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Research Paper

Resilience of Swiss summer farms: An interdisciplinary analysis of key challenges and adaptations

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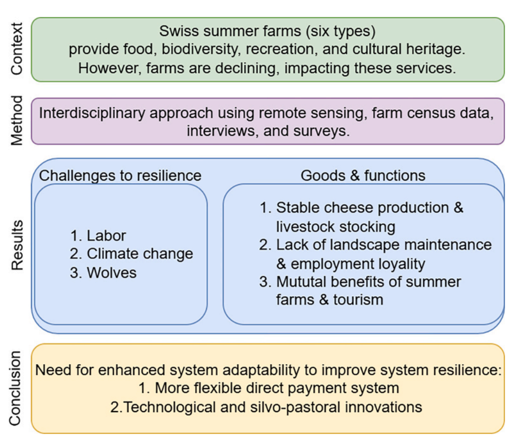
HIGHLIGHTS

- Swiss summer farms provide food, recreation, biodiversity, and cultural heritage.
- Resilience challenges include labour shortages, water scarcity, and wolf conflicts.
- Adaptation includes suckler cows and cheese production.
- Grazing and labour reduction lead to substantial woody-plant encroachment.
- System adaptability can be enhanced through flexible policies and innovations.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Summer farms in Switzerland provide a broad bundle of ecosystem services to society: they produce ruminant-based food, provide areas of recreation and biodiversity conservation, and are an important part of mountain cultural heritage and tourism. However, the activity of these farms is declining, with mostly negative implications for the services they provide.
OBJECTIVE: To preserve the remaining summer farms, it is crucial to understand the factors that make them resilient. In this study, we therefore analysed the resilience of Swiss summer farming systems by identifying key challenges, describing supply of private and public goods as well as functions, and highlighting factors that enhance or decrease resilience.

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METHODS: We used an interdisciplinary approach, integrating insights from agronomy, ecology, economics, sociology, livestock, and food science. We described the particularities of this farming system, characterised the challenges that farms face, and analysed the provision of selected private and public goods as well as functions. For this, we used remote sensing and farm census data, interviews, and survey questionnaires.

RESULTS AND CONCLUSIONS: Key challenges to resilience include labour constraints, climate change-induced water scarcity, and human-wolf conflicts. Despite these challenges, the production of cheese, the main product of most farms, has been resilient. Further, overall livestock stocking remained stable due to system reserves from direct payments, and summer farms continued to be important for tourism in rural areas. As an adaptation strategy to mounting labour shortages, summer farms increasingly kept suckler cows, which demanded less labour. Labour shortage was both a result of and further reinforced by employees spending fewer seasons on summer farms due to the job's seasonality. Both labour shortage and reduced grazing pressure contributed to a loss of 10 % of summer farming area to shrub and woody plant encroachment and forest succession, which indicated a substantial lack of landscape maintenance as a public good. We emphasize the need for a more flexible direct payment system, as well as digital and silvo-pastoral innovations, to enhance system adaptability and improve resilience.

SIGNIFICANCE: This study is the first to analyse Swiss summer farm resilience and highlights a lack of landscape maintenance, due to shrub encroachment. The findings underscore the need for flexible direct payment systems and innovations such as digital tools and silvo-pastoral practices to enhance system adaptability and resilience.

1. Introduction

Since millennia, farmers in Switzerland have brought their livestock to upland summer farms during short mountain vegetation periods (Garcés-Pastor et al., 2022; Schwörer et al., 2015). These summer pastures cover 30 % of Switzerland's land surface and are of high societal importance, as they provide food production, biodiversity conservation, soil carbon storage, cultural heritage, and other ecosystem services (Bürgi et al., 2013; Pauler et al., 2025). They also provide a picturesque landscape and contribute to the economy through tourism as a cultural ecosystem service. As of December 2023, the Swiss Alpine[1] season ("Schweizer Alpsaison") of these summer farms has been added to the representative list of the UNESCO Intangible Cultural Heritage of Humanity. However, the number of operational farms in both the summering and permanent-residency zones is declining, leading to farm structural change (Meyer et al., 2024). This raises pertinent questions about the resilience of summer farming in Switzerland.

The resilience of farming systems is crucial for food production and the provision of ecosystem services, and research on resilience has gained increasing attention in recent years (Darnhofer, 2014; Folke et al., 2010; Herman et al., 2018; Huber et al., 2013). With Meuwissen et al. (2019) conceptualising a framework for assessing farming system resilience, research has increasingly analysed the resilience of farming systems in different geographical regions and across production systems (Adhikari et al., 2021; Camacho-Villa et al., 2023; Perrin et al., 2020). Moreover, some aspects of the resilience of mountain farming and summer pastures have been researched (Brunner and Grêt-Regamey, 2016; Mayer et al., 2022; Nettier et al., 2017; Schirpke et al., 2017). However, no research has explored the resilience of summer farms in Switzerland from an interdisciplinary perspective for a holistic understanding of the challenges and solutions. To analyse summer farm resilience, we define resilience following the definition of Meuwissen et al. (2019, p. 2) as: "*[…] ability to ensure the provision of its desired functions in the face of often complex and accumulating economic, social, environmental and institutional shocks and stresses, through capacities of robustness, adaptability and transformability*".

One of the functions of summer farms in Switzerland, and a major provisioning ecosystem service, is the production of dairy and meat products (Bürgi et al., 2013; Hafner and Schwörer, 2018), including specialty cheese, which makes up 14.5 % of all cheese production in Switzerland during summer season.[2] These products are associated with higher animal welfare compared to valley livestock due to (almost) all-day pasture access and a high share of roughage in the grassland-based fodder of mountain pastures. In the lowlands, the pressure on milk production has increased due to the conflict between food and feed production (Muscat et al., 2020). However, at higher elevations, ruminant livestock farming provides food from feedstuffs with low opportunity cost on marginal land that are not suitable for arable food production, which reduces competition between food and feed production (Muscat et al., 2020). On these mountain summer pastures, livestock farming transforms grass into diary and meat products. High demand for animal-source foods has led to growing land use changes, increased greenhouse gas emissions, and increased water use globally (Willett et al., 2019). However, summer farming has a special environmental context. Indeed, at higher elevations due to harsher environmental conditions, grassland-based livestock farming is the only agricultural option to produce food. Therefore, animal-source food production on summer farms is not in conflict with food production for direct human consumption, which is an opportunity to contribute to sustainable diets (Van Zanten et al., 2019; Willett et al., 2019; Zehnder et al., 2023). Despite these advantages, mountain farming is subject to structural change: the number of farms has been decreasing from 7472 to 6663 between 2003 and 2021, while average farm size has been increasing, with detrimental implications for livelihoods and the environment (Gellrich et al., 2008; Cocca et al., 2012; Munroe et al., 2013; Mink and Mann, 2022). Furthermore, summer farming is increasingly affected by rising temperatures due to climate change, which has led to a longer vegetative season and thus higher forage yield (Pauler et al., 2025; Rumpf et al., 2022). However, extended drought periods during summer are more frequent, with consequent water scarcity.

