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Spatial arrangement of action-oriented versus hybrid agri-environmental schemes: implications for the optimisation of grassland ecosystem services

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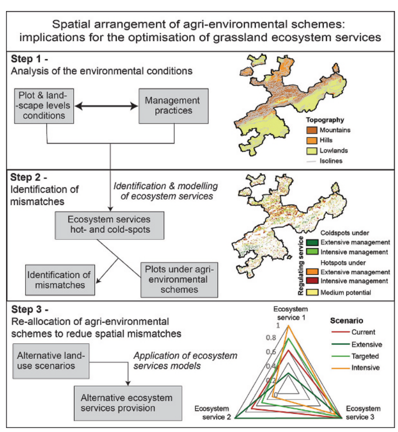
HIGHLIGHTS

- Extensive grasslands are often located on marginal lands.
- Action-oriented extensive meadows partly overlap with yield hotspots.
- Grasslands under agri-environmental scheme may bring several co-benefits.
- Spatial targeting of schemes enhances regulating services and minimizes yield loss.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: The potential of agri-environmental schemes to create synergies among biodiversity conservation and further ecosystem services while accounting for the trade-off with food production is still widely overlooked.
OBJECTIVE: This paper provides a methodological framework to improve the effectiveness of agri-environmental schemes in permanent grasslands at the regional level.
METHODS: The framework comprises three steps that integrate existing approaches to provide decision-makers with a structured and systematic approach for holistic assessments of ecosystem service and guide the spatial targeting of agri-environmental schemes. Step 1 focusses on better understanding the current system and in particular of how agri-environmental measures co-vary with environmental characteristics that are relevant for

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agricultural production, biodiversity, and further ecosystem services. Step 2 assesses spatial (mis)matches between the current allocation of agri-environmental schemes and ecosystem services hot- and cold-spots. Step 3 focuses on reducing mismatches through a reallocation of agri-environmental schemes.

We illustrated our framework in the canton of Solothurn, Switzerland, to examine how environmental conditions for differently designed agri-environmental schemes (action-based vs. hybrid) and spatial heterogeneity can support synergies between biodiversity and two regulating ecosystem services (climate regulation and pollination) and reduce trade-offs with forage production at the regional level.

RESULTS AND CONCLUSIONS: Our stepwise framework provides a guideline to assess and improve the effectiveness of agri-environmental schemes in grasslands. Each step is methodologically flexible and can be adapted to specific contexts, including the selection of ecosystem services, appropriate indicators, and modelling approaches.

In our case study, extensive grasslands, especially those in hybrid schemes, were predominantly situated on marginal lands, when compared to intensively managed grasslands. Over 90 % of pastures (grazed grasslands) under each of the two agri-environmental schemes overlapped with hotspots of regulating services. Around 15 % of meadows (mown), under each of the two agri-environmental schemes, overlapped with yield hotspots, resulting in considerable trade-offs with food production. 34 % of the grassland area could be set aside for biodiversity conservation instead of being used for (intensive) forage production, as it was located in potential hotspots of regulating ecosystem services and on potential yield coldspots. Pastures under agri-environmental schemes generally showed a better fit with yield coldspots and regulating ecosystem services hotspots than respective meadows. Spatial targeting reduced trade-offs in some cases, but it did not eliminate them, as the focus on specific services reflected local geographical constraints.

SIGNIFICANCE: Our stepwise framework offers insights for the spatial planning of agri-environmental schemes at the regional scale. It serves as a practical tool for spatial planners and decision-makers to enhance the efficiency of environmental management interventions, by supporting the supply of multiple ecosystem services while minimizing trade-offs with agricultural production. The application of the framework suggests that spatial targeting of biodiversity conservation schemes could enhance their effectiveness and reduce trade-offs between regulating and provisioning ecosystem services at the regional scale. Effective reallocation of the schemes should be grounded in environmental contexts that also promote high biodiversity.

1. Introduction

Sustaining biodiversity requires more space than currently attributed. Kunming-Montreal Global Biodiversity Framework Target 3 has as an objective to protect at least 30 % of the planet by 2030 for biodiversity conservation (CBD, 2022). Permanent grasslands can make a significant contribution to this target (Poux and Aubert, 2022). In addition to biodiversity conservation, grasslands provide multiple ecosystem services and contribute to food security, with biodiversity playing a fundamental role in providing these services (Mace et al., 2012; Bengtsson et al., 2019; Schils et al., 2022). The European Nature Restoration Law has pointed out the need of restoring grassland ecosystems to enhance their biodiversity and the services they provide (Regulation (EU) 2024/1991).

Agri-environmental schemes are a funding mechanism aiming to provide financial support to farmers to support biodiversity and the many different ecosystem services provided by grasslands (Boetzl et al., 2021). They can have diverse designs and scopes (Schaub et al., 2023). For instance, *action-oriented* agri-environmental schemes reward farmers for adopting environmentally friendly practices (Kampmann et al., 2012), while *result-oriented* schemes focus on delivering specific positive environmental outcomes, often monitored by site-specific measurements such as presence of specific indicator plant species. Combinations of different designs of agri-environmental schemes, for instance of action- and result-oriented schemes, also exist (i.e., *hybrid* schemes; Bredemeier et al. 2022).

An increasing number of studies assesses different designs of agri-environmental schemes, e.g., in terms of institutional settings and involved actors or (set of) characteristics (Bredemeier et al., 2022; Kreft et al., 2023; Sattler et al., 2023). However, empirical knowledge on how environmental conditions influence the spatial placement and effectiveness of agri-environmental schemes is still lacking (Olivieri et al., 2021). This considerably restricts effective land-use planning.

While agri-environmental schemes often officially target one specific environmental outcome such as biodiversity (Knop et al., 2006), they may also generate synergies, such as between biodiversity and carbon sequestration (Verhagen et al., 2018; Albrecht et al., 2020). Yet, the relationships between biodiversity and ecosystem services are variable across space and management (Wehn et al., 2018), and trade-offs between ecosystem services, e.g. regulating versus provisioning services, can arise (Le Clec'h et al., 2019b). A one-fits-all agri-environmental schemes that serve all demanded ecosystem services is not possible (Olivieri et al., 2021), but accounting for the trade-offs and the environmental conditions, is required to ensure an effective and efficient land-use planning (Huber et al., 2021), with lower opportunity costs for farmers and less losses in societally relevant food production (Wunder et al., 2018).

In Switzerland, policies are strongly committed to protecting biodiversity and ecosystem services, particularly on agricultural lands (FOEN, 2012). Farming activities have shaped the landscape, creating a mosaic of land-uses, with varying environmental impacts, and that compete for limited space. In Switzerland, farmers need to comply with the so-called "proof of ecological performance" to receive direct payment. This proof of ecological performance contains, among others, the requirement to have a minimum 7 % of the farm area of all arable and grassland farms to be registered as Ecological Compensation Area (ECA) to qualify for direct payments (Huber et al., 2023). ECA can be linked to an action-oriented (hereafter ECA1) or to a hybrid agri-environmental scheme (hereafter ECA2), i.e., the combination of an action- and a result-oriented scheme. Famers may register areas where the agricultural yield, which has a market value, is naturally reduced, for example by topography, so that losses in production due to agri-environmental schemes are rather low (Klaus et al., 2024). However, such marginal areas might also have a reduced potential for other ecosystem services, e.g. regulating services. This may result in mismatches between the desired targets of agri-environmental schemes and the actual contribution of the land under these schemes.

This paper aims to provide a methodological framework that integrates existing approaches and tools to improve the effectiveness of agri-environmental schemes in grasslands at the regional level. It addresses the knowledge gaps in understanding the role of environmental conditions for differently designed agri-environmental schemes and how the spatial heterogeneity of these conditions can be exploited to reduce trade-offs between and support synergies of biodiversity conservation and regulating ecosystem services in permanent grasslands.

The study focusses on the canton of Solothurn, as a proof of principle, for providing guidelines to improve the effectiveness of agri-environmental schemes in grasslands at the regional level. Although applicable at larger scales, the cantonal level is in Switzerland due to decentralized policy-making. Our results provide a framework that enhances the understanding of where in a landscape, i.e., an area composed of multiple farms, farmers spatially target action-oriented versus hybrid agri-environmental schemes. This framework allows to test the potential of a reallocation of these schemes, by identifying spatial (mis)matches, and thus potentially suggest alternative allocation of grasslands parcels targeted by agri-environmental schemes that reduce the trade-offs between provisioning and regulating ecosystem services. In that sense, this methodological framework provides a basis for optimizing the spatial distribution of agri-environmental schemes.

2. Material and methods

2.1. Conceptual approach: overall methodological framework

This study followed three major steps that constitute the methodological framework (Fig. 1) as a structured set of procedures. The three steps rely on existing approaches and tools and integrate them to provide decision-makers with a structured and systematic approach to facilitate holistic assessments of ecosystem service and support spatial targeting of policies. We illustrated our conceptual framework flows in the case of the canton of Solothurn.

Step 1 provides a better understanding of the current system and in particular of how agri-environmental measures co-vary with environmental characteristics that are relevant for agricultural production, biodiversity, and further ecosystem services. Understanding how parcels under intensive management, action-oriented or hybrid agri-environmental schemes differ in environmental characteristics is essential for assessing the effectiveness of such schemes, as these characteristics may be critical for biodiversity conservation (Gonthier et al., 2014; Pörtner et al., 2021). Key variables in this step are linked to management practices, and a set of environmental variables at both plot and landscape levels.

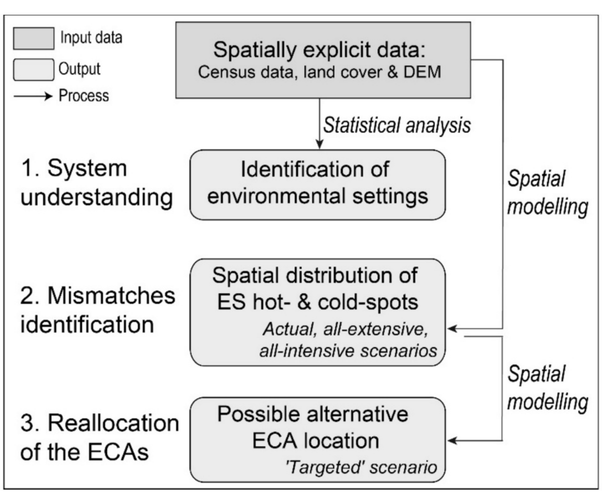

Fig. 1. General three-step methodological framework of this study. ES stands for Ecosystem Services and ECA stands for Ecological Compensation Area, the terminology used for the Swiss agri-environmental schemes studied.

In the canton of Solothurn, we identified the environmental setting (soil, topography, etc.) in which farmers implement action-oriented or hybrid agri-environmental schemes.[1] We analysed the current spatial distribution of all considered ECA1- and ECA2-grasslands as well as their intensive counterparts. We relied on spatially explicit census data at the parcel level and environmental characteristics of these parcels, related to the topographical and soil conditions.

