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RESEARCH ARTICLE

Designing where to crop and where to graze: a spatial approach toward sustainable farming

Amelie Kreuzer[1] · **Felix Herzog**[1] · **Daniel Bretscher**[1] · **Pierluigi Calanca**[1] · **Anna Edlinger**[1,2] · **Anina Gilgen**[1] · **Olivier Heller**[1] · **Annelie Holzkämper**[1] · **Sonja G. Keel**[1] · **Julian Klein**[1] · **Lutz Merbold**[1] · **Chloé Wüst-Galley**[1] · **Ivo Strahm**[3] · **Sonja Kay**[1]

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Abstract

The world's growing population raises concerns about future food security. At the same time, environmental challenges such as climate change, biodiversity loss, and the depletion of natural resources must be addressed, calling for a transformation of agriculture. This need is exacerbated by the limited availability of land suitable for arable farming. In this study, we examined the potential of agricultural land for arable farming and grassland use in Switzerland, under the premise that agricultural land use should align with the biophysical and environmental capacity of each location. In an iterative co-design process with scientists and public authorities, we elaborated three scenarios for agricultural transformation, which progressively incorporated (i) biophysical constraints (soil, climate, and topography) and (ii) environmental constraints (soil loss and eutrophication due to risk of erosion), as well as (iii) greenhouse gas emissions from drained organic soils. Our results show that the allocation of 40% arable land and 60% grassland in the most restrictive scenario closely resembles the current distribution (46% and 54%), respectively. However, the scenarios also revealed significant spatial shifts between arable land and grassland at the local level: only two-thirds of today's arable land areas match their natural site conditions. Evidence from this study underscores the critical importance of site-adapted transitions of agricultural land use and the need for site-adapted management alternatives for farmland presently assigned to inadequate land use. Overall, this research provides a novel contribution by allowing the identification of hotspot areas for agricultural transformation at the local scale. We show that these site-specific land use analyses are essential for guiding effective land use planning and policy advice that strengthen the integrity of environmental performance and agricultural productivity, and support the development of targeted and sustainable land use strategies.

Keywords Agricultural suitability · Erosion · Land-use planning · Organic soils · Spatial analysis

1 Introduction

There is growing concern that feeding the world's increasing population is becoming more challenging due to the rising vulnerability of agricultural production to climate change, biodiversity loss, and the degradation of natural resources (FAO 2018). Agricultural production is not only impacted by climate change and environmental degradation, but also contributes to them. Therefore, it is crucial that agricultural land is used efficiently and sustainably (UNGA 2015; UN DESA 2024), with arable land being prioritized for growing food directly for human consumption (Foley et al. 2011). Hence, it is vital to identify farmland where climate and soil quality (FAO 1976; Diepenbrock et al. 2009; Wang 2022; Demir 2024), resistance to soil erosion (FAO 1976; Wang 2022), and terrain factors that affect mechanization (FAO 1976) enable the cultivation of crops for human consumption.

The global proportion of agricultural area allocated for growing livestock feed has increased enormously in recent years (Schader et al. 2015; Mottet et al. 2017; Pexas et al.

✉ Amelie Kreuzer
amelie.kreuzer@agroscope.admin.ch

[1] Research Division Agroecology and Environment, Reckenholzstrasse 191, Agroscope, Zurich 8046, Switzerland

[2] Wageningen Environmental Research, Wageningen University & Research, Wageningen, Netherlands

[3] Federal Office of Agriculture, Schwarzenburgstrasse 165, 3003 Bern, Switzerland

2023). Around 50% of global agricultural land (2.5 billion ha) is currently used for livestock production, of which 80% is grassland. It is estimated that approximately 35% (0.7 billion ha) of the global grassland could be used as arable land (Beal et al. 2023). These land use transitions could potentially contribute to improving global food supply (van Zanten et al. 2016), particularly in view of the anticipated growth of the global population (UN 2024).

In response to changes in land use, climate, and concerns about food security and nutrition, several studies have examined the suitability of agricultural land for arable farming. Most studies are solely based on current land cover and make assumptions about land use changes, such as Eitelberg et al. (2015), who reviewed estimations of global availability of arable land from 15 studies. These estimations varied by a factor of three, mainly due to institutional assumptions, such as restrictions on converting forest or grassland to arable land. Schneider et al. (2022) conducted a global assessment of land suitability for different crops, accounting for biophysical constraints and assumptions for land use regulations, and found that 43% of the agricultural land in Europe is available for arable farming. However, Demir (2024) showed for a Turkish province that artificial areas are expanding into highly suitable agricultural areas. Dornik et al. (2024) assessed the spatial relationship between agricultural suitability and current land use and conducted a high-resolution geospatial assessment for different crop types across Europe, using a range of eco-pedological indicators. They concluded that these crops were not grown in the optimal location and should therefore be redistributed to the most suitable arable land.

Arable farming, serving the production of food, typically involves comparatively intensive management and resource use and can contribute to environmental degradation (Raven and Wagner 2020; Crippa et al. 2021; Benton et al. 2021; Dursun et al. 2025). For example, conventional tillage can accelerate erosion in susceptible areas, such as slopes (Montgomery 2007; Panagos et al. 2015), which not only threaten soil fertility and long-term productivity but can lead to eutrophication of surface waters and reduced biodiversity (Boardman and Poesen 2006). Similarly, organic soils are exceptionally fertile but vulnerable to carbon losses via greenhouse gas emissions when drained for agricultural production (Hiraishi et al. 2014; Evans et al. 2021).

