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# Organic farming is more related to topography than to soil characteristics in extensively and intensively managed grasslands in Switzerland

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ABSTRACT

Organic farming and other agri-environmental schemes (AES) are important policy tools to support environmental-friendly agriculture. Often, AES require a direct reduction of actual management intensity to sustain biodiversity and non-marketable ecosystem services. In addition to lower management intensity, differences in topography and soils between AES and non-AES land can occur, driven by the targeted placement of AES in the landscape. Many of the latter effects of an AES are, however, widely unknown and frequently ignored, limiting a comprehensive understanding of how organic farming and other AES deliver environmental outcomes. We analysed pedological, topographical and other spatial characteristics of parcels under two grassland AES, i.e., organic farming (vs. conventional) and extensive management (vs. intensive). Thus, this study assessed whether organic farming is related to differences in topography and soil conditions in both extensively and intensively managed grasslands in the study region in the north of Switzerland. Therefore, we combined a regional-scale spatial analysis of permanent grassland parcels and a soil survey. Both AES were tested not only in interaction with each other but also within the two main harvest types, i.e., meadows (mainly mown) and pastures (mainly grazed), resulting in eight distinct grassland types that were studied. Results show both AES to be linked to differences in soil nutrients as well as topographical and other spatial characteristics. We found interactions of the two AES with the harvest type, i.e., meadow versus pasture. This was particularly pronounced for extensively managed conventional meadows, which were frequent at low elevation and on land potentially suitable for arable farming. Extensively managed pastures and all organic grasslands exhibited reduced production conditions (i.e., higher elevation, steeper slope, lower soil phosphorus concentrations). Yet, differences between organic and conventional grasslands were by tendency more pronounced in intensively than extensively managed grasslands. Our results show that farmers preferentially adopted both AES on land not ideal for intensive production, with the exception of many extensively managed meadows in low elevations. Our study therefore demonstrated that an assessment of the ecological outcomes of an AES must not only account for *direct* effects via management restrictions but also for *indirect* effects via spatial targeting by farmers. More research is still needed to assess and compare direct and indirect effects of AES to support evidence-based policymaking and improve spatial targeting of different land-use types.

## 1. Introduction

Reducing the environmental impact of food production is a major goal of agricultural policymaking. A primary policy strategy are thus agri-environmental schemes (AES) such as organic farming, which reduce the intensity of land management, especially fertiliser and pesticide applications, to create beneficial environmental outcomes such as biodiversity and non-marketable ecosystem services (Batáry et al.,

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2015; Gomiero et al., 2011; Pallett et al., 2016). While governments assign large budgets to AES, their efficiency is debated (Kleijn and Sutherland, 2003; Pe'er et al., 2020), underlining the need to better understand how AES lead to positive environmental outcomes.

When assessing the impact of an AES on biodiversity and ecosystem services, both direct and indirect effects need to be considered (Fig. 1). While *direct* AES effects act via changing current land management, such as reductions in nutrient availability as a result of restrictions on the amount or type of fertiliser, *indirect* AES effects result from long-term processes and the respective (inherent) environmental setting, linked to where farmers place AES. For example, the steeper the slope, the higher the elevation or the more distant a parcel is from the farm, the less suitable it is for intensive production (Kampmann et al., 2012; Le Clec'h et al., 2019; Peter et al., 2008). In such locations, farmers might preferentially decide to participate in an AES as they expect lower losses in yield, i.e., lower opportunity costs (Gabriel et al., 2009). In contrast, such unproductive locations can be particularly attractive for biodiversity conservation as they might have a long tradition of extensive management and a higher abundance of semi-natural habitats, potentially leading to improved connectivity and a higher effectiveness of AES (Arponen et al., 2013; Kampmann et al., 2012). However, the combination of *direct* and *indirect* AES effects on biodiversity and ecosystem services as well as potential interactions of different AES were rarely studied, limiting our understanding of the current and future effectiveness of agri-environmental policies. To advance the understanding of the effectiveness of AES, we studied the interaction of two contrasting grassland AES in Switzerland, i.e., the production system *organic farming* and the eco-scheme *extensive grassland management*. AES parcels were tested for significant associations with soil conditions, site topography and other spatial characteristics.

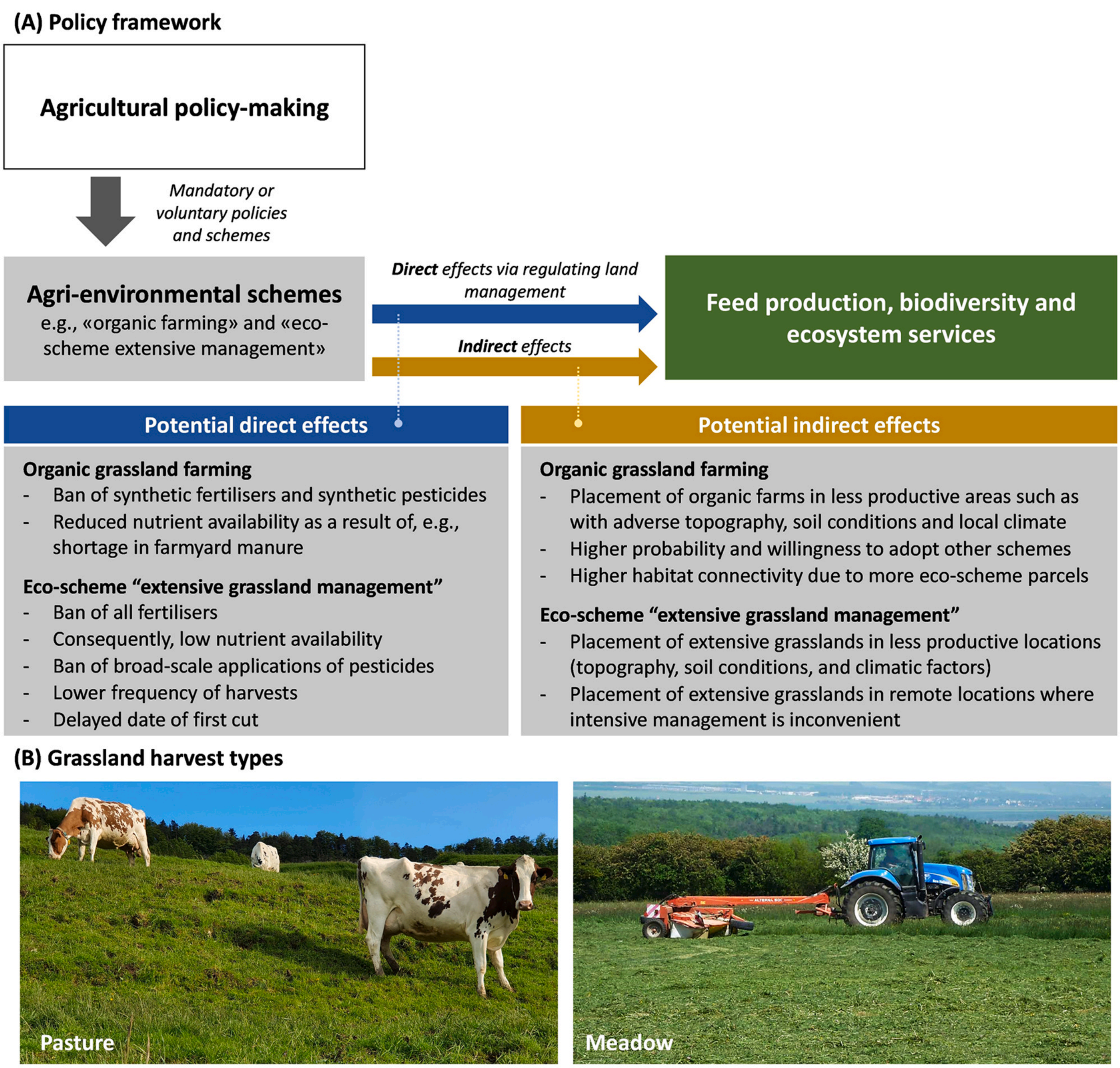


**Fig. 1.** (A) Potential direct and indirect effects of agri-environmental schemes (AES) on ecosystem services and biodiversity at the parcel scale, specifically referring to two grassland AES in Switzerland, i.e., organic farming and the eco-scheme "extensive management". While direct effects act via changes in grassland management intensity, indirect effects are the result of especially the respective environmental setting in which parcels were registered for an AES. Note that indirect AES effects are not necessarily caused by AES but result from non-random placement of AES in the landscape. (B) Grasslands harvest types, i.e., pastures (predominantly grazed by livestock) versus meadows (predominately mown), are likely to interact with the adoption and placement of AES due to specific requirements such as an even surface for large machinery for mowing.