Swiss summer farming is also threatened by a lack of skilled labour to care for livestock during the summer period, which can strain farm productivity (Meyer et al., 2024). Farm labour opportunity costs in Switzerland are high, as there are more profitable non-farm employment opportunities. The work is physically demanding, working days are long, and living conditions on summer farms such as housing are basic, which challenges attracting and retaining qualified and motivated workers (Herzog et al., 2016; Stauder et al., 2023). Moreover, the seasonality of summer farming is challenging, as workers need to find jobs

[1] In Switzerland, the average summer farming season lasts for 100 days. Depending on the altitude and the year's weather, it can start anywhere from May and June, lasting until September to October.

[2] This corresponds to 4 % of year-round cheese production in Switzerland. Own calculations based on Swiss Alpine Farming Association, 2023, Federal Office for Agriculture, 2023 and TSM Treuhand GmbH, 2024.

outside of the farming season during the winter (Calabrese et al., 2014).

Finally, wolf predation of livestock is an additional physical and psychological stressor to farmers. Mitigating predation of livestock by wolves requires livestock protection measures such as fences, shepherding, nighttime confinement, deterrence and guarding animals such as dogs (Treves et al., 2009). However, this increases production costs and economically viable livestock protection can only be attained with a minimum number of livestock, especially sheep (Eiselen, 2012). This may subsequently lead to farm structural change, as well as abandonment of some summer farming as shown by Mink and Mann (2022) and Mink et al. (2023).

To understand the resilience of mountain farming in Switzerland, it is crucial to explore the factors contributing to its vulnerability in more detail. For that reason, we ask three research question to structure our analyses and to deepen our understanding: (i) To what key challenges must summer farms be resilient? (ii) For what purpose must summer farms be resilient? That is, which products and functions must they continue to provide in the future? (iii) Which resilience capacities of summer farms can be identified?

As the resilience of a farming system is seldom driven by a single factor, it is important to use an interdisciplinary lens. Thus, we considered summer farming resilience from the perspectives of agronomy, ecology, agricultural economics, sociology, livestock science and food science by analysing remote sensing, farm census, survey questionnaire, and qualitative interview data. Insights from this holistic approach helped in the discussion of how to address the specific challenges of summer farms. We also provided a tentative discussion of factors that contribute to resilience and which adjustments need to be made to, for example, the direct payment system.

2. Materials and methods

Our exploration of the resilience of Swiss summer farming was based on the resilience framework of Meuwissen et al. (2019), which guided our analysis in four steps, as shown in Fig. 1.

First, we described the farming system—in our case, transhumant summer farming in Switzerland—and associated subsystems. Second, we identified challenges specific to the farming system and each subsystem, offering insights into the specificities and nuances of each subsystem. Third, we analysed the desired private and public goods provided by the farming system. This includes developing indicators, operationalising them, and assessing their performance. The differentiation between private and public goods is important for effective policy design. As the provision of public goods such as landscape maintenance by farmers benefits the whole society, their provision often requires government intervention, such as public support policies. Individual farmers may lack the incentive to invest in these public goods because the benefits are shared by everyone, even those who do not contribute—that is, the free-rider problem. Fourth, we explicated resilience capacities and attributes, such as robustness, transformability, diversity, and system reserves. See S2 for a detailed step-by-step guide to the steps taken in our analysis.

2.1. Study area

In total, 476,677 ha (2013–2018 average) of Swiss national territory consists of upland pastures used for summering, which we plotted in Fig. 2 (Federal Statistical Office, 2023). These are spatially separated from the home farm or communally owned. A substantial 25 % of the total livestock in Switzerland is kept on these summer pastures for, on average, 100 days during the summer (Mack et al., 2013). Summer pastures extend the fodder base and free labour and area on the home farms for winter fodder production (Bürgi et al., 2013). These summer farms are located above the year-round inhabited settlements and constitute an important part of the transhumance (Herzog and Seidl, 2018; Jurt et al., 2015).

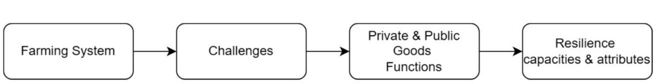

Fig. 1. Workflow to assess farming system resilience. Adapted from Meuwissen et al. (2019).

2.2. Farming system

Following Meuwissen et al. (2019), the first step in assessing a farming system's resilience is to characterize the farming system itself. For this, we used the typology of Swiss summer farms by Meyer et al. (2024) as the basis for our subsequent analyses. The typology was generated using census data of 5900 farms, representing 87 % of the total summer farm population for the year 2021. The data was processed, combining unsupervised clustering and expert assessment to generate a typology. In the clustering process, socioeconomic farm-level and spatial variables were used to depict the farms' infrastructure and biophysical environment. The resulting typology consists of six types: private dairy farms, communal mixed cattle and dairy farms, communal cattle farms, remote farms, small, private cattle farms and sheep farms. The types differ in terms of organizational structure, herd composition, biophysical environment, and accessibility.

To increase our understanding of this farming system to a more detailed level, we used each farm's geographic location, obtained from the Swiss Agricultural Policy Information System, to characterize farm size (measured as normal stocking units) as well as environmental conditions. These environmental conditions included elevation, slope, and average precipitation from 1980 to 2010, which were derived using the point value of the farm location. The data were obtained from the open government data platform *opendata.swiss*, which is publicly available at a 250 m grid resolution, providing a nuanced picture of the different farming sub-systems.

2.3. Identifying challenges

We identified relevant challenges to summer farms based on two workshops held in spring 2022 and autumn 2023. The first workshop was held with summer farmers, agricultural advisory services, and agronomic research personnel, with 60 participants in total. This workshop was publicly announced via a cantonal education and advisory centre for agriculture and participation was voluntary. In the second workshop, 12 summer farming experts were drawn from the research network of the Swiss Centre of Excellence for Agricultural Research ("Experimental Station Alpine and Mountain Farming") (Meyer, 2022). They were asked to list the five top challenges faced by summer farms today in an open format, without any pre-defined suggestions, and the answers were surveyed using *mentimeter*[3] and subsequently clustered, which generated similar terminologies. The answers were then ranked according to the number of similar answers mentioned and the creation of a word cloud that helped in understanding the importance of the respective challenges (see Fig. S1).[4] This was accompanied by a comprehensive literature overview of current research on mountain and summer farm challenges, as described in the Introduction section, to provide a stylised overview of these challenges.

[3] *Mentimeter* is a platform that is able to generate real-time feedback of participants during meetings via mobile devices or webpage.

[4] Ranking answers based on the number of times they have been mentioned assumes that their salience is equivalent to their importance. However, salience may also depend on how recently a topic was discussed in media or in policy.