Global sustainability efforts emphasize the need for agricultural systems that operate within the carrying capacity of the planet, ensuring that the increasing food demand is met without depleting biological and physical resources (UNGA 2015). Accounting for these and other challenges, Demir (2024) targeted land use strategies that optimize the allocation of arable land in such a way that the biophysical conditions of a given field allow for sustainable crop production. At the same time, excessive use of natural resources, such as freshwater, must be prevented and biodiversity preserved (Wang 2022; Demir 2024).

These challenges are particularly important for Switzerland. As a mountainous country with hilly landscapes, arable farming is limited by natural conditions to the lowlands of the Swiss Plateau between the Alps and the Jura mountains (Fig. 1). About 38% of Switzerland's utilized agricultural area (UAA) is managed as arable land (including ley), 58% as permanent grassland, and 4% as permanent crops and fruit orchards. This corresponds to around

Fig. 1 Swiss agricultural land use is characterized by large grassland areas, both in the lowlands and in the mountainous regions. More than 50% of the current arable land is devoted to livestock feed production (Photo credit: Gabriela Brändle, Agroscope).

1 million hectares in total (FSO 2024a). More than 50% of the Swiss arable land is used to produce animal feed such as ley, silage maize, and fodder grain, whereas only on the rest of the land crops are grown for direct human consumption (SFU 2024). Even though Switzerland's level of self-sufficiency varies by food category, it is only 53% overall when imported animal feed is considered (FOAG 2024). Given the scarcity of agricultural land, the use of arable land to produce animal feed is a growing cause of concern (Bystricky et al. 2023; Ineichen et al. 2023). To maintain the current level of food sovereignty and to overcome feed-food competition on arable land, Switzerland's predicted rapidly growing population (FSO 2020) will require an expansion of arable land dedicated to producing food for direct human consumption (Swiss Federal Council 2022) along with a transformation of the food system (FOAG et al. 2023).

Historical evidence of land use patterns in Switzerland from the mid-nineteenth century indicates that there is ample potential for using agricultural areas as arable land, as large parts of the Swiss Plateau were used for grain cultivation at that time (Brugger 1979, 1985). Nonetheless, the abolition of protective tariffs and the expansion of the railway infrastructure allowed for cheaper wheat imports, reducing the profitability of arable farming and shifting land use on the Swiss Plateau towards grassland-based cattle farming. Consequently, these economic and political driving forces led to changes in land use from the 1860s onwards and are largely responsible for the current land use (Kreuzer and Bürgi 2021). Yet, the growing awareness to reduce feed-food competition and to mitigate the impact of climate change on the agricultural sector, while maintaining or improving food self-sufficiency, calls for an evaluation of the boundaries of converting agricultural land use.

In a joint inter- and transdisciplinary process involving experts from the Swiss Federal Office for Agriculture (FOAG) and agricultural researchers, this study developed scenario-based pathways for potential arable land use in Switzerland. We examined which areas of Switzerland's current UAA have the potential to be used as arable land, considering different biophysical and environmental constraints. This was enabled by field-specific land use data for all Swiss farms (FOAG 2021).

Specifically, we (i) developed scenarios for the transformation of Swiss agriculture in an iterative co-design process. Based on these scenarios, we identified (ii) which areas are suitable for arable farming and (iii) which areas should exclusively be used as grassland due to their environmental vulnerability. Using Switzerland as a case study, we present a framework for agricultural land suitability evaluation that contributes to the international discourse on sustainable land use transitions.

2 Materials and methods

2.1 Co-design process for developing scenarios for transformation

We developed scenarios for agricultural transformation through a co-design process (Kleinsmann and Valkenburg 2008) involving a public authority, the FOAG, and scientists specialized in soil, climate, biodiversity, and landscape research. Up to 25 participants from both the administration and the scientific community contributed to the process. The analysis was based on the spatially explicit land use information for all Swiss farms, which is a counterpart to the Land Parcel Identification System (LPIS) database of the European Union (Baiamonte et al. 2023; Şimşek and Durduran 2023).

The co-design process was moderated by a core group of two scientists and two staff members from the federal authorities, who provided in-depth background information and key parameters to the expert group. In consultations with other scientists, relevant constraints impacting arable production were collected and evaluated. Through a series of workshops with the scientific community and the representatives of the federal authorities, the experts jointly discussed the respective state and systematically refined the parameters of the criteria. Criteria weighting was omitted throughout the analysis as the expert panel regarded all criteria as equally important for determining arable land and grassland allocation. A total of three workshops were held to address (a) arable and (b) grassland production and (c) a summary workshop to consolidate the results.

2.2 Scenarios for transformation

The scenarios visualized and assessed three distinct concepts for Swiss agricultural land use. The scenarios considered a number of biophysical criteria that allow for arable farming, including soil, topography (mechanical practicability), and climate. To address environmental concerns in agricultural management, additional criteria were considered in two further scenarios. These included the evaluation of erosion risk to protect soils and preserve surface and groundwater resources as well as carbon sinks in agricultural areas (Boardman and Poesen 2006; Dursun et al. 2025). In addition, the protection of organic soils was emphasized (Fig. 2), which serve as important carbon sinks and should no longer be drained and managed intensively, as this results in irreversible soil degradation and thus compromises the carrying capacity of soil ecosystems (Leifeld et al. 2019; Wüst-Galley et al. 2020). As

