expert knowledge) to the calculated labour requirement for the SNGLs activities. This adjustment reflects the increased labour intensity resulting from the isolated locations of SNGLs. Please note that this was introduced in addition to the extra machinery costs. Table 2 summarises the key parameters of the modelled grassland activities. All the parameters and their data sources are provided in supplementary material 1.

Model constraints The optimal agricultural production pattern had to meet the following restrictions: market conditions (producer prices, hay export contracts, demand for biomass heating plants); EU agricultural regulations for receiving AEPs (maintaining permanent grassland, crop diversification, and ecological focused area); crop rotations; and available resources (land and labour). Table 3 lists all the restrictions implemented in the BEFM in the baseline scenario, which provides a model output based on the observed values of the required parameters.

The following assumptions were made. First, the observed allocation of land among the three site types—SNGLs, permanent grassland, and arable land—was assumed to be fixed, preventing any expansion/reduction of the existing levels. This fixed distribution aligns with current regulations in the study region, where the transformation of SNGLs into permanent grassland or arable land is infrequently observed and the conversion of permanent grassland into arable land is expressly prohibited under the European Agricultural Policy’s greening measure (CAP), with few exceptions.

Second, we assumed that the regional farm was obliged to follow all the constraints listed in Table 3 to receive AEPs. Field beans and peas were considered ecological measures, as growing legumes is a typical greening measure. Regarding crop diversification, we checked whether the number of arable crops chosen in the baseline simulation was close to the observed number of crops, rather than adding a constraint to the model.

Third, the maximum capacity (stable places) of livestock was fixed based on observed livestock levels. Thus the model determines the optimal LU within this range.

Fourth, all livestock animals must follow a specific dietary plan, which differs across animals. The minimum intake level of net energy for lactation, crude protein, and crude fibre must be satisfied, while intake of dry matter must not exceed certain levels. These values were calculated based on DLG (1997). The nutritional values of the feed were taken from Piirsalu et al. (2019) for grass on SNGLs and from FEEDBASE (Agroscope, et al., n.d.) for other

Table 3 Modelled constraints (regulations, conventional practices, and the reflection of reality) implemented in the baseline simulation

SNGLs	Permanent grassland	Arable land	Livestock husbandry
• Fixed share (31%) • Maximum biomass production for bioenergy (<1200 t = equivalent to one biomass heating plant) • Upper limit of exporting hay[a] (<2500 t)	• Fixed share (12%) • The existing permanent grassland must be maintained • Upper limit of exporting hay[a] (<2500 t)	• Fixed share (57%) • Crop diversification • Ecological measures (>5% of AL) • Crop rotation (refers to the observed crop share and consultation with experts in agronomy—cereals <60%, wheat <40%, green maize <40%, oats <4%, potatoes <25%, rapeseeds <25%, buckwheat <2%)	• Fixed stable capacity • Nutritional needs of net energy lactation, crude protein, crude fibre • Maximum intake of dry matter • The upper limit of grazing based on the standard feed ratio in the ARC (2021) • Grazing SNGLs only for beef cattle and sheep

[a]The production of hay for export (e.g. to Saudi Arabia) is possible both on SNGLs (semi-natural grassland)

kinds of feed. In addition, we assumed that all the necessary feed was supplied through the above-described field activities, i.e. buying feed was not considered, which reflects regional practices according to regional experts.

Validation of the parameters We validated the initial parameters used for the baseline scenario as follows. First, we ensured that the deviation of the land use pattern in the baseline simulation regarding crop choice and area size from the observed land use pattern was minimised. Second, we ensured that the determined livestock number reached the maximal livestock capacity, which is equal to the observed level. Third, we checked whether the ratio of the ingredients of feed determined in the BEFM (grazing, hay, silage, and concentrates) matched the standard feed ratio recommended by the ARC (2021) as much as possible.

Ecological Modelling of the Habitat Quality of Agricultural Land Use

General approach

The ecological part of the integrated land use modelling was carried out using the HVM (Brandt and Glemnitz 2014, Glemnitz et al. 2015). This model can be used to determine the habitat quality of agricultural land for indicator bird species. The habitat quality for these indicator bird species is suitable for reflecting the biodiversity of agricultural land, both on arable land and grassland (Brandt and Glemnitz 2014) and thus can be used to assess the impact of the different incentive schemes on the habitat quality of arable land and grassland. The HVM differentiates between two types of habitat use of the bird species on grassland: 1.) breeding habitat and 2.) feeding habitat and overlays the habitat preferences of the indicator species with the potential habitat suitability of each agricultural land use activity. Based on these activities and their respective crop shares the results can be up-scaled to the regional scale per applied scenario (Glemnitz et al., 2015). Two indices were derived per indicator species the breeding habitat index, which expresses the relative number of successful breeds per species and year and the feeding habitat index, which expresses suitable habitat conditions for feeding. The index values for single species were aggregated for some interpretations.

Assessing the habitat preferences of the bird indicator species

On the one hand, information on habitat requirements was used for the modelling, whereby an adjustment was made to the bird requirements of the species in the study region for the five bird indicator species for arable land by regional bird experts: skylark (*Alauda arvensis*), lapwing (*Vanellus*

vanellus), whinchat (*Saxicola rubetra*), red-backed shrike (*Lanius collurio*), and yellowhammer (*Emberiza citrinella*). The two grassland species, corncrake (*Crex crex*) and grey partridge (*Perdix perdix*), were specifically selected to cover the regional bird species occurrences in Estonia on grasslands and their habitat requirements were newly compiled by expert parametrisation according to Brandt and Glemnitz (2014).

Assessing the potential habitat suitability of the agricultural land use activities

Over all 14 land use systems on grasslands including abandoned SNGLs and 29 land use systems on arable land, the potential habitat suitability was assessed. The vegetation structure was provided over the growing season by the particular land use systems, the cultivation period of the crops or grassland vegetation in 10-day periods, and necessary agricultural measures were compiled (Brandt and Glemnitz 2014). To do so, the definitions for breeding habitat suitability and feeding habitat suitability by Brandt and Glemnitz (2014) were used. The individual species' values estimated with HVM in this study were combined to create average values. Then the highest value of all the values calculated for both breeding and feeding birds was adjusted to 1.0 and any other values were scaled to this highest score. Figure 3 presents the adjusted habitat index values of land use systems on grassland. All the results from HVM including land use systems on arable land are provided in the supplementary material 2. The indices can be broken down to single species if needed to deliver assessments on the impacts on e.g. conservation foci on single species.

Matching the habitat preferences with potential habitat suitability agricultural activities and up-scaling

The bird habitat preferences of each bird species were matched with the provision of potential habitat qualities of each land use system (Brandt and Glemnitz 2014). The habitat suitability for breeding and the habitat suitability for feeding were summarised for the contributing bird species and analysed separately (Glemnitz et al., 2015). The regional habitat quality was subsequently assessed by combining the summarised breeding habitat values and the summarised feeding habitat values of each agricultural activity with the respective crop shares of these activities in the region per applied scenario (Glemnitz et al., 2015).

Scenario Development

We developed a baseline scenario and four regionally relevant agricultural policy scenarios that described different economic conditions for grassland use as follows.

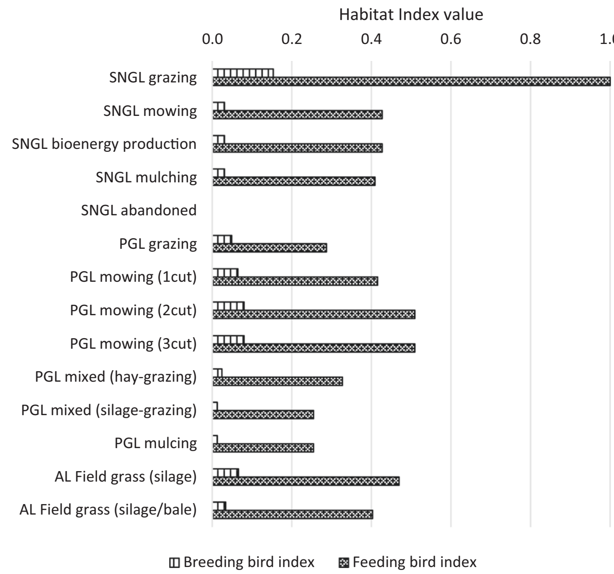

Fig. 3 Habitat values of particular grass activities for breeding and feeding farmland birds. SNGL means semi-natural grassland. PGL permanent grassland. AL arable land

- Baseline scenario (simulated existing conditions): The land use simulated with the BEFM in this scenario replicates the existing regional agricultural land use, which is used for comparison in the following policy scenarios. Therefore, all the parameterisations in this scenario are based on the current data, which reflect the present land use.
- Scenario 1 (compensation payment for SNGL maintenance): Compensation payments are paid for maintaining SNGLs. We varied the level of payments between 0 and 200% of the current payment level. The payment levels for AEPs remained unchanged.
- Scenario 2 (higher livestock numbers of beef cattle based on premium meat brands produced on SNGLs): This scenario assumes a national marketing strategy for beef produced on SNGLs. We assumed higher livestock numbers in the region by subsidies for stable buildings, which we modelled as changes in the maximum capacity for beef cattle from 0 to 5000 LUs. The current total LUs of beef cattle in the region is 3200 LUs.
- Scenario 3 (increase in other countries' demand for hay): This scenario reflects the current agricultural strategy of Estonia to increase the demand for grass products. We changed the export demand for hay from 0 to 5000 t. The current demand is 2500 t. In this option, the BEFM can choose the location of hay production (SNGLs and/or permanent grassland).
- Scenario 4 (bioenergy production—construction of biomass heating plants by regional heat suppliers): This scenario reflects the ongoing effort to search for alternative uses of grass on SNGLs. Currently, one