*Organic farming*, a farm-scale AES, is seen as an environmentally friendly way to produce food by facilitating nutrient cycling while reducing external inputs (e.g., Gabriel et al., 2010; Smith et al., 2019). Yet, organic farming requirements specifically for permanent grassland management are rather weak as they only prohibit the use of synthetic fertilisers and pesticides but allow intensive use of organic fertilisers. Nevertheless, organic grassland farming can have long-term effects on soil conditions such as reduced nutrient availability, for example, of phosphorus (P; Gosling and Shepherd, 2005; Klaus et al., 2013). Previous studies also reported spatial patterns in the distribution of organic farms, which were, for example, more frequent in locations with a harsher regional climate (Cudjoe and Rees, 1992). Thus, organic grassland farms might also differ from conventional ones in the topography and composition of their farmland. Yet, this has never been comprehensively explored.

*Eco-schemes* are widespread AES to ensure low management intensity in different habitat types to support biodiversity on the parcel scale. Regulations for the studied Swiss eco-scheme "extensive grassland management" considerably restrict management intensity (e.g., fertilisation is completely banned; Klaus et al., 2023; Knop et al., 2006) and thus can lead to lower soil fertility. Highly beneficial effects of different types of extensive grassland management AES have been proven for biodiversity (Klaus et al., 2023; Ravetto Enri et al., 2020) and several ecosystem services (Richter et al., 2024; Schils et al., 2022). Like for organic farming, the adoption of Swiss eco-schemes by farmers was also shown to be related to the local environment (Kampmann et al., 2008; Ravetto Enri et al., 2020).

The way of harvesting grassland yields depicts an important management decision, which interacts with the local environment and thus potentially also with AES effects (Socher et al., 2013; Tälle et al., 2016). The grassland harvest type can be a *meadow* (dominated by mowing) or a *pasture* (dominated by grazing). Fertilised meadows often occupy parcels with best growth conditions and uncomplicated topography to enable use of large machinery. Meanwhile, grazing of pastures is less restricted by slope, elevation and microtopography leading to pastures potentially occupying more adverse production conditions such as sloping terrain (Stumpf et al., 2020). Since farmers' decision for a preferred harvest type depends on the local conditions, realized harvest types likely interact with participation in a grassland AES. Yet, this has, to our knowledge, never been tested.

Focussing on organic farming in extensively managed (eco-scheme) and intensively managed (no eco-scheme) grasslands, we studied several aspects of topography and soil conditions that are relevant for agricultural production, biodiversity, and further ecosystem services. We studied eight distinct grassland types that result from the full-factorial combination of the two previously described grassland AES (i.e., organic grassland farming and eco-scheme extensive management) with the harvest type, i.e., pasture versus meadow (Fig. 1). We combined a spatial analysis of agricultural census data and a soil survey to assessed field-scale differences in pedological, topographical and further spatial attributes of the eight grassland types. In addition, we evaluated compositional differences in organic versus conventional cattle farms in view of the proportion of extensively managed (eco-scheme) grasslands. Specifically, we hypothesised the following:

**(H1).** Organically managed grasslands show less suitable production conditions compared to conventional grasslands, for example, higher elevation, steeper slopes and lower soil nutrient concentrations. These differences will, however, only be present in intensive but not in extensively managed (eco-scheme) grasslands.

**(H2).** Associations of both AES, i.e., organic farming and extensive management, with topography, spatial attributes and soil characteristics significantly differ between grassland harvest types, i.e., meadows and pastures.

**(H3).** Organic cattle farms have higher shares of extensively managed (eco-scheme) grasslands than conventional farms.

The insight provided by our study will help to assess how both AES are co-varying with topography (i.e., targeted placement of AES at the landscape) and inherent soil conditions (e.g., soil texture) as well as differences in nutrient availability. Understanding the interactions between the two AES and how these differ between meadows and pastures opens new avenues for improved AES design. This knowledge can further help recognizing and modelling the landscape-scale distribution of land-use types and associated environmental and agricultural outcomes such as the feed-food conflict.

## 2. Methods

### 2.1. Study region

We studied permanent grasslands, i.e., grasslands not included in the crop rotation for at least six years, in the Swiss canton of Solothurn in the North-West of Switzerland (Fig. 2A). The canton covers 790.5 km$^2$ and contains a wide range of environmental conditions stretching from the agriculturally favourable plain (400–550 m a.s.l.) in the south to the undulating Jura mountains in the north (up to 1445 m a.s.l.). The bedrock of the latter mountain range is mostly calcareous limestone while in the plain soils developed from sandy to loamy alluvial and glacial sediments. The canton is dominated by permanent grassland that covers two thirds of the agricultural area (Le Clec'h et al., 2019). In contrast to the intensively agriculturally used plain (lowland zone), which contains arable land and grassland, mountainous areas are covered with forest and grassland (mountain zone; BLW, 2022; Fig. 2B). Considerably more, but on average smaller parcels of permanent grassland are located in the lowland zone in the canton of Solothurn (n = 13236; 71 % of all grassland parcels; 52 % of total permanent grassland area) compared to the mountain zone (n = 5516; 29 % parcels; 48 % grassland area).

### 2.2. Study design and agri-environmental schemes

Our study is composed of three approaches, (i) a regional assessment of the topography and the spatial setting of the AES (Section 2.3.), (ii) a field sampling of 92 plots to assess relations between AES and soil characteristics (Section 2.4.), and (iii) a farm-scale assessment of the proportion of different grassland types on organic versus conventional cattle farms within the study region (Section 2.5.; Fig. 3).

The study focused on eight main types of permanent grassland in Switzerland, outside alpine areas, combining the two AES "organic farming" (vs. non-organic = conventional) and eco-scheme "extensive management" (vs. intensive = fertilisation allowed). In the following, extensively manged grasslands will be referred to as *extensive grasslands*. Both intensive and extensive grasslands can be managed as one out of two harvest types, i.e., pasture (predominantly grazed) or meadow (predominantly mown; Figs. 1 and 2C-E). Note that these harvest types do not strictly separate purely mown versus grazed swards as in practice meadows are occasionally grazed and pastures sometimes mown depending on forage needs and to maintain desirable sward composition (Klaus et al., 2023). The eight grassland types make up 99 % of the total grassland area (98 % of parcels) of the canton and can be seen as representative also for other Central European landscapes dominated by permanent grassland. This grassland typology follows the structure of the Swiss agricultural statistics. In this study, the term '*grasslands*' encompasses both meadows and pastures.

*Organic farming* facilitates nutrient cycling on farm while reducing external inputs and has to adhere to the regulations of organic farming in Switzerland, prohibiting the use of synthetic fertilisers and synthetic pesticides (Bio Suisse, 2020). Lower upper limits for fertiliser applications apply in organic (e.g., 135 kg available nitrogen (N) per hectare and year on average at low elevations) compared to conventional