Grasslands offer vital ecosystem services beyond food production, helping address issues like biodiversity loss and climate change. However, managing them for multiple services is complex due to trade-offs (Neyret et al., 2023). Spatial strategies are needed to reduce trade-offs and support landscape multifunctionality. Identifying areas that deliver high ecosystem services with minimal yield loss is key to assessing agri-environmental schemes and improving environmental outcomes. Step 2 allows the assessment of (mis)matches between the current allocation of agri-environmental schemes and ecosystem services hot- and cold-spots, i.e. areas naturally providing, respectively, low, and high amounts of one or several ecosystem services, respectively Schröter and Remme (2016) and Le Clec'h et al. (2016). Comparing current locations of agri-environmental schemes with cold- and hotspots allows to assess the synergies and trade-offs between provisioning and regulating ecosystem services in a multifunctional agricultural landscape. It also allows to identify (mis)matches of current allocation of agri-environmental schemes as well as the potential gains from rearranging the spatial allocation of agri-environmental schemes.

Key variables in step 2 are linked to management practices, environmental variables and ecosystem services, for instance derived from field work, remote sensing data, census data. These variables are critical to provide information on the spatial distribution of ecosystem services provision in the study area.

In the canton of Solothurn, we analysed the extent to which grassland parcels assigned to hybrid agri-environmental schemes better match environmental hotspots for regulating ecosystem services (climate regulation, pollination) and avoid hotspots for provisioning services (i.e., trade-offs with food production) than action-oriented schemes. These services are critical in grassland systems and are likely to respond to land-use land-cover change in an agricultural landscape (Krimmer et al., 2019; Le Clec'h et al., 2019; Bullock et al., 2021). The indicators we chose to characterize the two services have successfully been used in previous studies to characterize grassland ecosystem services in relation to parcel management and further factors (Le Clec'h et al., 2019a, 2019b; Huber et al., 2022; Schaub et al., 2025). Cold- and hotspots of ecosystem services were identified based on the ecological capacity of the parcels, i.e. the natural contribution to ecosystem services supply independently of the current management intensity under an all-extensive scenario and an all-intensive scenario, i.e., considering that all parcels were extensively managed and all parcels were intensively managed, respectively. We used the terminology "actual" and "potential" supply to refer to the supply of ecosystem services under the current conditions and under the conditions in one of the scenarios, respectively.

Effective targeting of agri-environmental schemes requires the systemic evaluation of environmental challenges in a spatially explicit manner. This ensures that countermeasures are focused on critical locations and that the spatial allocation of schemes can be optimized (Albert et al., 2016; Früh-Müller et al., 2019). Step 3 of our framework proposes a spatial reallocation of agri-environmental schemes, based on the identification of context-specific information (Step 1) and the spatial distribution of hot- and coldspots of ecosystem services (Step 2).

In Solothurn, we investigated the potential of a targeted scenario to

[1] action-oriented (management restrictions only) and a hybrid (combination of action- and result-oriented; i.e., management restrictions and presence of key indicator plant species.

reallocate agri-environmental schemes in order to reduce the trade-offs between provisioning and regulating services. This targeted scenario suggests the spatial arrangement in which agri-environmental schemes could enhance multiple environmental benefits (spatial overlap with ecosystem services hotspots) while minimizing yield losses (spatial overlap with yield coldspots). This enabled us to assess the proportion of potentially suitable areas for biodiversity conservation and areas suitable for productive grasslands, for the Jura and the plateau parts of the study region separately. These alternative locations for ECA-grasslands can support high supply of regulating ecosystem services, while decreasing the risk of reducing agricultural yields and preventing abandonment of grassland parcels in marginal areas.

2.2. Study area

The canton of Solothurn is located in the north-west of Switzerland (Fig. 2). It covers 791 km^2 at an elevation ranging between 277 and 1445 m.a.s.l., with a flat plain in the south of the canton, created by the Aare River and its tributaries, and the undulating foothills of the Jura Massif in the north. Agriculture is the dominant land-use in the canton. The total utilized agricultural area of Solothurn comprises 246 km^2 covered mainly by permanent grasslands (67 % of the total utilized agricultural area), croplands (32 %) and rotational, temporary grassland (14 %; FSO 2019). In 2019, the canton comprised 1133 farms. The average utilized agricultural area per farm was 26.6 ha distributed across on average 17 parcels.

Across the canton, the environmental conditions of grassland parcels vary widely in terms of soil type and depth, topography, elevation, and further factors such as surrounding land-use types (Klaus et al., 2024). The diversity of these environmental conditions, the dominance of grassland as the main land-use type, and the relatively high proportion of utilized agricultural area under environmental schemes make the canton of Solothurn a highly suitable study area to analyze how environmental factors determine the uptake and distribution of grasslands under agri-environmental schemes and their ecosystem services.

2.3. Data

Two spatially explicit datasets were used in this study (Table 1). We used spatially explicit census data about management practices at the parcel level and extracted remote sensing-based data about the environmental conditions of each parcel (DEM, land-cover classification). All data about the environmental conditions was extracted using the average of each variable per parcel.

2.4. Parcel agricultural management

Data about the agricultural management in 2019 were obtained from census data (GELAN, 2019) and were given at the parcel level. We considered a total of 20,841 parcels (FSO, 2019), divided between three main groups: parcels under intensive management, parcels under action-oriented schemes, called ECA type 1 (hereafter ECA1), and parcels under hybrid schemes, called ECA type 2 (hereafter ECA2[2]; Table 2). The ECA2 guidelines inherently incorporate ECA1 guidelines, due to their tiered structure. Consequently, we have conceptualized ECA2 as an additional layer on top of ECA1. It is important to clarify that when we refer to "ECA1" in this study, we are specifically referring to "ECA1 without ECA2", while "ECA2" includes both ECA1 and ECA2 guidelines.

We included six distinct grassland types in our study, based on their management regime and intensity (Table 3), because different grassland types all provide different levels of biodiversity and ecosystem services (Beckmann et al., 2019; Le Clec'h et al., 2019a, 2019b). We used scientific literature to further characterize these six classes, according to their management (Blüthgen et al., 2012), e.g., in terms of amount of fertilizer, frequency of mowing or grazing. We assumed that grasslands are well-balanced in species composition (i.e., they comprise 50 to 70 % of grass; Huguenin-Elie et al., 2017). Other land-use and land-cover types were omitted from the analyses, including other types of ECA grassland such as mountainous summer pastures and fen grasslands, which account for only a very small proportion of the total grassland area (< 4 %). We define meadows as grasslands that are harvested predominantly by mowing and pastures as characterised by grazing (Table 3). Census data gives information about the real landscape and management practices at the parcel level. This means that our results are given for the spatial distribution of permanent grasslands in Solothurn in 2019, assuming no change in management regime over time. While management practices can also alternate, we did not account for such alterations, although they are likely to significantly affect the supply of ecosystem services, both regulating and provisioning, over time.

The area covered by ECA1-grasslands, i.e. extensive meadows and extensive pastures under the action-oriented scheme that are not additionally registered as ECA2-grasslands, represents 77 % of the total area of ECA-grasslands in canton of Solothurn (GELAN, 2019). In total 68 % of the total area of ECA1-grasslands are extensive meadows and 32 % are extensive pastures.

2.5. Environmental characteristics

A Digital Elevation Model (DEM) of the Copernicus Land Monitoring Service of the European Environment Agency (European Union, 2018) at a resolution of 25 m provided data about the topographical features of the study area. The topography data informed the elevation (in meters a.s.l.) at every pixel. Slopes synthesized the altitudinal difference between two adjacent pixels and were provided as percentage. The Topographic Position Index (TPI) compares the elevation of a cell of the DEM to the average elevation of the surrounding around that cell (Guisan, 1999; Mokarram et al., 2015). We used a three-cell radius to compute the TPI. A TPI < 0 indicates a valley position, a TPI > 0 indicates ridges and areas with a TPI ≈ 0 are flat. Finally, we derived the Topographic Wetness Index (TWI) from the DEM as proxy for soil moisture, calculated from slope and upstream contributing area orthogonal to flow direction (Kopecký et al., 2021). These four variables were treated as quantitative, continuous data.

We extracted the compound-factor "soil suitability for agricultural production", officially used to estimate the production potential of a parcel (FOAG, 2005). Soil suitability was based on slope, geology (type and depth of bedrock), and soil water regime. This factor consisted of five ordinal levels, from 1 (very suitable for agricultural production) to 5 (inappropriate for production).

Information about the land-use land-cover was extracted from the Corine Land Cover for Switzerland (http://www.wsl.ch/en/projects/corine-switzerland.html). We calculated the Simpson's diversity index to estimate the diversity of the landscape surrounding each pixel (three-cell radius). Finally, we calculated the shortest linear distance of each grassland parcel to a patch of semi-natural habitat (forests, scrub and/or herbaceous vegetation associations and open spaces with little or no vegetation).

2.6. Application of the stepwise methodological approach

Our approach follows the three steps of the suggested methodological framework (Fig. 1). We applied the three-step approach to the canton of Solothurn, building upon previous studies in the same study area (e.g., Le Clec'h et al. (2019b); Huber et al. (2022)).

We conducted descriptive statistics to reveal spatial patterns at the regional level, and not for predictive purpose. All statistical analyses (i.e., comparison of mean, standard deviation and multinomial

[2] We considered grassland ECA1 and ECA2 to be distinct units, for modelling purposes. Yet, we are aware that in practice ECA2 often only covers a part of a parcel according to a vegetation record performed by an official observer.