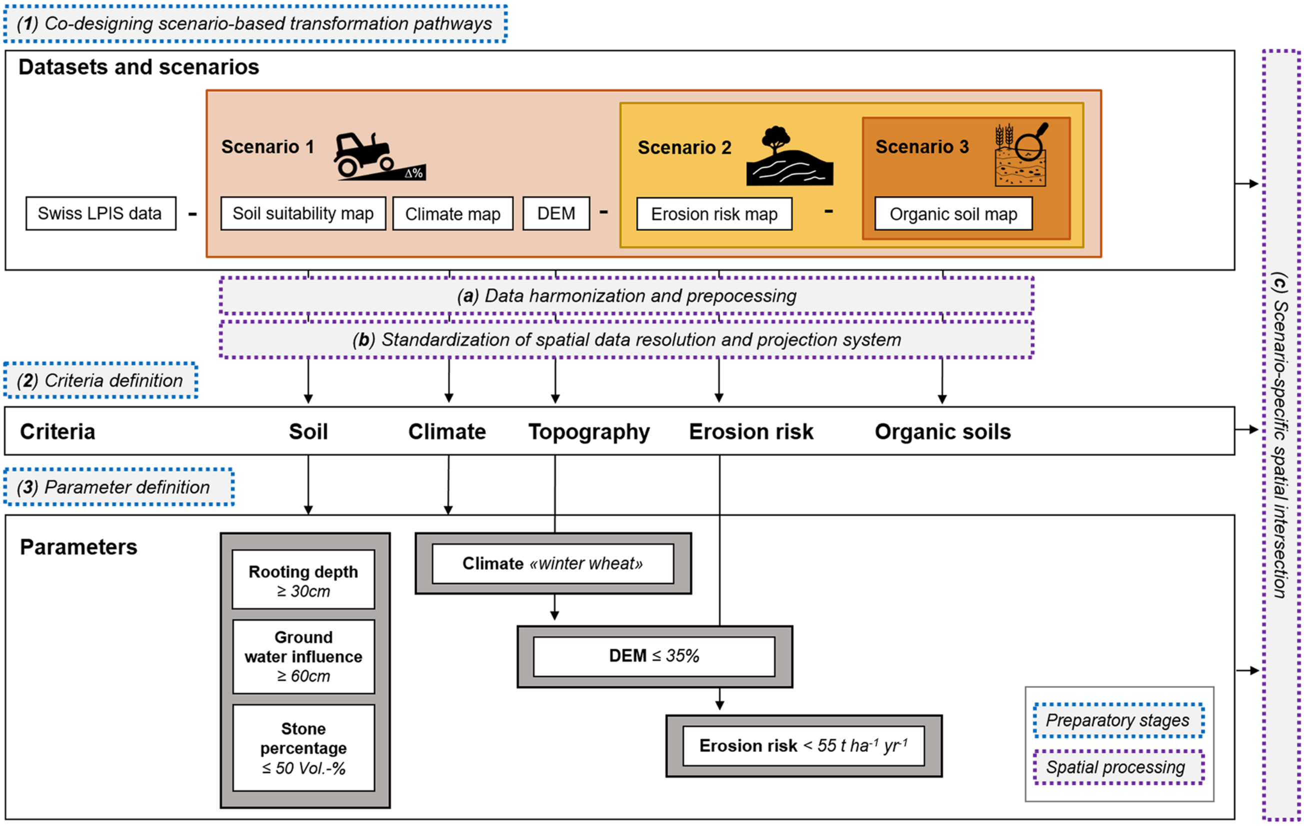

Fig. 2 Schematic overview of the study's methodological framework. Scenario 1 (tractor-slope symbol) consists of the criteria soil (soil suitability map of Switzerland), climate (climate "winter wheat" represented by the climate suitability map for the cultivation of winter wheat), and topography (DEM, digital elevation model of Switzerland). Scenario 2 (impaired soil symbol) is based on results of scenario 1 and additionally excludes high-erosion risk areas (based on the map of potential soil erosion risk in arable land). Scenario 3 (intact-soil symbol) is based on scenario 2 and additionally excludes organic soils (map of organic soils in Switzerland). Steps 1, 2, and 3 refer to the preparatory stages, while steps (a), (b), and (c) illustrate the processing steps integrated in the spatial analysis.

a precondition, it was assumed that ecological focus areas, e.g., wildflower strips or hedgerows in agricultural land, would remain unchanged in all scenarios, as they make a substantial contribution to farmland biodiversity (Meier et al. 2024). Similarly, permanent crops, such as vineyards, were excluded from the analysis. Seasonal alpine summer pastures of high mountainous areas were also excluded from this analysis. As for grasslands, the study refers exclusively to "permanent grassland," excluding ley in crop rotations. For clarity, the term "grassland" is used consistently throughout.

2.3 Data framework and parameter definition for the scenarios

We applied a stepwise approach by progressively increasing biophysical and environmental constraints resulting in three scenarios of potential arable land and grassland areas (Fig. 2). Scenario 1 maximized the potential for arable land and considered the criteria soil, climate, and topography. Scenario 2 was based on the results of scenario 1 and additionally accounted for environmental constraints by excluding agricultural areas with a high risk of erosion. Scenario 3 targeted the reduction of greenhouse gas emissions by additionally excluding organic soils. The spatial analysis was based on the extent of the UAA, which was obtained from the Swiss LPIS data from 2021 (FOAG 2021). In scenario 1, the soil suitability map of Switzerland (Frei et al. 1980) was used to identify the agricultural soils that are suitable for growing arable crops. The three following soil properties were specified: we retained soils with (i) a minimum rooting depth of ≥ 30 cm, (ii) a groundwater influence of ≥ 60 cm depth, and (iii) a stone percentage of ≤ 50 Vol.-%. The digital elevation model (DEM) of Switzerland (Swisstopo 2022) was applied to exclude farmland exceeding agricultural land with a slope gradient > 35%, which we adopted as the threshold for mechanized crop management (Estler and Pfahler 1985; Frielinghaus 2002). As a surrogate for climatic restrictions, we applied the climate suitability map for the cultivation of winter wheat by Holzkämper et al. (2015).