Table 4 Simulated land use patterns in the baseline scenario within each site type

SNGLs	ha	%	Permanent grassland	ha	%	Arable land	ha	%
Grazing	5328	43%	Mulching	7298	86%	Winter wheat/reduced tillage	7757	40%
Abandoned area	5219	42%	Mowing/1 cut	611	7%	Winter rapeseeds/ploughing	4848	25%
Mowing/1cut	1346	10%	Mixed (silage-grazing)	559	%	Spring barley/direct seeding	2909	1%
Bioenergy production	632	5%				Field grass-silage	1763	9%
						Field beans/direct seeding	970	5%
						Spring barley/reduced tillage	757	4%
						Buckwheat/reduced tillage	388	2%
Total	12,524	100%	Total	8468	100%	Total	19,392	10%

SNGLs semi-natural grasslands. (Source: own calculations)

biomass heating plant operates with a biomass demand of 1200 t of hay produced on SNGLs. According to the current regulations, only hay produced on SNGLs can be supplied to the heating plant. Therefore, unlike in Scenario 3, the choice of grassland in the BEFM was restricted to SNGLs. We changed the demand for such plants for hay from 0 to 4800 t.

Land Use Impact Assessment

The scenarios were assessed with the above-explained applied models in terms of economic and ecological consequences, using the following three sets of indicators:

1. (Social) the share of used SNGLs to the total available SNGLs for agriculture, as a proxy for maintaining cultural heritage
2. (Economic) the regional GM and the market-generated GM of the region, as a proxy for rural economic profitability
3. (Ecologic) the two habitat quality values (habitat suitability for breeding and habitat suitability for feeding) of the region, as a proxy for farmland biodiversity

The used SNGLs were calculated by subtracting the simulated unused (abandoned) SNGLs from the total available SNGLs for agriculture. The regional GM, as maximised by the BEFM, can be an indicator of the overall income level of farm holdings in the region. The market-generated GM was calculated by subtracting all public payments from the regional GM; thus this metric reflects the ability of a region to continue to make profits in domestic and international markets, i.e. the market integration of regional agriculture. The habitat quality value of the region was calculated by multiplying the area of each farm activity by the corresponding habitat index value and dividing it by the total area of the region, given the assumption of a linear relationship between the habitat quality value and its area. All of these indicators were calculated at the regional scale.

Results

Baseline Land Use Pattern

In the baseline scenario, 58% of the SNGLs are used for agricultural production, most of which are used for grazing, while 42% of the available SNGLs are abandoned (unused) (Table 4). On permanent grassland, mulching is the dominant use (86%) (Table 4). The chosen arable crops are presented with management options. Winter wheat (reduced tillage), winter rapeseeds (ploughing), and spring barley (direct seeding) account for 80% of the arable land (Table 4). Field beans were grown on 5% of the arable land.

How Will Different Economic Conditions Influence the Agricultural Use of Semi-natural Grasslands?

In scenario 1 (compensation payments, top-left in Fig. 4), the model showed a typical reaction to a targeted payment. The results changed stepwise until the next profitable level was reached, and then another activity was replaced by the subsidised activity. In particular, a payment level between 0% and 60% of the current level led to a sharp increase towards current levels of the SNGLs (from 0% to 57%, Fig. 4). However, no clear changes can be seen between 70% and 180% of the payment level (Fig. 4).

Scenario 2 (higher livestock numbers, top-right in Fig. 4) resulted in rather complex changes. With an increasing number of beef cattle, the share of used SNGLs continuously increased to a peak of 72% at 2800 LUs and then declined until a level of 3400 LUs. No further change was observed beyond that level. This finding indicates that it was not profitable for the model to further increase the number of beef cattle above 3400 LUs.

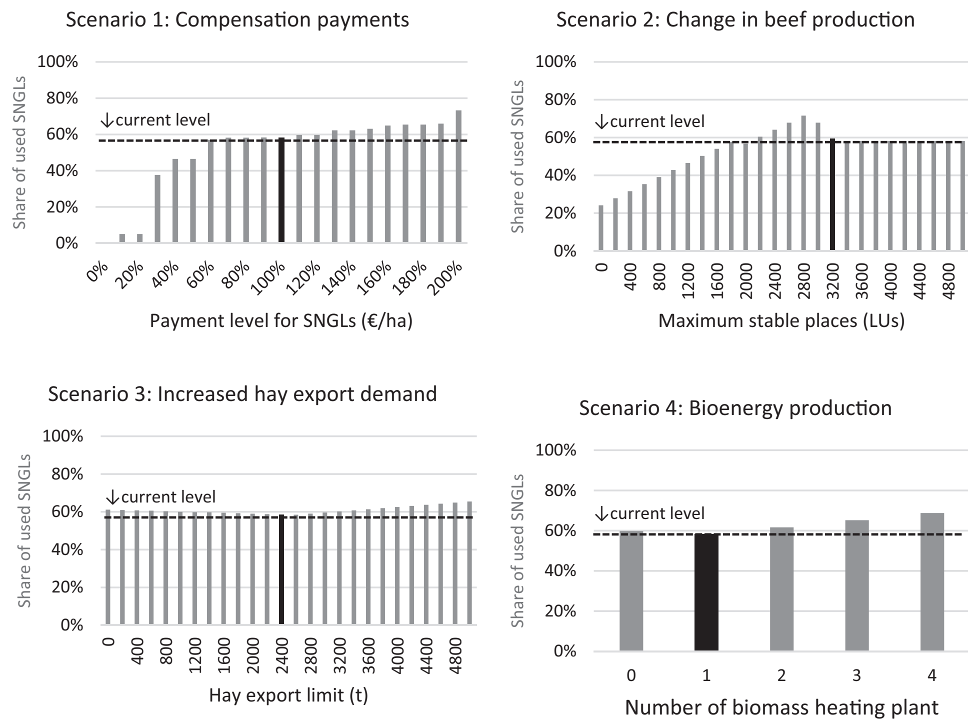

Fig. 4 Changes in the share of used SNGLs (semi-natural grasslands) to the total available SNGLs for agriculture in the study region under different scenarios. The black-filled bars indicate the current conditions, that is, the simulated baseline land use pattern. The horizontal dotted lines indicate the level of SNGL use in the baseline simulation (58%). LUs mean livestock units. (Source: own calculations)

In scenario 3 (increased hay export demand, bottom-left in Fig. 4), two patterns of change could be observed. The used SNGLs declined until the 3000 t hay demand limit was reached but then started to increase beyond that level. This temporal decline of SNGL use is associated with the model behaviour for seeking efficient fodder production; hay production for export was carried out on SNGLs due to higher profitability but a part of fodder production shifted from SNGLs to permanent grassland to compensate for the increased demand for labour used on SNGLs. Therefore, the overall use of SNGLs declined. Increasing demand for hay beyond 3000 t was realised by reducing the number of beef cattle to bypass a labour shortage. Therefore, fodder production was shifted back to SNGLs as a reduction in beef production saved labour resources.

In scenario 4 (construction of biomass heating plant, bottom-right in Fig. 4), a pattern of change similar to that in scenario 3 was observed. The reason for this model behaviour was that hay production for export and grass for the heating plant were both produced on SNGLs due to relatively high profitability, although in scenario 3, hay production could have originated from either SNGLs or permanent grassland. Since the other conditions are equal in scenarios 3 and 4, the results show the same pattern of changes.

How Will A Change in Grassland Use Affect Rural Economic Profitability and Farmland Biodiversity?

Figure 5 shows the changes in the regional GM and the market-generated GM in the study region across the different scenarios. The difference between them indicates the total amount of government budget (public payments) paid to the region, which is indicated with a line in Fig. 5. Relatively large effects on the regional GM and the market-generated GM can be observed in Scenarios 1 and 2 (Fig. 5). In scenario 1, the gap between the regional and the market generated GM became increasingly wider, which indicate an increasing government budget. The changes in the regional GM and market-generated GM exhibit comparable tendencies across all the scenarios; the change in the regional GM corresponds to the change in the used SNGLs. Due to the compensation payments for SNGLs, an increase in SNGLs led to an increase in the regional GM. In contrast, the market-generated GM decreased as the use of SNGLs and the regional GM increased. Nonetheless, as the land use decision in the BEFM is based on the regional GM, including public payments, the model first favours the use of SNGLs, even though it results in a reduction in the market-generated GM.