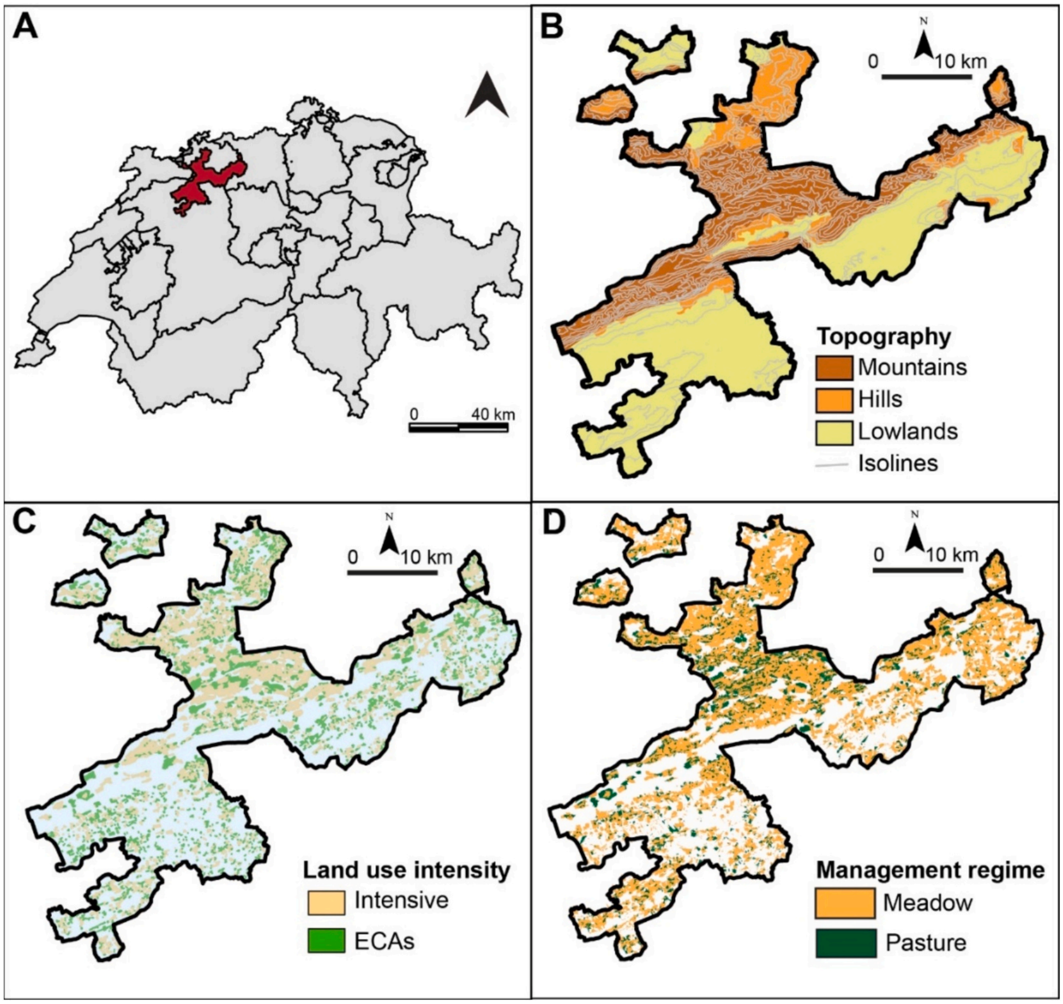

Fig. 2. (A) Location of the canton of Solothurn in Switzerland, (B) its topography, (C) the location and management intensity of all permanent grassland parcels separated into (D) meadows (predominately mown) and pastures (predominately grazed). The Jura mountains comprise the area north-west of the plateau part of the canton, which is characterised by low elevations (southernly lowlands in 2B).

regressions) were supplemented with Chi-square tests for factors, and with both Kruskal-Wallis tests and pairwise *t*-tests with Bonferonni correction (Cabin and Mitchell, 2000) for quantitative variables ($p = 0.05$ as significance level).All statistical analyses were conducted in Rkward (Friedrichsmeier and the RKWard Team., 2022), using the packages MASS (Venables and Ripley, 2002), readxl (Wickham and Bryan, 2019), nnet (Venables and Ripley, 2002). All R codes will be shared upon request. All spatial analyses were conducted in ArcGis Pro.

Step 1. Understanding the current system: how agri-environmental measures co-vary with environmental characteristics that are relevant for agricultural production, biodiversity, and further ecosystem services.

Step 1 of our framework therefore focuses on identifying differences in environmental characteristics among parcels under different agricultural management practices. To achieve this, we examined the environmental settings where farmers implemented action-oriented and hybrid agri-environmental schemes. These settings were characterised by land-use decisions and associated scheme types, specifically: (i) species-rich extensive grasslands (ECA2-grasslands), (ii) less biodiverse extensive grasslands (ECA1-grasslands), and (iii) species-poor intensive grasslands.

We illustrated this step by conducting analyses based on the spatial location of the parcels and combined census data and variables related to topographical and soil conditions (Table 1). We examined differences between the grassland types in these variables based on their average value, mode, and standard deviation. We also computed multinomial logistic regressions and associated Chi-square, for meadows and pastures separately, to estimate the odds of the presence of ECA1 and ECA2 as compared to intensive management, given the environmental characteristics of the parcels ($p = 0.05$ for significance level, for all tests).

Step 2. Assessing (mis)matches between the current allocation of agri-environmental schemes and ecosystem services hot- and cold-spots.

The second step of our framework involves identifying spatial mismatches between the current allocation of agri-environmental schemes and the hot- and cold-spots of ecosystem services. This step aims to ensure the supply of high levels of multiple ecosystem services without compromising agricultural yields. It is further divided into three methodological substeps: 1) Building indicators to identify ecosystem services hot- and cold-spots, 2) Identifying these hot- and cold-spots under alternative land-use scenarios, and 3) Analyzing mismatches between the current allocation of agri-environmental schemes and the identified hot- and cold-spots. We further illustrated these steps and substeps by assessing (mis)matches between current allocation of agri-environmental schemes and hot- and cold-spots of agricultural yields and two regulating services in the canton of Solothurn.

2.6.1. Building up indicators of hot- and coldspots ecosystem services

To assess (mis)matches between parcels under both agri-environmental schemes and potential hotspots for climate regulation and pollination versus coldspots for forage production, we first analysed the potential supply of the three ecosystem services following a

Table 1
Summary of input data. NA was used in the case of factors. See Tables 2 and 3 for further details on the associated grassland management.

Dataset sources (year)	Data (unit/ levels)	Min	Max	Mean
Census data, GELAN (2019)	Regime (meadow, pasture)	NA (categorical data)		
	Intensity (intensive, ECA1, ECA2)	NA (categorical data)		
	Distance to farm (m)	0	32,551	559
	Area (ha)	> 1	25.84	0.83
DEM, Copernicus Land Monitoring Service (2018)	Elevation (m)	306	1363	591
	Slope (%)	0	153	14
	TWI (index)	3	24	7
	TPI (index)	−14	10	−0.1
Corine Land Cover (2018), http://www.wsl.ch/en/projects/corine-switzerland.html	Simpson (index)	0	0.85	0.71
	Distance to (semi-) natural habitat (m)	0	3283	203
FOAG (2005)	Soil suitability for arable agriculture (five ordinal levels)	1 (very suitable)	5 (inappropriate)	NA

Table 2
Overview of the two agri-environmental schemes in the study area. See Table 3 for management details.

Type of Grassland Plot	Abbreviation	Number of observations (total $n = 20,841$)	Notes
Action-oriented scheme	ECA1	8140 (23 % of the grassland area)	No check on effectiveness included.
Hybrid scheme	ECA2	2460 (10 %[a] of the grassland area)	As result-oriented schemes require enrollment in action-oriented schemes, these are here labeled as hybrid. Before the scheme is granted, plots are screened for plant species indicating high biodiversity.
No scheme (= intensive)		10,241 (67 % of the grassland area)	No enrollment in ECA.

[a] The 10 % ECA2-grasslands are not included in the 23 % ECA1-grasslands.

Table 3
Management requirements considered to distinguish the six permanent grassland types, which relate to the official grassland typology as part of the Swiss agricultural statistics. Each parcel is characterised by one management regime and one intensity level. For further details, see Klaus et al. (2023).

Regime/Intensity	Intensive (no scheme)	Extensive ECA1 (Action-oriented scheme)	Extensive ECA2 (Hybrid scheme)
Meadow: Grassland that is predominantly mown but grazing is allowed.	Fertilization allowed and widely practiced. Multiple cuts a year allowed depending on fertilization intensity and productivity. Farmers can choose the way and timing of harvesting biomass and, within the legal constraints, the intensity of fertilization (Klaus et al., 2023). They are mainly used for intensive forage production, often silage and high-quality hay for food production (e.g., dairy and beef).[a]	No fertilization, no mulching, and no broad-scale application of pesticides. Delayed first cut (depending on agricultural zones as from mid-June in the lowlands), which allows only for haymaking, but no silage cut. Minimum management is one cut per year, with more cuts being allowed. Grazing allowed only in autumn. Covers 68 % of the total area of ECA1-grasslands.	Same requirements as for ECA1, plus obligatory presence of six indicator plant species.[b] No use of grass conditioner. Covers 71 % of the total ECA2-grassland area.
Pasture: Grassland that is predominantly grazed but cutting is allowed.	Fertilization allowed and widely practiced. High stocking density frequently practiced. Within the legal constraints, farmers can choose the intensity of fertilization (Klaus et al., 2023).	No fertilizer addition and broad-scale application of pesticides. Cutting allowed only as cleaning cut after grazing. Minimum management is one grazing event per year. No supplementary feeding on the parcel. No restriction on timing of grazing. Covers 32 % of the total area of ECA1-grasslands.	Same requirements as for ECA1-pastures, plus obligatory presence of six indicator plant species. Further criteria to ensure the parcel is not dominated by plants that are indicators of high nutrient availability. Covers 29 % of the total ECA2-grassland area.

[a] In a representative study in the same area, intensive pastures and meadow were fertilized on average with 60 (max 174) and 99 (max 203) kg available nitrogen, including organic and inorganic sources, respectively (Richter et al., 2024).
[b] Vascular plant species or species groups are used as indicators for high ecological quality. In Switzerland, different lists are in place for different habitat types, i.e., for meadows (separated into areas north and south of the Alps as well as divided based on the regional biodiversity potential; the number of available indicator species ranges from 36 to 46; FOAG, 2014). The Swiss cantons modify their lists according to regional conditions.

modelling approach under four different regional scenarios. We focused on quantifying three indicators of ecosystem services (bee species richness as an indicator of pollination and carbon (C) sequestration, as an indicator of climate regulation for regulating services and yield as an indicator of forage provision for the provisioning service). We used the multi-sources statistical models described in Le Clec'h et al. (2019b) to estimate the three ecosystem services indicators based on the management and environmental parameters at the parcel level (Table 4, Appendix A and see Le Clec'h et al. (2019) for details about the models parameters). The parameters of the three models were validated by several experts. Their results (maps) were presented to farmers of the study area for validation and were further validated by means of a comparison with other grasslands studies in similar geographical contexts (e.g., Le Féon et al. (2010); Jäger et al. (2020)).

We combined the two previously described indicators of regulating ecosystem services into an overall aggregated ecosystem service score based on the statistical distribution of each ecosystem service indicator (Maes et al., 2012; Le Clec'h et al., 2016). We first normalized the two indicators by dividing the value for each parcel by the maximum value of the indicators across all parcels. The normalisation was needed to transform the two indicators with two different units into unitless indicators. Then we summed up these two normalized ecosystem services indicators into one indicator of regulating services using an equal weighting. Finally we transformed this overall indicator of regulating services into an ordinal score (one to four), using the quartiles as

Table 4
The three ecosystem services, their Common International Classification of Ecosystem Services (CICES) category and code, their indicators, units, and main modelling approaches used to quantify them (see Appendix A for more details on the modelling approaches).

Category of ecosystem service	Ecosystem service (CICES V5.1 code)	Indicator	Unit	Input data	Main approach
Provisioning	Forage Production (1.1.1.1)	Yield	Ton of Dry Matter per hectare (t ha y^{-1})	Regime, intensity, elevation, soil	Linear regression model, for each management regime. Model parameters (β_i) depend on the management intensity and were estimated by Huguenin-Elie et al. (2017). We added a correction for soil suitability (cf): $Yield = (\beta_0 - \beta_1 \bullet Elevation) \bullet cf$
Regulating	Climate Regulation (2.2.6.2)	C sequestration (composite variable)	Ton of C per hectare and year (t C ha y^{-1})	Regime, intensity, elevation, estimated yield, and N fertilizer	C sequestration (C_{seq}) was computed from the NEE (Net Ecosystem Exchange), C_{input} and C_{export}[a]: C_{seq} = -NEE + C_{input} - C_{export}
	Pollination (2.2.2.1)	Bee species richness	Number of species (wild bees and bumblebees)	Regime, intensity, distance to forest, slope	Linear model, whose parameters (γ_i) were estimated by Le Clec'h et al. (2019): $Bee\ Species\ Richness = \gamma_0 + \gamma_1 \bullet Regime + \gamma_3 \bullet Distance\ to\ the\ forest + \gamma_4 \bullet Slope$

[a] NEE being a function of management regime and elevation, C_{input} being a function of the amount of recommended nitrogen fertilizers (N) spread on the parcel and the C/N ratio in the fertilizers and C_{export} being a function of the agricultural yield and the constant 0.47 (IPCC, 2006) for meadows and of C exported for pastures.

thresholds for the elaboration of the 4-levels ordinal score (Petter et al., 2013). Yield was likewise transformed based on the quartile.