In scenario 2, the criteria of scenario 1 were supplemented with the risk of soil erosion derived from the map of potential soil erosion risk in arable land by Bircher et al. (2019). The map is based on the empirical model RUSLE (revised universal soil loss equation) and is representative of a bare fallow, as the C-factor (cover and management factor) was not included in the model. Therefore, our approach is very conservative as it can be assumed that the potential erosion risk is higher than in reality. Areas with a high risk of erosion, corresponding to a potential soil erosion rate of > 55 t ha^{-1} yr^{-1} (Prasuhn et al. 2013), were excluded from potential arable land and assigned to the grassland category. In scenario 3, the criteria from scenarios 1 and 2 were retained, but organic soils were additionally excluded from the area potentially suitable as arable land. The data used are based on the map of organic soils in Switzerland (Wüst-Galley et al. 2015).

2.4 Data analysis

We conducted Swiss-wide spatial analyses using geodata models in the ArcGIS Pro 3.2.2 software (Esri 2022). The workflow in the spatial analysis comprised three consecutive steps (Fig. 2): (a) data harmonization and preprocessing, (b) standardization of spatial data resolution and projection system, and (c) scenario-specific spatial intersection. To provide a coherent basis for the analysis, the Swiss LPIS data, originally varying across administrative units (clusters of Cantons), were merged and harmonized into a uniform and consistent dataset for the entire UAA. For spatial intersection with other geodata sets, the UAA data were resampled and standardized to a uniform grid resolution of 25 × 25m. All geodata were projected into the Swiss national projection system (CH1903+_LV95) to ensure spatial compatibility and accuracy. Subsequently, all spatial data were pre-processed by rasterizing (soil data) or resampling (topography, climate, and erosion risk) to the same standardized spatial resolution. Finally, potential arable land and grassland was determined by intersecting spatial data on the agricultural area with the specific criteria defined for each scenario. Based on the current arable land and grassland, the following areas were classified, respectively computed for the scenarios (Table 1):

3 Results

The current arable land in Switzerland is largely confined to the lowlands, whereas grassland dominates the hilly and mountain regions. Given that permanent crops (18,768 ha) and ecological focus areas (168,916 ha) remained unchanged in the study and seasonal alpine summer pastures were not considered in the agricultural suitability evaluation, the starting point of our analysis consists of currently 383,745 ha of arable land (46%) and 451,352 ha of grassland (54%). Therefore, the respective scenarios will only account for land use transitions between arable land and grassland (Fig. 3 and Table 2).

3.1 Scenario 1: maximum potential arable land area

Scenario 1 resulted in a map showing the maximum potential arable area. Compared to the current area of arable land, scenario 1 showed an increase in arable land by 72% (from 383,745 to 660,214 ha) due to favorable topographical conditions (Fig. 4 and Table 2). Correspondingly, the total grassland surface decreased by 61% (from 451,352 to 174,883 ha). This resulted in land use proportions of 80% arable land and 20% grassland. Almost 90% of the current arable land (342,642 ha) met the criteria for scenario 1 (*continuous arable land*), while 29% (133,780 ha) of the total grassland will remain as such (*continuous grassland*). The remaining 41,103 ha (10%) of current arable land did not meet the requirements for

Table 1 Overview of the calculated land use categories derived from the scenario analysis.

Land use category	Description of land use
Current arable land & current grassland	Extracted from the Swiss LPIS data. Permanent crops and ecological focus areas were not considered in the analysis and remained unchanged in the scenarios. Similarly, seasonal alpine summer pastures, which are not part of the UAA, were not included
Continuous arable land	Corresponds to the agricultural area that is currently used as arable land and continues to be used as such, as it meets the defined criteria in the respective scenario
Potential arable land	Corresponds to the agricultural area that is currently used as grassland but could be converted to arable land, as it meets the defined criteria in the respective scenario
Continuous grassland	Corresponds to the agricultural area that is currently used as grassland and continues to be used as such, as it does not meet the defined criteria to be converted to arable land in the respective scenario
Potential grassland	Corresponds to the agricultural area that is currently used as arable land but could be converted to grassland, as it does not meet the defined criteria to be used as such in the respective scenario