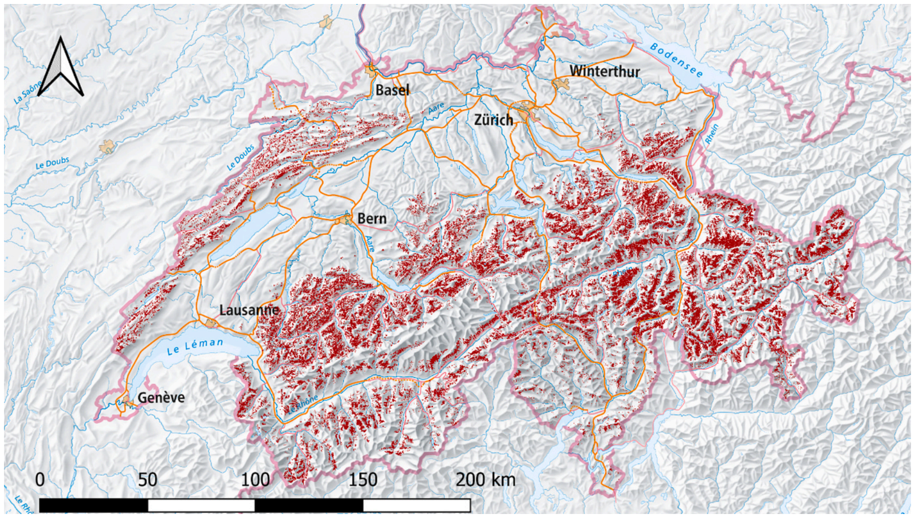

Fig. 2. Map of spatial distribution of summer farming area (red) in Switzerland (45°49′05″N & 47°48′30″N and 5°57′23″E & 10°29′31″E), based on data of the Swiss Land Use Statistics of the Federal Statistical Office (2019). Backgroung (c) swisstopo.

2.4. Analysing private and public product supply and functions of summer farms

A resilient farming system provides a continuous supply of private and public products and functions[5] to society, as derived from the definition of resilience by Meuwissen et al. (2019). To analyse this supply, we used the indicators of goods and functions listed in Table 1.

2.4.1. Private goods of summer farms

The provision of private goods includes milk, cheese and meat, which constitute the fundamental provisioning ecosystem service of Swiss summer farms. To analyse the provision of these goods, we operationalised private goods provision as annual milk production (in kg/year), annual cheese production (in kg/year), animals (as number of animals on a farm in normal stocking units/year[6]), and animal type (goats, sheep, dairy cows, suckler cows, and other cattle) (Table 1, rows 1–3). We gathered this data from the Federal Statistical Office and the Federal Office for Agriculture and provided descriptive statistics over timeframes that are available and relevant to assessing farming system resilience, commonly starting in 2001 (Federal Statistical Office, 2022, 2023, 2024; Federal Office for Agriculture, 2021). We also calculated changes in direct payments for each livestock category and per reform year to be able to explain changes in stocking of animals and the composition of animal types from policy reforms (see Table S5 for details).

Table 1
Overview of selected goods and functions, indicators, and their operationalisation of Swiss summer farms used to analyse the farming system's resilience.

	Goods and functions	Indicators	Operationalization
1	Private goods	Milk	Annual milk production [kg/year]
2		Cheese	Annual cheese production [kg/year]
3		Meat	Animals [NSU/year] and animal types
4	Public goods	Landscape maintenance	Pastureland [ha] and associated land use transitions
5	Functions	Employment	Number of operational farms per year
6			Number of seasons spent on a farm by employee
7		Tourism	Number of tourist arrivals and overnight stays per municipality

[5] We do not differentiate between private or public functions.

[6] One normal livestock stocking unit (NSU) corresponds to one forage-consuming livestock unit for 100 days during summer. One forage-consuming livestock corresponds to one dairy cow.

2.4.2. Public goods of summer farms: landscape maintenance

To analyse the provision of public goods, we analysed the area used for summer farming across Switzerland (plotted in Fig. 2 for the year 2018), as well as the associated land use transitions (Table 1, row 4). Land use transitions from summer pastures to other agricultural land, forest and non-productive between 1985, 1997, 2009, and 2018 were quantified based on the data of the Swiss Land Use Statistics elaborated by the Federal Statistical Office (Federal Statistical Office 2019). This dataset was based on 4.1 million fixed observation points on a regular grid of 100 m overlaid onto aerial photographs. The points were classified into 72 land-use categories by photo interpretation, merged with additional information, such as national, cadastral, and topographic maps. These were labelled by the year of publications (i.e. 1985, 1997, 2009, and 2018), but the aerial photographs were taken 3–6 years before publications, since the whole country cannot be overflown for photographs in a single year. For display, we summarised the 72 land-use categories into four groups: "summer pasture" (classes 45–49), "agricultural land without summer pastures" (classes 37–44), "forest and shrubs" (classes 50–60 and class 64), and the rest were classified as "non-productive". Transitions from one land use type to another were evaluated between every two subsequent publication years (e.g. 1985 to 1997) in total and on a regular grid of 10 × 10 km^2 by calculating the percentage of observation points changing from "summer pasture" to other groups relative to the total number of "summer pasture" points. The grid resolution of 10 × 10 km was selected to stabilize results that illustrate trends in space and time. Since average proportion of summering area in 10 × 10 km grid cells is 13 % and of these only 1.4 % change land use, a finer resolution would have led to considerable bias, shown a very patchy pattern and be less interpretable then the 10 × 10 km resolution.

2.4.3. Employment and tourism as functions of summer farms

One basic aspect of the resilience of the farming sector is the provision of livelihoods to farmers via employment and associated downstream services to the region. This includes, among others, contract labour as well as cultural ecosystem services such as cultural heritage and tourism. We therefore used three indicators for the farming systems function (Table 1, rows 5–7).

First, there must be a sufficient number of summer farms to employ both family and contract labour. We therefore used the number of operational summer farms as a basic indicator associated with family and contract labour employment. We derived this data from annual farm statistics from the Swiss Agricultural Policy Information System of the Federal Office of Agriculture for the years 2002–2021 (Federal Statistical Office, 2022).