Figure 6 shows the changes in the habitat index values for breeding and feeding farmland birds across the scenarios. Little impact can be seen in the breeding habitat index values because the differences in the vegetation structure and the intensity of management activities among the land use systems on grasslands were not large (Fig. 3). In contrast, the feeding habitat quality for birds greatly changed in scenarios 1 and 2 (top-left and top-right in Fig. 6). This relatively large change is due to the high value of feeding birds for grazing on SNGLs compared to the other large values (Fig. 3). Therefore, if the use of SNGL changes

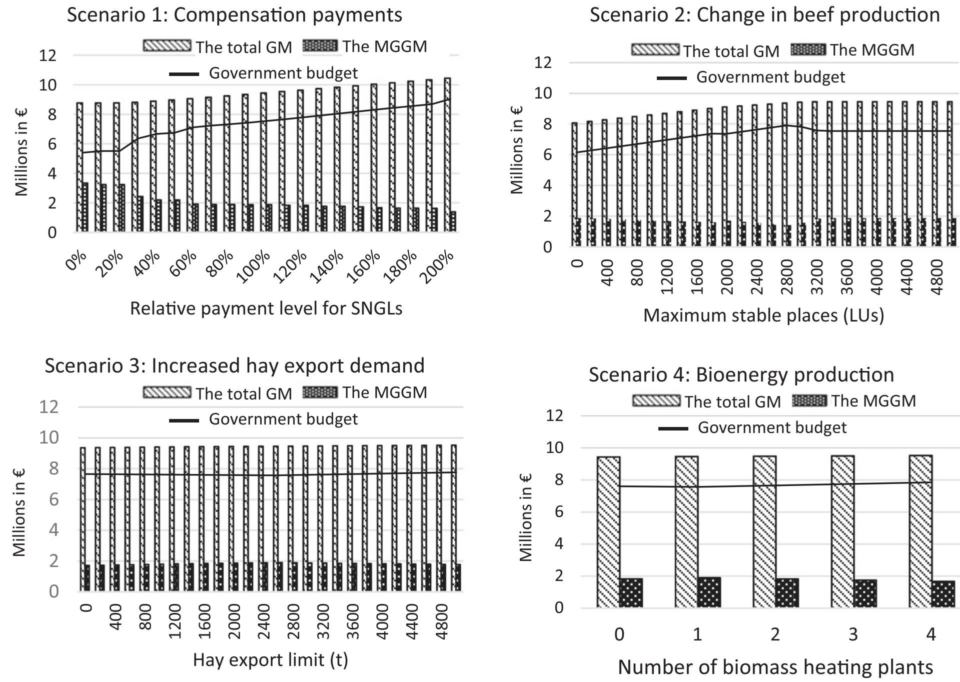

Fig. 5 Change in the regional GM (gross margin) and the MGGM (market-generated gross margin) of the study region over the different scenarios. LUs mean livestock units. (Source: own calculations)

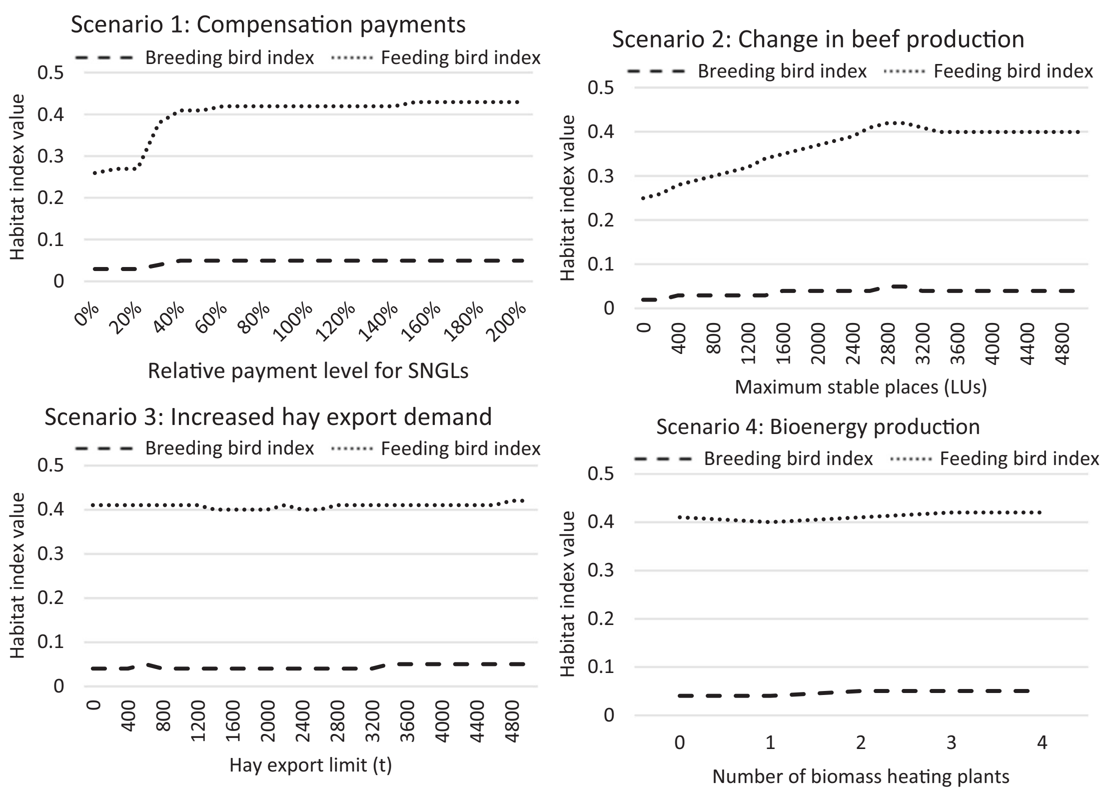

Fig. 6 Change in habitat index values for breeding and feeding farmland birds across different scenarios. SNGLs means semi-natural grasslands. LUs mean livestock units. (Source: own calculations)

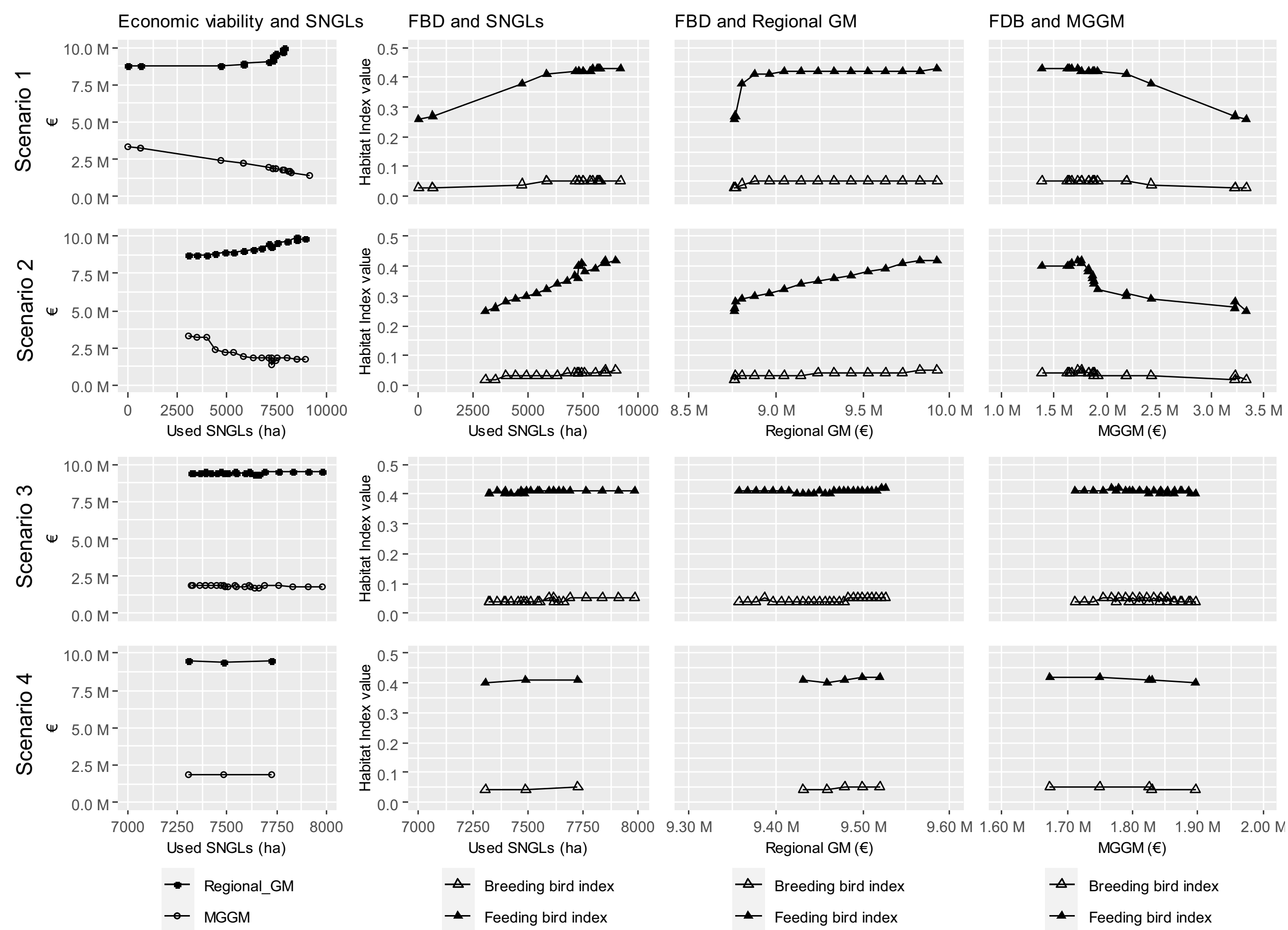

Fig. 7 Relationship between the values of used SNGLs (semi-natural grasslands) (ha), the regional GM (gross margin) (€), the MGGM (market generated gross margin) (€), and FBD (farmland biodiversity) across scenarios (the results of scenario 1–4 are arranged in rows from the top to the bottom). (Source: own calculations)

significantly, the value for feeding birds will also change significantly.