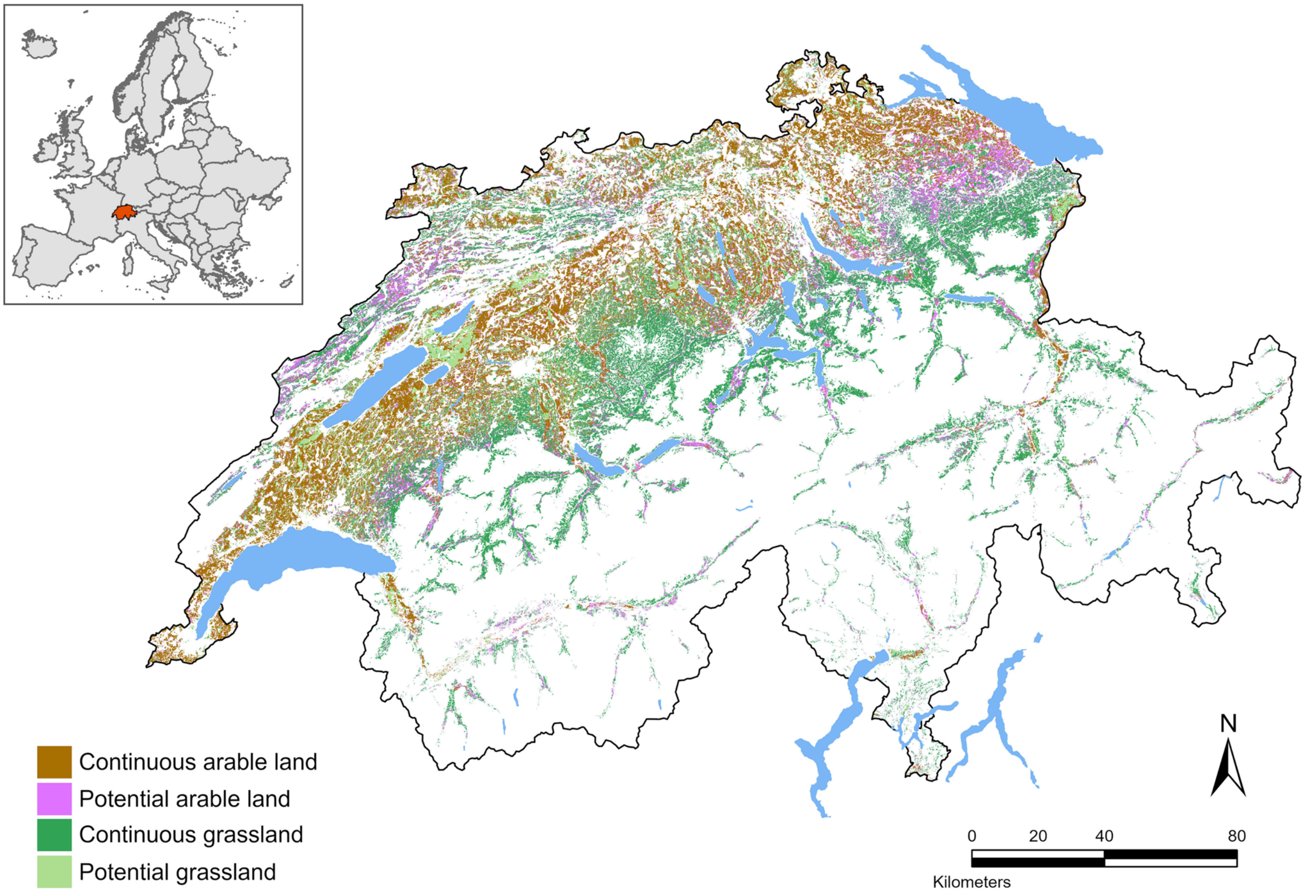

Fig. 3 Spatial distribution of the derived land use categories for arable land and grassland in Switzerland for scenario 3. Ecological focus areas managed for biodiversity, permanent crops, and alpine summer pastures are not depicted.

Table 2 Absolute (ha) and relative distribution (%) of the agricultural land use categories in the current distribution (CU) of arable land and grassland, as well as in the scenarios (S1: scenario 1, S2: scenario 2, S3: scenario 3), and a comparison of the respective scenario areas to the current area in percent [Δ SX- CU]

Land use category	CU		S1		Δ S1 - CU	S2		Δ S2 - CU	S3		Δ S3 - CU
	[ha]	[%]	[ha]	[%]	[%]	[ha]	[%]	[%]	[ha]	[%]	[%]
Current arable land	383,745	46									
Total area arable land			660,214		72	352,548		-8	338,081		-12
Continuous arable land			342,642	90		232,948	61		222,661	58	
Potential arable land			317,572	71		119,600	26		115,420	25	
Current grassland	451,352	54									
Total area grassland			174,883		-61	482,549		6	497,016		9
Continuous grassland			133,780	29		331,751	74		335,937	75	
Potential grassland			41,103	10		150,798	39		161,079	42	

soil, climate, and/or topography and should therefore be converted to grassland (*potential grassland*). Conversely, 71% of the current grassland (317,572 ha) is misused (*potential arable land*).

3.2 Scenario 2: accounting for the risk of erosion

In scenario 2, the total arable land declined by 8% (from 383,745 to 352,548 ha) compared to the current land use. Correspondingly, the total grassland surface increased by 6%

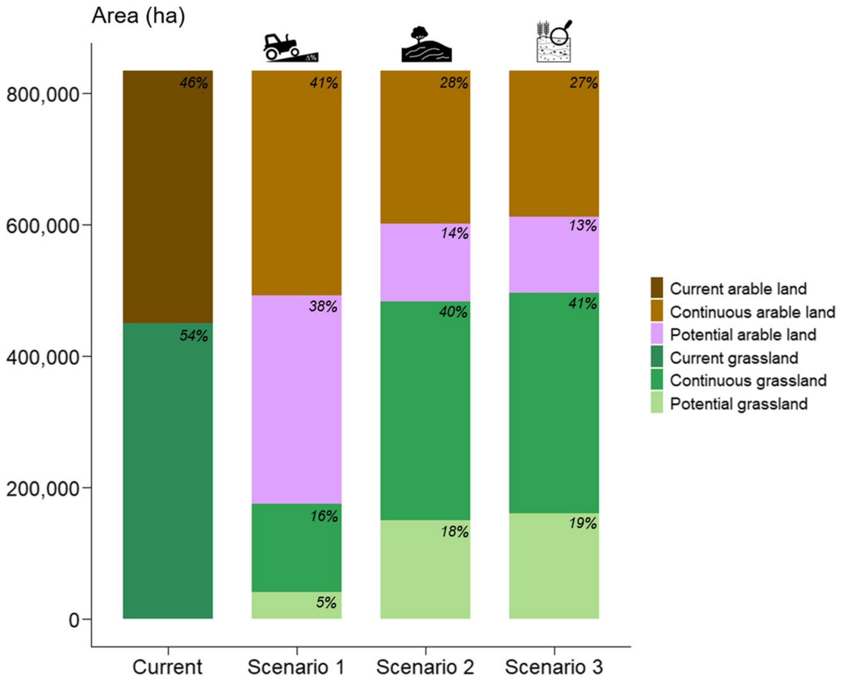

Fig. 4 Spatial distribution of arable land and grassland in Switzerland according to the current agricultural land use and the increasingly restrictive scenarios for transformation. The distribution of arable land and grassland across the scenarios comprises areas of arable land and grassland that remain in their use (continuous) and areas that could be converted (potential), presented in relative shares (%).