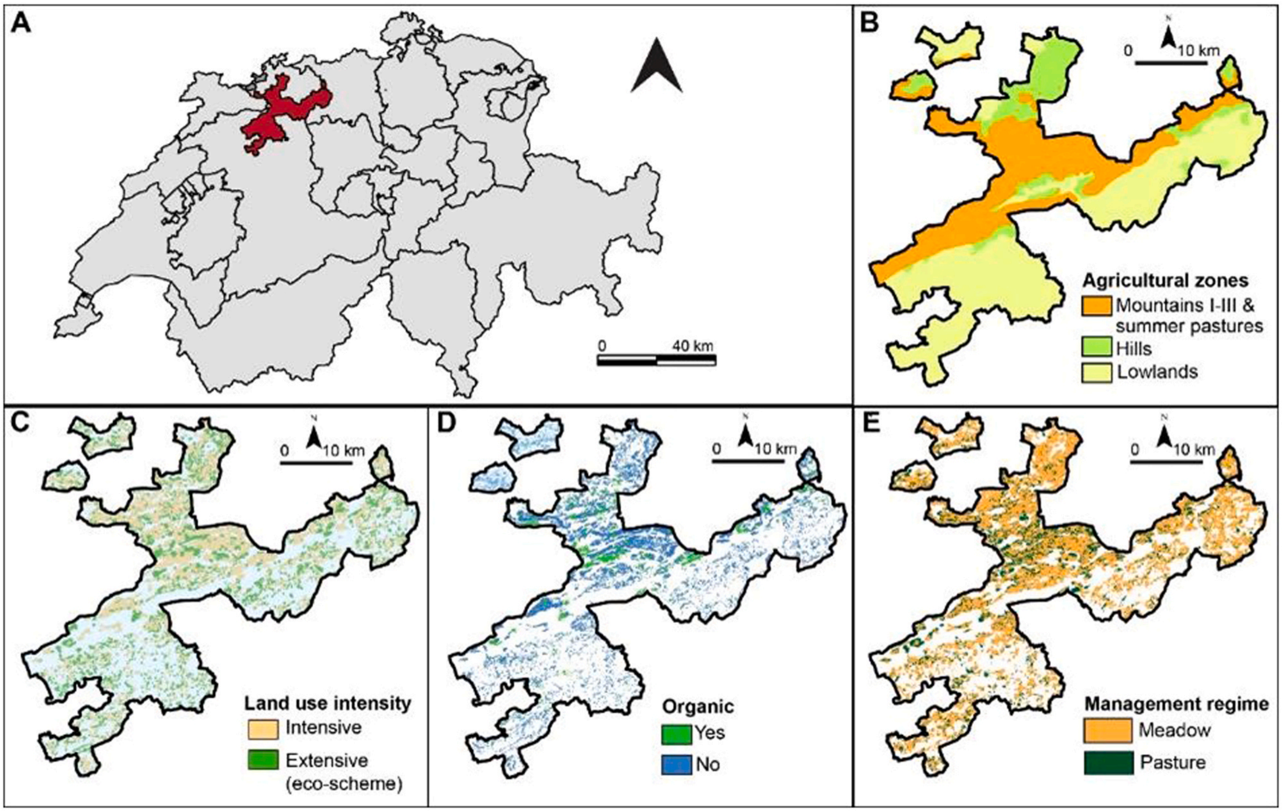


**Fig. 2.** Maps of (A) the study area, i.e., the canton of Solothurn, within Switzerland, (B) the study area separated into the agricultural zones (in this work, *mountains* are distinguished from *lowlands*, with the latter comprising the lowland and hill zones), (C) grassland parcels separated into intensive and extensive eco-scheme management, (D) grasslands separated into organic and conventional farming, and (E) grassland parcels split into meadow (predominantly mown) and pasture (predominantly grazed).

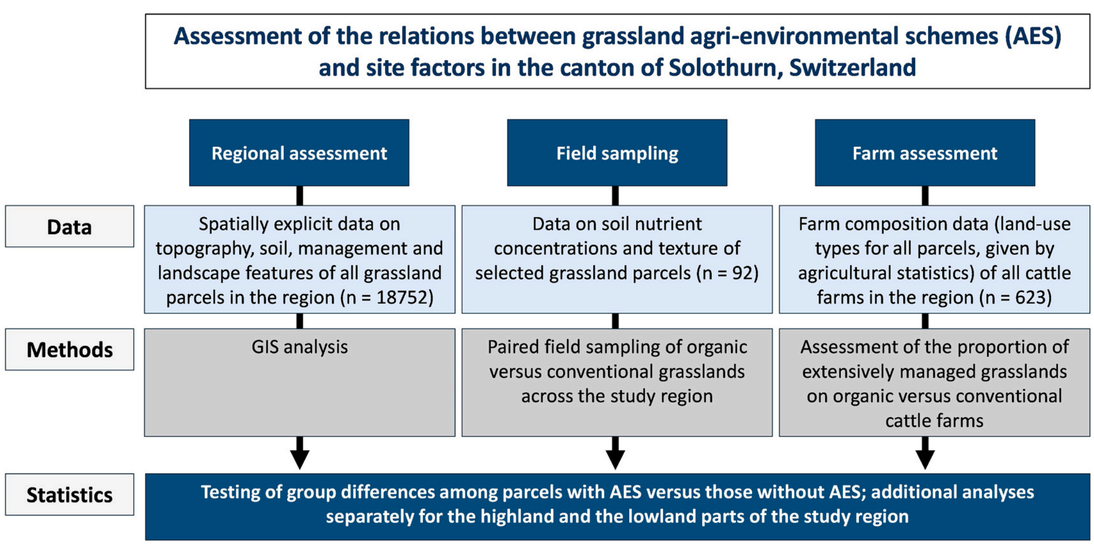


**Fig. 3.** Conceptual figure of the three-part methodology used in this study, composed of (i) a regional-scale GIS analysis of topographical and further spatial attributes of grassland parcels, (ii) a field sampling and soil analyses, and (iii) an assessment of the proportion of extensively managed (eco-scheme) grasslands on organic versus conventional cattle farms within the region (Fig, 2).

grassland management (i.e., on average 162 kg available N per hectare and year across all intensive conventional grasslands of a farm at low elevations; DZV, 2023). Swiss organic farming regulations prescribe ruminant feed to be organically certified and to originate from Switzerland, with a maximum of 5 % of animal dry matter intake being concentrates, which likely leads to reduced quantity and quality of farmyard manures on organic farms. In 2021, 21.5 % of the permanent grassland area of Switzerland were organically farmed and farmers receive AES payments for their organic grassland area (FiBL, 2023). Conventional (non-organic) grasslands are managed according to the guidelines of the “Proof of Ecological Performance”, which need to be followed to be eligible to receive agricultural direct payments (DZV, 2023). These regulations are based on the concept of integrated production and require, for example, a balanced nutrient budget for P and N at the farm scale.

The eco-scheme "*extensive grassland management*" is parcel-based and belongs to a family of Swiss eco-schemes targeting biodiversity conservation in different agricultural habitat types. Arable and grassland farmers must register 7 % of their farm area as any eco-scheme to be generally eligible for agricultural direct payments (DZV, 2023). Farmers can, however, voluntarily go beyond this proportion and register more land, qualifying for additional payments. In 2020, 22 % of the agricultural grassland area of Switzerland was registered as eco-scheme of the type "extensive grassland management", of which 63 % are extensive meadows and 37 % extensive pastures (BLW, 2021). Extensive eco-scheme grasslands must not be fertilised and require at least one utilisation per year to prevent succession. According to the main type of harvesting, *extensive meadows* and *extensive pastures* are distinguished by agricultural policies. *Extensive meadows* are cut not earlier than a set date depending on agricultural zone, for example, 15th of June at low elevations. The total annual number of cuts is not regulated and therefore mainly depends on growth conditions at the site. Autumn grazing of extensive meadows is permitted. *Extensive pastures* are primarily grazed by livestock, with grazing management of a parcel being rather unregulated to follow grass growth. Cleaning cuts are allowed but additional feeding of animals is prohibited on-site. Extensive pastures are allowed to contain up to 20 % of unproductive land such as rocks or shrubs. Note that in the lowlands per-ha AES payments are twice as high for extensive meadows compared to extensive pastures, while this difference is negligible in the mountain zones (DZV, 2023). See Klaus et al. (2023) for further details on the grassland types studied here.

### 2.3. Regional assessment of topography and spatial setting

The first part of this study used spatial census data of the agricultural statistics of Switzerland at the parcel scale linked to the grassland types and digital agricultural maps related to topography and soil conditions. Our analyses systematically assessed all grassland parcels from the eight types described above, while other land use types were omitted. In total, 18752 grassland parcels were contained in this part of the analysis (Fig. 2). Data about parcel management and size were obtained from census data of the Swiss agricultural statistics. A Digital Elevation Model of the Copernicus Land Monitoring Service of the European Environment Agency (European Union, 2018) at a resolution of 25 m provided data about the topography of the canton and informed about the elevation at each cell. Slopes were calculated based on the elevational difference between two adjacent cells and are given as percentage. We further calculated the index of Simpson's diversity to estimate diversity in land use types of the landscape surrounding each parcel (3-cell radius). This analysis considered 19 classes of land-use types, clustered in "artificial surfaces", "agricultural areas", "forest and semi natural areas", "wetlands", and "water bodies". We also calculated the Euclidian distance of each grassland parcel to (i) the closest patch of a (semi-) natural habitat (i.e., forests (broad-leaved, coniferous and mixed) and scrub and/or herbaceous vegetation associations as considered in the Corine Land Cover data; http://land.copernicus.eu/global), and (ii) to the farm building the parcel belonged to. In addition, we extracted the compound-factor "soil suitability for agricultural production", officially used to estimate the production potential of the soil at a specific location (FOAG, 2005). Soil suitability for agricultural production synthesized information such as slope, soil type, and soil water regime, and was expressed as a factor consisting of five ordinal levels, with 1 = *very suitable for agricultural production* to 5 = *widely inappropriate soil for agricultural production*. Suitability for arable farming is strongly restricted at level 4 and especially level 5. Note that these maps consider several soil characteristics but might not include all factors that could locally inhibit intensive grassland or arable management, as the information used for the maps is not based on parcel-level measurements but a synthesis of different geographical maps (FOAG, 2005).

