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Understanding the Heterogeneity of Swiss Alpine Summer Farms for Tailored Agricultural Policies: A Typology

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Understanding the heterogeneity of agricultural production systems is important both for the design of targeted and tailored policies and for providing effective extension services. In Switzerland, seasonal grazing of alpine pastures during summer is important for many farms, but also for biodiversity conservation. However, these so-called alpine summer farms are threatened by water scarcity due to climate change, the lack of skilled labor, and human–wolf conflict, resulting in the abandonment of farms and loss of biodiversity. Swiss agricultural policies govern alpine summer farms with uniform policy interventions through direct payments to address these challenges. However, these farms are highly heterogeneous in terms of socioeconomic and biophysical conditions, and we lack an understanding of their structure. We investigate the heterogeneous structure of Swiss alpine summer farms by using census data (N = 5900) and a mixed-methods approach combining unsupervised clustering techniques and expert assessment to generate a farm typology. Our methodological approach enriches the existing socioeconomic farm-level data with spatial data to depict the farms' infrastructure and biophysical environment. Our results suggest 6 types that differ in terms of organizational structure, herd composition, biophysical environment, and accessibility: (1) private dairy farms; (2) communal mixed cattle and dairy farms; (3) communal cattle farms; (4) remote farms; (5) small, private cattle farms; and (6) sheep farms. We also anticipate challenges for each cluster and discuss optimization and policy measures. This will help develop targeted policies tailored to specific alpine farm types, addressing both climate and farm structural change.

Keywords: *summering; transhumance; clustering; spatial data; accessibility.*

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Introduction

Grazing of alpine pastures is an integral part of global transhumance (Jurt et al 2015; Herzog and Seidl 2018). In Switzerland, seasonal farming of these pastures constitutes an important source of livelihoods for farmers (Herzog et al 2013). These pastures, which are referred to as *summering pastures*, provide important ecosystem services such as biodiversity, replenishing groundwater, and safeguarding the population against natural hazards, such as landslides and avalanches (Bürgi et al 2013). Through their diverse flora and typical landscape, summering pastures are integral to the visual appeal of Swiss tourism, which is a sector of considerable importance to mountainous areas, such as the Swiss cantons of Grisons and Valais (Leimgruber 2021). However, the grazing of summering pastures is threatened by challenges such as water scarcity from climate change, a lack of skilled labor, and human–wolf conflict, which have led to farm structural change (Gellrich et al 2008; Cocca et al 2012; Mink and Mann 2022). This change decreases the number of farms and often increases farm size, which results in the transitional abandonment of less-productive and more-challenging-to-manage summer farms and their pastures, which comes with detrimental implications for livelihoods and the environment (Munroe et al 2013).

Being aware of these challenges, the Swiss government provides direct payments to sustain alpine summer farms to ensure their continued operation. These direct payments are given to alpine summer farms, largely administered through Normal Stocking Units (NSUs), with 1 NSU corresponding to 1 forage-consuming livestock unit for 100 days during the summer. However, this is a "one-size-fits-all" approach that may not accurately reflect the actual needs of livestock. It also does not consider factors such as remoteness and topography, which drive farm production costs. Therefore, the current system may be inadequate to address the variations in the alpine farm's production conditions, which are a result of historical processes and natural conditions that created the current plethora of structural arrangements in Swiss alpine summer farms (Bürgi et al 2013). In order to address these specificities, we need an understanding of the structural heterogeneity for effective policy support.

This understanding will help twofold. First, the developed farm typology will depict the heterogeneity of alpine farm structures and thus make it possible to consider the diversity in potential reactions of these farms to trends and challenges (Huber et al 2024). By considering the specific characteristics of different types of farms, policymakers can design targeted interventions, allocate resources more effectively, and address the specific challenges faced by each farm type in an informed manner. Second, the farm typology will be used to develop tools for extension services, for example. The tools will be specifically geared to the structural characteristics of the identified farm types, enabling extension services to provide more tailored recommendations to alpine summer farm managers for optimizing their farms economically and environmentally. For example, using a sample of the farm typology, we are currently collecting data on economic performance indicators in order to gain insights into cost and performance optimization potential. Furthermore, an evaluation of how to best recruit long-term labor for each farm type is underway, which will provide information about ideal conditions for long-term farm employment and improve farm management. Finally, all of this will inform an assessment of the resilience of Swiss alpine farming.