For both regulating ecosystem services and yield, 1 was attributed to the values lower than the first quartile, 2 and 3 were attributed to values between the first quartile and the median, and between the median and third quartiles, respectively, and 4 was attributed to the values higher than the 3rd quartile. We defined hotspots parcels that matched the highest value score (score = 4), coldspots parcels that matched the lowest value score (score = 1) and categorised grassland parcels as supplying medium supply, when they matched the scores 2 or 3. While methods to determine hotspots are limited by the effects of the subjective choice of converting continuous values of ecosystem services in discrete categories (Eigenbrod et al., 2010), we relied on a scoring approach that was considered by Le Clec'h et al. (2016) as being appropriate to spatially determine ecosystem services coldspots and hotspots.

2.6.2. Identifying hot- and cold-spots under regional-level scenarios of management intensity

We modelled the supply of three ecosystem services under three different regional-level scenarios: the actual region, an all-extensive regional scenario, and an all-intensive regional scenario. (i) The actual region reflected the management as described in the census data (2019). (ii) In the all-extensive regional scenario, we assumed all parcels of grasslands to be under extensive management, as extensive management is the intensity for all agri-environmental schemes in our study. Under extensive management, we modelled the supply of the three ecosystem services based on the capacity of ecological features affecting those ecosystem services. Previous research has shown the overall positive effect of extensive management of the two studied regulating ecosystem services (Le Clec'h et al., 2019b). (iii) In the all-intensive regional scenario, we assumed all parcels of grasslands to be under intensive management. The all-intensive scenario reflected the maximal yields farmers could get.

The location of ECA2-grasslands remained the same across all regional scenarios, except in the all-intensive regional scenario that did not comprise any ECA-grasslands. The management regime remained the same across all regional scenarios, because in many cases pastures cannot be converted into meadows due to uneven soil surface, rocks or steep slopes inhibiting cutting activities.

2.6.3. Analyzing the mismatches

We analysed (mis)matches between the modelled potential cold- and hotspots of regulating and provisioning ecosystem services (all-extensive and all-intensive scenarios) with the actual location of ECA-grasslands and intensive grasslands from the census data (baseline or actual situation). We did so by identifying the location of parcels whose environmental prerequisites could increase agri-environmental schemes' efficiency in ecosystem services supply (overlap with hotspots) with least reductions in high forage production at the regional level (overlap with yield coldspots). The identification of hotspots and coldspots, because it was derived from all-extensive and all-intensive scenarios, was conducted independently of actual management intensity. The identification of (mis)matches provides the option to assign alternative locations for ECA-grasslands to lead to a more efficient implementation of such schemes as compared to the actual situation.

We then analysed the geographical and environmental settings in which ECA1- and ECA2-grasslands with high yield potential (hotspot) or low regulating ecosystem services (coldspot) potential were implemented, making a distinction between meadows and pastures. As for step 1, we conducted analyses based on the spatial location of the parcels and combined census data and variables related to topographical and soil conditions. We examined the statistical distribution of these variables based on their average value, mode, and standard deviation. We also computed multinomial logistic regressions and their associated Chi-square ($p = 0.05$), to estimate the odds of the presence of ECA1 and ECA2 as compared to intensive management, given the potential supply of regulating services (all-extensive scenario) and the potential yield (all-intensive scenario).

Step 3. Reducing mismatches through a reallocation of agri-environmental schemes, using a targeted scenario.

Step 3 focuses on reducing mismatches through a reallocation of agri-environmental schemes. This step builds upon steps 1 and 2 and do not require specific variables nor indicators. In the Canton of Solothurn, we illustrated step 3 using one possible scenario, referred to here as the "targeted" regional scenario. To be noted that this scenario should be taken as one possible example of reallocation and is by no means an optimization. Depending on the goals of the study applying our framework, we would recommend using spatially explicit optimization procedure that account for neighbour effect (adjacency), distance to the farm, stricter rules to achieve efficiency of land use and clear thresholds (minimum target) for yield and other ecosystem services. For policy targeting and evaluation, more advanced and spatially explicit optimization approaches are recommended. However, simpler methods may still be useful for rapid assessments, awareness-raising, and agenda setting. Depending on the specific goals of a study applying our framework, we recommend the use of optimization procedures that incorporate spatially explicit constraints—such as adjacency effects, proximity to farms, stricter efficiency rules for land use, and clearly defined thresholds (e.g., minimum targets for yield and other ecosystem services).

We modelled the supply of three ecosystem services under a possible "targeted" regional scenario, defined as follows:

- For parcels that were characterised with high or very high yield potential (score 3 or 4), management was set to intensive.
- For parcels that were characterised with high or very high potential of regulating services (score 3 or 4) while not being yield hotspots (score 1 or 2), management was set to extensive.
- All remaining parcels were allocated as intensive, to sustain agricultural activity, which best mimics the current agricultural situation in which grassland management outside ECAs primary aims at producing feed. This assumption does not allow us to conclude that it matches the current or future demand for agricultural yield.

The management regime and the location of ECA2-grasslands remained the same than under the current situation.

We estimated the potential supply of the three ecosystem services under this 'targeted scenario'. We revealed trade-offs and synergies between yield and regulating ecosystem services at the regional level. To do so, we estimated and compared the supply of ecosystem services under 1) the current management of the grassland parcels, 2) the all-extensive regional scenario, 3) the all-intensive regional scenario, and 4) the "targeted" management regional scenario.

3. Results

3.1. *Agri-environmental schemes are implemented on rather marginal land*

Extensive grasslands enrolled in agri-environmental schemes (ECA-grasslands), especially in the hybrid schemes (ECA2-grasslands), were overall placed on rather marginal, i.e., higher elevation, steeper slopes, dryer soils, distance to farm and are smaller compared to intensively managed grasslands (Table 5). Results from the multinomial logistic models can be found in Table B1. We found parcels of the three intensity levels to differ in most environmental variables (e.g., elevation for both meadows and pastures), while some differences occurred only for some of the levels (e.g., the average TWI differed between ECA1- and intensive grasslands and between intensive and ECA2-grasslands, both for meadows and pastures). There were no differences regarding the TPI. Variation within intensity levels was quite homogenous for all environmental variables. Both types of ECA-grasslands tended to be significantly further away from the respective farm and much smaller than intensive parcels.

Overall, compared to intensive grasslands, ECA1-grasslands were on average located on steeper slopes (Δ = +0.7 %), especially in pastures (Δ = +8 %; Table 5). While ECA-meadows were on average found on slightly lower locations than intensive meadows (Δ = −22.5 m), ECA-pastures were on average located on considerably higher elevations than intensive pastures (Δ = +112 m). ECA-grasslands were generally located on drier soils than intensive grasslands, as indicated by significant differences in TWI average values. Most of pastures were located on soils that are unsuitable for agriculture, independently of their intensity level. A higher share of ECA-pastures, especially ECA2-pastures, were located on unsuitable soils (55 %, 63 % and 37 % of the area covered by ECA1-, ECA2- and intensive pastures, respectively). A large number of parcels of ECA1-meadows were located on very suitable soils for agricultural purposes. Yet, when looking at the area covered by ECA1-meadows, almost half (47 % of the total area of ECA1-meadows) matched with poor or unsuitable soil quality for agricultural production, versus 35 % of the total ECA1-meadows area matching with good or very good soil for agricultural production.

Differences could also be observed between types of ECA-grasslands, as ECA2-grasslands were located at higher elevation than ECA1-grasslands, in meadows and especially pastures (Δ = +45 m (+8 %) and Δ = +110 m (+16 %), respectively). Similarly, ECA2-grasslands were located on steeper slopes than ECA1-grasslands, again more pronounced for pastures than meadows (Δ = +4 % and Δ = +6 %, respectively). ECA2-pastures were located on drier parcels than their ECA1-pastures counterparts (i.e., lower TWI with Δ = 0.35).

Table 5
Differences in environmental conditions and management between extensive (ECA1, ECA2) and intensive meadows and pastures as currently realized (actual region). The Chi-square test (soil suitability) and all Kruskal-Wallis tests (all other variables) were significant ($p < 0.05$), except for TPI, for both meadows and pastures. Pairwise *t*-tests with Bonferroni correction, conducted separately for meadows and pastures, are indicated by superscript letters, with identical letters denoting significant differences between two or more levels (e.g., elevation is significantly different across all levels of intensity and TWI is significantly different for i) intensive versus ECA1 and ii) ECA1 versus ECA2). Levels without any common letters are not significantly different from each other (e.g. intensive versus ECA2 for TWI).

		Meadow			Pasture		
		Intensive	ECA1	ECA2	Intensive	ECA1	ECA2
Elevation (m)	mean	587[a]	554[a]	599[a]	614[a]	701[a]	811[a]
	Sd	149	136	156	175	199	192
Slope (%)	mean	14[a]	12[a]	16[a]	15[a]	22[a]	28[a]
	Sd	11	12	13	12	15	16
TWI	mean	6.93[a]	7.33[a,b]	6.93[b]	6.87[a,b]	6.15[a]	5.80[b]
	Sd	2.35	2.64	2.51	2.53	2.13	2.02
TPI	mean	-0.12	-0.09	-0.06	-0.18	-0.17	-0.12
	Sd	0.99	0.53	0.64	1.14	0.71	0.86
Soil suitability	Mode	4	1	4	5	5	5
Simpson index	mean	0.72[a]	0.69[a]	0.7[a]	0.70[a]	0.72[a]	0.71
	Sd	0.08	0.09	0.09	0.09	0.07	0.07
Distance to forest (m)	mean	195[a]	244[a,b]	208[b]	183[a]	106[a]	45[a]
	Sd	277	429	446	301	202	96
Distance to farm (m)	mean	825[a,b]	980[a]	1070[b]	397[a]	727[a]	719
	Sd	1310	1263	1045	917	1,245	945
Area (ha)	mean	0.89[a,b]	0.51[a]	0.52[b]	1.43	1.38	1.22
	Sd	1.46	0.61	0.76	2.00	2.26	1.80
Parcels	n	7,571	6,912	2,084	2,670	1,228	376

3.2. *(Mis)matches in spatial placement of agri-environmental schemes*

The analysis of mismatches between actual and potential supply of the provisioning ecosystem service (agricultural yield) and regulating ecosystem services (score calculated from aggregating bee species richness and C sequestration) under the realized situation, the all-intensive and the all-extensive scenarios, showed that ECA-grasslands were only partly placed on locations that had potential to supply a high level of regulating services (Table 6). We find significant differences for most ecosystem services across the three intensity levels (e.g., yield and regulating services under the current situation, in meadows) or for some of the levels (e.g., yield and regulating services under the current situation, in pastures). While the averages of yield and

Table 6
Differences between the average scores of regulating ecosystem services (pollination and climate regulation) for the actual region and under all-extensive scenario (green) and between the yield for the actual region and all-intensive scenario (yellow). In brackets, actual share of the grassland type in the region.