Second, we analysed whether there is a change in employees' loyalty over the years, that is, if employed workers return year after year to the farm, using the number of seasons spent on a farm as an indicator. For this, we conducted a survey in the winter of 2023–2024, using a convenience sample as there was no structured contact information of alpine farming employees available. The survey was distributed by multiple channels: through websites and newsletters of zalp.ch and alpwirtschaft.ch, various cantonal sections of the Swiss Alpine Economy Association, among former participants in summer farming courses, by summer farmers individually and in WhatsApp groups among peers. This resulted in responses by 366 farm employees. As there is no information on the number of potential respondents and employees on summer farms in general, no definitive conclusions can be made about response rate. We compared the results of the survey to studies carried out in 2000 by Rudmann (2004), who made her assessment based on national stakeholder surveys and interviews in two case study locations: Grisons and Obwalden. In 2014, Calabrese et al. (2014) conducted 120 interviews, using standardised questionnaires to analyse the loyalty of summer farm employees. Our comparison evaluated the number of seasons spent on a summer farm and whether there was a change in summer farming employees' decisions to return to summer farming the following year. If so, we asked whether employees would return to the same farm. This is important because training employees in the peculiarities of various farms is time-consuming and therefore costly, as highlighted by Stauder et al. (2023) and experts involved in our study. Failing to keep employees on a farm may in the medium term increase the risk of under- or overuse of grazing areas, cause biodiversity loss as well as afforestation and consequently lead to the potential abandonment of summer farming areas (Stauder et al., 2023). Finally, we conducted 13 qualitative in-depth interviews in summer and autumn 2024 with employees who had returned to the same farm season to provide information on their motivations to return to summer farming each year.

Third, we analysed the trend in tourist arrivals and overnight stays for a representative sample of Swiss municipalities from the Federal Statistical Office for the years 2013 to 2023 (Federal Statistical Office, 2024). Tourism is important to many mountainous areas and pastures of summer farms are integral to the visual appeal of tourists (Leimgruber, 2021). Especially skiing tourism is a strong driver of regional economic development (Troxler et al., 2024) and this recreational experience constitutes a cultural ecosystem service. Further, in areas with summer farming, tourists can enjoy the picturesque landscapes and consume farm products, such as speciality cheese. In return, tourism supports summer farming through the income generated from tourists visiting the farms and cheese sales. We therefore tracked potential changes in the association between summer farming and tourism by summarising the number of tourist arrivals per municipality from 2013 to 2023. We normalised number of tourist arrivals per municipality by the number of inhabitants per municipality to correct for the size of the municipality. We then differentiated whether a municipality had summer farming on its jurisdictional area, derived from the agricultural zone boundaries provided by the federal office of agriculture (Federal Statistical Office, 2019).

3. Results

3.1. Swiss summer farming system

Using Meyer et al.'s (2024) farm typology and each farm's geographic location, we characterised the farm subsystem's environmental conditions, as shown in Fig. 3.

The Swiss summer farming system is dominated by private dairy farms (37 % of all summer farms), with favourable production conditions, such as low elevations and slopes and high yearly precipitation. Communal mixed cattle and dairy farms (23 % of all farms) are the largest farms, with similarly favourable production conditions than privately owned dairy farms. These farms are very similar to communal cattle farms, which are smaller in size and constitute only 8 % of all farms. Remote summer farms (9 % of all farms) and sheep summer farms (9 % of all farms) are large, with steep slopes at high elevation, resulting in a short vegetation period despite the high precipitation. Small private cattle farms (15 % of all farms) are found at the lowest elevations and gentle slopes.

3.2. Challenges to Swiss summer farming systems

We illustrate the challenges faced by summer farms in Fig. 4, which we derived from both expert workshops and a literature review. Climate change, wolves and labour shortage on the left side of the figure result in the merging of further challenges, indicated by arrows.

Clean and cold water in sufficient quantities is essential for fodder production, animal troughs, human consumption, and the cooling and processing of milk. Summer farms face an increasing threat of water scarcity due to winters with reduced snowfall at mid-elevation, the increased frequency and intensity of summer droughts, and higher evapotranspiration due to climate change. Increasing temperatures have also led to higher biomass growth at the beginning and end of the mountain farming season (see Fig. S3 for a stylised graph of biomass growth under climate change).

Further, undergrazing, increases in temperature, and enhanced precipitation variability generated a comparative advantage for trees or shrubs over grasses, leading to woody plant encroachment (Gherardi and Sala, 2015; Straffelini et al., 2024; Van Auken, 2009). Undergrazing from pasture understocking is a result of successive land extensification and the abandonment of marginal areas (Archer et al., 2017; Van Auken, 2009). Therefore, it is essential to have an appropriate number of animals grazing the pastures to limit woody plant encroachment (Pauler et al., 2022). To optimise pasture grazing by livestock, it is also beneficial to have animals that are suitable for grazing under challenging mountain conditions (Pauler et al., 2022).

Woody plant encroachment was also fostered by the lack of labour required for pasture maintenance (Gellrich et al., 2008). Proper pasture management requires labour to divide pastures for grazing and to ensure access to water for livestock. However, there was a reduction in the number of workers on summer farms available to perform these tasks, as the efficiency of valley farms increased due to technological advances that resulted in fewer farmers needed to manage the land (Flury et al., 2012; MacDonald et al., 2000). Recruiting labour for the mountain economy became increasingly challenging due to the comparatively low salary and the considerable workload with extended working hours (Rudmann, 2004). Moreover, the predation of wolves on livestock increased the workload of farmers even more. Indeed, the need for more livestock protection measures, such as increased fencing, resulted in increased physical and psychological stress. Predation incidences led to summer farm abandonment (Mink and Mann, 2022). Additionally, experienced cheesemakers were hard to find, as the seasonal nature of the work often conflicted with other employment opportunities.

3.3. Private goods provision – Meat, milk, and cheese

In panel A of Fig. 5, we plotted the development of the overall stocking from 2000 to 2021 as well as the composition by animal type. The overall stocking levels were stable from 2000 to 2021 at around 300,000 normal stocking units (NSU). However, a notable shift in livestock composition occurred, marked by an increase in suckler cows (+312 %) and a decrease in dairy cows (−15 %) and sheep (−18 %). The

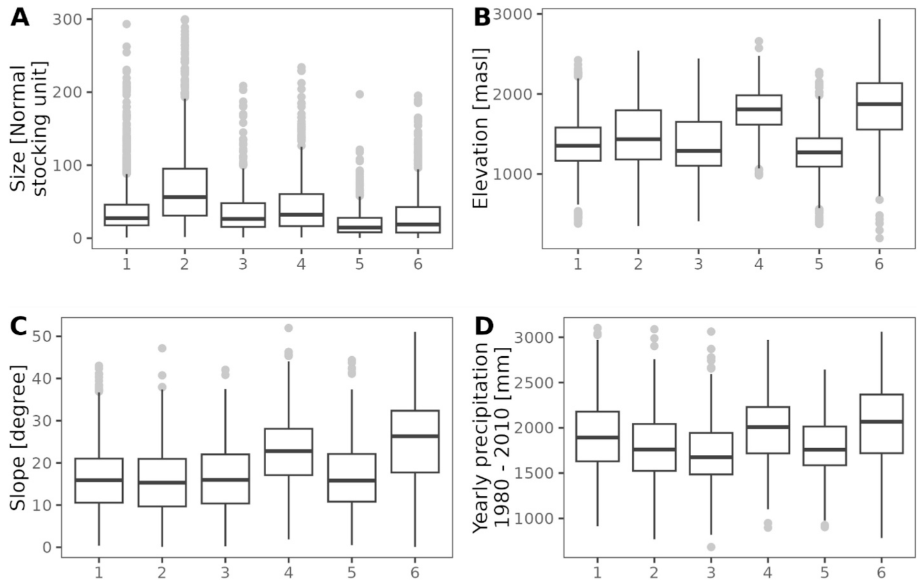

Fig. 3. Characteristics of Swiss summer farming system by sub-type on x-axis. Numbers correspond to (1) private dairy farms, (2) communal mixed cattle and dairy farms, (3) communal cattle farms, (4) remote summer farms, (5) small private cattle farms, and (6) sheep summer farms. Panels correspond to farm size (panel A, outliers capped at 300 units), elevation (panel B), slope (panel C), and average yearly precipitation between 1980 and 2010 (panel D).