This study adds to the understanding of the heterogeneity of Swiss summer alpine farms by investigating the structure of such farms quantitatively. It makes 3 important contributions: First, we generate a novel farm-level dataset for Switzerland's alpine summer farms that incorporates farm-level and spatial data. Second, we develop a typology of Swiss alpine summer farms that accounts for their organizational structure, herd composition, biophysical environment, and remoteness. Finally, we provide an initial discussion of ways to improve and address challenges via optimization and policy measures for each identified cluster.

Farm typology studies partition heterogeneous farms into groups of similar farms and have been conducted in many different contexts and geographical settings, commonly using sample data (Hardiman et al 1990; Köbrich et al 2003; Usai et al 2006; Graskemper et al 2021; Kaur et al 2021). For the case of Europe, Bartkowski et al (2022) give an overview of a multitude of farm typology studies, as well as their approaches and methods used. For Swiss alpine farms, Herzog et al (2013) highlight the heterogeneity and complexity qualitatively but do not provide a systematic overview of these farms. Therefore, no studies have quantitatively investigated the structure of alpine summer farms.

The remainder of this study is structured as follows: We first present background information on the Swiss alpine summer farms' trends, challenges, and current policy support. We then document the materials and methods used, including data and the analytical steps for building the typology. The results are then presented, followed by an initializing discussion of ways to improve and to address challenges via optimization and policy measures for each identified cluster, as well as a conclusion.

Background of Swiss alpine summer farms

In Switzerland, alpine summer farms serve as an extension of the fodder base during the summer months for, on average, 100 days and relieve production areas on the home farms for winter fodder production (Bürgi et al 2013). The farms and their pastures are located above the settlements inhabited year-round and below unproductive mountain areas (Federal Office for Agriculture 2021). As defined by the Swiss Federal Office for Agriculture, alpine summer farms "... are managed during the summer season and serve the summer grazing of ruminants ... they consist exclusively of grassland, which is adapted to the location and is to be used with graduated intensity" (Federal Office for Agriculture 2023a).

Alpine summer farms are important for Swiss agriculture because about 11% of the Swiss national territory and one third of its farmland—476,677 ha on average (2013–2018)—consists of summering pastures in the European Alps and Jura mountains (Herzog and Seidl 2018; Federal Statistical Office 2023). A substantial 25% of the total Swiss livestock is kept on alpine summering pastures from June to September (Mack et al 2013).

The traditional cultivation methods used in alpine summering pastures have established a greater diversity of species than would typically exist in purely untouched natural ecosystems (Mack et al 2013). Today, Swiss summering pastures have become biodiversity hotspots, hosting 250 vascular plant species, including 8 of the country's 12 endemic vascular plant species (Lauber et al 2013). They also encompass three quarters of the country's protected wetlands and dry meadows, highlighting their significance (Stöcklin et al 2007; Lauber et al 2013).

Trends and challenges

The number of summer farms declined from 7472 to 6663 between 2003 and 2021, leading to fewer farms and an increasing farm size (Gellrich et al 2008; Federal Office for Agriculture 2022). As farming practices modernize, smaller and family-owned alpine farms may struggle to adapt and subsequently stop farming, leading to a loss of cultural heritage, including local landscapes, traditional agricultural practices, and knowledge (von Glasenapp and Thornton 2011). There are 4 main factors that have accelerated this development.

First, although climate change leads to an increase in vegetation productivity, this is unlikely to outweigh negative effects, including reduced water availability, reduced albedo, thawing permafrost, and habitat loss (Rumpf et al 2022). Reduced water availability due to climate change may disrupt livestock management.

Second, although the number of farms has decreased steadily overall, the number of livestock sent to summering pastures between 2000 and 2021 has remained stable (Federal Office for Agriculture 2022). However, there are 2 underlying and opposing trends in livestock stocking that threaten biodiversity-rich alpine summering pastures, namely the abandonment of land and intensification of land use. These have also been observed in other European mountain regions (Pornaro et al 2013).

On the one hand, farmers have understocked or abandoned marginal grasslands in recent decades (Pornaro et al 2013; Spörri et al 2023). This has led to an annual decrease in available pastures of around 1000 to 2400 ha because of bush and forest succession (Gellrich et al 2007; Bollmann et al 2012; Herzog and Seidl 2018). This decline has been influenced by advances in dairy cow breeding, where cows struggle with energy deficits and give lower milk yields at higher elevations (Imfeld-Mueller 2013), making them unsuitable for steep slopes and marginal land (Federal Office for Agriculture 2022). Therefore, some farmers pursuing intensified milk production have lost interest in the traditional practice of summer farming. Although the number of suckler cows has tripled, this has only partially replaced the decline in dairy cows and heifers (Herzog and Seidl 2018).