### 2.4. Soil sampling and laboratory analyses

For part two of the methodology, the soil sampling, we selected 92 permanent grasslands across the canton (Figure S1 in Appendix A). Study parcels covered all eight grassland types and represented a wide gradient in land-use intensities, ranging from fertilisation of up to 200 kg available N to extensive meadows and pastures without any fertiliser additions (Richter et al., 2024). Plots were arranged in pairs of organic and conventional grasslands that had to (i) be of the same type (i.e., intensive meadow, intensive pasture, extensive meadow, or extensive pasture), (ii) have similar exposition, elevation and topography, and (iii) be located in close proximity. This approach helped to control as much as possible for environmental differences between organic and conventional grasslands. We did, on the contrary, not control for topographical and further differences among extensive eco-scheme versus intensive grasslands, and pastures versus meadows, as we were specifically interested how the actual environmental setting of these grassland types differ. For further information on plot selection please see Richter et al. (2024).

In 2020, a soil sampling campaign was conducted to measure phosphorus (P), potassium (K), and magnesium (Mg) concentrations, as well as soil pH and texture (i.e., fractions of sand, silt and clay). Per plot, with a soil auger, 20 cores were taken to a depth of 20 cm along two 18-m intersecting transects. Samples were pooled, soil sieved to 2 mm, and dried at air temperature. For soil texture, organic matter was removed with hydrogen peroxide using a SP 50 Robotic Analyzer, and texture was measured with a SP 2000 Robotic Clay Fraction Analyzer (both, Skalar Analytical B.V., Breda, The Netherlands). Plant-available nutrient concentrations were measured photometrically (Evolution 220 with Cetac ASX-520, Thermo Fisher Scientific, Waltham, MA, United States) after Olsen extraction with 0.5 M $NaHCO_3$ ($P_{Olsen}$; Olsen and Sommers 1982) as well as after extraction with demineralized water ($P_{H20}$, $K_{H20}$ and $Mg_{H2O}$; weight ratio soil:water = 1:10). Soil pH was measured potentiometrically in a suspension of air-dried soil in water (weight ratio soil: water = 1:3.3).

### 2.5. Composition of farm area of cattle farms

The third part of the methodology uses agricultural census data on the farms within the study region. As organic farming might not only be related to differences in soil and topography on the parcel scale but can also exhibit differences in the uptake of other AES on the farm scale (Mack et al., 2020), we compared organic versus conventional cattle farms regarding their agricultural land, especially with regard to intensive and extensive (eco-scheme) grasslands. The focus was set to cattle farms as these are a major farm type in the region and can be widely based on permanent grassland. Therefore, we first identified cattle farms according to the following criteria reported in the census data: Cattle farms were defined to have a total agricultural area larger than 2 ha, at least ten livestock units with at least 75 % of the livestock units being cattle, and the share of arable land must not exceed 70 % of the farms` total agricultural area (Hoop and Schmid, 2019). For each cattle farm in the study region, we assessed the average share of the previously described eight grassland types plus that of arable land and of the category "other", which included rare types of land use and other eco-schemes. The sum of all these land use types depicts the total agriculturally used area of the farms (excluding build land). This analysis was done for the canton as a whole and separately for the lowland and the mountain parts, as these can differ in the dominant farming systems (BLW, 2022; Mack et al., 2020).

### 2.6. Statistical analyses

To analyse topographical and further spatial factors, linear regression models were used to test for significant group differences linked to the AES organic farming (versus conventional), extensive eco-scheme management (versus intensive), and the harvest type (pasture versus meadow). These models included the three main effects and all possible two-way interactions. Please note that since topography pre-determines the uptake of AES, our statistical analysis searched for group differences and does not infer a causal effect of an AES on topography. For the soil properties, the same was tested using linear mixed models including the three main effects and all possible two-way interactions plus "plot pair" as random factor (i.e., each plot pair of one organic and one conventional grassland according to pairwise plot selection). Step-wise backward selection was used to find the best model (*lmerTest* package; Kuznetsova et al., 2017), and the pseudo $R^2$ was extracted for mixed models using the *MuMIn* package (Barton, 2023). For soil texture, to avoid issues with testing cumulative proportions, we only ran a test for sand content, which best described differences in soil substrate in the study area. Diagnostic plots were used to check whether model assumptions were met, and results were obtained with the *summary* call. To check for significant differences in the proportions of extensive grasslands, i.e., the sum of extensive pastures and meadows, on organic versus conventional farms, we used the pairwise Wilcoxon test. All analyses were performed with R version 4.2.0 in RKWard Version 0.7.0b (Friedrichsmeier et al., 2022).

## 3. Results

We found both grassland agri-environmental schemes (AES), i.e., organic farming and extensive eco-scheme management, to be closely related to differences in topography and soil conditions. In some cases, the two AES strongly interacted with each other and/or with the grassland harvest type, i.e., meadow versus pasture. When mentioning *grasslands* in the following, this includes both meadows and pastures, which may however also be mentioned separately if relevant.

### 3.1. Extensive eco-scheme grasslands interact with harvest type

In the canton-wide assessment of topographical and spatial features, all main factors and almost all interactions tested were significant for extensive eco-scheme management (n = 18752; Table 1). However, these differences between extensive and intensive grasslands considerably interacted with harvest type, and often also organic farming. Extensive pastures showed least beneficial production conditions, with high elevations and steep slopes, and they also exhibited highest Simpson's diversity of surrounding land uses (Fig. 4; Table 1). On the contrary, extensive meadows occupied most productive locations in the whole dataset, on low elevations and flat slopes. Noteworthy, especially conventional extensive meadows were most frequent on the best soils, i.e., soil suitability class 1, indicating potential suitability for arable farming. All other grassland types, including intensive grasslands but also extensive organic meadows, were most frequent on soils of class 4 or 5, indicating very low to no suitability for arable farming (Table 1). When analysing soil suitability only for lowland locations (n = 13236 grassland parcels), not only extensive conventional meadows (39 % of lowland parcels) but also extensive organic meadows (3.5 %) and all intensive pastures (13 %) were located on land potentially suitable for arable farming. In line with this, all grassland types under both organic and conventional farming occurred basically on all soil suitability classes, but with considerable differences among types. Extensively managed (organic) pastures were least frequently found on soils potentially suitable for arable farming (Figure S2 in Appendix A).

Conventionally managed extensive meadows were the overall second most frequent grassland type with regard to parcel numbers, only exceeded by the number of intensive (conventional) meadows (Table 1). Almost 75 % of all extensive grasslands in the whole study region were extensive conventional meadows located in lowlands (i.e., 5150 parcels), revealing this grassland type to be a very widespread eco-scheme on conventional farms in agriculturally favourable locations and to dominate the average vale (e.g., estimate) effect of extensive management shown in Table 1. Extensive (conventional) meadows also showed the by far largest distance from (semi-)natural habitats, which was again not the case for extensive organic meadows and both types of extensive pastures. Extensive grasslands were generally located further away from the farm building than intensive grasslands (Table 1). This was, however, mainly driven by intensive pastures being particularly close to farm buildings, likely because of their use for frequent grazing near the respective stables.

With regard to soil conditions, extensively managed grasslands showed significantly lower soil P, K and Mg availability compared to intensive management (Fig. 5; Table 1). Soil pH was slightly but significantly lower in extensive grasslands, which exhibited slightly acidic conditions (average pH 6.1–6.6) compared to rather neutral conditions in intensive grasslands (average pH 6.7–6.9). Differences in soil texture between extensive and intensive grasslands were marginal and not statistically significant (Table 1).