What Trade-offs Are Observed between the Examined Indicators?

Figure 7 plots the values of all the indicators (used SNGLs, regional GM, market-generated GM, and breeding and feeding bird indexes) calculated for the scenarios to show their relationships. The results are arranged in rows from scenarios 1–4, going from the top to the bottom. A similar tendency can be observed for scenarios 1 and 2 (Fig. 7, the top and second rows, respectively). The regional GM increased as the agriculturally used SNGLs expanded. In scenario 1, the use of SNGLs was driven by increased compensation payments, and in scenario 2, by increasing livestock numbers. However, the market-generated GMs in scenarios 1 and 2 both declined. The relative change of the market-generated GM is larger compared to that of the regional GM. Similar relationships were found for farmland biodiversity; farmland biodiversity and the used SNGLs are positively related. In scenarios 3 and 4 (Fig. 7, the third and fourth row), the values of the examined indicators showed no drastic change, as these scenarios had only moderate impacts on the use of SNGLs (Fig. 4).

Discussion

Interpretation of the Results

Economic conditions influencing the use of semi-natural grasslands

The baseline results imply that a substantial portion of permanent grassland would be left over for mulching, in case grasslands were used efficiently for feeding purposes. This result is influenced by the lower livestock numbers in the region relative to the area size: 1280 dairy cows, 2760 beef cattle, and 2772 sheep (ARIB, 2022). Mulching neither contributes to fodder nor hay production and is chosen solely as it is a minimum requirement for the payout of AEPs. This aligns with the actual strategy of land managers in the region, as confirmed through personal communication. The prevalent use of permanent grassland for mulching suggests that fodder production on SNGLs remains more profitable than that on permanent grassland due to compensation payments favouring SNGLs. However, these payments conceal the higher production costs on SNGLs, leading to an inefficient allocation of farm labour to SNGLs, despite the lower productivity.

The policy scenarios involving changes in compensation payments (scenario 1) and livestock capacity (scenario 2) had greater effects on the use of SNGLs than the scenarios involving changes in export limits (scenario 3) and bioenergy production (scenario 4). Overall, the results imply that the current level of compensation payments offers sufficient financial incentives for land managers to manage SNGLs. However, increasing public budgets in scenario 1 beyond the current level had only limited effects because of unchanged relative profitability among activities, whereas in scenario 2 the area used for SNGLs showed complex changes. Several economic factors accounted for this finding. As Fig. 4 shows, the first choice for fodder production for feeding beef cattle of the model was SNGLs, as it is more profitable to produce fodder on SNGLs. However, labour became a limiting factor at the peak level (2800 LUs); thus, some fodder production shifted from SNGLs to less labour-intensive activities on the permanent grassland to enable a further increase in the number of cows and earn more profits. A farm labour shortage in the study region was indeed confirmed by Kikas et al. (2016). In addition, the finding that unchanged land use further beyond a level of 3400 LUs indicates a labour shortage and only moderate GMs for beef cattle; compared to having more cattle, a higher GM could be obtained by allocating labour to the rather profitable mulching. This result is in line with Mõtus et al. (2017) and was also observed in Europe in general (Lherm et al., 2017; Manevska-Tasevska et al., 2014). This situation is attributed to the high production costs (e.g. labour, energy, and inputs) of European farming (Hocquette et al., 2018). The effects of moderate GMs on beef-fattening cattle also became apparent in scenario 3 (Fig. 4). Because hay production for export is more profitable than beef production, a higher demand for hay led to a reduction in the number of beef-fattening cattle to continue to produce hay for export on SNGLs. Similar to the case of mulching, hay production on SNGLs for export and biomass production for heat generates more profit than maintaining beef-fattening cattle. Therefore, the lower demand for feed shifted fodder production back to SNGLs and led to an increase in the used SNGLs.

The impacts of the use of semi-natural grasslands on economic profitability

The comparatively high impacts on the use of SNGLs in scenarios 1 and 2 resulted in considerable changes in the regional economic profitability, contributing to the overall income level of farm holdings in the region. When the compensation payments were abolished (to a level of 0%), there was a significant impact on SNGLs; while all the areas of SNGLs were abandoned, the market-generated GM reached the highest level among all scenarios. A similar increase in production through sacrificing biodiversity-rich land use was also found by Guillem et al. (2015) and Nishizawa et al. (2023). However, a further increase in the compensation payments beyond 60% in scenario 1 caused increasing windfall profits for landowners: the government budget continued to increase without clear effects on the use of SNGLs. A negative effect was also observed on the market-generated GM. Due to the higher production costs of managing SNGLs compared to those of permanent grassland, increasing the use of SNGLs pushed overall production costs higher. Therefore, increasing public budgets caused crowding-out effects and obstructed the market integration of regional agriculture. Crowding-out effects are generally referred to as situations where increased government spending leads to a decrease in spending in the private sector. This trade-off was more apparent in scenario 1 than in scenario 2, indicating that solely relying on compensation payments can weaken the ability of the agriculture sector to generate profits.

The impacts of the use of semi-natural grasslands on farmland biodiversity

Regarding farmland biodiversity, used grasslands are more important as feeding habitats for farmland birds than for breeding. All the scenarios showed a stronger impact on feeding habitat quality than on breeding habitat quality. An increase in the feeding habitat quality for birds was brought about by an increase in public budget dependency. The quality of grasslands used as feeding habitat for birds was highly sensitive to the use of SNGLs, as the change in their feeding habitat index value was nearly identical to the change in the use of SNGLs. This result means that returning SNGLs to extensive land use has beneficial effects on their role as feeding habitats for typical farmland birds. This finding is in accordance with Buckingham et al. (2006), who differentiated two groups of feeding behaviour and preferences: Species feeding on soil-dwelling invertebrates prefer short swards, while species feeding on sward-dwelling invertebrates or seeds prefer heterogeneous swards. A study by Katayama et al. (2015) revealed that the richness and abundance of agricultural wetland species in summer were negatively associated with both intensification and abandonment. Abandonment of grassland use on SNGLs might support breeding habitat suitability, e.g. wet grassland specialist bird species (Hanioka et al., 2018). Nevertheless, a comprehensive literature overview by

Elliott et al. (2023) concluded that maintaining grassland management is crucial for supporting biodiversity conservation, including birds in European grasslands.

Methodological Limitations

Due to the limited data and inherent complexity of SNGLs, several factors had to be simplified. First, only two types of habitats (coastal and alluvial meadow) could be considered in the BEFM. Even though they were the main habitats in the study region (53%) (ARIB, 2022), there are various habitats in the study region, including wooded pasture, wooded meadows, alkaline fens, and calcareous grasslands. The yields and nutritional levels and the compensation payments are also differentiated across different habitat groups in Estonia, all of which affect the productivity and profitability of grassland-based livestock production (Loucougaray et al., 2015). Second, we implicitly assumed that the restoration of SNGLs was possible regardless of site conditions and restoration costs. In reality, the efforts to restore SNGLs are affected by the extent of abandonment at the site (Joyce, 2014); the longer the fields have remained unused, the more challenging their restoration becomes. This reality indicates varied restoration costs and labour requirements. The different habitats of SNGLs and the site conditions are relevant not only to land use decision-making but also to the quality of farmland biodiversity. Many studies show the importance of incorporating landscape approaches into SNGL conservation efforts for biodiversity, in which the species composition and heterogeneity or configuration are taken into account (Harlio et al., 2019; Brüggeshemke et al., 2022).

In addition, some limitations of the approach employed for land-use modelling in this study should be noted. The tendency of LP models to overspecialise and produce jumpy solutions, particularly in a regional farm approach, may lead to more extreme land use patterns that would not occur in reality. However, it is a tolerable approach, given the lack of spatially explicit farm data and a relatively small case study area. Such issues can be handled by incorporating as many realistic land use restrictions as possible, including regulatory, agronomic, and biophysical conditions (in this study, the location of SNGLs) and by calibrating the model so that outcomes closely match the actual land use pattern, as explained in 2.3.2 Modelled agricultural activities and constraints.

Lastly, future studies should capture the long-term impacts of economic conditions on more extensive indicators relevant to sustainable rural development, such as biophysical conditions (e.g. soil quality or water availability) to consider their sustainability and multiple species groups to avoid over-interpretation of single species effects (Gossner et al., 2016; Gregory et al., 2019). Even though the scope of this study was the evaluation of the impacts of short-term land-use decisions, incorporating dynamic impacts into land-use modelling for a more comprehensive assessment would enhance the relevance and applicability of findings for long-term adaptive policy measures. This can be done by building feedback loop structures that enable the consequences of changing land use to be fed back into decision-making (Paul et al., 2019; Rodriguez-Gonzalez et al., 2020).