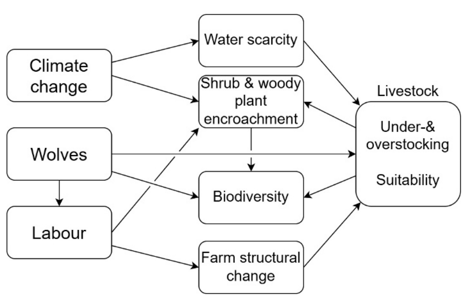

Fig. 4. Challenges to the Swiss summer farming system.

number of other cattle is relatively stable.

In panel B, we plotted the development of both cheese and milk production, which are final consumer products and constitute a provisioning ecosystem service. Panel B shows a decrease in milk production from 2003 to 2020 by −7 % (from 101,821 t to 95,400 t). However, Fig. 5 also shows an increase in cheese production from 2003 to 2020 of 17 % (from 4729 t to 5678 t). Although milk production decreased, farmers adapted by switching to cheese making, showcasing their ability to capture more value within the supply chain.

We further investigated the case of sheep farms, as these have seen the largest decrease in stocking of −18 % from 2003 to 2021. Sheep farms are defined as farms that exclusively herd sheep, and we plot the sheep stocking per grazing system in Fig. 6.

Sheep farms are increasingly relying on shepherding, with sheep kept under a permanent shepherd increasing by 179 % from 2003 to 2020. At the same time, sheep kept under permanent grazing, that is sheep staying on the same pasture throughout the summer season, decreased by 73 % in the same period. Sheep kept in a rotational grazing system, that is sheep change pastures in a regular time interval, has decreased by 21 % in that period. The number of livestock killed by wolves increased substantially from 2003 to 2020, from 38 to 815 livestock killed per year (black dots in Fig. 6).

3.4. *Public goods provision – Fate of summer pasture landscape*

Our analysis of the Swiss land use statistics (Federal Statistical Office, 2022) indicated a continuous loss of summer grazing area. In 1985, when the point-based stereoscopic interpretation of aerial images was carried out for the first time, 543,372 ha (measured at 100 m grid points) were classified as summer pastures. The most recent survey published in

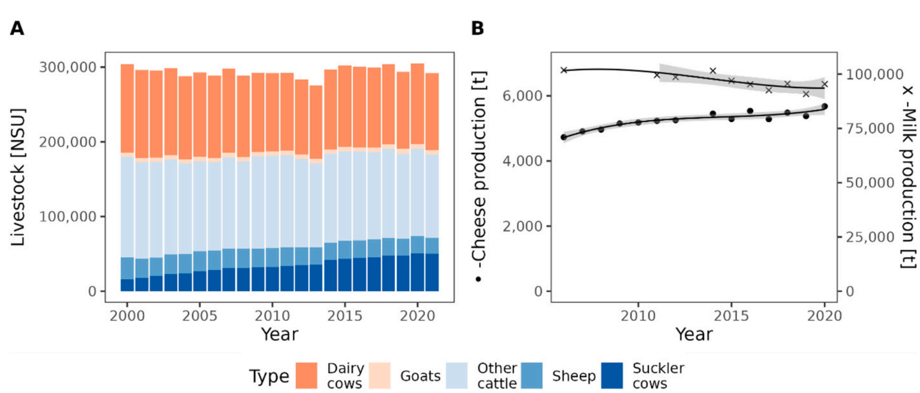

Fig. 5. Panel A: Development of summer farm stocking (y-axis in normal stocking units [NSU], as defined in footnote 4) by livestock type over the years (x-axis). Panel B: Development of quantities (y-axis) of milk (crosses) and cheese (round dots) production per year (x-axis). Lines indicate smoothed 3-order splines for approximation of long-term trends.

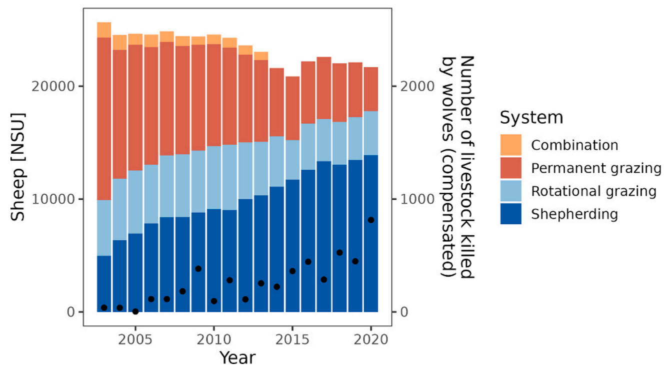

Fig. 6. Development of sheep stocking (left y-axis in NSU) per grazing system in relation to livestock killed by wolves (black dots and right y-axis) per year (x-axis).

2018 recorded 503,312 ha of summer pastures and thus an absolute loss of around 40,000 ha. Although more summer pastures were lost (56,899 ha), some new ones were also identified (16,839 ha; Fig. 7).

In total, 90 % of the summer pastures were largely resilient to changing socioeconomic and climatic conditions and thus stayed in the "summer pasture" category. Fig. 8 shows the fate of the 10 % of summer pastures that have undergone changes in four land use types since 1985.

The majority (i.e. 73 %) of these summer pastures were lost to woodland. Nearly 42,000 ha of pastureland was overgrown by tall forest (13,071 ha), forest succession communities and tall shrubs (14,940 ha), and dense dwarf shrubs (13,669 ha).

Summer pastures were also replaced by non-productive land use, namely traffic infrastructure (1365 ha; mainly roads), buildings (1375 ha), ski lifts (178 ha) and avalanche barriers (290 ha). The interpretation of these results is double-sided. On the one hand, construction activities reduced summer pasture area. However, an improved infrastructure can increase the resilience of the surrounding pastures or may even be the precondition for keeping a summer farm running and prevents abandonment.