### 3.2. Organic grasslands more related to topography than soil characteristics

Each type of organically managed grassland turned out to be considerably higher in elevation (estimate: +70 m) and slightly steeper than the conventional counterpart (Fig. 4; Table 1). These differences can be related to a biased distribution of these grasslands in the study region: Organic grasslands were considerably less frequent in the lowlands of the region (9 % of grassland parcels, 10 % of grassland area) compared to the mountainous part (22 % parcels, 27 % area). The mode of soil suitability was similar for organic and conventional grasslands (Table 1), with the already mentioned exception. Yet, organic grasslands were more often on particularly unsuitable soils that their conventional counterparts (Figure S2 in Appendix A). It is noteworthy that not only soil suitability but also topography of extensive meadows differed considerably between organic and conventional management, highlighting strong interactions among the two AES studied and with harvest type. In addition, organic grassland parcels were larger and closer to (semi-) natural habitats (estimate: −31 m) than conventional ones (Fig. 4; Table 1). Organic compared to conventional parcels were also more distant from the related farm building. Yet, there was no difference in the Simpson's diversity index of neighbouring land uses between organic and conventional grasslands.

Organic grasslands exhibited generally lower $P_{Olsen}$ concentrations than conventional ones, while $P_{H20}$ concentrations differed only in intensive grasslands and $K_{H2O}$ concentrations only in intensive pastures (Fig. 5; Table 1). Yet, these effects were statistically not or only marginally significant due to a large variability in concentrations and the absence of strong differences in P and K concentrations in extensively managed organic versus conventional grasslands. Organic grasslands exhibited only marginally lower $Mg_{H2O}$ concentrations than conventional grasslands (Table 1). Similarly, organic grassland farming was not significantly related to differences in soil texture or soil pH.

### 3.3. Composition of organic and conventional cattle farms

In the whole canton, we identified in total 623 cattle farms according to the criteria given in methods Section 2.4. With only 7.7 % of cattle farms being organic, organically managed cattle farms were less frequent in the lowlands as compared to 22.4 % in the mountainous area. Both organic and conventional cattle farms contained considerably higher proportions of extensive grassland in the mountain compared to the lowland zones (Fig. 6). Across the entire canton, organic cattle farms had a considerably higher share of extensive eco-scheme (+11 %) and also intensive grasslands (+11 %), but less arable land (-23 %) than conventional cattle farms (Fig. 6). The Wilcoxon test run on the share of extensive grasslands proved this difference to be highly significant (p <

**Table 1.** (

(A) Topographical and spatial characteristics of all eight grassland types specified in the methods section (n = 18752). Group differences were tested using linear regression models (lm). (B) Soil characteristics of all eight grassland types (n = 92). Group differences were tested with linear mixed models (lmer). Final models based on backward selection, which has removed the random factor in the model for $K_{H2O}$ and therefore changed the final model to a normal lm. For soil texture only one model was run, i.e., for sand content, to avoid statistical issues with testing cumulative proportions. Conv = conventional, org = organic, log = "yes" indicates data was log-transformed before testing. Predictors with p > 0.05 are given in bold. Asterisks indicate significance levels: n.s. > 0.05 ≥ "*" > 0.01 ≥ "**" > 0.001 ≥ "***"; df = residual degrees of freedom.

**(A) Topography and spatial characteristics**

| | | **Intensive** | | | | **Extensive (eco-scheme)** | | | | **Model statistics (linear regressions)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Meadow** | | **Pasture** | | **Meadow** | | **Pasture** | | | | | | | | | |
| | | **Conv** | **Org** | **Conv** | **Org** | **Conv** | **Org** | **Conv** | **Org** | ***R²*** | ***p*** | ***df*** | ***log*** | **Predictor** | **Estimate** | **t** | ***p*** |
| **Elevation** | mean | 571 | 643 | 590 | 697 | 537 | 628 | 659 | 796 | 0.10 | *** | 18745 | no | **Organic** | 70.74 | 15.2 | *** |
| m | sd | 136 | 196 | 157 | 220 | 121 | 185 | 183 | 215 | | | | | **Pasture** | 18.8 | 5.52 | *** |
| | | | | | | | | | | | | | | **Extensive** | −34.26 | −13.49 | *** |
| | | | | | | | | | | | | | | **Organic:Pasture** | 39.74 | 5.5 | *** |
| | | | | | | | | | | | | | | **Organic:Ext.** | 21.56 | 3.41 | *** |
| | | | | | | | | | | | | | | **Pasture:Ext.** | 104.23 | 18.66 | *** |
| **Slope** | mean | 15.2 | 18.2 | 18.2 | 21.0 | 13.2 | 18.1 | 26.1 | 29.4 | 0.08 | *** | 18745 | no | **Organic** | 0.14 | 8.08 | *** |
| % | sd | 11.2 | 12.9 | 13.7 | 14.6 | 11.7 | 13.2 | 15.1 | 15.1 | | | | | **Pasture** | 3.09 | 10.87 | *** |
| | | | | | | | | | | | | | | **Extensive** | −1.95 | −9.22 | *** |
| | | | | | | | | | | | | | | Organic:Pasture | −0.74 | −1.23 | n.s. |
| | | | | | | | | | | | | | | **Organic:Ext.** | 1.54 | 2.87 | ** |
| | | | | | | | | | | | | | | **Pasture:Ext.** | 9.65 | 20.71 | *** |
| **Area** | mean | 0.85 | 1.15 | 1.40 | 1.60 | 0.49 | 0.67 | 1.19 | 1.98 | 0.06 | *** | 18745 | no | **Organic** | 0.22 | 5.01 | *** |
| ha | sd | 1.37 | 1.90 | 1.92 | 2.39 | 0.57 | 0.79 | 2.01 | 2.81 | | | | | **Pasture** | 0.51 | 15.78 | *** |
| | | | | | | | | | | | | | | **Extensive** | −0.38 | −15.9 | *** |
| | | | | | | | | | | | | | | **Organic:Pasture** | 0.19 | 2.82 | ** |
| | | | | | | | | | | | | | | Organic:Ext. | 0.06 | 1.04 | n.s. |
| | | | | | | | | | | | | | | **Pasture:Ext.** | 0.27 | 5.17 | *** |
| **Distance to farm** | mean | 293 | 339 | 184 | 180 | 381 | 367 | 294 | 310 | 0.04 | *** | 18745 | no | **Organic** | 37.48 | 3.84 | *** |
| m | sd | 285 | 436 | 317 | 271 | 297 | 340 | 330 | 276 | | | | | **Pasture** | −113.44 | −15.91 | *** |
| | | | | | | | | | | | | | | **Extensive** | 85.41 | 16.05 | *** |
| | | | | | | | | | | | | | | Organic:Pasture | −17.4 | −1.15 | n.s. |
| | | | | | | | | | | | | | | **Organic:Ext.** | −39.36 | −2.92 | ** |
| | | | | | | | | | | | | | | **Pasture:Ext.** | 36.56 | 3.13 | ** |
| **Distance to (semi)-natural habitats** | mean | 237 | 213 | 231 | 151 | 288 | 195 | 169 | 77 | 0.01 | *** | 18745 | no | **Organic** | −30.72 | −1.98 | * |
| | sd | 475 | 465 | 448 | 289 | 547 | 516 | 402 | 172 | | | | | Pasture | −9.38 | −0.83 | n.s. |
| m | | | | | | | | | | | | | | **Extensive** | 49.28 | 5.83 | *** |
| | | | | | | | | | | | | | | Organic:Pasture | −32.31 | −1.34 | n.s. |
| | | | | | | | | | | | | | | **Organic:Ext.** | −54.28 | −2.53 | * |
| | | | | | | | | | | | | | | **Pasture:Ext.** | −102.81 | −5.53 | *** |
| **Simpson's diversity** | mean | 1.74 | 1.74 | 2.20 | 2.34 | 1.90 | 1.99 | 2.38 | 2.49 | 0.01 | *** | 18745 | no | Organic | 0.97 | 0.13 | n.s. |
| | sd | 2.12 | 2.15 | 2.21 | 2.26 | 2.16 | 2.18 | 2.22 | 2.24 | | | | | **Pasture** | 46.27 | 9.23 | *** |
| | | | | | | | | | | | | | | **Extensive** | 16.02 | 4.28 | *** |
| | | | | | | | | | | | | | | Organic:Pasture | 9.52 | 0.9 | n.s. |
| | | | | | | | | | | | | | | Organic:Ext. | 6.25 | 0.66 | n.s. |
| | | | | | | | | | | | | | | Pasture:Ext. | 0.04 | 0 | n.s. |
| **Soil suitability** (factor) | mode | 4 | 4 | 5 | 5 | 1 | 5 | 5 | 5 | | *no test performed* | | | | | | |
| Parcel count (n) | | 6799 | 1012 | 2358 | 390 | 6157 | 765 | 976 | 295 | | | | | | | | |