Implications for Policy-making

Our findings show that compensation payments and livestock capacity can play a significant role in enhancing regional economic profitability and farmland biodiversity in marginalised agricultural areas. However, increasing compensation payments and livestock capacity from the current level resulted in a limited effect. This phenomenon causes, on the one hand, increasing windfall profits, an inefficient allocation of labour and a lower market-generated GM, on the other hand, crowding-out effects. To enhance the continued management of SNGLs for agriculture, increased demand for grassland products is essential (Waldén and Lindborg, 2018). In particular, grassland-based beef production plays the most important role (Nitsch et al., 2012; Bengtsson et al., 2019). However, since its profitability is not high and labour is scarce, fodder production is easily replaced with mulching or just aimed at exporting hay. Currently, compensation payments for SNGL are not tied to beef production, so one approach could include linking them to the maintenance of a minimum livestock density per unit area of grassland. Such payment schemes would incentivise land managers to maintain or increase livestock numbers and revitalise livestock production in the country. As a market-based solution, establishing premium brand beef that is fed on SNGLs might be a promising effort not only to secure the economic viability of beef production in the long term (Hocquette et al., 2018) but also to safeguard species-rich habitats (Magda et al., 2015). This trend has been gradually developed in the study region as consumer preferences for "locally" and "ecologically" produced agricultural products are increasing (Feldmann and Hamm, 2015; Rytkönen et al., 2018). A support scheme for grassland-based production that pays out land managers for positive effects on carbon sequestration could be also an option in the future in Estonia (Hall, 2018).

Another highlighted finding is that labour availability plays a decisive role in determining the use of SNGLs. As Kikas et al. (2016) found, the older age of farmers and lack of successors are strongly related to abandonment. As shown in this study, managing SNGLs is labour-intensive due to their isolated locations. Even though compensation payments help increase the use of SNGLs, farm labour, which is already a scarce resource in the region, will be consequently more inefficiently allocated. Therefore, conservation measures for SNGLs should not focus solely on reintroducing traditional management practices (Valkó, et al., 2018), which are not economically viable or profitable; rather, the implementation of cost-effective management practices to reducing labour requirements is the key to successfully restoring SNGLs. This could involve strategies, such as utilising more efficient machines or establishing specialised service providers, particularly if the profitability is high enough. As the factors that hinder the use of SNGLs might change depending on local conditions, such strategies should be adapted to local conditions (Plieninger et al., 2016).

Conclusions

Various economic conditions can substantially influence all aspects of sustainable rural development in a marginalised agricultural region. The use of SNGL is closely related to rural economic profitability and farmland biodiversity. Our findings imply that the current level of compensation payments for SNGL management provides land managers with sufficient financial incentives, and increasing the use of SNGLs is likely to have large positive effects on habitat quality, especially for feeding birds. Among the scenarios, compensation payments for SNGLs and the number of beef cattle had a stronger influence on the use of SNGLs; however, a further increase in the payment level above current levels increased windfall effects and worsened inefficient labour allocation, as the labour shortage is the main bottleneck. The relatively high profitability of mulching, the labour shortage, and the moderate profitability of beef production are all factors that hamper the use of SNGL. As for the impact on regional economic profitability, the increased use of SNGLs caused crowding-out effects and lowered the regional market-based GM due to the relatively high costs of managing SNGLs. Nonetheless, compensation payments contribute to the overall income level of farm holdings in the region. Overall, intervening in beef production levels might be more effective in increasing the use of SNGLs given its smaller negative impacts on economic profitability, but should be accompanied by cost-effective and labour-efficient management practices, which will eventually lead to increasing profitability of beef production. Such measures will also promote the alternative use of products, such as bioenergy production.

Data Availability

All data supporting the findings of this study are available in/from the Estonian nature information system (Estonian Environment Agency), the Estonian Semi-Natural Community Conservation Association and the Register of Agricultural Support and Agricultural Parcels (Agricultural Register and Information Board), an Estonian farm data handbook (Agricultural Research Centre in Estonia), Statistics Estonia (https://www.stat.ee), FEEDBASE (https://www.feedbase.ch/), and an agricultural handbook of Brandenburg in Germany (MLUK).

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Compliance with Ethical Standards

Conflict of Interest The authors declare no competing interests.

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5. General discussion

This section provides answers to the research questions introduced in Section 1.4.1 Overall objectives and research questions based on the findings obtained from three case studies that were synthesised according to the process defined in the LUS. In this context, the following subsections first summarise each case study, namely, their context, methodology, and key findings. After answering the research questions, the methodology developed for this PhD study is reviewed, and implications for policymaking and further studies are explored.

5.1 Summary of case studies

5.1.1 Summary of Case Study 1

The case study area in CS1 is known for traditional agroforestry and encompasses cherry orchards and meadows for livestock production. This agroforest system includes regional biodiversity hotspots (Kay et al., 2018), but orchard meadows have declined in abundance in recent decades (ALW, 2019). Given such regional features and the current development of agricultural landscapes, CS 1 was established to investigate whether the current AES provided land managers with sufficient financial incentives to maintain orchard meadows and to assess the cost-effectiveness of the AES. As the objective of this study involved farm-level decisions, a BEFM of the present regional agriculture and agroforestry system was developed for simulating land use changes at the farm level under *ceteris paribus*, with variable payment levels for the AES. Farm heterogeneity was explicitly considered in the BEFM, as representative farm types in the case study area had different characteristics. An ecological model (SALCA-BD) was coupled with the BEFM for biodiversity assessment to develop an integrated modelling framework.

The findings suggest that given the current payment levels and land use policy, which permits the conversion of existing grassland to arable land, the existing orchard meadows in farmland areas and current biodiversity levels are likely to be threatened if land managers only prioritise economic profits. This result implies that the current agri-environmental policies in Switzerland strongly favour the cultivation of arable crops, especially cereals (Giannitsopoulos et al., 2020). This aligns with the core strategy of the country's agricultural policy for reducing dependency on other nations for food (OECD, 2022). Therefore, increasing the payment for the AES would help preserve more orchard meadows. A distinctive increase in orchard meadows at the regional scale was observed at 150% of the current subsidy payment level. The cost-effectiveness initially declined beyond the current level but reached a maximum at this level (150%) and then declined again beyond that point. As orchard meadows increased in abundance, the share of farmland needed for fodder production increased to maintain the same livestock size, which led to a decrease in the efficiency of fodder production. Another key finding was that the effects of changing payment levels for the AES varied across farm types. Two factors played a part here. Notably, the greater the share of the payments from the AES to the farm's total GM and the greater the number of livestock were, the less incentive there was to adopt more environmental measures unless the payments from the AES substantially increased. This finding suggests that differentiating the payments for the AES according to the characteristics of farm types could increase the cost-effectiveness of the AES strategy (Armsworth et al., 2012).

5.1.2 Summary of Case Study 2

Using the same case study area as that used for CS 1, CS 2 assessed the long-term impacts of the interaction trends of global land use drivers on regional agricultural land use and explored the conditions needed for achieving multifunctional agricultural land use in the long term. The highlight of the methodology in this case study was the development of a systematic scenario approach that was integrated into the modelling framework developed in CS 1. Three contrasting regionally specific scenarios that incorporated future socioeconomic changes and captured the impacts of climate change were developed. As outlined in Section 1.3.1 Land use drivers, changes in regionally specific land use drivers were determined based on the existing scenarios for the agri-food system at the European scale in 2050 (Mitter et al., 2020) and the scenarios for climate change at a global scale (RCP). The quantitative projection of these regional scenarios involving future land use was conducted with the extended version of the BEFM developed in CS 1.

The results revealed that three scenarios led to contrasting land use changes, specifically in orchard meadows, farm production levels, and biodiversity. This finding is consistent with the results of Popp et al. (2017) and Doelman et al. (2018), who projected future land use changes at large scales under the same SSP framework. As long as the current AES continues, which was assumed to be the case in the SBL-Agri-SSP2 (regional agriculture on the business-as-usual scenario path) scenarios, multifunctional landscapes are likely to be maintained. The share of the payments from the AES to the farm's GM was found to be high enough that regional land use strategies could resist external shocks, such as yield or market price changes. With the additional socioeconomic changes considered in the SBL-Agri-SSP1 (regional agriculture on the organic sustainable path), e.g., increased financial support for ecological measures, increased farm labour supplies, and consumer preferences that favour local farm production, more diversified land use was achieved, including commercial cherry production combined with meadows for livestock production. In contrast, the SBL-Agri-SSP5 (regional agriculture on a liberalised path), with no environmental measures or subsidy schemes and a focus on global markets, led to simplified agricultural landscapes without orchard meadows, mostly including a few kinds of arable crops with intensive management. Farm structure in this scenario, which was implemented in the BEFM as a land use driver, also changed significantly compared to the current structure of farms.