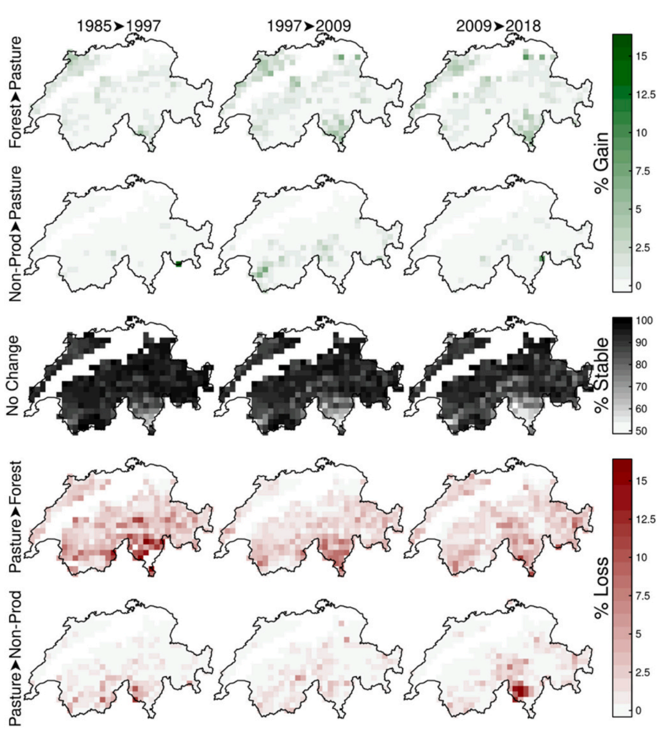

Fig. 7. Land use change in the Swiss summering area based on the Swiss land use statistics classification of the Federal Statistical Office in four recording dates (1985, 1997, 2009, 2018). Given is the percentage of summer pastures which were gained from forest or unproductive areas (green), which did not change in land use (grey) or were lost as pastureland (red) relative to the total summer grazing in each 10 × 10 km grid cell. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Summer pastures were also lost to vegetation-free areas (1092 ha) caused, for example, by avalanches, mud slides, rock debris, or was covered by unproductive plant communities (7366 ha), such as river-bank vegetation, marshes, or sparse vegetation at the altitudinal vegetation limit. This development was caused by the highly dynamic natural conditions of the mountains. Consequently, almost as much pastureland was gained from unproductive or vegetation-free zones (6050 ha) as was lost to it. Although natural events can destroy pastures, new pasturelands can be recovered from sites that have been previously destroyed by natural events. Thus, natural, mountain-typic fluctuations do not impair the resilience of summer farming in general.

Moreover, increasing temperature led to a loss of glaciers and firn snow in mountain areas (Rumpf et al., 2022). Thus, one could have expected an increase in pastureland in melted free areas. Indeed, a few spots covered by glaciers or firn in 1985 were classified as pastureland in 2018. However, the overall numbers were very small (45 ha for glaciers and 359 ha for firn), and some pastures were even newly covered by snow (125 ha). Consequently, the gain of new pastureland from former ice- or snow-covered sites was not nearly as fast as the loss due to wood encroachment or human construction activities. Notably, these ice-free areas were recolonised by pioneer vegetation communities whose biomass productivity is extremely low and cannot replace the loss of much more productive pasture areas at lower elevations (Mainetti et al., 2021). Therefore, it is not able to support summer pasture significantly.

Finally, there were also changes of areas between summer pastures and other agricultural land uses, mainly grassland, resulting in a net loss of 1467 ha from 1985 to 2018. These are due to correction of cadastral boundaries which are considered to distinguish grasslands on home farms and summer pastures.

3.5. *Summer farming functions – Farm survival, employees' loyalty and tourism*

The number of summer farms decreased by 11 % from 2003 to 2020 (see Fig. S4, own calculation based on Federal Statistical Office, 2022). This suggests, on average, fewer employment opportunities for family and contract labour. However, since overall stocking remained constant throughout the same period (see Fig. 4, panel A), abandoned farms have likely been taken over by other summer farms, who subsequently increased their grazing area. Furthermore, due to the substantial rise in shepherding, this suggests a small increase in employment opportunities for non-family farm labour on sheep farms.

With regards to employees' loyalty, the results from our survey show that employees spend 6.4 seasons on *any* summer farm and return to the *same* summer farm on average for 2.23 seasons. The range of seasons was 1 to 55, with a standard deviation of 7.3. Respondents who do not return to summer farming at all highlight the seasonality of the job, that is, the difficulty of combining this 'summer-only-job' with another job. Compared to 2004, Rudmann (2004) suggested employees' loyalty to summer farms as broadly 'sufficient'. In 2014, Calabrese et al. (2014) showed that employees spend 8 summer seasons on such farms on average. The range of seasons spent was large, ranging from 1 to 41 seasons (SD 8). The results of our survey indicate that employees spend 6.4 seasons on any summer farm, which is 1.6 less seasons compared to the study by Calabrese et al. (2014). Moreover, we asked those who planned to return to the same farm. Of the 185 returnees, 66.3 % planned to return to the same summer farm, while 27.2 % did not and 6.5 % were undecided. Finally, data from the 13 qualitative in-depth interviews with employees who returned to the same farm season revealed that they drew their loyalty to mountain farming from the

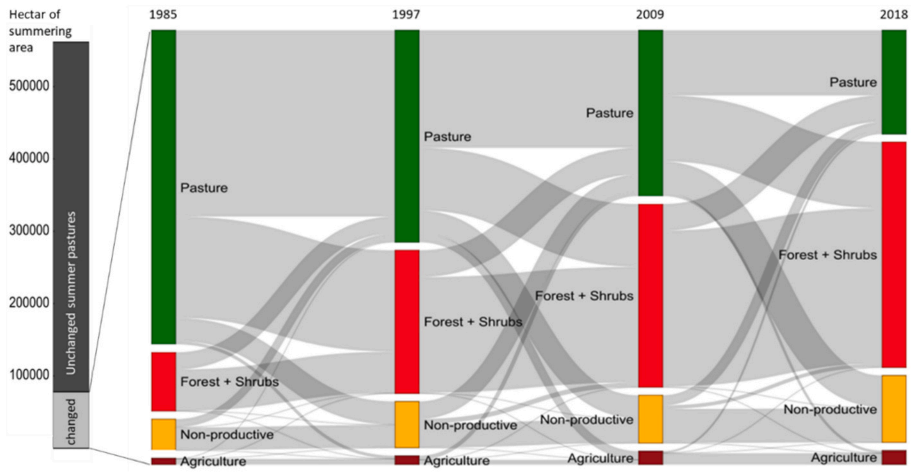

Fig. 8. Land use change in the Swiss summering area over four decades. 90 % of summer pastures were maintained as pastureland (dark grey), but 10 % changed their land use type at least once since the first publication in 1985 (coloured).

meaningfulness they associated with this work.