(from 451,352 to 482,549 ha). However, 61% of the current arable land aligns with the requirements (*continuous arable land*), while 39% of the surface (150,798 ha) was excluded as it did not meet the criteria of reduced erosion risk. This area should therefore be converted to grassland (*potential grassland*). As for grassland, 74% of the area (331,751 ha) originally classified in this land use category fulfills the criteria applied (*continuous grassland*), while 26% of the surface (119,600 ha) had the potential to be converted to arable land (*potential arable land*). The overall distribution of the agricultural area resulted in 42% arable land and 58% grassland for scenario 2, closely reflecting the current land use (Fig. 4 and Table 2).

3.3 Scenario 3: protecting organic soils

In scenario 3, organic soils that had been classified as potentially arable in scenario 2 were reassigned to the grassland category. As compared to the current use, scenario 3 entailed a decrease of arable land by 12% (from 383,745 to 338,081 ha) and an increase of grassland by 9% (from 451,352 to 497,016). About 58% of the current arable land (222,661 ha) remained unchanged (*continuous arable land*), while 42% of the surface (161,079 ha) was either prone to erosion risk or consisted of organic soils and should therefore be converted to grassland (*potential grassland*). Therefore, the extent of potential grassland of scenario 3 was the largest among all scenarios (Fig. 3). Almost 75% of the grassland surface (335,937 ha) does not fulfill the requirements for arable land (*continuous grassland*). On the other hand, 25% of the current grassland, equivalent to 115,420 ha, revealed the potential to be converted to arable land (*potential arable land*). The proportions of 40% arable land and 60% grassland were similar to scenario 2 and the current use (Fig. 4, Table 2).

3.4 Local land use transitions

Although the shares of arable land and grassland in scenario 3 were similar to the current status, about one third of the Swiss farmland could potentially be reallocated from arable land to grassland or vice versa to better match site-specific conditions. The resulting potential transitions between arable land and grassland can be clearly depicted at the local level (Fig. 5). An example illustrating the transition from grassland to arable land is depicted for an area in the Swiss Pre-Alps (Fig. 5a). Although the region is currently dominated by grassland, our analysis suggests that it has the potential to be used as arable land across all scenarios according to the criteria applied. Figure 5b shows an example of a region in the Swiss Jura Mountains, where large areas of arable land do not meet the biophysical and environmental criteria to be used as such. This could result in land use transitions from arable land to grassland.

4 Discussion

The current agricultural land use is the result of historical development that did not necessarily account for sustainability or its inherent site conditions. This study therefore

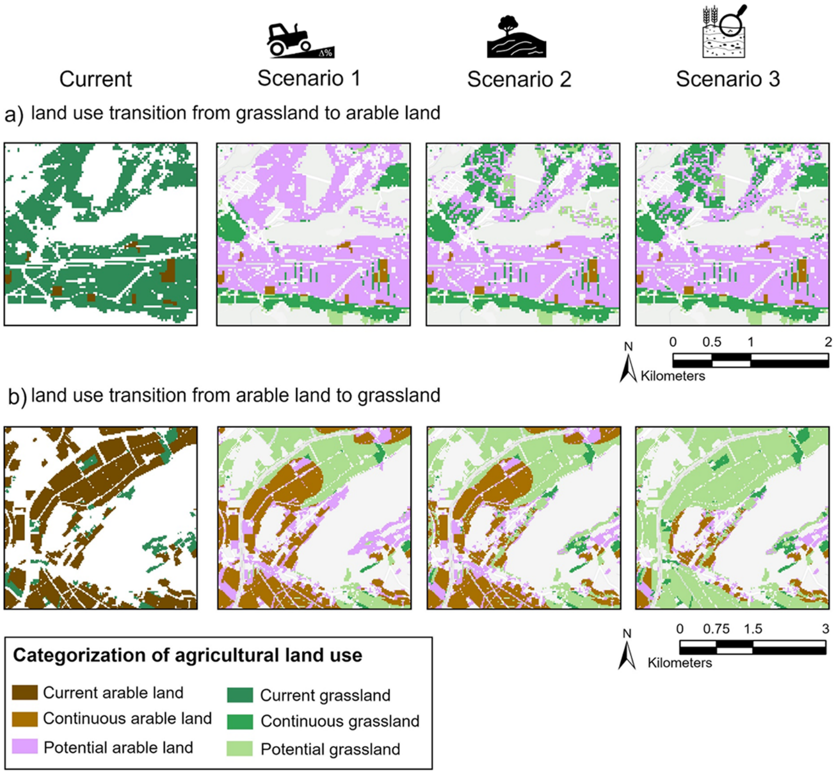

Fig. 5 Transition examples of agricultural land use for the three scenarios compared to the current distribution in two different regions in Switzerland. **a**) The potential land use transition from currently used grassland to arable land in a region in the Swiss Pre-Alps and **b**) the transition from currently used arable land to grassland in the Swiss Jura Mountains. Only farmland is shown against the background of all other land uses in white (i.e. forest, infrastructure, surface waters).

developed scenarios for transformation for Swiss agricultural land use through a co-design process, representing a spectrum of potential transformation pathways and associated opportunities. The spatial analysis showed that although the allocation of arable land and grassland in the most restrictive scenario is similar to the current use, only about two-thirds of the current arable land area is suitable for the inherent site conditions. This indicates considerable potential for local shifts between agricultural land uses.