5.1.3 Summary of Case Study 3

In CS 3, a different case study area with different landscapes from the areas investigated in CS 1 and CS 2 was chosen to demonstrate the transferability of the ILUM framework to another European region. The case study area in CS 3 includes abundant SNGLs (semi-natural grasslands), which not only offer valuable habitats for various kinds of species (Villoslada Peciña et al., 2019) but also contribute to rural development, such as tourism and the preservation of cultural heritage (Veidemane, et al., 2019). However, in recent years, an increasing number of SNGLs have been abandoned (Prangel et al., 2023), which has led to concerns about the degradation of biodiversity and sustainable development in rural communities (Dengler et al., 2020; EEA, 2020). To explore the effects of different economic incentives on the use and preservation of SNGLs, four locally adapted agricultural scenarios were developed (changing the level of compensation payments, livestock capacity, hay exports, and bioenergy production). The corresponding effects on regional land use were assessed with the newly developed BEFM for this case study area coupled with an HVM (habitat value model) from three aspects of sustainable rural development: cultural heritage (represented by the area of SNGLs), economic viability (approximated by the regional GM and the market-generated GM (MGGM) and calculated by subtracting the governmental budget from the regional GM), and farmland biodiversity (approximated by the bird habitat quality index).

Changing compensation payments and livestock capacity had the greatest impacts on the use and preservation of SNGLs. Although compensation payments contributed to the overall income level of farm holdings in the region, a further increase above 60% of the current level had only marginal effects and increased windfall profits. Regarding farmland biodiversity, a positive relationship between SNGLs and habitat quality for bird breeding and feeding was verified. However, due to the high maintenance costs for SNGLs, the expanded use of SNGLs led to a decline in the MGGM and less efficient labour allocation, with a labour shortage as the main bottleneck (Kikas et al. 2016). This study revealed several economic factors that hampered SNGL utilisation: the moderate profitability of beef production, labour shortages, and relatively high profitability for mulching. Overall, adjusting beef production levels might be most effective for increasing the use of SNGLs given the small negative impacts of this approach on economic viability. To promote the use of SNGLs, it is necessary to increase the demand for alternative uses of grass products with cost-effective and labour-efficient management practices to make grass and fodder production more profitable (Waldén and Lindborg, 2018).

5.2 To what extent do socioeconomic factors influence regional agricultural land use compared to the impacts of climate change?

The effects of changing payment levels for the AES as a key socioeconomic factor were investigated in all case studies. In general, the AES aims to offer land managers payments to compensate for the costs and income loss incurred from implementing environmentally friendly land uses or farm management options. The findings showed that changing the payment levels critically influenced the targeted land use and enhanced farmland biodiversity in both Switzerland and Estonia. As CS 2 and CS 3 demonstrated, the abolition of such payments led to an almost complete conversion of grasslands to arable land or abandoned land and a substantial decline in the regional GM and biodiversity, which is in line with the results of Hanley et al. (2012). This was mainly because the share of AEP in the total farm GM was greater than 50% in both study areas. This suggests that farmers in these regions are highly dependent on AEP for their income. Because of this high dependency, the impacts of changes in market conditions—represented by input and output prices or demand for particular agricultural products in CS 2 and CS 3—were not clear. This implies that regional agricultural land use can be resistant to market changes as long as farms' incomes are largely paid from the AES. Similar findings were also reported by Lehmann et al. (2013) and van Vliet et al. (2015).

Compared to the effects of changes in AEP, regional land use appeared to be unaffected by climate change. The impacts of climate change on crop yield changes and the decision to adopt new crops were captured in CS 2 based on the two existing climate scenarios, one of which (RCP8.5) is often referred to as “the worst-case scenario” among the RCPs (Hausfather & Peters, 2020). However, a distinct difference between the crop yields simulated with these two scenarios was not observed, as similarly reported by Audsley et al. (2006). In both scenarios, the relative yield difference compared to the present yield levels was within plus or minus 3.5% for all examined crops. Overall, arable crop yields increased, whereas grass crop yields decreased. This trend was most apparent under RCP4.5 (i.e., the continuation of the current trend). Such contrasting impacts of climate change on arable land and grass crop yields suggest that climate change can further expand the current area of arable land (Kirchner et al., 2015; Pröbstl-Haider et al., 2016) and negatively affect the continuation of the grass-based feed system (Trnka et al., 2020), which is broadly adopted by Swiss farms. Nonetheless, the results of the SBL-Agri-SSP2 scenario, which follows RCP4.5 and represents the current course of socioeconomic development, showed that the current grasslands, including orchard meadows, are resistant to crop yield changes driven by climate change. This indicates that the adverse impacts of climate change on grassland yields could be counteracted if the Swiss AES continues to offer substantial financial support to farmers (Fronzek et al., 2019; Stehfest et al., 2019).

5.3 What farm type characteristics influence land managers' decision-making in response to underlying land use drivers?

In CS 1 and CS 2, different farm characteristics were explicitly considered separate units of land use in the BEFM. The farm data obtained from the Swiss case study area were clustered into five different types based on the following six variables: the areas of arable land, grassland, and orchard meadows; the number of milk and suckler cows; and the livestock intensity. This approach helped distinguish among farm structures, farm management schemes, and farm systems, encompassing factors such as labour availability, livestock capacity, system type (free-range or mixed), type of feed (participation in grass-based milk production), and one biophysical factor (slope of fields).

In CS 1, the difference in farm characteristics was found to be a determinant of willingness to adopt the AES, which is consistent with the results of Paulus et al. (2022). This finding indicates that the opportunity costs of adopting further AESs are different across farm types. The degree of dependency on AEP and livestock size was one factor that influenced this opportunity cost, and the greater the dependence was, the lower the opportunity cost. For example, smaller farms were more dependent on AEP, so they adopted more biodiversity measures in the AES context to obtain a slight increase in AEP.

In CS 2, future changes in farm structures, management practices, and livestock systems across the farm types distinguished in CS 1 were scientifically specified in the process of regional scenario development, as explained in Section 1.3.1 Land use drivers. For example, the following changes in farm types were identified: the number of farms, average farm size, and livestock capacity of large dairy farms in the SBL-Agri-SSP1 scenario decreased, whereas those of small dairy farms remained almost the same. In the SBL-Agri-SSP5 scenario, which included globally oriented production and no agri-environmental policies, small dairy farms and small farms were no longer in operation. These changes were ensured to be consistent with the respective framework conditions defined in the Eur-Agri-SSPs. These future changes in farm types were incorporated into future scenarios as land use drivers in the BEFM. As a result, contrasting future land uses across farm types were observed. For example, in the SBL-Agri-SSP1 scenario, only farms with livestock could support orchard meadows for commercial cherry production, while in the SBL-Agri-SSP5 scenario, larger farms, which were the only farm types that survived, cultivated a few crops without orchard meadows. This study suggests that accounting for differences in farm characteristics is crucial for identifying factors that affect the decision-making process on farms.

5.4 What trade-offs can be expected due to the promotion of biodiversity-rich land use?

In the Swiss study area, orchard meadows were the targeted land use type for biodiversity conservation, while in the Estonian study area, SNGLs were targeted. Both types of land use involved extensively managed grasslands, which are mainly used for livestock production. These grasslands are managed without synthetic inputs and are cut once a year. Compared to those in more intensively managed grassland areas, grass yields and nutrient contents were lower. As these conditions were captured in the BEFM, increased use of this type of grassland led to an increase in the total area used for fodder production to compensate for the degradation of forage quantity and quality (CS 1). Consequently, in the Swiss case studies, the amount of arable land allocated for growing cash crops decreased. This finding was also reported by

Loucougaray et al. (2015) and Pavlu et al. (2021). In the Estonian case study, this particular trade-off between the production of cash crops and extensively managed grasslands was not observed. This is because in Estonia, the conversion of semi-natural and permanent grasslands into arable land is forbidden under the EU's common agricultural policy, except organic farms. Nonetheless, the increased use of SNGLs caused a decrease in the productivity of fodder production, as was the case for the Swiss studies.

Another trade-off was revealed because of the labour-intensive nature of maintaining the targeted land uses. The maintenance of extensively managed grasslands is inexpensive in terms of inputs, but it is costly in terms of labour use. In the case of orchard meadows, additional labour hours are needed to maintain cherry trees. In the case of the SNGLs in the study area in CS 3, additional labour hours are needed for travelling to the SNGL sites, which are located mostly in the coastal area further away from the farmstead. Therefore, CS 2 and CS 3 revealed that farm labour availability plays a critical role in the land allocation scheme for farmland in response to the drivers of targeted land use. In CS 2, more diversified land use than current land use was achieved in the SBL-Agri-SSP1 scenario. This was due to the assumption that more farm labour would be available in 2050 than at the present level, which is consistent with Eur-Agri-SSP1; specifically, more educated young people are assumed to work in the agricultural sector in 2050 than at present. In contrast, in the SBL-Agri-SSP5 scenario, in which a lower labour supply was considered, all the orchard meadow area disappeared, and most of the land was converted to arable land, which requires less farm labour. One scenario in CS 3 (changing livestock capacity) also showed that due to limited farm labour, increasing livestock production failed to constantly increase the use of SNGLs. These findings broadly support the conclusion of Dietrich et al. (2014) and Wang et al. (2020) that investment in productivity improvement is indispensable for achieving sustainable agricultural land use while ensuring the current level of food production.