Fig. 9 is a plot of municipalities with summer farms that had higher numbers of both tourists visiting (panel A) and tourist overnight stays (panel B) relative to their number of inhabitants, compared to areas without summer farming. These numbers also increased throughout 2013–2023 and suggest the importance of summer farming for tourism. In 2020, the COVID-19 pandemic resulted in substantial dips in the overall number of tourists due to global and local travel restrictions. However, there was no visual difference in the recovery of tourist numbers between municipalities with and without summer farming, as tourism recovered well after the pandemic in both groups.

4. Discussion

4.1. Private goods provision

We showed that the provision of private goods by Swiss summer farms has been stable, and our findings clearly suggest that summer farming has been resilient in this regard, despite many challenges to the farming system. Overall, stable stocking on summer pastures indicates robustness as a resilience capacity, because direct payments have played a pivotal role, being paid for livestock taken to the summer farm during the season (Meyer et al., 2024). Each reform of the Swiss direct payment system increased payments by, on average, 29 % per reform (based on own calculations, see Table S5 for details). Therefore, direct payments have served as a crucial systemic reserve, providing financial stability amid uncertainties, which is a resilience attribute.

Although stocking remained stable, we also showed a notable transformation in livestock composition due to an increase in the number of suckler cows and a decrease in that of dairy cows and sheep. The increase in the suckler cow number can be explained as an adaptation strategy of the farming system: because labour has become a limiting factor in mountain agriculture, livestock with high labour requirements, such as dairy cows, are replaced by suckler cows with lower labour requirements (Gazzarin and Jan, 2024). In addition, milking and cheese production require maintaining a certain level of infrastructure. In situations in which an investment would need to be made but economic pressures are high, changing to suckler cows might be a sensible adaptation.

Moreover, we have shown increasing wolf predation since 2003. On sheep farms, this increases labour requirements for livestock protection measures, as this requires employment of shepherds and investment into

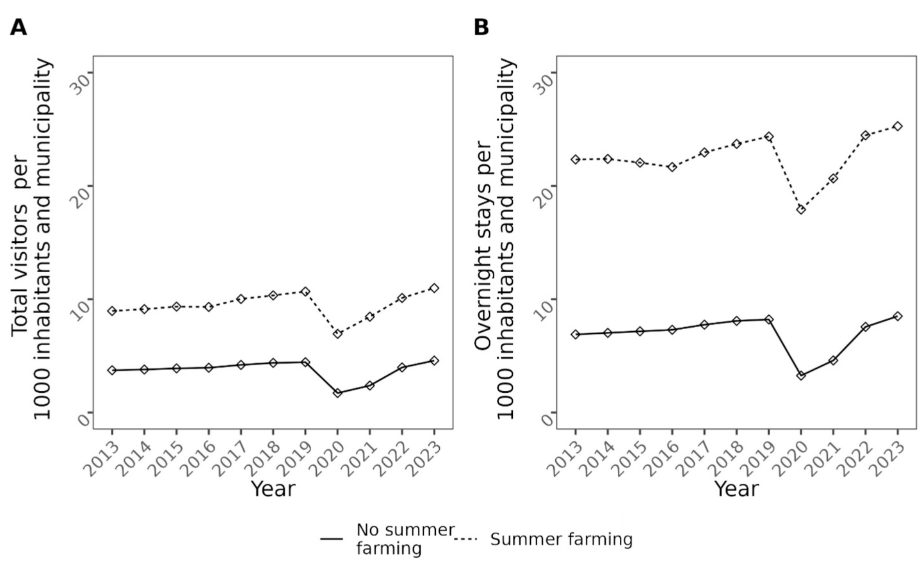

Fig. 9. Tourist visitors (y-axis, panel A) and tourist overnight stays (y-axis, panel B) per 1000 inhabitants and municipality per year for 100 municipalities across Switzerland. Municipalities are differentiated by whether a municipality has a summer farming area on its jurisdictional area (solid line) or not (dashed line).

material for protection measures which some farms are unable to cope with (Department for the Protection of Livestock Agridea, 2024). In total, this resulted in decreased sheep stocking, which is in line with findings of Mink and Mann (2022). Areas that can only be grazed by small ruminants but cannot be protected against wolf attacks with reasonable effort are thus often abandoned. However, in other cases, the sheep farming system has adapted by increasing the shepherding of the remaining sheep flocks (Mink et al., 2023). This resilience capacity to deal with predation from wolves is supported by three key factors. First, direct payments have offered financial stability in the long term and each reform of the Swiss direct payment system increased payments by, on average, 29 %. Direct payments for sheep under shepherding culminate in 650 CHF per NSU as of 2024 (see Table S5 for details). However, direct payments for permanent grazing without any shepherding of sheep have remained stable since 2002, at 120 CHF per NSU (FOA, 2021). This has provided an incentive for summer farms to transform into more shepherding. Second, emergency programs have provided critical support during wolf attacks, such as extra fencing material (Department for Protection of Livestock Agridea, 2024). Third, digital innovations, such as drones, can enhance operational efficiency and potentially reduce physical and psychological stress (Walter et al., 2017). These outcomes have contributed to sheep farms' adaptability in the face of evolving challenges as the counterfactual decrease in stocking would have been more substantial without these three key factors. However, the overall decrease in stocking still indicates a lack of resilience.

Summer farmers transformed a higher share of the milk produced into label cheese, which aligns with market demand dynamics, as consumers demand more specialty cheese from these summer farms (Böni and Seidl, 2012; Schulz et al., 2018). Of particular importance are the liberalisation of the cheese market on June 1, 2007, the definitive abolition of the milk quota on May 1, 2009, and the abolition of the quota system in the European Union on April 1, 2015 (Swiss Farmers Union, 2024). In addition, the abolition of the Euro-Swiss Franc floor by the Swiss National Bank on January 15, 2015, drastically changed the valuation of the Swiss Franc vs. the Euro. All these factors have led to a structural change away from milk production and towards cheese production due to the increased exportation of cheese, again suggesting a transformability as a resilience capacity. However, the marketing of products from summer farms presents a significant challenge, as the Swiss cheese market is currently saturated, particularly in regions where mountain specialties are produced.

4.2. *Landscape maintenance as a public good*

As the summer farm system is not capable of providing landscape maintenance as a public good, we suggest that the summer farm's resilience is insufficient in this regard. The largest share of lost pastureland is encroached by woody plants, which is caused by an insufficient stocking rate. Less favourable pastures, such as steep or stony areas, remote pastures with little infrastructure, and grasslands of low forage quality, are underused or even abandoned for multiple reasons. Some factors include a strong reduction of bud-browsing small ruminants, especially goats (Fig. 1 in Pauler et al., 2022), and more selective grazing by modern, more productive livestock breeds (Pauler et al., 2020), which reduces foraging pressure on woody plants that benefit from the rising temperatures. In parallel, fewer trees and shrubs are cut down due to a lack of labour and less demand for local fuel wood and construction materials. Shrub encroachment goes along with a loss of biodiversity (Pornaro et al., 2013; Zehnder et al., 2020) and an appealing landscape (Soliva et al., 2010).