	Actual intensity level	Intensity level under scenario: Intensive	Extensive
Meadow	*All meadows (80%)*	*4.69*	*0.31*
	ECA1 (34%)	8.71	0
	ECA2 (10%)	8.35	0
	Intensive (36%)	0	0.67
Pasture	*All pastures (20%)*	*2.49*	*0.34*
	ECA1 (6%)	6.77	0
	ECA2 (2%)	6.29	0
	Intensive (13%)	0	0.55
All grasslands (100%)		4.24	0.31

regulating services were not always significantly different between ECA1 and ECA2, significant differences were systematically found between intensive and each of the ECAs management. Table B4 displays the average scores of ecosystem services across the grassland types for the actual region ("Actual") and under the all-extensive or all-intensive scenarios and the results for the pairwise t-tests and Kruskal-Wallis tests. Results from the multinomial logistic models and boxplots showing the variability of the potential supply within the grassland types can be found in Table B5 and Fig. 3.

Meadows showed generally higher provisioning ecosystem service than pastures (Fig. 3). On average current ECA1-meadows had a slightly higher and ECA2-meadows a slightly lower potential yield than the intensive parcels in the all-intensive scenario, meaning that given the same intensity level, ECA1-meadows were on average located in a more productive location than intensive meadows. In contrast, ECA-pastures, especially ECA2-pastures, showed lower yields than the intensive pastures in the all-intensive scenario. Yield was highly variable within the intensive grasslands, for both meadows and pastures, under the current management. Variability increased for all categories under the all-intensive scenario (Fig. 3).

Ecosystem service hot- and coldspots revealed (mis)matches in spatial placement of agri-environmental schemes. ECA-grasslands only partially overlapped with potential hotspots of regulating services, although the overlap was large for ECA-pastures. ECA-meadows, especially ECA1-meadows, largely overlapped yield hotspots, exhibiting strong trade-offs with production.

Potential yield hotspots covered over 16 % of the total grasslands area in Solothurn, mainly in the flat Southern part (Fig. B1 and Table B2). These hotspots were almost all managed as meadows, mostly as ECA1 and ECA2 (Tables 7 and B1). A high share of ECA-meadows, mainly ECA1-meadows (35 %) were located on yield hotspots, while no ECA1-pastures were located on yield hotspots (Table 7). Potential yield coldspots covered a large proportion of the total grasslands area in Solothurn (ca. 44 % of the area under grassland management) and were mainly located in the central part of the canton on high lands and steep slopes (Fig. B1). Around 24 % of intensive meadows and 39 % of ECA-meadows were located on yield coldspots, while almost all ECA-pastures and 77 % of intensive pastures were located on yield coldspots (Table 7).

Potential hotspots of regulating ecosystem services covered over 40 % of the total grasslands area in Solothurn (Table B2 and Fig. B1). These hotspots of regulating ecosystem services could mainly be found in the central part of the canton, on drier soil at higher elevation, close to semi-natural habitats (Fig. B1). Approximately 9 % of regulating hotspots were managed as meadows, mainly under intensive management (Table B2). 31 % of regulating hotspots were managed as pastures, mainly under ECA-grassland management. 12 % of ECA1- and 16 % of ECA2-meadows were located on hotspots of regulating services, while almost all ECA-pastures were located on hotspots of regulating services (Table 7). Potential coldspots of regulating ecosystem services covered only a small proportion of the total grasslands area in Solothurn (ca. 16 % of the area under grassland management) and were mainly located in the South of the canton on lower lands (Fig. B1). Most of potential coldspots of regulating ecosystem services could be found in parcels currently under intensive management (19 % of the intensive meadows and 2 % of intensive pastures, depicting 8 % of total grassland area). The same share of the area currently covered by ECA-grasslands matched with potential coldspots of regulating ecosystem services (8 % of the total grassland area), which mostly concerned ECA-meadows.

We assumed here that an optimal placement of ECA1- and ECA2-grassland implies a match with yield coldspots (avoiding trade-offs) and regulating ecosystem services hotspots (increasing synergies). When assessing the modelled potential for provisioning and regulating ecosystem services together, we found 6 % of the grassland area was a

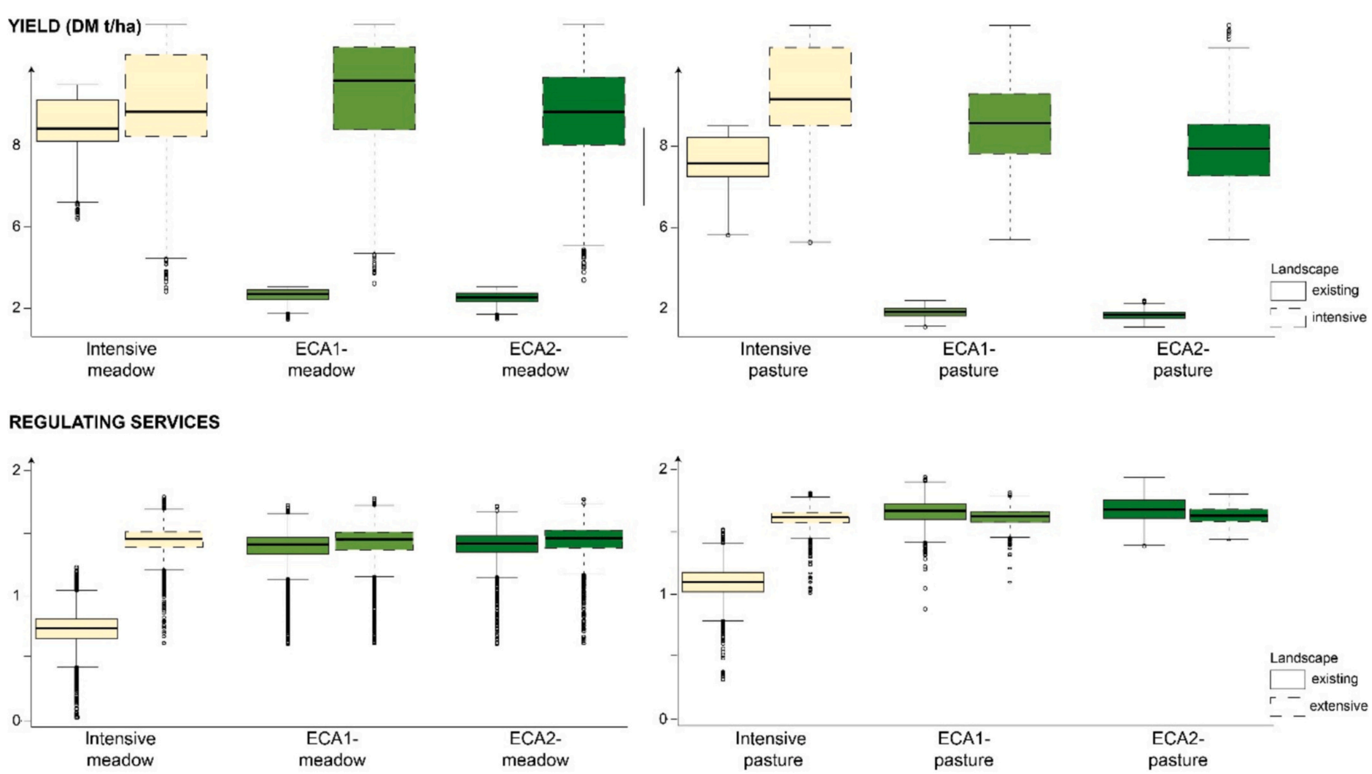

Fig. 3. Statistical distribution of the yield and regulating services under the current and all-intensive (yield) and all-extensive (regulating) scenarios. Pastures showed generally higher regulating ecosystem services than meadows. At the regional level, the regulating ecosystem services score slightly increased under the all-extensive scenario, as compared to the baseline (actual) situation ($\Delta = +0.31$ on average, all grassland types considered). On average both current ECA1-pastures and ECA2-pastures had a higher potential regulating ecosystem services score than non-ECA-pastures in the all-extensive scenario. The variability of the regulating services was rather low across all grassland types under the current management and under the all-extensive scenario (Fig. B1).

Table 7
Share of area of each grassland type overlapping with potential hotpots (score of 4 = uppermost quartile; in red) and coldspots (score of 1 = lowermost quartile; in green) of yield and regulating ecosystem services in the actual region. Medium supply corresponds to a score of 2 or 3 (in yellow). Note that for regulating ecosystem services, scores of C sequestration and bee species richness have been standardized and summed before being converted into a composite score. See Table B2 for information on the share of the total grassland area overlapping with potential hotpots and coldspots. ECA stands for Ecological Compensation Areas, i.e. extensive grasslands under action-based and hybrid scheme, respectively.

			Share of ECA1 (%)	Share of ECA2 (%)	Share of Intensive (%)
Regulating ecosystem services	Meadow	Coldspot	30	28	19
		Medium	58	55	64
		Hotspot	12	16	17
		Total	*100*	*100*	*100*
	Pasture	Coldspot	1	0	2
		Medium	4	7	7
		Hotspot	96	93	92
		Total	*100*	*100*	*100*
Yield	Meadow	Coldspot	15	24	24
		Medium	*49*	51	*59*
		Hotspot	35	25	17
		Total	*100*	*100*	*100*
	Pasture	Coldspot	94	99	77
		Medium	6	1	23
		Hotspot	0	0	0
		Total	*100*	*100*	*100*

Table B4
Average scores of regulating ecosystem services (combination of pollination and climate regulation) and yield across the grassland types for the actual region ("Actual") and under the all-extensive or all-intensive scenarios. Thus, the comparison of these values indicates the effect of the different management intensities on ecosystem services. The pairwise t-tests with Bonferroni corrections and Kruskal-Wallis tests were run separately for meadows and pastures and for each variable and scenario. Pairwise *t*-tests with Bonferroni corrections and Kruskal-Wallis tests (significant for all variables) were performed separately for meadows and pastures. Superscript letters indicate significant differences, with identical letters denoting significantly different levels (e.g., all levels in meadow are significantly different for the actual yield, and pairs of levels in meadow (i) intensive versus ECA1 and ii) ECA1 versus ECA2) for yield under the all-intensive scenario). Differences between all grasslands, independently of their intensity level were not tested.