On the other hand, where farmers still pursue dairy production, overstocking pastures with dairy cows results in overgrazing when dairy cows need to satisfy increasing energy demands from breeding advances (El Benni and Finger 2013; Herzog and Seidl 2018). To prevent degradation from overstocking and intensification, labor-intensive grazing management strategies, such as rotational pastures and active herding, are necessary but are financially viable only for larger herds (Schulz et al 2018). Therefore, biodiversity-rich alpine summering pastures are threatened by both the abandonment and the intensification of land use. Importantly, both processes can occur on a single farm pasture, mediated by the distance to the farm building.

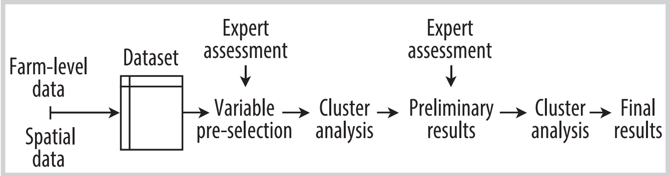
Third, and at an interplay with farm and farmland abandonment, the return of wolves has caused (the risk of) livestock depredation, which necessitates labor- and capital-intensive prevention measures. This human–wolf conflict can contribute to farm exit and farm structural changes (Mink and Mann 2022; Mink et al 2023).

Fourth, the limited availability of skilled laborers to look after livestock during the summer period can strain farm productivity. Because the job market in Switzerland offers more lucrative nonfarm employment opportunities, this increases farm labor opportunity costs. Even if the choice of working on an alpine farm is mainly driven by motivational values and not pecuniary ones (Calabrese et al 2014), attracting and retaining qualified and motivated workers to these remote farms with physically demanding work remains a key challenge for the maintenance of summer farms (Herzog et al 2016). Human–wolf conflict is an additional physical and psychological stressor that adds to the issue of labor scarcity, which can hinder efficient farm management and potentially lead to operational inefficiencies, as well as increased production costs.

Policy support

Various agricultural policy measures have been used to support alpine farms that are facing the above challenges, to varying degrees of effectiveness. These measures include direct payments, market support through labeling indicating geographical origin, research, extension services, and structural assistance. Direct payments consist of payments for livestock, ecological focus areas, and landscape quality to ensure both livestock stocking and biodiversity conservation. These direct payments are allocated based on NSUs. Market support involves government-backed labeling such as Protected Designation of Origin ("PDO/AOP"), protecting distinct alpine specialties in competitive markets (Maye et al 2016). Structural aid encompasses investment aid, property consolidation regulations, and cooperation between farms, including facilitating joint projects and initiatives, such as collective pasture management (Federal Office for Agriculture 2023b). Although agricultural policy assists alpine summer farms through financial support in countering structural changes, the suitability of these policy support measures for different farm types remains uncertain.

FIGURE 1 Data preparation and cluster analysis workflow incorporating expert assessment.



Material and methods

We used a mixed-methods approach to generate a typology of Swiss alpine summer farms, which we describe in a workflow diagram in Figure 1 and in more detail in the following sections.

In the first step, we connected farm-level administrative data (including structure and production orientation) and used the georeferenced farm location to add variables that depict the environmental conditions and accessibility of the farm in a single data frame (see Data). Then, we preselected variables for clustering, based on the approach described below under "Variables selection." In the first workshop, alpine farming experts from cantonal agricultural offices assessed the validity of the selected cluster variables. We subsequently ran the cluster analysis again. In the second workshop, we let the experts assess the results and then adjusted the cluster analysis (ie variable selection and number of clusters) based on their feedback. This produced the final results of the typology.