As there is a political and social will to maintain summer pastures, 8051 ha of woodland has been cleared since 1985 and classified as pastureland again. However, the loss of pastureland to woodland is five times higher than the reverse, indicating the low resilience of Swiss summer farming to wood succession, although Swiss farmers have received direct payments for pastures where they hinder forest and shrub encroachment. In fact, to access the current direct payments, which are essential for the maintenance of summer farms, farmers must respect an average animal stocking rate defined for each summer farm, which has generally been based on the average stocking rate in the late 1990s. Variations in 110 % excess or 75 % shortfall are allowed with respect to this average stocking rate, but in favourable years, pasture yield may exceed the permissible stocking rate variations. For this reason, farmers are often obliged to go down from summer pastures once the maximum permitted stocking rate is reached, leaving unconsumed fodder and not taking full advantage of the increasingly abundant grass growth in autumn. A more flexible direct payment system linked to actual grass production each year would therefore allow for better adaptation to the effects of climate change and, thus, greater resilience of the entire system. Moreover, increasing investments in water retention basins to provide water reserves for the drought-prone summer months would also be beneficial for better resilience in the face of climate change impacts.

4.3. *Summer farm functions*

The decline in the number of farms indicates that some summer farms are not resilient to the identified challenges and are given up. Thus, these farms did not possess enough adaptation capacity to withstand shocks or pressures. The remaining summer farms have increased their farm size, gradually transforming the farming system from many small to fewer larger farms – a process seen in many farming systems in Europe (Eurostat, 2023). This also implies that fewer employees are available for the many farm tasks, and in addition, fewer employees return to summer farms each year. This is reflected in the decreasing number of seasons spent by employees on summer farms. Together, this stresses farm productivity and favours woody plant encroachment as the farming system transforms, but not in a way that provides resilience for landscape maintenance.

Our results suggest that employees spent fewer and fewer seasons on any or the same summer farm, compared to Rudmann (2004) and Calabrese et al. (2014). Rudmann (2004) pointed out the seasonality of the job as a crucial challenge, which might limit loyalty in the future and reflects the same sentiment of the respondents in our study. Our qualitative interviews suggest that those employees who stayed, drew their loyalty to summer farming from the meaningfulness they associated with this work. They prioritised seasonal mountain farming over other job possibilities. Thus, they consciously chose a more modest lifestyle and organised their lives during the summer season. This has become more challenging in recent years due to developments in the labour market and wider societal changes, consistent with Rudmann's (2004) expectations 20 years ago. Although some employees will stay year after year, the seasonality of employment requires adaptation of summer farms towards more sustainable employment conditions. This could be provided by more flexible work arrangements for off-season employment, fostering partnerships with local businesses and job-sharing agreements. This should be combined with technological advances and innovations such as virtual fencing (Fuchs et al., 2024) or drones (Walter et al., 2017), which have the potential to reduce the farmers' workload. This may also reduce physical and psychological stress and therefore make this seasonal job more attractive.

The higher relative numbers of tourists and overnight stays in municipalities with summer farming indicate that summer farms contribute to the attractiveness of these rural areas. The significant dip in tourism numbers during the COVID-19 pandemic was a universal trend caused by travel restrictions and did not undermine the important role of summer farming in tourism. However, the increasing lack of landscape maintenance may have a detrimental effect on the provision of recreation experiences as an ecosystem service for tourists, due to the loss of summer farm's picturesque pastures.

5. Limitations and future perspectives

In our study, we could not directly measure employment or farmers' and employees' incomes and relied on the number of farms and seasons spent on summer farms as a proxy for a decent livelihood. Therefore, future research that surveys employment and income data for summer farms, like the Swiss Farm Accountancy Data Network (Renner et al., 2018), could provide insights on bolstering the resilience of Swiss summer farms. Further, our study was limited by using landscape maintenance of summer farms as a proxy for the ecosystem services their pastures provide. These services include habitat for pollinators, climate change mitigation, aesthetic landscapes for recreation, and biodiversity conservation (Pauler et al., 2025). Using more direct measures of these services is therefore an exciting future research avenue to create a detailed picture of Swiss summer farm resilience.

As the marketing of products from summer farms presents a significant challenge, due to the saturated Swiss cheese market, it is essential to design and implement effective marketing strategies in regions other than the production region, to ensure the economic viability of these products in the future. To improve landscape maintenance, the development of silvo-pastoral systems with hardy livestock breeds may allow for the restoration of pasture areas invaded by woody plant species. Hardy livestock breeds are often better able to exploit the forage potential of woody species, which has been demonstrated by recent examples of the fight against the invasion of green alder in alpine pastures (Nota et al., 2024; Pauler et al., 2022). Furthermore, grazing in a mosaic of pasture and shrubland areas could increase the grazing system's resilience, allowing for the diversification of fodder resources and providing supplementary fodder during summer droughts. Shaded shrubland areas are also more drought-resistant and can allow for the reduction of heat stress effects on animals. These aspects call for the design of a more flexible direct payment system and other monetary incentives for farmers to develop silvo-pastoral systems and conserve the picturesque landscapes of summer farms. Future research would therefore need to clarify on how to optimally design these policies. Together, this would allow for better adaptation to the increasing effects of climate change and, thus, greater resilience of the entire system.

6. Conclusion

We show that Swiss summer farms exhibit mixed resilience across private and public goods provision and functions. While private goods provision remains resilient, supported by direct payments and adaptive livestock management, landscape maintenance as a public good is less resilient, indicated by continuous pasture loss due to woody plant encroachment. The transformation of the Swiss summer farming systems towards fewer, larger farms and seasonal employment challenges resilience due to fewer employment opportunities for family and contract labour. However, targeted policy adaptations—such as more flexible direct payments, investments in water retention, and technological innovations—could enhance the system's long-term sustainability. Strengthening employment conditions and marketing strategies is also crucial to ensuring economic viability and preserving the cultural and ecological value of Swiss summer farming.

CRediT authorship contribution statement

Maximilian Meyer: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sandra Contzen:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis. **Michael Feller:** Writing – review & editing, Writing – original draft, Investigation. **Caren M. Pauler:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation. **Massimiliano Probo:** Writing – review & editing, Writing – original draft, Investigation. **Alexander Röösli:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Remo S. Schmidt:** Writing – review & editing, Writing – original draft, Investigation. **Manuel K. Schneider:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT 4.0 to improve the readability of the text. After using ChatGPT 4.0, the authors reviewed and edited the content as needed. Therefore, the authors take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data and code

Code and data are provided in the supplementary materials, except for survey data, which is available upon request from the authors. The processing steps are to be done as per the description in the manuscript.

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