**(B) Soil characteristics**

| | | **Intensive** | | | | **Extensive (eco-scheme)** | | | | **Model statistics (model selection, stepwise backward)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Meadow** | | **Pasture** | | **Meadow** | | **Pasture** | | | | | | | | | |
| | | **Conv** | **Org** | **Conv** | **Org** | **Conv** | **Org** | **Conv** | **Org** | ***Model*** | ***R²*** | ***df*** | ***log*** | **Predictor** | **Estimate** | **t** | ***p*** |
| **P Olsen** | mean sd | **37.0** | **29.9** | **40.8** | **21.8** | **11.2** | **12.0** | **21.1** | **13.3** | lmer | 0.32 (marginal) | 41 | yes | Organic | −0.05 | −0.48 | n.s. |
| mg $kg^{-1}$ | sd | 28.2 | 24.6 | 28.3 | 11.7 | 4.1 | 3.6 | 14.5 | 6.5 | | | | | Pasture | 0.27 | 1.52 | n.s. |
| | | | | | | | | | | | | | | **Extensive** | −0.74 | −4.73 | *** |
| | | | | | | | | | | | | | | **Org:Pasture** | −0.41 | −2.30 | * |
| **P $H_2O$** | mean sd | **5.7** | **4.6** | **7.5** | **4.3** | **1.6** | **2.1** | **2.3** | **2.0** | lmer | 0.23 (marginal) | 42 | yes | **Extensive** | −0.78 | −4.28 | *** |
| mg $kg^{-1}$ | sd | 5.0 | 4.3 | 10.1 | 4.3 | 0.7 | 0.6 | 1.3 | 0.8 | | | | | | | | |

(*continued on next page*)

**Table 1.** ( (*continued*)

| (A) Topography and spatial characteristics | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **K $H_2O$** | mean sd | **28.9** | **29.0** | **51.1** | **31.2** | **10.9** | **10.7** | **13.5** | **17.4** | lm | 0.38 (adjusted) | 85 | yes | **Pasture** | **0.31** | **2.59** | * |
| mg $kg^{-1}$ | sd | 22.9 | 18.8 | 38.8 | 25.2 | 3.4 | 2.7 | 4.8 | 5.6 | | | | | **Extensive** | −0.81 | −6.77 | *** |
| **Mg $H_2O$** | mean sd | **19.4** | **16.9** | **14.2** | **13.3** | **6.8** | **9.4** | **10.8** | **22.3** | lmer | 0.18 (marginal) | 40 | yes | Pasture | −0.22 | −1.04 | n.s. |
| mg $kg^{-1}$ | sd | 14.4 | 15.4 | 10.4 | 9.6 | 2.6 | 10.8 | 7.3 | 22.3 | | | | | **Extensive** | −0.79 | −3.71 | *** |
| | | | | | | | | | | | | | | **Pasture:Ext.** | **0.77** | **2.23** | * |
| **pH** | mean sd | **6.75** | **6.76** | **6.85** | **6.66** | **6.35** | **6.12** | **6.58** | **6.45** | lmer | 0.10 (marginal) | 44 | no | **Extensive** | −0.42 | −2.69 | * |
| | sd | 0.51 | 0.47 | 0.49 | 0.60 | 0.94 | 0.70 | 0.78 | 0.63 | | | | | | | | |
| **Sand** | mean sd | **17.4** | **17.3** | **22.6** | **24.7** | **21.6** | **23.4** | **17.0** | **13.2** | | *no model with significant predictors identified* | | | | | | |
| % | sd | 6.5 | 6.0 | 13.2 | 14.4 | 15.5 | 13.6 | 11.4 | 3.7 | | | | | | | | |
| **Silt** | mean sd | **35.1** | **38.2** | **34.7** | **36.1** | **35.0** | **34.0** | **32.7** | **33.1** | | *no test performed* | | | | | | |
| % | sd | 6.89 | 7.63 | 4.91 | 6.40 | 5.32 | 5.83 | 2.28 | 3.32 | | | | | | | | |
| **Clay** | mean sd | **40.5** | **37.3** | **36.1** | **32.9** | **37.1** | **36.5** | **40.6** | **46.4** | | *no test performed* | | | | | | |
| % | sd | 7.36 | 7.13 | 10.97 | 11.14 | 12.79 | 11.74 | 9.78 | 4.96 | | | | | | | | |
| Number plots (n) | | 17 | 17 | 12 | 12 | 11 | 11 | 6 | 6 | | | | | | | | |

0.001). Yet, this effect of organic farming got smaller when lowland and mountain farms were analysed separately: In the lowlands, less arable land on organic (-10 %) compared to conventional farms was mostly compensated by an increase in extensive (+3.2 %) and intensive grasslands (+4 %). Yet, the difference in the share of extensive grasslands was not statistically significant for the lowland farms ($p = 0.144$). In contrast, in the mountainous area, organic cattle farms had a significantly higher share of extensive grasslands than conventional farms (+14 %, $p < 0.001$), which was mostly at the cost of intensive grasslands (-8 %) and arable land (-5 %) on organic farms. Thus, in the mountain zones, the proportion of extensive eco-scheme grasslands was more than 50 % higher on organic compared to conventional cattle farms.

## 4. Discussion

This work assessed grassland parcels of two AES, i.e., extensive (eco-scheme) management and organic farming and found both AES to be significantly related to differences in many pedological, topographical and other spatial characteristics. As hypothesized (H1), differences between organic and conventional grasslands were more pronounced in intensive compared to extensive grasslands. Extensive and organic management were both associated with worse production conditions (i.e., higher elevation, steeper slope, lower soil P) when compared to their counterparts, but with one big exception, i.e., extensive conventional meadows. These differences in the inherent environmental setting of AES parcels in topography likely lead to (indirect) effects of AES on biodiversity and ecosystems services, which are additional to (direct) effects of AES via restricting the intensity of grassland management (Kampmann et al., 2008; Klaus et al., 2023; Ravetto Enri et al., 2020). Since AES and non-AES parcel clearly differed in landscape-scale spatial factors, these should be considered when the effectiveness of an AES is evaluated. Such a combination of beneficial direct (i.e., management-related field-scale) and indirect (i.e., landscape-scale) effects was shown to be highly important for biodiversity conservation (Gonthier et al., 2014). Yet, as hypothesized (H2), we found strong interactions of the two AES with the harvest type, i.e., meadows versus pastures.

### 4.1. Extensive conventional meadows stand out

Completely contrary to extensive pastures, extensive conventional meadows frequently occupied quite productive locations potentially suitable for arable agriculture, especially in the lowlands. However, the soil suitability map used here is relatively coarse (FOAG, 2005), so even in regions of arable farming, extensive meadows might still be placed in locations where arable farming is hindered by local factors such as by a pronounced microrelief or high soil moisture. Extensive meadows in agriculturally favourable locations would likely be a result of the obligation to have 7 % of the area of all arable and grassland farms in Switzerland registered as any type of eco-scheme, with an allowed maximum distance of 15 km between eco-scheme parcel and farm (DZV, 2023). As extensive meadows are relatively easy to manage even for arable farms without livestock, and, in lowlands, generate higher per-hectare payments than extensive pastures (DZV, 2023), extensive meadows appear to be the preferred eco-scheme to fulfil this 7 % requirement (Knop et al., 2006). However, on average in our study area, arable farms had 13.7 % of their farm area managed as any type of eco-scheme (data not shown). This high number somewhat contradicts many extensive meadows to be located on land potentially suitable for arable farming. Locally adverse production conditions and high opportunity costs for intensive management (Huber et al., 2021; Schaub et al., 2023, and references therein), which are not accounted for by the soil suitability map used here, might therefore have (additionally) led to farmers registering additional land for extensive eco-scheme management. Alternatively, or in addition, farmers have registered more land for eco-schemes as they were open to questions of nature and