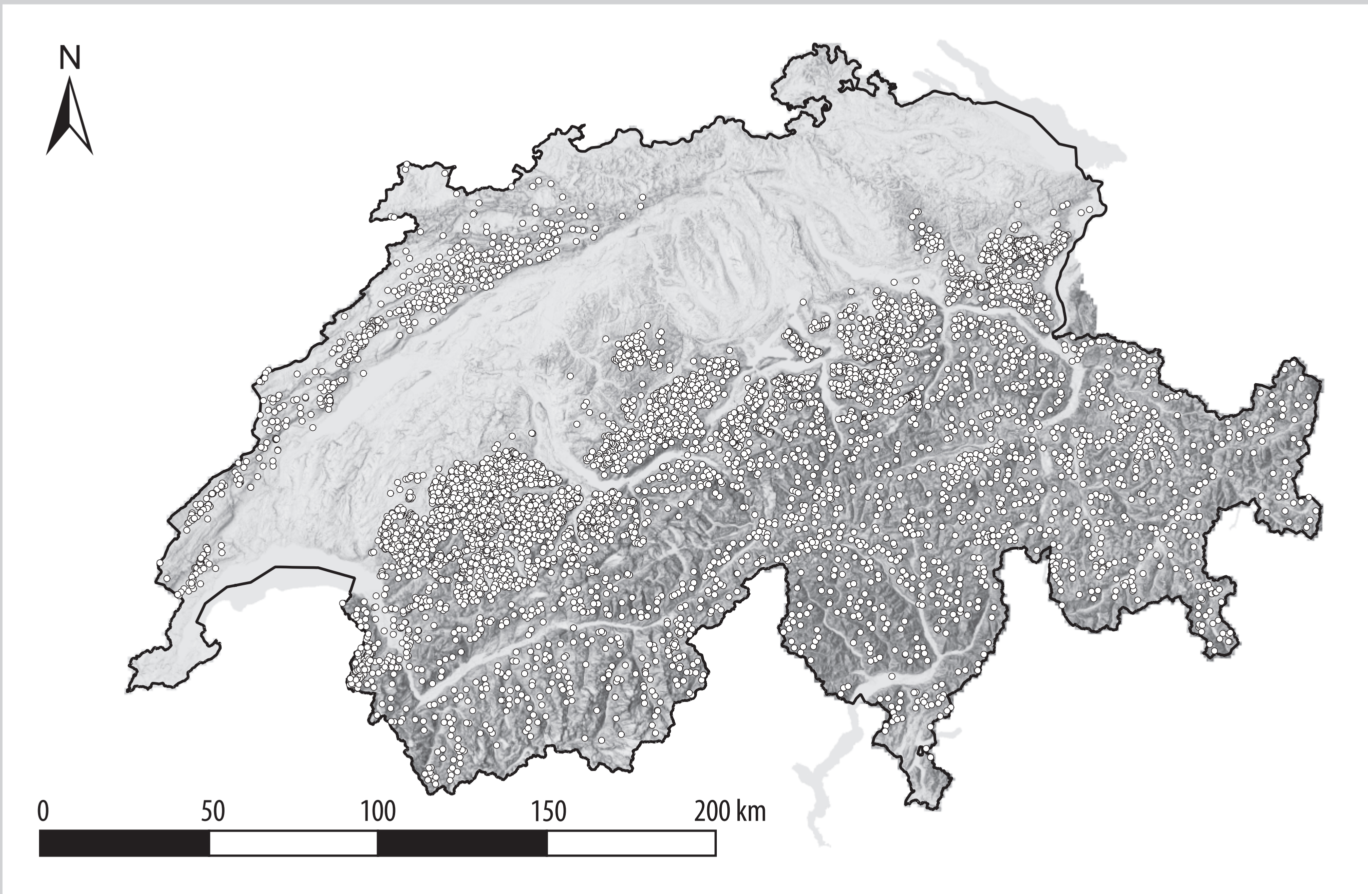
These workshops were held with 4 alpine farming experts from the Swiss cantons of Grisons, Valais, Uri, and Bern. These 4 cantons cover 43% of all Swiss alpine summer farms. We drew these experts from the overarching research network "Experimental Station Alpine and Mountain Farming," which the present study is embedded in and which aims at strengthening the resilience and sustainability of Swiss alpine farming (Meyer 2022).

Data

Our research relied on 2 sources of data. First, we obtained census data from the Swiss Agricultural Policy Information System, which included information from 5900 alpine summer farms. This dataset represented 87% of the total observations of the Swiss alpine farm population in 2021. The data covered variables on farm structure, ownership form, and information on farmed animals. The farm entities were either natural and legal persons or public corporations and municipalities with their civil law domicile or registered offices in Switzerland.

Second, the farm-level data were georeferenced, that is, the point location of the main farm building was given by x and y coordinates, which we have mapped in Figure 2.