5.5 What role do agri-environmental payments play in supporting practices that enhance farmland biodiversity?

As discussed in Section 5.2 To what extent do socioeconomic factors influence regional agricultural land use compared to the impacts of climate change?, AES payments can enhance targeted land use and thus farmland biodiversity. However, the obtained findings also suggest that the effectiveness of this mechanism is largely dependent on the payment level; in CS 1 and CS 3, windfall profits increased as payments increased beyond the current level. This finding was also noted by Bartolini et al. (2021). Increased windfall profits occurred because no distinct land use change occurred despite increased payment levels for the targeted land use. This increased windfall profit manifested as the decreasing cost-effectiveness of AESs in CS 1. The choice of crop activities in the BEFM is dependent on their relative profitability among crop activities given the underlying constraints. In CS 1 and CS 3, a moderate increase in AEP hardly changed the relative profitability of crops but rather caused an increase in governmental expenditure without apparent effects. The already high dependency of Swiss and Estonian farms on AEP explains this result. Other recent studies, such as those of Ait Sidhoum et al. (2023) and Mennig and Sauer (2020), reached similar conclusions.

Furthermore, the relationship between the adoption of the AES and its effects on farmland biodiversity showed complex changes. Compared to that in the Estonian case study, in which the SNGL had a substantial effect on habitat quality, the level of farmland biodiversity was not entirely dependent on the extent of orchard meadows in the Swiss case studies. The biodiversity scores of the farm activities in grassland areas were found to be much greater than those in arable land areas; even the score for intensive grassland was still greater than that for any of the activities in arable land areas with organic management. Therefore, grassland conservation is the key to farmland biodiversity (Kachler et al., 2023). In Switzerland, instead of implementing mandatory regulation, which is the case in Estonia, the country leverages incentive-based schemes to enhance grassland use. One of them is the promotion of a grass-based feed system. Land managers receive extra payments per hectare of grassland if the share of roughage contained in the feed is above a certain percentage. Given the role of grassland in preserving farmland biodiversity, measures aimed at preventing the conversion of grassland to arable land are likely to be effective.

5.6 Methodological reflection

In this PhD study, an integrated land use modelling framework is proposed to simulate land use changes considering land managers' decision-making processes. This approach to land use assessment can provide policymakers with information on the potential consequences of introducing new policies, as land managers are moderators between policies and the manifestation of agricultural land use changes (Malawska et al., 2014; van Vliet et al., 2015). In this modelling, land use changes were simulated not only among broad land-use categories (SNGLs, permanent grasslands, orchard meadows and arable land) but also among different intensity changes within these categories; this is particularly important when the impacts of land use changes on the environment are examined because differences in agricultural management practices can be indicative of varied environmental impacts (Levers et al., 2016). Furthermore, by including livestock production in the BEFM, CS 3 demonstrated the crucial effect of grassland-based livestock systems on regional land use, particularly for biodiversity conservation. As such, the incorporation of various systems associated with regional land use in the ILUM made it possible to conduct a multifaceted analysis of land use changes. The subsequent discussion focuses on the limitations of the BEFM, as it represents the core model of the developed land use assessment framework.

First, decision-making by land managers in all case studies was based solely on the assumption that land managers choose farming and cropping practices to maximise their total GM. Therefore, profit seeking is the single motive for decision-making behaviour. This behavioural assumption has proven to be valid in some European regions (Rounsevell et al., 2003; Audsley et al., 2006). However, other motives beyond profit maximisation affect land use decision-making (Drechsler, 2021). For instance, regional agriculture can be closely connected to the long-succeeding traditions and customs of a family farm or regional agriculture, which often shape unique agricultural landscapes (Assandri et al., 2018). The landscapes with orchard meadows in the Swiss study area are an integral part of the identity of the local people. Some farms keep the trees regardless of whether they are profitable (personal communications). As personal values associated with tradition affect land-use decisions, the role of tradition is a particularly important subject to be addressed in the agricultural context (Roellig et al., 2016; Vasilescu et al., 2023). Nonetheless, applying such a simple assumption for simulating land use changes as this study did can reveal the competitive relationships among land uses from an economic point of view (Plieninger et al., 2016) and provide insights into economically optimal resource allocation for farmland to alleviate trade-offs resulting from targeting particular land use types (Zhang et al., 2014).

Second, the procedure for model evaluation was limited in this study: the extent to which the results from the BEFM developed for this PhD study were sensitive to exogenous parameters was not fully investigated. Model evaluation is necessary to ensure the reliability of a model itself and its outcomes (Janssen and van Ittersum, 2007). In this context, initial parameterisation in a calibration procedure must be carefully performed so that the land use simulated with the BEFM closely matches the observed land use. However, as Janssen and van Ittersum (2007) noted, the comparison between model outcomes and actual land uses should be explicitly discussed because this gap indicates the ability of a model to come close to reality (Thompson, 1982). The validation of model outcomes via sensitivity analysis is a critical process, particularly when the data are uncertain (Reidsma et al., 2018). Kokemohr et al. (2022) showed that farm-level decisions are sensitive to price, yield and livestock performance. Demonstrating possible variations in model outcomes can increase model credibility. Even though it is beyond the scope of this PhD study, a systematic model evaluation could improve the overall reliability of the BEFM and its outcomes.

Finally, perhaps the most critical limitation of this PhD study is that future farm labour demand was incorporated into the BEFM based on current technology, i.e., no explicit implementation of new technology for crop and livestock management was considered. The demand for farm labour will certainly change depending on what kind of new farming technology is adopted in the future (Nolte & Ostermeier, 2017). One key finding of CS 2—a sufficient labour supply is a prerequisite for achieving diversified agricultural land use—would have to be revised if technological developments consistent with the described socioeconomic changes in the SBL-Agri-SSP1 increase productivity in terms of labour. Several studies have identified technological development as a land use driver that has a significant impact on future land use in Europe (Ewert et al., 2005; Janssen et al., 2011; Kanellopoulos et al., 2014). To address the research gap that few studies have endogenously implemented technological changes in agricultural sector models, Dietrich et al. (2014) and Wang et al. (2020) focused on investment in productivity improvements for sustainable agricultural land use. Explicitly considering technological changes is perhaps more relevant in an area in which a labour shortage hinders sustainable agricultural development. A large potential change in land use might occur if technological development circumvents such a problem (Charlton and Kostandini, 2021).

5.7 Implications

5.7.1 Implications for policymaking

The case studies conducted for this PhD study revealed the two important roles of the AES for regional agricultural land use: while the AES increases the profitability of biodiversity-rich land uses, providing financial incentives to land managers to use such land uses, it makes regional land use more resistant to external land use drivers such as market and climate changes. The land uses that were the focus of this PhD study were both tied to extensively managed grasslands, which were found to be critical for farmland biodiversity. The conversion of grasslands into arable land, even though it is managed without synthetic input, degrades overall farmland biodiversity. Therefore, grassland-targeted AESs are the most legitimate measures for conserving farmland biodiversity. Considering the current trend that grasslands are gradually being converted to arable land in European agricultural landscapes (Lüker-Jans et al., 2016), grassland conservation measures that provide economic advantages and maintain grasslands over other competing land uses must be implemented. Given the low level of economic profitability for land users and the low quality of fodder, financial support for maintaining extensively managed grasslands is necessary for land managers (Kachler et al., 2023).

Even so, increasing payments for agri-environmental measures beyond the current levels will likely result in limited effects, potentially increasing windfall profits and decreasing cost-effectiveness. In addition, such land uses can be relatively labour intensive. This indicates that with a limited farm labour force, the existing financial support might not be sufficient for maintaining these land uses and could worsen inefficient labour allocation. Because such limiting factors vary across regions, an AES should be adapted to local conditions to enhance its effectiveness (Kristensen et al., 2016; Stürck et al., 2018). Therefore, improving the profitability of grassland management without increasing governmental budgets is a desirable strategy for farmland biodiversity conservation. Such strategies can include utilising more efficient machines or establishing specialised service providers. Adopting alternative uses of the biomass produced from grasslands is also a promising strategy for grassland conservation (Roellig et al., 2016). In Switzerland, adopting mandatory regulation similar to the existing EU policy that prohibits the conversion of permanent grasslands into arable land could be considered. Conversely, the EU could contemplate introducing incentive-based schemes to promote grassland-based products, similar to those implemented in Switzerland. Additionally, considering increasing consumer preferences for "locally" and "ecologically" produced agricultural products (Feldmann and Hamm, 2015; Rytkönen et al., 2018), the strategies for promoting regionally produced food related to extensively managed grasslands can be leveraged to increase the profitability of agricultural production on grasslands (Herzon et al., 2022), for instance, by granting labels or establishing brands. These strategies may also have the potential to attract younger generations to work in the agricultural sector.

Policymakers should be informed of both the positive roles and the potential limitations of AEP. For this reason, it is important to understand what resources are required to maintain biodiversity-rich land uses compared to the resources needed for other competing land uses and to what extent there are disadvantages or advantages among land uses. This information regarding how a particular land use type competes with other land uses can facilitate cost-effective AEP development given the potential trade-offs caused by the promotion of biodiversity. Furthermore, policymakers should be aware of the different effects of agri-environmental policies depending on the characteristics of farms, which are attributed to different opportunity costs for adopting AESs. If such differences in farm characteristics are reflected in policymaking, the current “one-fits-for-all” policies could be more effective through selection and concentration (Kristensen et al., 2016; Lankoski, 2016; Piñeiro et al., 2020).