4.1 Scenario results

Scenario 1 showed the strongest difference to the current situation. This suggests a high potential for arable land use and is in line with the study by Schneider et al. (2022), who determined the suitability of the agricultural area based on biophysical characteristics on a global scale. An important difference between the present study and the analysis by Schneider et al. (2022) is that they also considered wetlands, forests, and protected areas as potentially cultivable land. In contrast, our study only examined agricultural areas classified as current arable and grassland, excluding forests, wetlands, and protected areas (ecological focus areas). The main reason for the substantial increase of potential arable land of approximately +318,000 ha in scenario 1 is that we assumed arable farming to be feasible up to a slope of 35% due to technological developments and advancements in agricultural automation (Polzin and Hughes 2023). According to Frielinghaus (2002), mechanized management of agricultural use is technically feasible on even steeper slopes of up to 45%, and implementing this criterion would have increased the extent of potential arable land area in scenario 1 even further.

Scenarios 2 and 3 are more restrictive and the area of arable land did not differ much from today's area for arable land. However, the scenarios predicted a partial redistribution of arable land and grassland areas; large stretches of grassland in the Swiss lowlands could be converted into arable land. Yet, grassland systems maintain high carbon stocks (Feigenwinter et al. 2023; Wen et al. 2023) due to the undisturbed soil, the accumulation of root biomass and litter resulting from the input of plant biomass through continuous photosynthetic carbon uptake (Dondini et al. 2023). Thus, converting grassland to arable land would significantly reduce soil organic matter content, leading to increased CO_2 emissions and other greenhouse gas emissions compared to agricultural land with intact grassland (Vellinga et al. 2004; Merbold et al. 2014; Reinsch et al. 2018) as well as a loss of biodiversity (van Zanten et al. 2016). Furthermore, grassland systems are typically used for livestock farming, which generate high greenhouse gas emissions through enteric fermentation and manure management (Gerber et al. 2013). Currently, these emissions might not be offset by carbon sequestration from existing grassland (Wang et al. 2023).

Due to the exclusion of organic soils, the difference in the total area of potential arable land between scenarios 2 and 3 was only about 4000 ha, respectively 4%. Arable land on organic soils in Switzerland accounts for approximately 84,000 ha (8%) of the total agricultural area and is very productive, often used for vegetable production (Roeoesli and Egli, 2024). Nevertheless, as these areas are drained to allow crop production and horticulture, they are characterized by the continuous decomposition of organic matter in aerobic conditions. This leads to soil subsidence, which entails a higher risk of flooding or local wet and dry patches in the field (Page et al. 2020) and eventually strong negative impacts on productivity (Wüst-Galley and Leifeld 2025). It can also be difficult to drive heavy machinery on fields after rainfall and, depending on the underlying mineral soil, a depleted root zone will lead to reduced yields (Verhoeven and Setter 2010; Hiraishi et al. 2014; Erkens et al. 2016; Ferré et al. 2019; Egli et al. 2020). Moreover, the loss of organic matter and high greenhouse gas emissions from these soils (Joosten et al. 2016a) contradict the Swiss National Soil Strategy (Swiss Federal Council 2020) as well as the Swiss National Climate Strategy for Agriculture and Food (FOAG et al. 2023). Reducing the negative impact of farming on organic soils can be achieved by increasing water levels and implementing corresponding land management strategies (Tanneberger et al. 2021; Freeman et al. 2022). However, such changes are generally linked to a reduced income under the current economic conditions (Ferré et al. 2019; Wüst-Galley and Leifeld 2025). Research into economically viable alternatives for the agricultural use of organic soils is ongoing (Fabian et al. 2024). Paludicultures have been proposed as an alternative land management strategy for peat soils (Joosten et al. 2016b; Tanneberger et al. 2022). These allow fields to remain in agricultural production while providing a natural habitat and preserving their importance for hydrology and biodiversity as well as their function as carbon storage (Noble et al. 2018; Evans et al. 2021). The production of paddy rice is another alternative that is currently experimented by several farmers in the Swiss lowlands (Fabian et al. 2024; Bulas et al. 2025). Yet, most of these alternatives are only economically viable if farmers are financially compensated by agri-environmental schemes for the yield foregone or for the ecosystem services they provide by implementing these nature-based practices (Tanneberger et al. 2022).

4.2 General approach and limitations of the study

This study focused on the national scale of Switzerland, involving collaboration between a public authority and scientists, and used the most suitable, spatially explicit dataset available. We did not allow for agricultural expansion into other land cover types, as current legislation bans forest conversion to farmland (Swiss Federal Assembly 1991). Also, we did not account for the ongoing loss of farmland to settlements in the lowlands and for abandonment in the mountain regions (FSO 2024b), nor for the effects of climate change on future use of agricultural land. The results therefore are static for the time of the analysis. On the other hand, the advantage of this straightforward approach is that it is transparent and fosters communication among stakeholders, such as farmers, planners, and policy makers.