		Average Yield score		Average regulating ecosystem services score		Share of grassland type in region (%)
Current land-use		Actual	Scenario (all-intensive)	Actual	Scenario (all-extensive)	
Meadow	*All*	*6.44*	*11.13*	*1.08*	*1.39*	*80*
	ECA1	2.66 ^{a}	11.37 ^{a,b}	1.38 ^{a}	1.38 ^{a}	34
	ECA2	2.54 ^{a}	10.89 ^{b}	1.39 ^{a}	1.39 ^{a}	10
	Intensive	10.97 ^{a}	10.97 ^{a}	0.73 ^{a}	1.40 ^{a}	36
Pasture	*All*	*6.46*	*8.95*	*1.31*	*1.65*	*20*
	ECA1	1.84 ^{a}	8.61 ^{a}	1.66 ^{a}	1.66 ^{a}	6
	ECA2	1.69 ^{b}	7.98 ^{a}	1.68 ^{b}	1.68 ^{b}	2
	Intensive	9.25 ^{a,b}	9.25 ^{a}	1.09 ^{a,b}	1.64 ^{a,b}	13
All grasslands, irrespective of the management regime		6.44	10.68	1.13	1.44	100

hotspot of yield but a coldspot of regulating ecosystem services (11 % of the grassland parcels), while 34 % was a coldspot of yield but a hotspot of regulating ecosystem services (18 % of the grassland parcels; Fig. 4 and Table B3).

ECA-pastures generally showed a better fit with yield coldspots and regulating ecosystem services hotspots than ECA-meadows. 7 % of the area under ECA1- and 11 % of the area under ECA2-meadows matched with yield coldspots and regulating ecosystem services hotspots and 92 % of both the area under ECA1- and of the area under ECA2-pastures matched with yield coldspots and regulating ecosystem services hotspots (Table B3). Only less than 0.1 % of the total grassland area in Solothurn, and of the grassland parcels, matched with hotspots of both yield and regulating ecosystem services, indicating unavoidable trade-offs for a very small area.

3.3. The potential of a reallocation

The '"targeted" regional scenario suggested an overall intensification of the landscape, Solothurn being an area highly suitable for agricultural production. Under that scenario, 69 % of the grassland parcels were intensive, i.e., 58 % of the total grassland area (versus 61 % of the parcels and 49 % of the area in the actual situation). Under this scenario, yield largely increased and regulating services sightly decreased, as compared to the current situation, leading to a smaller gap between the supply of these two ecosystem services category (Fig. 5). In the "targeted" regional scenario, the supply of ecosystem services per hectare increased in ECA1-grasslands for regulating services, and in intensively used parcels for both provisioning and regulating services. Reducing the provisioning – regulating services trade-off led to 29 % of the used agricultural area and 9 % of the entire area of the canton under ECA-grasslands.

4. Discussion

Our study provides a guideline to assess and improve the effectiveness of agri-environmental schemes in grasslands at the regional level. The stepwise framework presented here serves as a practical tool for decision-makers to enhance the efficiency of environmental

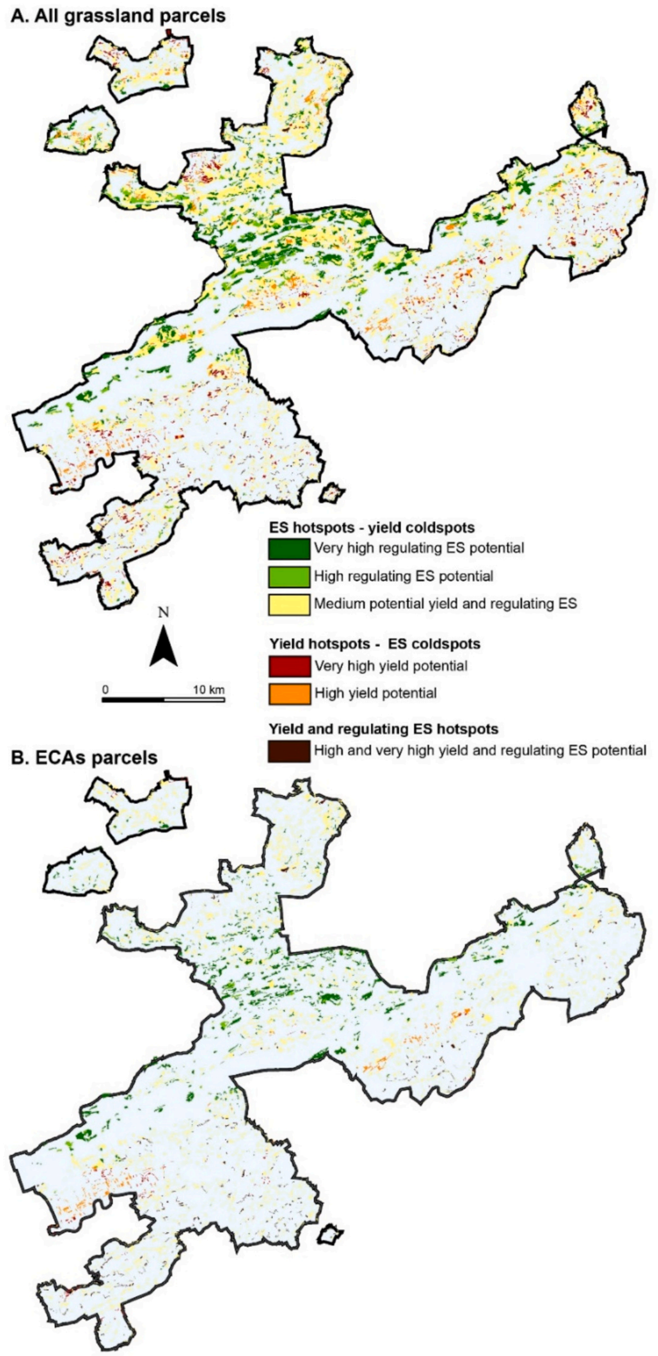

Fig. 4. Spatial distribution of yield and regulating ecosystem services hotspots and coldspots across grassland parcels in the canton of Solothurn. "High potential" corresponds to a score of 3 and "Very high potential" to a score of 4, based on the quartiles. (A) All parcels were considered and represented. (B) Only parcels of ECA-grasslands presented. ES stands for Ecosystem Service(s) and ECA for Ecological Compensation Area.

management interventions. Each step offers methodological guidance that is highly flexible and adaptable to specific contexts, including the selection of ecosystem services, their indicators, and modelling approaches.

4.1. Application of the three-step framework to the case of Canton of Solothurn

As part of Step 1 of our framework, we demonstrated that extensive ECA-grasslands were typically located on land less favourable for intensive agriculture, with drier soils, steeper slopes, and higher elevations than intensive grasslands. This aligns with previous findings (Klaus et al., 2024; Huber et al., 2021), which reported higher AES enrolment on steep or distant parcels, likely due to lower opportunity costs compared to more productive, frequently grazed pastures near farm buildings.However, our study provides additional insight by highlighting differences between the two types of agri-environmental schemes. For instance, we found that ECA2-grasslands (hybrid schemes) were generally situated on less favourable land than ECA1-grasslands, helping to minimize losses in provisioning services. Since ECA2-grasslands harboured ecologically valuable vegetation, we highlight the role of environmental conditions and restricted management intensity, in shaping grassland biodiversity (Klimek et al., 2007; Ravetto et al., 2020; Kampmann et al., 2008, 2012; Mack et al., 2020).

As part of Step 2 of our framework, our study highlighted that 40 % of the total grassland area of the region was located in potential hotspots of regulating ecosystem services, including 34 % that were also located on potential yield coldspots. 34 % of grassland area could thus be set aside for biodiversity conservation instead of being used for (intensive) forage production in naturally unfavourable locations. This would even go beyond the 30 % target (Kunming-Montreal Global Biodiversity Framework, Target 3).

We also showed that effective ecosystem service and biodiversity conservation requires more strategic, landscape-level planning, especially to prevent land abandonment and maintain multifunctionality. While ECA-grasslands were somewhat spatially targeted to support ecosystem service multifunctionality (Manning et al., 2018), mismatches for both ECA1- and ECA-2 grasslands remained, especially regarding their potential to balance provisioning and regulating services, especially for meadows. However, ECA2-grasslands avoided yield hotspots more frequently than ECA1-grasslands. ECA-pastures showed better spatial targeting, likely due to terrain limitations (Klaus et al., 2023) and lower payment incentives. Because of the location of ECA-grasslands on land that is unfavourable to intensive agricultural production, a certain share of ECA1- and especially ECA2-grassland parcels could be prone to abandonment or afforestation, if farmers did not receive financial compensation to maintain their management (Isselstein et al., 2005). Their abandonment may lead to a decline in both biodiversity and ecosystem services (Prangel et al., 2023).

Step 3 was illustrated through a possible "targeted" regional scenario. This scenario led to intensified grassland management in areas suitable for intensive agriculture, primarily in the lowlands, where ECAs were registered to meet the mandatory 7 % farm area requirement (Huber et al., 2023). While spatial targeting reduced trade-offs in some cases, it did not eliminate them, as the focus on specific services reflected local geographical constraints. This suggests that trade-offs between biodiversity conservation and agricultural production cannot be entirely resolved in regions highly suitable for intensive agriculture.

4.2. Strengths and limitations

We think our study contributes to the literature by developing a general framework to improve the effectiveness of agri-environmental schemes in grasslands at the regional level, incorporating multiple ecosystem services. Our study underscores the role and potential of agri-environmental schemes in fostering synergies between biodiversity and targeted ecosystem services, while also accounting for trade-offs with food production. It enhances our understanding of how action-oriented, result-oriented, and hybrid schemes differ in their capacity to mitigate trade-offs and enhance synergies among environmental benefits. While we applied our approach to a specific region (Canton of Solothurn) where trade-offs between ecosystem services/biodiversity and food production are very strong, due to the presence of the Swiss plateau and the Jura mountains, the study can be seen as a proof of concept to present a conceptual approach. It will still be relevant in itself for a

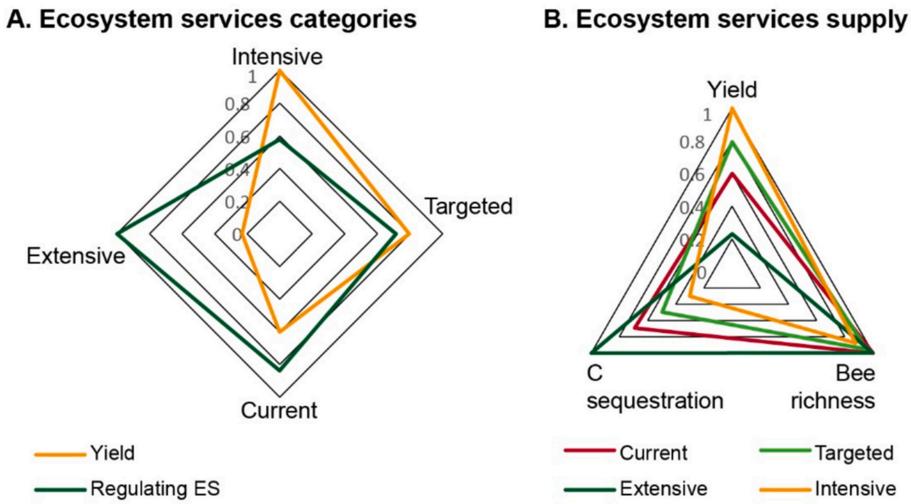

Fig. 5. Trade-offs between provisioning and regulating ecosystem services at the regional level under different management scenarios (current, all-intensive, all-extensive, targeted, which is spatially targeted at the regional scale), for (A) the ecosystem service categories and (B) individual ecosystem service supply. We standardized the modelled ecosystem services values between 0 and 1.

direct application, as agri-environmental decision making in Switzerland is partly taken at the cantonal level. Yet, an up-scaling might imply some adjustment in the models, e.g., to integrate climatic variations, which can be strong at the national level.