From the perspectives of land managers and other stakeholders, a farm-level modelling approach embedded with farm typology could aid in engaging in communication with scientists (Prost et al., 2023). This, in turn, could make it possible to design agri-environmental policies that are specific to the needs of various farm types (Hanley et al., 2012; Wunder et al., 2020) and allow policy-makers to assess each farm's environmental performance. Studies exploring the effects of farm heterogeneity on agri-environmental policies and land use decisions continue to be a focal point in the literature on farm-level modelling, as demonstrated by Saint-Cyr et al. (2019), Finger et al. (2022), and Huber et al. (2023).

5.7.2 Implications for further studies

Farm heterogeneity in the modelling framework was found to be a key factor for understanding how regional agricultural land use could change in response to land use drivers. This approach is relevant for exploring future regional land use because various changes at the farm level, such as structural changes or the phase out of small-scale farms, are expected to occur during this period (Nolte & Ostermeier, 2017), as also observed in CS 2. In particular, depending on the pathways of future agricultural technological development, existing farm systems could be transformed into different systems (Stringer et al., 2020). Given the critical roles of farm structural changes in shaping regional land use (Kristensen et al., 2016), further studies should explicitly incorporate dynamic changes in various farm types into the simulation of land use. This challenge can be addressed by coupling the proposed framework with external models that can simulate changes to farm systems within the existing modelling framework, such as agent-based models (Beckers et al., 2018). This model coupling approach could also make it possible to implement diverse land-use decision behaviours or interactions among land managers in the BEFM beyond sheer profit seeking (Uthes et al., 2011; Guillem et al., 2015; Reidsma et al., 2015), which is of particular importance at the local scale (Verburg et al., 2019). The systematic approach proposed in this PhD study for modelling land use changes facilitates interdisciplinary model integration. By building modular modelling systems in the BEFM, a comparative static model can be further applied without modifying the fundamental model structure (Britz et al., 2021).

Similarly, future studies should explicitly consider the adaptation of new agricultural technologies to the BEFM. Notably, one major challenge is that the precise impact of research and development on technological change remains unclear (Dietrich et al., 2014). Technological development in agriculture and technological adoption by land managers are influenced by multiple interconnected factors (Ruzzante et al., 2021; Zegeye et al., 2022). For example, advancements in agricultural technology over the next few decades are expected to arise from the development of new markets for agricultural products, as seen in the bioenergy sector (Burgess and Morris, 2009). Considering the critical role of agricultural technologies in land-use decision-making, it is essential to identify plausible new technologies adopted by land managers and describe how they will affect crop profitability, crop choice, and farm labour demand in future scenarios.

Finally, among European agricultural studies, the recognition of the diversity of today's farms is increasing (Adenuga et al., 2020; Guarín et al., 2020; Finger & El Benni, 2021), reflecting the limitations of "one-fit-for-all" policies (Britz, et al., 2016). These studies highlight the different needs of diverse farms with various adaptation and development options across regions (Stringer et al., 2020). The diversification of farms and farm systems is an important aspect of rural development policy in Europe (Vroege et al., 2020). By considering multiple environmental goals in the optimisation process of land use decision models and diversity in decision-making by land managers, agri-environmental policies might better support the development of sustainable agricultural land use in rural areas.

6. Conclusions

In today's fast-paced world, land managers are compelled to continuously adapt to the evolving environment driven by socioeconomic and biophysical changes, inevitably manifesting as land use changes at the farm or regional scale. To assess the impacts of regional agricultural land use changes in response to various land use drivers, this PhD study proposes an integrated land use assessment framework that makes it possible to simulate land use changes through land managers' decision-making and assess the corresponding impacts on the socio-ecological systems.

In search of prominent land use drivers, the results indicate that socioeconomic drivers, particularly AESs, play a dominant role in agricultural land use in the examined case study areas, as the impacts of changes in AEPs on land use were more pronounced than those of other land use drivers. The high dependency of farm GM on payments from the AES provided a certain level of resistance of land use to external changes, such as those associated with market prices and climate change. In this PhD study, climate change affected crop choice rather than crop yield.

Further analysis shows that the effects of AES on agricultural land use were not uniform but differed across farm types, depending on the farm structure, farm size, livestock system, and dependency on the AEP, all of which influenced the opportunity cost of each farm type for adapting agri-environmental measures. Farm structures pronouncedly changed under the set of framework conditions for the liberalised path conditioned with globally oriented farm production and no agri-environmental policies, with notable impacts on future land use.

Extensively managed grasslands play a critical role in enhancing farmland biodiversity. Such biodiversity-rich land uses are not economically profitable without financial support due to the low efficiency of fodder production in terms of yields, forage quality, and labour use. However, increasing payment levels in AESs beyond the current level will increase windfall profits and reduce the cost-effectiveness of the AES. As a result of the extension of biodiversity-rich land, some trade-offs must occur, such as reduced cash crop production or labour reallocation.

This PhD study concluded that it is critical for farmland biodiversity to maintain extensively managed grasslands. AEP is indispensable for land managers because biodiversity-rich land uses are less profitable and productive than other land uses for fodder production. Because of the characteristics of extensively managed grasslands, solely relying on the AEP is likely to decrease the cost-effectiveness of the AEP. Therefore, policy-making should be directed at grassland conservation with cost-effective management practices to reduce trade-offs while considering the local factors that hinder the promotion of biodiversity-rich land uses and the heterogeneous effects of land use drivers depending on the characteristics of farms

7. Overall summary

Agriculture today is under increasing global land use pressure: to provide food efficiently while accounting for the ecological consequences of agricultural land uses. This thesis aims to identify prominent, regionally relevant land use drivers and assess their socio-ecological impacts on regional agricultural land use, considering land managers' decision-making processes. To achieve this, an integrated land use impact assessment framework was developed to evaluate the socio-ecological impacts of land use changes in rural regions of Switzerland and Estonia. The results reveal that socioeconomic drivers, particularly agri-environmental schemes (AES), play a dominant role in agricultural land use in both study areas. Changes in agri-environmental payments (AEP) on land use were found to have a more pronounced impact on land use than other divers. To enhance farmland biodiversity, orchard meadows and semi-natural grasslands—both extensively managed—were identified as critical. However, financial support for these grassland types is essential, as they are unprofitable due to low productivity in terms of yields, forage quality, and labour efficiency. Nonetheless, increasing AEP for these grassland uses beyond the current level is likely to worsen the trade-offs: windfall profits rise and the cost-effectiveness of AES declines as more resources (e.g. land and labour) will be allocated to those less productive land uses. In conclusion, improving the profitability of extensively managed grassland management without increasing governmental budgets is a desirable strategy. This could be achieved by, for example, enhancing management efficiency to address labour shortages or by branding locally and ecologically produced grass-based products to create market opportunities for land managers. Yet, the Estonian case study suggests that purely demand-driven measures are insufficient to sustain extensive grassland use, as usage reserves in more intensively managed grasslands are prioritised and exploited first.

8. Gesamtzusammenfassung

Die Landwirtschaft steht weltweit unter zunehmendem Druck, Nahrungsmittel effizient bereitzustellen und gleichzeitig die ökologischen Folgen der Flächennutzung zu berücksichtigen. Ziel dieser Dissertation ist es, wichtige, regional relevante Treiber der Landnutzung zu identifizieren und ihre sozio-ökologischen Auswirkungen zu bewerten, welche sich wiederum auf die landwirtschaftliche Flächennutzung auswirken. Hierfür wurde ein integrierter Modellierungsrahmen entwickelt und auf ländliche Regionen in der Schweiz und in Estland angewendet. Die Ergebnisse zeigen, dass sozioökonomische Faktoren, insbesondere Agrarumweltmaßnahmen, die landwirtschaftliche Nutzung maßgeblich beeinflussen. Änderungen bei den Agrarumweltprämien haben stärkere Auswirkungen auf die Landnutzung als andere Einflussfaktoren. Zur Förderung der Biodiversität in der Landwirtschaft wurden Streuobstwiesen und naturnahes (extensiv bewirtschaftetest) Grünland als entscheidend eingestuft. Diese Flächen sind aufgrund ihrer geringen Produktivität in Erträgen und Futterqualität, als auch ihrer geringen Arbeitseffizienz oft unrentabel, was finanzielle Unterstützung unverzichtbar macht. Dennoch könnten Prämien, die über das derzeitige Niveau hinausgehen, Zielkonflikte verschärfen: Mitnahmeeffekte würden zunehmen und die Kosteneffizienz der Maßnahmen abnehmen. Daher ist es sinnvoll, die Rentabilität der extensiven Grünlandbewirtschaftung zu steigern, ohne die öffentlichen Haushalte zu belasten – etwa durch effizientere Bewirtschaftungsmethoden zur Behebung des Arbeitskräftemangels, die Förderung alternativer Grasprodukte und die Vermarktung lokal und ökologisch erzeugter Produkte aus Grünland. Die Studie in Estland zeigt jedoch, dass rein nachfrageorientierte Maßnahmen nicht ausreichen, um die Nutzung von extensivem Grünland dauerhaft zu sichern, da Nutzungskapazitäten in intensiver bewirtschaftetem Grünland Vorrang haben und zuerst ausgeschöpft werden.

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