FIGURE 2 Map of farm spatial distribution (white dots) in Switzerland (45°49′05″N and 47°48′30″N, and 5°57′23″E and 10°29′31″E). (Map by Maximilian Meyer; source of background image: swisstopo 2017)



The geographic farm building location allowed us to set the farm in relation to its spatial environment. We used data on roads and tracks provided by OpenStreetMap to depict the farms' accessibility. To do this, we analyzed whether roads or tracks were found in a 500 m buffer around the farm, where we used 500 m to account for potential uncertainty in both farm coordinates and accessibility data. We provide an illustrative example of assessing the accessibility of 2 farms in Figure 3.

The farm in the west has a tarred or dirt road in its buffer, so we considered it to be accessible by car or truck via a road, which contrasts with the farm in the east, which can only be accessed by foot via a track. Elevation was derived from a digital elevation model using the point value of the farm location. The digital elevation model is provided by the open government data platform opendata.swiss, which is publicly available at a 250 m grid resolution and measured as meters above sea level.

Variable selection

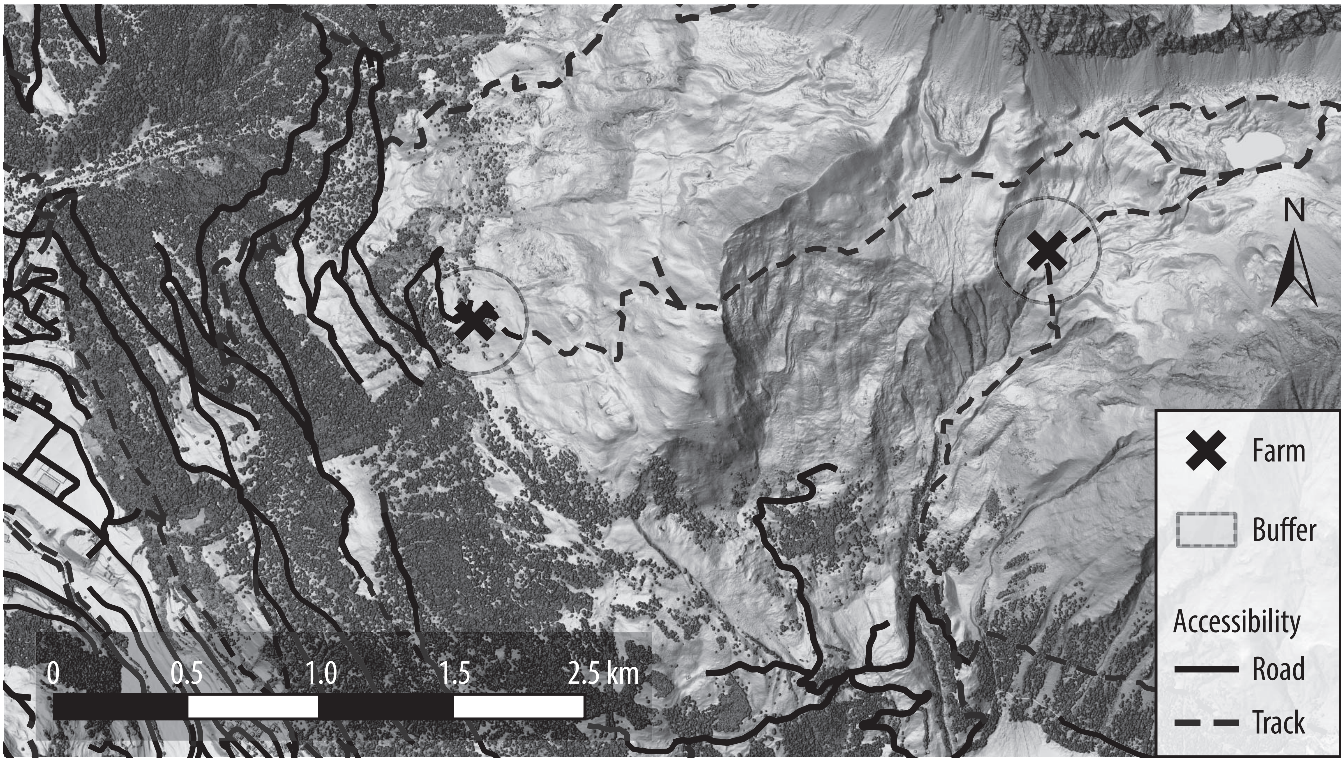
For the selection of variables, we followed the suggestions of Alvarez et al (2018), who stated that developing a typology should be directed by hypotheses concerning the unique characteristics of local agriculture, as well as the factors and processes contributing to variations among farming systems, such as biophysical and socioeconomic conditions. The hypotheses should be based on the typology objective, on prior expert knowledge, and on theories of farm diversity in the study area. The central question that underlies our selection of all variables was: What drives farm economic and environmental performance?