The framework is based on the application of various concepts and approaches, such as the development of indicators for multiple ecosystem services and hotspot mapping. Its main innovation lies in the integration of these elements to evaluate the (potential) effectiveness of agri-environmental schemes and agri-environmental policy instruments more broadly. A further novelty is the integration of multiple spatial scales, from plot to regional level, which can enhance the effectiveness of not only agri-environmental schemes but also broader environmental policies by reducing trade-offs between ecosystem services and environmental objectives. The framework's simplicity and flexibility—both in terms of the methods and data it can incorporate—make it robust and applicable across different ecosystems, spatial scales, and geographical contexts.

By incorporating multiple spatial scales—plot, landscape, and region—our framework is applicable to a range of decision-makers operating at different institutional levels. Our framework supports the design and implementation of more effective policies by addressing a key challenge: reducing critical spatial mismatches between targeted environmental outcomes and their underlying drivers (Klaus et al., 2024). The regional approach adopted in this study promotes the efficient allocation of agricultural and environmental resources, thereby mitigating spatial leakage, where farmers intensify management on other fields to maintain overall productivity when participating in agri-environmental schemes. This regional approach may be relevant for policy makers and community of farmers, while considering the level of the individual parcels and its environmental conditions. We argue that considering these two spatial levels, parcel, and landscape, is critical to enhance the effectiveness of the schemes.

Our study focuses on the actual allocation and effectiveness of agri-environmental policies—an area that remains underexplored in the scientific literature, particularly in quantitative and spatially explicit way (Galler et al., 2015). Furthermore, while most existing studies concentrate on a single environmental outcome, such as biodiversity, or on a single ecosystem service (Bullock et al., 2021), our approach is more holistic. By considering multiple ecosystem services—and with potential for further expansion—it provides valuable insights for future policy and decision-making.

Despites its strengths, our study shows four main limitations. First, although examining more than a single service, our analysis was limited to three ecosystem services. Grasslands, however, provide a broader array of services, including cultural services such as recreation (Martínez Pastur et al., 2016) and aesthetics (Lamarque et al., 2011). Nevertheless, our framework is highly adaptable in terms of the ecosystem services it can accommodate. Applying it requires careful selection of ecosystem services, e.g. to avoid double counting, and their indicators to align with the context and needs of the target area.

Second, the framework relies on the use of models that naturally come with assumptions, limitations, and uncertainties (Burkhard et al., 2013; Le Clec'h et al., 2019a), potentially reducing uptake by decision-makers (Barton et al., 2024; Walther et al., 2025). Our models were built based on scientific literature, field data, and expert knowledge and were published in scientific literature (Huguenin-Elie et al., 2017; Le Clec'h et al., 2019b). Their results, for the case study area, were validated by experts, and are aligned with other studies (e.g. Le Féon et al. (2010); Jäger et al. (2020)). However, in the case study of Solothurn, our ecosystem services models were not trained with data coming from ECA1- versus ECA2-grasslands, for example regarding differences in plant community composition and plant diversity but considered only two intensity levels within each management regime (i.e., extensive, as ECA1- and ECA2-grasslands together, versus intensive grasslands). Data availability was a crucial limitation in this respect, as sufficient data on ecosystem services indicators were not available for a sufficient number of ECA1- versus ECA2-grasslands. Yet, as the same management restrictions apply to both types (both include action-oriented regulations), and as we account for differences in many spatial factors such as height and slope, we consider our approach robust. Further research should explore distinctions between action-oriented (ECA1) and hybrid (ECA2) schemes and their effects on multiple services. Additionally, we did not analyze interactions between schemes like organic farming and their combined impact on ecosystem services.

Third, we transformed continuous ecosystem service values into ordinal scores based on quartiles, offering an accessible overview of hotspots and coldspots (Petter et al., 2013; Le Clec'h et al., 2016). While useful for prioritization, this approach is subjective, does not assess demand, and overlooks relationships between services. Nonetheless, scoring facilitates hotspot identification and is adaptable across ecosystems and spatial scales (Bagstad et al., 2017). Its flexibility enables application across different ecosystem services, spatial scales, and ecosystem types. Specific indicators of ecosystem services can be scored based on policy objectives or prior knowledge.

Fourth, grassland coverage in regional-scale scenarios was arbitrarily defined, simplifying the complex decision-making process behind management changes. While this complex decision making process is beyond the scope of our research, we acknowledge that doing so, we ignore the complexity of farmers' decisions and of land use allocation. When applying our framework, we recommend scenarios to be constructed in relation to the demand in ecosystem services and the environmental challenges faced by the region of study, as well as use of reallocation algorithms that capture the complexity of land use dynamics. Additionally, we assumed that management regimes (e.g., meadow vs. pasture) remain constant for parcels, though they may alternate. Future research should examine how such temporal changes influence ecosystem services. Nevertheless, we are confident that the categories we use represent the actual management. Management categories from census data were previously compared with field data in the same study area, resulting in a very good match of ca. 98 % (Richter et al., 2024).

Because of these limitations, our approach, and in particular the outputs for the case study of Solothurn, should therefore be considered carefully and treated as a framework on which futures studies can build up. The framework suggested in this study could be readily extended to incorporate uncertainties, for instance, by utilizing Monte Carlo simulations to account for variability stemming from regression analysis. It could also be adapted to other modelling approaches, enabling a more comprehensive assessment of the underlying uncertainties in the system.

4.3. Methodological framework to improve the effectiveness of environmental management interventions in agricultural landscapes

Our methodological framework aims at improving the effectiveness and efficiency of agricultural and environmental conservation efforts by identifying and reducing the mismatches between areas targeted by agri-environmental schemes and ecosystem services hotspots. These mismatches often result from spatial misalignment between policy implementation and ecosystem services supply, which has been identified as a possible limitation of agri-environmental schemes (Galler et al., 2015; Longo et al., 2021). While such mismatches may result from various factors, e.g. insufficient understanding of ecological dynamics or prioritization of certain conservation goals over others, we believe that this study represents a first step in addressing scale mismatches between management decisions at the individual parcel level and broader regional or national policy objectives.

To reduce these mismatches, our conceptual framework focuses on the ecological components, while we acknowledge the importance of other components such as costs for farmers. Adapting the framework to address economic considerations, such as opportunity costs from production shifts or the reduction of income loss from strategic allocation of the subsidies, could enhance its utility.

Our framework adopts a regional perspective on the spatial targeting of agri-environmental schemes, contrasting with much of the existing literature, which typically focuses on parcel-level interventions and single-output benefits. By considering broader spatial scales, this study accounts for regional variations relevant to policy decisions. Balancing parcel-level environmental conditions with regional-scale policy goals is critical to reduce scale mismatches and enhance the schemes' effectiveness (Urwin and Jordan, 2008). Expanding the scale of interventions from farm to region offers opportunities to better balance biodiversity conservation with agricultural production, as suggested by Kampmann et al. (2012).

Reducing spatial mismatches between policy interventions and ecosystem service supply has been identified as a critical factor in improving the effectiveness of agri-environmental schemes (Nguyen et al., 2022). Our study contributes to this growing body of literature by emphasizing the need for landscape- and regional-scale approaches to maximize the potential of agri-environmental schemes while minimizing trade-offs with agricultural production (Westerink et al., 2017; Falco et al., 2021; Nguyen et al., 2022). This is particularly significant given the increasing recognition of grassland conservation under frameworks like the EU Habitats Directive (92/43/EEC, 1992) and the Swiss Ordinance on the Protection of Nature and Cultural Heritage (Council, T.S.F, 1991).

Avoiding the placement of extensively managed habitats in productive regions could at the same time also lead to very species-poor areas almost exclusively dominated by intensive agricultural production, with low potential supply of many regulating and cultural ecosystem services. Addressing these challenges (spatial mismatches) requires targeted interventions to align agri-environmental schemes with ecosystem service hotspots, thereby maximizing multifunctionality while optimizing agricultural practices and land use in general.

The innovative framework presented in this study integrates spatial statistics and ecosystem service mapping using reproducible methods and freely available data. This operationalizes the ecosystem services concept for land-use planning and management, enabling policymakers and land managers to identify areas where agri-environmental schemes could deliver substantial ecological and socio-economic benefits. By promoting a more comprehensive and sustainable approach to agricultural management, this framework enhances the consideration of ecosystem services in future grassland management. By highlighting mismatches between current land-use priorities and the spatial distribution of ecosystem service supply, the study encourages a shift toward more informed and ecologically sound management.

Our framework is inherently spatially explicit and has the potential to become a powerful tool for agricultural policy and spatial planning of agri-environmental schemes. First, it can assist decision- and policy-makers in understanding the ecological characteristics associated with high levels of biodiversity. This is essential for a better integration of ecosystem services and biodiversity into spatial planning (Van der Biest et al., 2020), effective spatial targeting of agri-environmental schemes and an increased adoption of result-oriented and hybrid schemes by farmers. Second, our framework simultaneously captures agricultural production, ecosystem services, and biodiversity. Although these three dimensions are interconnected, they are often addressed separately through siloed approaches. Spatial planning of agri-environmental schemes plays a key role in assessing the spatial implications of such disconnected policies, enabling planners to mitigate or compensate for their impacts and trade-offs and thus support more informed and holistic decision-making (Rozas-Vásquez et al., 2018; Albert et al., 2020). Third, our framework facilitates the integration of ecosystem services and biodiversity into spatial planning of agri-environmental schemes and offers guidance on maximizing their synergies or minimizing trade-offs, especially for services that may conflict biodiversity (Rodríguez et al., 2006). In this way, the framework helps unlock opportunities for multifunctionality and the transformation of trade-offs into synergies. Fourth, while the interrelationships between ecosystem services and biodiversity are often overlooked (Cimon-Morin et al., 2013), interventions that favour one service over another can have cascading effects on biodiversity conservation (Kandziora et al., 2013). Existing conservation areas are in many cases suboptimally located to simultaneously prioritize both ecosystem services and biodiversity (Ramel et al., 2020). Our framework can identify spatial units where biodiversity conservation aligns with the enhancement of ecosystem service supply (Vaz et al., 2021). It can also be used to delineate priority areas at broader spatial scales where the supply of one or more ecosystem services can be maximized while minimizing the loss of potentially conflicting services. Finally, by relying on modelling and scenario analysis, our framework can support spatial planning in identifying trade-offs between policy objectives related to agricultural production, biodiversity conservation, and ecosystem service provision, as well as objectives in other policy domains (Geneletti, 2011).

5. Conclusion

Our study offers a methodological framework to improve the spatial targeting and effectiveness of agri-environmental schemes in grasslands.

By assessing the environmental settings and ecosystem services associated with action-oriented (ECA1) and hybrid (ECA2) agri-environmental schemes, we highlight their potential to deliver multiple co-benefits beyond biodiversity conservation.