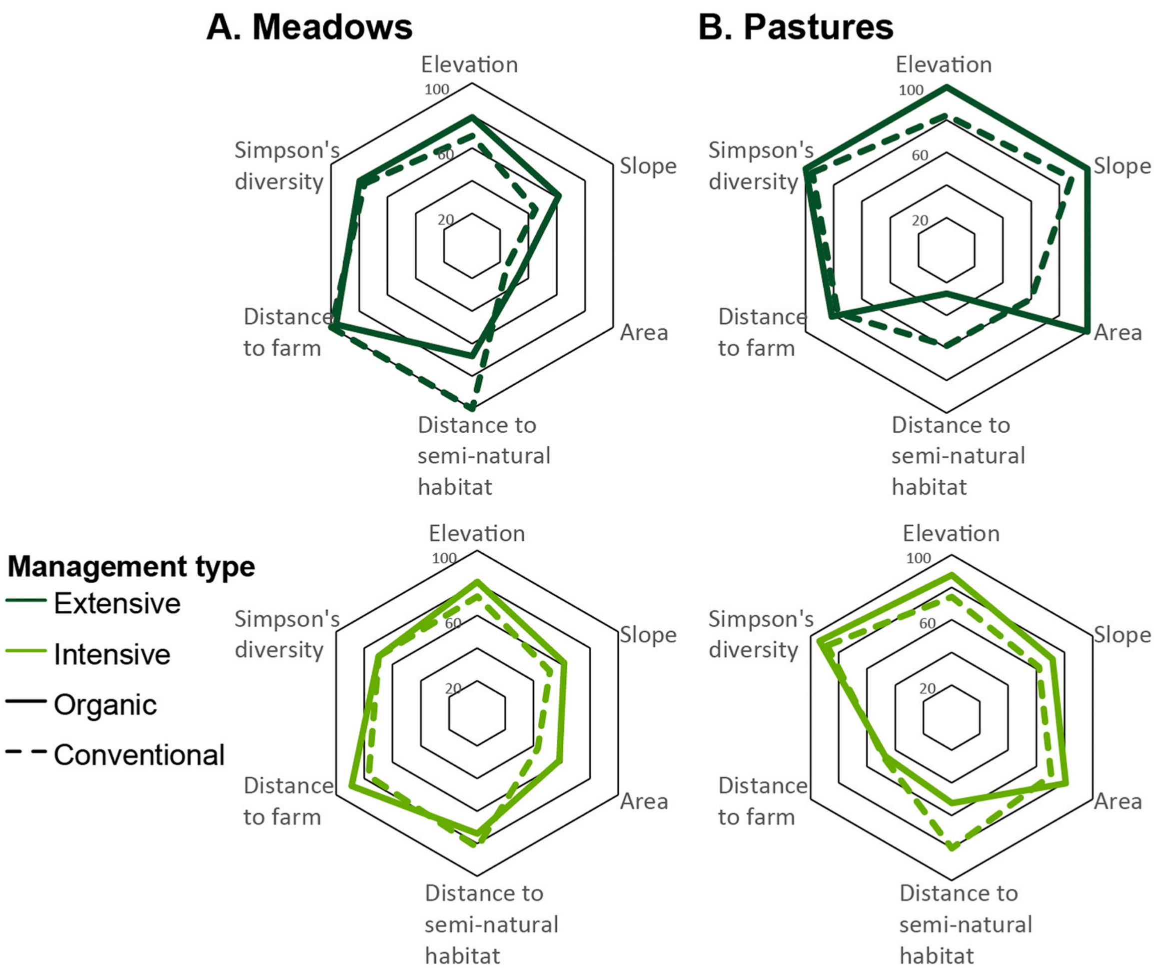


**Fig. 4.** Differences in topography and spatial characteristics between the eight grassland management types assessed for all parcels within the study region. Data shown in this radar plot was averaged for each of the eight grassland types and normalised to make them unitless, with the highest average becoming a value of 100. See Table 1 for standard errors and statistically significant differences among grassland types.

biodiversity conservation and/or interested in related payments. This can, however, not be finally answered by our dataset and requires further socio-ecological research. Given the potentially agriculturally valuable soils below extensive grasslands, these are still subject of discussion as whether they could be converted into arable land to increase food security in Switzerland, underlining intensification and conversion still threaten permanent grasslands in European regions (Schils et al., 2020; Spörri et al., 2023). Since conservation research has highlighted the great importance of conserving biodiversity also in intensively managed landscapes (e.g., Kleijn and Sutherland, 2003), in which AES effects of biodiversity can even be greater than in complex landscapes (Batáry et al., 2010; Tscharntke et al., 2005), it is clearly a societal task to balance the needs of biodiversity conservation and food security also in productive regions of arable farming.

### 4.2. Extensive eco-scheme pastures with lowest productivity potential

Other than extensive meadows, extensive pastures were clearly placed on unproductive locations with poor soil suitability and steep slopes. Thus, extensive pastures barely compete with arable food production but rather depict the only way to produce food on such marginal land (Garmendia et al., 2022). Yet, these adverse production conditions are often highly beneficial for biodiversity conservation because management on such rather extreme locations might have never been intensified in the past (Klimek et al., 2007; Socher et al., 2013). Thus, these locations might still harbour the historic and highly valuable species communities that are the result of hundreds of years of low-intensity grassland management (Deák et al., 2021; Feurdean et al., 2018). Therefore, eco-scheme AES payments compensate for lower productivity and at the same time help to prevent succession towards forest, which would cause the loss of these often highly species-rich habitats (Meier et al., 2022; Ravetto Enri et al., 2020). In times of dietary changes, the extraordinarily high biodiversity and multifunctionality associated with low-intensity grazing land requires focussing livestock farming at these sites to prevent their abandonment and to reduce the feed-food conflict (Isselstein et al., 2005; Schils et al., 2022).

### 4.3. Organic grassland farming placed in less productive locations

Similar to extensive eco-scheme grasslands but to a smaller extent, organic grasslands were found to be located on less productive land, especially at higher elevations and with a tendency towards lower topsoil P concentrations, compared to conventional grasslands. This is in line with previous findings of organic farming being more common in less productive regions such as with a harsher climate (Cudjoe and Rees, 1992; Gabel et al., 2009). When considering a potential yield gap in organic grasslands, it is important to notice especially P availability was statistically marginally but quantitatively rather strongly reduced in organic grassland soils. This adds to rather unequivocal results of previous studies on nutrient availability in organic grasslands (Gosling and Shepherd, 2005; Hathaway-Jenkins et al., 2011; Klaus et al., 2015).

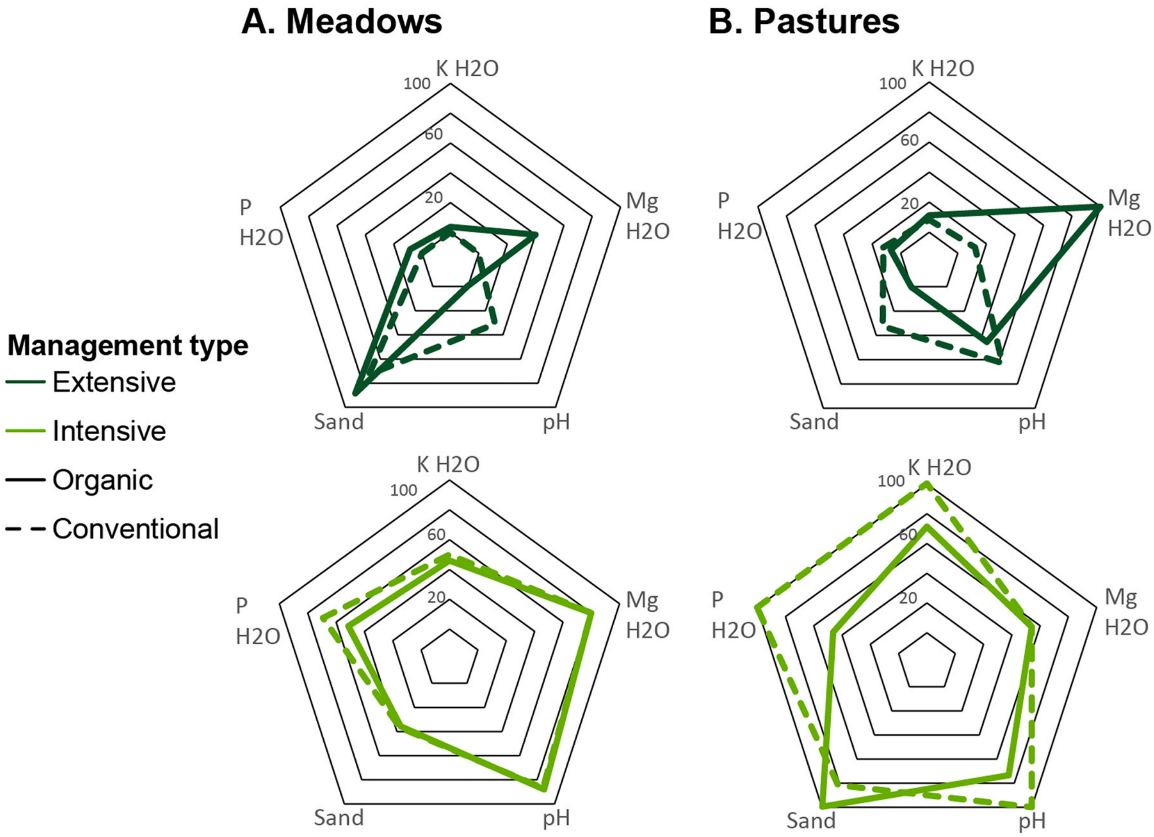


**Fig. 5.** Differences in soil characteristics between the eight grassland management types assessed for the 92 parcels sampled across the study region. Data shown in this radar plot was averaged for each of the eight types and normalised to make them unitless, with the max average becoming a value of 100. See Table 1 for standard errors and statistically significant differences among types.