This is a relevant question because, first, a lack of profitability (as a measure of economic performance) was shown to be a key factor driving summering pasture abandonment since the 1950s (Schulz et al 2018), and second, the provision of diverse ecosystem services by summering pastures, including biodiversity (as a measure of environmental performance), is of societal interest.

Our analysis used 7 clustering variables that were selected based on the above procedure and on consultations in 2 workshops with experts. We explain the specification and underlying hypothesis for the selection of each variable as follows (see also Table 1).

1. *Total livestock* in NSUs: This is a proxy of the farm's herd size. It is designed to align with the pasture's carrying capacity and is, therefore, also linked to the size of the pasture; that is, higher NSUs indicate a larger farm area. These aspects have been shown to be important for economic performance (Blättler et al 2013; Raaflaub et al 2013).
2. Whether the farm has *dairy cows* (yes/no), and therefore produces milk: Milk production is one of the most important business activities in Swiss alpine farming, but it also has environmental implications because of

FIGURE 3 Illustrative example of assessing farm accessibility by using farm coordinates and OpenStreetMap data. (Map by Maximilian Meyer; source of background image: swisstopo 2020)



significant water usage and manure management (Rad and Lewis 2014; Herrero et al 2016).

3. Whether the farm has *sheep* (yes/no): Sheep are important for landscape management but also prone to wolf predation, thus requiring cost-intensive herd protection measures (van Eeden et al 2018; Pauler et al 2022; Vogt et al 2022). Wolf presence can also postpone lambing and calving and shift it spatially to wolf-proof barns. This tends to have a negative effect on the productivity of the mothers because the birth intervals are extended and the health risk inside a barn is increased.
4. Whether the farm has *cattle* (yes/no): Cattle are usually associated with extensive grazing, including suckler cows, and have gained importance in the last decade (Herzog and Seidl 2018). Although dairy cows sensu stricto belong to cattle, we defined cattle as all cattle except dairy cows. We abstained from using suckler cows as an additional clustering variable, as the requirements for forage quality and the associated labor time, for example, for herding for suckler cows, are similar to those of other cattle. A further distinction would also have increased the complexity of the typology without any gain in information. However, the challenges and corresponding policy support for these farms are likely similar.
5. The farm's *ownership* status (private single or collective): This captures the institutional arrangement of the farm and how and by whom decisions are made. This variable, therefore, depicts collective action, which has implications for economic performance (Barham and Chitemi 2009; Michalek et al 2018) but also environmental performance because of land degradation (Sklenicka 2016). For Swiss farms, Stevenson (1991) has shown that single ownership of private dairy farms has a substantial effect on economic performance. Further, although private farms in single ownership are often smaller in area, they do not necessarily have lower NSUs, because the area is more productive (Werthemann et al 1982). As private farms tend to be smaller, they may have higher structural costs and subsequently higher costs per unit output. Together, ownership plays a decisive role in farm performance.
6. The farm's *elevation* above sea level (in meters): This is an indicator of farm pastures' productivity resulting from environmental conditions and harshness (Ara et al 2021).
7. The farm's *accessibility*, where we distinguish between farms that have road connection by tarred or dirt road and those that do not (see the motivating example in Figure 3): This has an influence on the farm's production costs and market access, but also environmental performance, because accessibility is an important driver of land use and land cover change (Schielein et al 2021).

We provide summary statistics of all these variables in Table 1. Almost 90% of alpine summer farms host cattle, two thirds host dairy cows, but only 13% host sheep. A total of 65% of the farms are privately organized. The farms investigated are located at an average elevation of 1456 m, and 80% of them have a road connection to the main farm building.

Additionally, these selected variables are exogeneous to the farm; that is, they cannot be changed—at least not in the short run—by the farm. Therefore, future policy support may help in addressing the specific challenges of all farms in a given farm type/cluster that farmers themselves cannot adequately address.

TABLE 1 Summary statistics of variables used for clustering alpine summer farms to generate a farm typology.

Variable	Mean	SD	Median	Min	Max
Total NSUs	43.47	46.65	29.15	0.14	846.48
Has dairy cows (%)	67.63				
Has cattle (%)	88.54				
Has sheep (%)	13.14				
Is private (%)	64.17				
Elevation (m)	1456.40	387.89	1410.00	197.70	2647.87
Has road access (%)	80.57				

Note: SD, standard deviation; Min, minimum; Max, maximum.