An important limitation regarding data availability relates to the soil suitability map. Up-to-date and precise soil information is generally indispensable for identifying the areas of agricultural land that can be used as arable land (Demir 2024). This study used the soil suitability map of Switzerland (Frei et al. 1980), which dates from 1980 and still is the only soil map available at the national scale. However, it is afflicted by methodological and content-related deficiencies limiting its pedological significance. This restriction arises as soil properties in this map were homogenized over large areas (Vökt and Pazeller 2003; Keller et al. 2018), resulting in the spatial heterogeneity of the soils not being as adequately represented as in the other data sources. There are more detailed soil maps with high resolution soil data available at the regional level (Rehbein et al. 2019), which could enhance more accurate decision-making for arable land designation at the field level. An assessment of crop-specific soil requirements using agronomic suitability maps could additionally define the extent of arable land (Keller et al. 2024). Soil mapping efforts at the national level are ongoing (Swiss Federal Council 2023), thus providing a more suitable data basis for future evaluation. Furthermore, drainage of agricultural land was not included in the study as data on drainage was not available for Switzerland at the time of the study. Béguin and Smola (2010) estimate that about one-fifth of the Swiss farmland is drained. Accordingly, the potential area of arable land could be larger as many of the water-logged surfaces which were excluded might be suitable for arable farming if drained (Koch and Prasuhn 2020).

Additional room for interpretation is given due to the choice of criteria for the individual scenarios. Topography is a major constraining factor when determining the suitability of agricultural area for arable farming (van Asselen and Verburg 2012; Jarasiunas 2016) in a mountainous country such as Switzerland. However, soil conservation practices such as no-till, mulch sowing, or cover cropping can enable crop production even on steep slopes (Prasuhn 2020; Polzin and Hughes 2023). This justifies the high slope threshold of 35% for arable farming in this study. Yet, it is also important to link slope with soil depth (Jarasiunas 2016). Böttcher et al. (2009) and Pimentel and Burgess (2013) point out that steep, shallow slopes are particularly prone to erosion, while fine-textured soils with low organic matter are even more vulnerable. As a consequence, the area at high risk of soil erosion (Prasuhn et al. 2013) that was excluded from arable land use might change if site-adapted farm practices such as contour farming were applied (Farahani et al. 2016).

Climate suitability for crops was based on the available climate suitability map for the cultivation of winter wheat, although we are aware that climatic requirements of crops can vary substantially (Holzkämper et al. 2015; Heinz et al. 2024). Moreover, the map is based on data from 1980 to 2010 and does not consider current and future changes in climate (Holzkämper et al. 2015). However, rising temperatures have resulted in more extreme heat, heavier precipitation events, and drier summers, all of which are increasingly affecting agricultural conditions. In addition, temperature conditions have also shifted upward by 100 m per decade over the past 60 years, further altering growing conditions (MeteoSwiss and ETH Zurich 2025). Furthermore, the climate map for winter wheat was not constrained by an altitude threshold. Thus, the modeled surface of potential arable land extends to altitudes of 2300 m above sea level in all scenarios, despite the fact that the production potential at higher altitudes is lower. Still, recent studies have pointed to the agricultural importance of less favored areas in mountain regions, as these serve as an important reserve for food production with ongoing global warming (Szabo and Grznár 2013; Gros-Balthazard 2022). For example, the Alpstein region, a mountain range in eastern Switzerland, is experiencing a revival of cereal production as it is benefiting from increasingly warmer temperatures (Lippuner 2023).

Furthermore, potential shifts in agricultural land use were evaluated without accounting for their socio-economic consequences (Zorn 2018; Ferré et al. 2019). In regions of the Swiss Plateau, for example, a shift from livestock to arable farming would require adjustments in the business models of the individual farms, and investments in equipment such as machinery or storage facilities and labor. On the other hand, farms that currently focus on arable farming would have to make long-term investments specifically for livestock farming. Consequently, local stakeholders should be involved in the process of agricultural transformation to bundle knowledge of site conditions and jointly discuss requirements, administrative constraints, and implementation strategies for future development pathways (Mehdi et al. 2018; Luu et al. 2024).

4.3 Potential applications

While the analysis was developed for the Swiss context, the analytical framework provides a transferable basis that can be adapted to other national settings, and the co-design process can be expanded to additional stakeholders, such as farmers, local authorities, or landscape planners. Furthermore, it provides a novel contribution by allowing site-specific identification of hotspot areas for agricultural transformation at the national scale. To address site-specific implications, local case studies involving multiple stakeholders could explore site-adapted transformation measures. This could serve both as platforms to address farmers' needs and prerequisites for agricultural transformation and as means to explore how trade-offs -such as those between carbon storage in organic soils, biodiversity, and livestock productivity -could be addressed in policy design. This may also form the basis for future research to elucidate ecological, economic, and social implications of transforming agricultural land use as well as enable comprehensive sensitivity analyses of the applied criteria and the evaluation of additional environmental factors.

5 Conclusion

Agricultural transformation is required to meet the increasing demand for food security in the future, while tackling pressing environmental challenges posed by climate change, biodiversity loss, and the depletion of natural resources. A fundamental prerequisite for a transition is the adaptation of agricultural production systems to site-specific biophysical and environmental conditions. This study presents the outcome from a co-design process involving scientists and administrators in charge of agricultural policy development. Spatially explicit analyses derived from scenarios for agricultural transformation showed that current agricultural land use in Switzerland can be transformed by adapting it to the inherent site conditions, underscoring the critical importance of supporting a sustainable and efficient use of agricultural land and natural resources. The study and its underlying approach provide a novel contribution by allowing site-specific identification of hotspot areas for agricultural transformation at the local scale. However, it also underscores the need for comprehensive data sets and modeling approaches to support effective land use planning and policy advice. Ultimately, our study provides a solid framework for developing more targeted and sustainable land use strategies that support the reconciliation of food security and agricultural productivity with environmental integrity.

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Data availability The dataset of the current agricultural land use and the scenarios is available in the repository (https://doi.org/10.5281/zenodo.17687485).

Code availability Not applicable.

Declarations

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Conflict of interest The authors declare no competing interests.

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