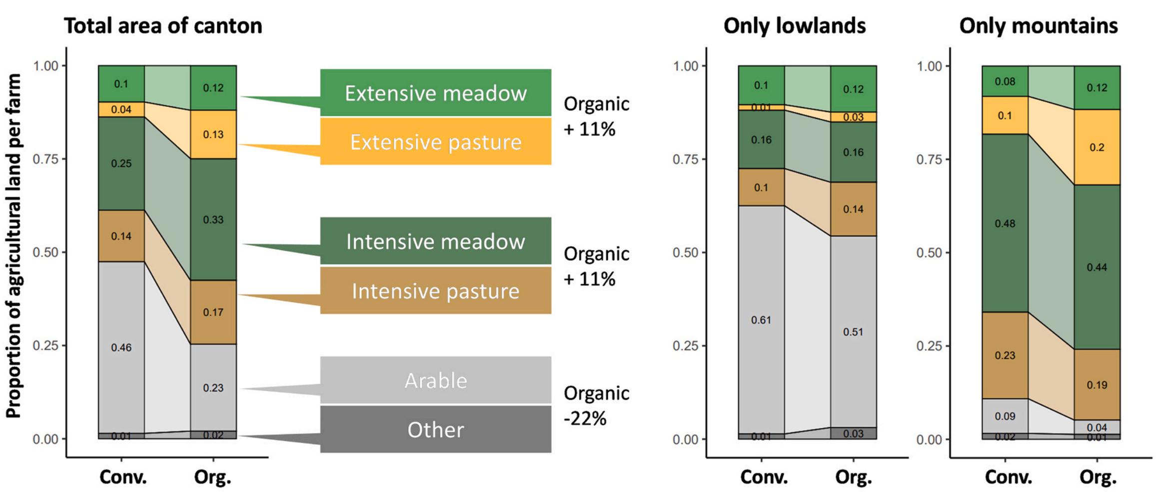


**Fig. 6.** Share of agricultural land per organic and conventional cattle farms in the whole study region (left) and separated into farms in lowlands versus mountains. The share of extensive grasslands (i.e., the sum of extensive meadows and extensive pastures) differs statistically significant between organic and conventional farms in the whole canton and the mountains (both $p < 0.001$), but not in the lowlands ($p > 0.1$). Organic and conventional farms were $n = 32$ and $n = 386$ in the lowland zones, and $n = 46$ versus $n = 159$ in the mountain zones, respectively.

Thus, P availability in organic soils is likely co-depending on site-specific land use history and associated residual stocks of P (Fagan et al., 2008). Such differences in nutrient availability were expected for intensively managed grasslands and can be explained by differences in fertiliser use at organic and conventional farms, particularly due to restrictions on the use of synthetic NPK fertilisers (Klaus et al., 2013; Schneider et al., 2014). According to our hypothesis (H2), we did not find strong differences in nutrient availability and soil suitability between organically and conventionally managed extensive grasslands. This was expected because fertilisation is completely forbidden for extensive eco-scheme grasslands (DVZ, 2023).

Our study shows that yields in organic farming can be co-determined by differences in management practices and differences in the environmental setting in which farmers adopted organic farming. This double effect needs to be considered when analysing potential yield gaps as well as environmental benefits of organic farming in heterogeneous landscapes. Similarly, van Dobben et al. (2019) found organic grassland farms in the Netherlands to be more frequent on wet soils, which restrict intensive farming, compared to conventional farms. Future research should focus on assessing the relative strength of the two effects (i.e., direct management-related vs. indirect topography-related) on the actual environmental outcomes of AES such as organic farming.

### 4.4. Extensive eco-scheme grasslands on organic cattle farms

As hypothesized (H3), we found a higher share of extensive eco-scheme grasslands on organic compared to conventional cattle farms. This difference was pronounced in the mountains, in which organic farms were generally more frequent than in the lowlands. Thus, organic mountain farms might be preferentially located in places that are particularly unproductive, especially regarding high-elevation locations. This pattern will most likely be driven by farmers adopting organic farming in locations where expected losses in production and other opportunity costs associated with organic farming regulations are relatively small (Gabriel et al., 2009; van Dobben et al., 2019). Yet, the question remains whether the higher share of extensive grasslands on organic farms is purely because of the placement of organic in less productive locations, or if it is also driven by organic farmers registering more eco-schemes than conventional farmers in the same situation. The latter was hypothesised by Mack et al. (2020) based on Gabel et al. (2018) finding a higher awareness of organic farmers for the importance of biodiversity conservation. In addition, organic farms might have less slurry production and a lower N surplus due to less concentrate in cattle rations compared to conventional farms, which means Swiss organic farmers might not be able to intensively fertilise large areas, even if they want to (Bettin et al., 2023). Independent of the underlying mechanism, our study proved organic farming to have a positive landscape-scale effect on biodiversity conservation and non-production ecosystem services, which are known to benefit from extensively manged farmland (e.g., Junge et al., 2011; Klaus et al., 2023; Meier et al., 2022; Ravetto Enri et al., 2020; Richter et al., 2024; Schils et al., 2022). This positive landscape-scale effect of organic farming, which can be additional to a field-scale effect, was also found by Gabriel et al. (2010) for biodiversity on dairy and mixed farms in the UK. In contrast, Schneider et al. (2014) found significant biodiversity gains at the field level to become smaller at the level of the farm and region. However, our findings strongly underline the need to consider farmland composition when assessing the effects of a farm-scale AES on the environment. Our findings can be seen as further justification for financial subsidies for organic grassland farming because organic grassland farming seems to support the management of low productive marginal land more than conventional farming. This is especially relevant to sustain economically less viable mountain agriculture and to avoid the loss of traditional mountain grassland systems that are known to be particularly important for biodiversity and cultural ecosystem services (Garmendia et al., 2022; Kampmann et al., 2012; Kirchner et al., 2015).

## 5. Conclusion

We found the placement of the two studied grassland AES, extensive eco-scheme management and organic farming, to be particularly related to topography and other spatial characteristics. This highlights the need to consider landscape-scale factors in evaluations of agricultural policies. Therefore, future AES research needs to overcome oversimplified paired-design approaches that do not take potential covariates into account. Instead, studied should comprehensively assess the many different ways how AES can lead to environmental outcomes.

Since organic farming was shown to be associated with a high share of extensive grasslands on farms, which likely has positive effects on biodiversity and related ecosystem services, consumers might want to directly support this farming system. The same could be true for livestock products originating from extensive pastures, which were clearly placed on unproductive marginal land. Such a consumer-driven food-system effect could strengthen sustainable agricultural production by focusing livestock grazing on land that cannot be used for arable food production. This study additionally showed policies like the mandatory 7 % of farm area to be managed as any eco-scheme to lead to rather unexpected placement of many extensive meadows in productive farming regions in Switzerland. However, future assessments are needed to analyse and quantify this potentially conflict between grassland biodiversity conservation and food production.

## CRediT authorship contribution statement

**Jean-Marc Delore:** Writing – review & editing, Conceptualization. **Solen le Clec'h:** Writing – review & editing, Visualization, Formal analysis, Data curation, Conceptualization. **Valentin H. Klaus:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Franziska Richter:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Andreas Lüscher:** Writing – review & editing, Supervision, Resources, Funding acquisition. **Nina Buchmann:** Writing – review & editing, Supervision, Resources, Project administration.

## Declaration of Competing Interest

The authors declare there are no competing financial interests/personal relationships.

## Data availability

Data will be made available on request.

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### Author contributions

VK and AL acquired the funding; VK led the project; VK, SLC and FR developed the idea with inputs from JMD and AL; FR led the soil sampling campaign; FR and SLC analysed the data with input from VK; VK wrote the paper with inputs from all authors and all authors agreed on the final version of the paper.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2024.109242.

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