Cluster analyses

We used a cluster analysis to develop a typology and group farms into homogeneous subgroups by minimizing within-group and maximizing between-group variance across the selected variables. As a clustering algorithm, we used partitioning around medoids (Kaufman and Rousseeuw 1990), which is based on the *k*-means algorithm and a partitioning method. The general principle of the algorithm is to minimize the average dissimilarities of a representative object to all other objects in the same cluster instead of minimizing the sum of the squared Euclidian distances between them. As a measure of dissimilarity, we used Gower's general similarity coefficient (Gower distance) because it makes it possible to measure the dissimilarity between 2 sampling units, regardless of type (dichotomous [existent/nonexistent], qualitative and quantitative characteristics) and, therefore, the level of the variable's scale of our mixed data (Gower 1971).

We determined the optimal number of clusters by (1) choosing the number of clusters that had a sufficiently large silhouette coefficient and (2) using feedback from expert workshops. We iteratively assessed both the clustering variables and associated outcomes with alpine farming experts in 2 workshops (see Figure 1) and reran our analysis based on the insights and critique, as suggested by Alvarez et al (2018). Drawing on their regional expertise, the experts diligently examined cluster assignments by considering geographical, socioeconomic, and cultural factors, using their knowledge of common patterns. Through collaborative discussions, they critically evaluated the findings, questioning variable selection and cluster validity, which led to a refined understanding of emerging patterns. As an example, after a discussion, annual precipitation was excluded from the cluster variables because it was correlated with elevation and therefore contributed little gain in information. Their valuable insights improved the typology's coherence and relevance to our research objectives.

Robustness of findings

The results of a classification may be sensitive to different methodological choices and the variables used for the classification. For this reason, we address the robustness of our findings in the following section.

First, we conducted hierarchical clustering as a robustness check, which can be found in Appendix S1 (*Supplemental material*, https://doi.org/10.1659/mrd.2023.00041.S1). This analysis corroborated the findings obtained with the partitioning around the medoids approach; that is, the results yielded very similar clusters.

Second, the variables *accessibility* and *elevation*, as well as *has sheep* and *has cattle*, are correlated, which may influence the results. In 2 separate runs, we therefore excluded elevation as well as *has sheep* and reran our analysis. This yielded very similar results to the main findings; that is, the clusters would have been interpreted the same way and therefore given the same names. This made us confident that this correlation does not influence the results, while taking into account elevation and sheep as clustering variables yields a more differentiated picture, giving clear-cut types that can be described and named well.

Third, one could argue that our results could be generated using a simple classification, based on expert judgment. However, cluster analysis can uncover patterns within the data without any predefined labels, as opposed to classification, which requires a labeled dataset to predict the class or category of new, unseen observations. Given that we did not know and did not want to assume any alpine farm types beforehand, we consider cluster analysis an appropriate method to create a farm typology.

Results

We present the results from the *k*-medoids cluster analysis in Table 2, which lists the identified typology of Swiss alpine summer farms. The optimal number of clusters was found to be 6, which corresponds to a silhouette coefficient of 0.65, indicating good within-cluster cohesion and between-cluster separation.

To interpret the clusters, we used 1 to 3 characteristics that were unique and distinguished the type from other types to make it distinct. Cluster 1 was characterized by a dominance of dairy cows (100%), with all farms being privately owned; therefore, we interpreted this cluster as *private dairy farms*. This form of alpine farming was the dominant form of farming and encompassed 2180 farms in total (37% of all farms investigated). In Cluster 2, the second largest type (23%), all farms were communally owned, with a mix of dairy cows and cattle, suggesting the title *communal mixed cattle and dairy farms*; notably, these farms had a substantial size of 73.82 NSU. Cluster 3 (8%) stood out with its communal ownership structure and dominance of cattle farming (94%); we named it *communal cattle farms*. Cluster 4 (9%) was characterized by remoteness because of the lack of

TABLE 2 Swiss alpine summer farm typology using *k*-medoids cluster analysis: summary statistics for private dairy farms (Cluster 1), communal mixed cattle and dairy farms (Cluster 2), communal cattle farms (Cluster 3), remote farms (Cluster 4), small private cattle farms (Cluster 5), and sheep farms (Cluster 6).