We exemplified the framework by assessing synergies and trade-offs between provisioning and regulating ecosystem services at the regional level. Our study led to three key findings that are highly relevant for policy makers. First, both ECA1- and ECA2-grasslands only partially overlapped with potential hotspots of regulating services, implying that spatial targeting of conservation schemes is currently sub-optimal. Second, we showed that the use of grassland, i.e., whether it is a pasture or meadow, matters for the current situation. ECA-pastures showed fewer trade-offs with production, as they rarely overlapped with yield hotspots, while ECA-meadows, which often did overlap and thus caused considerable trade-offs, are more common likely due to higher per-hectare payments. Thus, only ECA-pastures are currently already sufficiently spatially targeted to widely prevent trade-offs between production and biodiversity conservation. Finally, regionally reallocating ECA-grasslands, especially ECA-meadows, may lead to an increase in the supply of regulating ecosystem services and reduce trade-offs with feed production. Yet, such reallocation should be based on environmental settings that support high biodiversity, also keeping in mind the long time required to incease biodiversity in former intensive grasslands. Our study can be seen as general guidelines for the spatially explicit planning of future agri-environmental schemes at the regional scale.

Our analysis has implications for future research. More specifically, our approach is a first step toward a systematic assessment of action-oriented versus hybrid agri-environmental schemes, especially ex-post assessments. This will allow to provide ex-ante information about incentive mechanisms, e.g., collectives schemes, supporting multiple ecosystem services. Future research should aim to better understand farmers' preferences and their practical considerations that influence their decision-making regarding ecosystem services supply. It should ideally also explicitly incorporate uncertainties and societal demand into the assessment of these services. Such understanding is likely to increase the adoption of agri-environmental schemes and improve their fit in the landscape context in which they are implemented.

CRediT authorship contribution statement

Solen Le Clec'h: Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization. **Robert Huber:** Writing – review & editing, Methodology. **Robert Finger:** Writing – review & editing, Methodology. **Jean-Marc Delore:** Writing – review & editing, Methodology. **Franziska J. Richter:** Writing – review & editing, Methodology. **Valentin H. Klaus:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors have no competing interests to declare.

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Appendix A. Modelling approaches of the three indicators of ecosystem services

For agricultural yields, we used the parameters of a regression estimated by Huguenin-Elie et al. (2017). Potential yields for all grasslands were estimated depending on their regime and elevation (Eq. A1). Below 500 m.a.s.l, yield estimations are equivalent to those calculated at 500 m.a.s.l. Above 500 m.a.s.l, elevation was used as a continuous quantitative variable. We used a correction factor to adjust yield estimates according to the information about soil suitability for agricultural production for each parcel (FOAG, 2005). In the original study, the overall R2 was 0.83 for measurements across three management intensity levels, including "intensive", "mid-intensive" and "less intensive" (both not considered here). The overall R2 was 0.83. For the management intensity level "extensive", the yield estimation was taken from (Dietl, 1986).

$$Yield = (\beta_0 - \beta_1 \bullet Elevation) \bullet cf \quad \text{(A1)}$$

with Yield, the estimated yield (t DM/year) and with Elevation the average elevation of a parcel (in m) and cf the correction factor to adjust yield estimates according to the information about soil suitability for agricultural production.

We calculated C sequestration for each parcel by accounting for NEE (Net Ecosystem Exchange), C_{input} and C_{export}[3] (Eq. 2). A high C sequestration was the result of high C intakes (photosynthesis) and low C losses (C content in harvests). For that reason, we considered the opposite of the NEE, as a negative NEE corresponded to a high CO_2 uptake of the grassland system.

$$C_{seq} = -NEE + C_{input} - C_{export} \quad \text{(A2)}$$

with C_{seq}, the C sequestration (t C/ha/year), NEE the net ecosystem exchange (t C/ha/year), C_{input} the C imported in the system through fertilization and C_{export} the C exported from the system through harvesting (t C/ha/year). In the all-extensive scenario, C imported in the system through fertilization is null, as extensive management of Swiss grasslands implies no fertilization.

The application of a linear model created in Le Clec'h et al. (2019) enabled the estimation of bee species richness (indicator of pollination, Eq. A3). R2 = 0.41, based on $n = 53$ observations.

$$Bee\ Species\ Richness = \gamma_0 + \gamma_1 \bullet Regime + \gamma_3 \bullet Distance\ to\ the\ forest + \gamma_4 \bullet Slope \quad \text{(A3)}$$

[3] NEE being a function of management regime and elevation (R2 = 0.4, based on $n = 83$ observation), C_{input} being a function of the amount of recommended nitrogen fertilizers (N) spread on the parcel and the C/N ratio in the fertilizers and C_{export} being a function of the agricultural yield and the constant 0.47 (IPCC, 2006) for meadows and of C exported for pastures (R2 = 0.99, based on $n = 7$ observations).

Appendix B

Table B1
The relative log odds of the multinomial logistic regression depicting how the potential change in one unit of environmental variables is associated with the risk of the parcel being under ECA1 or ECA2, compared to intensive management.

	MEADOW		PASTURE	
	BFF1	BFF2	BFF1	BFF2
Elevation	0.999	1.000	1.002	1.004
Slope	1.010	1.026	1.024	1.036
TWI	1.048	1.046	0.952	0.967
TPI	1.125	1.211	1.003	1.058
Simpson index	0.026	0.101	4.377	1.538
Distance to forest	1.000	1.000	1.000	0.998
Distance to farm	0.999	0.999	1.000	1.000
Area	0.628	0.585	0.911	0.779

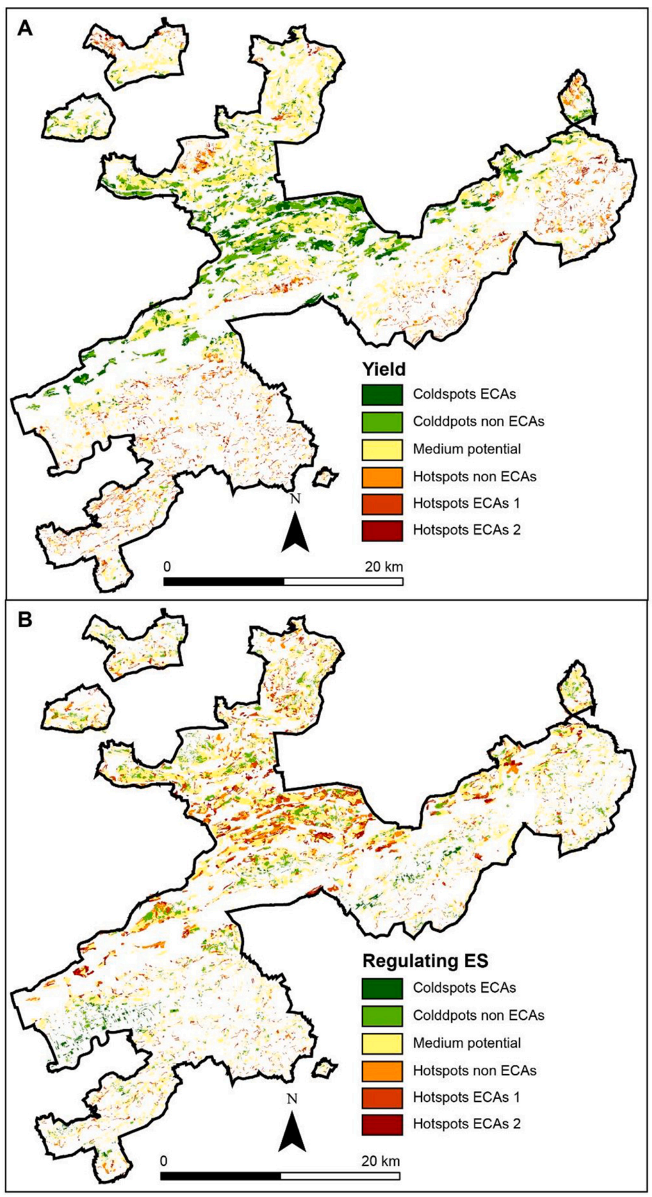

Fig. B1. Spatial distribution of potential hotspots and coldspots of (A) yield and (B) regulating ecosystem services (note that for reasons of readability, coldspots in ECA1- and ECA2-grasslands were combined). Colours on the maps are aligned with the ones in Table 5.

Table B2
Share of each grassland type (% of total grassland parcels) overlapping with potential hotpots (score of 4 = uppermost quartile) and coldspots of yield (score of 1 = lowermost quartile) and of regulating services. Medium supply corresponds to a score of 2 or 3. Note that for regulating services, scores of C sequestration and bee species richness have been standardized and summed before being converted into a score. Each parcel is accounted for in the calculation for both the regulating service and yield.

			ECA1	ECA2	Intensive
MEADOW	Regulating	Coldspot	11	3	10
		Medium	19	6	23
		Hotspot	3	1	3
	Yield	Coldspot	3	2	4
		Medium	16	6	22
		Hotspot	14	3	10
PASTURE	Regulating	Coldspot	0	0	0
		Medium	0	0	1
		Hotspot	5	2	11
	Yield	Coldspot	5	2	9
		Medium	1	0	4
		Hotspot	0	0	0

Table B3
Share of each grassland type (% of area and of number of parcels of only the specific grassland type) overlapping with combination of potential hotpots (score of 4 = uppermost quartile) and coldspots of yield (score of 1 = lowermost quartile) and of regulating services. Not all parcels were included in this table, as grasslands parcels that were neither a coldspot nor a hotspot were not considered here. Note that parcels with 'medium' supply of ecosystem services are not displayed in this table.

		ECA1	ECA2	Intensive
Meadow	Regulating and yield coldspot	1	1	2
	Regulating Hotspot and yield coldspot	**7**	**11**	**11**
	Regulating coldspot and yield hotspot	15	11	7
	Regulating and yield hotspot	0	0	0
Pasture	Regulating and yield coldspot	2	0	1
	Regulating Hotspot and yield coldspot	**92**	**92**	**74**
	Regulating coldspot and yield hotspot	0	0	0
	Regulating and yield hotspot	0	0	0
		% of area		
All grasslands	Regulating and yield coldspot	1		
	Regulating Hotspot and yield coldspot	**34**		
	Regulating coldspot and yield hotspot	6		
	Regulating and yield hotspot	0		

Table B5
The relative log odds of the multinomial logistic regression depicting how the potential change in one unit of Regulating services and of yield is associated with the risk of the parcel being under ECA1 or ECA2, compared to intensive management. Regulating services were assessed under the all-extensive scenario, whereas the yield was computed under the all-intensive scenario. Intensive, ECA1, ECA2 and management regime reflect the current management (2019). All chi-square tests, except for the models linking management intensity and regulating services in pastures, are significant, indicating that our multinomial logistic model significantly fits better than an empty or null model (i.e., a model with no predictors). Note that the number of ECA2-pastures is much lower than any other management category.

		ECA1	ECA2
MEADOW	Regulating	0.295	0.499
	Yield	1.276	0.954
PASTURE	Regulating	3.969	28.487
	Yield	0.652	0.410

Data availability

Data will be made available on request.

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