Cluster	Number of farms	% of all farms	Total NSUs	Has dairy cows (%)	Has sheep (%)	Has cattle (%)	Is private (%)	Elevation (m)	Has road access (%)
1	2180	37	37.01	100	4	97	100	1372.49	100
2	1350	23	73.82	100	6	97	0	1464.16	96
3	467	8	36.43	0	6	94	0	1355.45	80
4	523	9	46.08	87	13	98	72	1800.94	0
5	855	15	20.57	0	3	96	100	1275.48	91
6	517	9	33.08	0	91	6	72	1831.42	22

Note: Except for the number of farms and the percentage of all farms (Columns 2 and 3), mean and frequency values are presented for the clustering variables by cluster.

road access and high average elevation of 1800.94 masl, suggesting the term *remote farms*. This cluster was characterized by a mix of dairy cows (87%), cattle (98%), and sheep (13%). Cluster 5 (15%) had private ownership exclusively and hosted on average 20.57 NSU of cattle, which made it the cluster with the smallest farm size, so we called this type *small, private cattle farms*. Finally, because Cluster 6 was characterized by mainly hosting sheep (91%), we called it *sheep farms*. With the highest average elevation of 1831.42 masl, these farms also had limited road access (22%) and hosted 30.88 NSU.

Discussion and conclusion

Seasonal grazing of alpine pastures supports farmers and ecosystems globally. In Switzerland, climate change–related water scarcity, labor shortages, and human–wolf conflicts threaten these farms and the biodiversity of alpine summering regions. To date, the Swiss government has provided one-size-fits-all support to alpine summer farms, but understanding their diversity is crucial for this support to be effective. The present study improves our understanding of the farms' structure by developing a typology of Swiss alpine summer farms through creating and analyzing a novel dataset that includes farm-level and spatial information. To ensure the validity and reliability of the quantitative analysis, a qualitative assessment of the typology by cantonal agricultural experts was used in a mixed-methods approach. This is the first analysis to quantitatively characterize Swiss alpine farms by taking into account spatial environmental data on farm location and accessibility. This will help in the design of efficient farm support policies, extension services, and, ultimately, a transformation toward more sustainable and resilient alpine farming.

Compared with similar studies that have utilized cluster analysis to characterize different farming systems (Hardiman et al 1990; Köbrich et al 2003; Usai et al 2006; Graskemper et al 2021; Kaur et al 2021), our study complements the literature by covering 87% of the farm population of interest and not just a sample. Combined with the qualitative assessment provided by cantonal experts, this makes this farm typology a robust tool of high relevance for policymakers in Switzerland.

This typology is also of relevance for an international audience and scholars who plan to analyze the economic performance of farms in mountain regions with very heterogeneous structures and patterns. We achieved this by both systematically clustering the studied farming system and integrating accessibility, which is an important characteristic of mountain farms, into the typology. Because we used open-access OpenStreetMap data, available globally, other researchers may follow suit and implement this characteristic to improve future farm typologies in mountain areas.

Drawing from the cluster characteristics and findings from the literature on Swiss alpine farming, we anticipate challenges for the 6 clusters and propose optimization and policy measures to support these farms.

Pastures of the clusters *private dairy farms* and *communal mixed cattle and dairy farms* are likely challenged by intensification through steady increases in forage requirements by dairy cows (Pauler et al 2020). This can result in overgrazing, soil erosion, and high nutrient input on more accessible pastures, closer to the main farm building. We argue that the process of extensification, and resulting bush encroachment, is less likely on farm types with dairy cows. Providing sufficient forage to their dairy cows with higher energy demands to produce adequate milk yields is important to farmers, making them more likely to invest more time in pasture maintenance. Both *communal cattle farms* and *small, private cattle farms* practice extensive grazing and are likely to invest less in pasture maintenance, which can result in bush encroachment and subsequent loss of biodiversity. Intensification also occurs because regulated NSUs per farm have not been adjusted to the increasing forage requirements of dairy breeds arising from recent advancements in livestock breeding. This creates a mismatch between the historically set NSUs and the new feed requirements of dairy cows (Schulz et al 2018), which is a result of the 2 trends in livestock stocking. To address this mismatch, potential solutions could involve (1) enhancing grazing management, including increased rotational grazing systems that balance dairy cow and cattle forage demands, or (2) adjusting NSU regulation for livestock types according to their specific forage requirements. This is in line with findings of Finger and El Benni (2021), who highlighted that direct payments, although increasingly tailored, often overlook local conditions, including animal forage requirements.

The findings by Schulz (2011) and Schulz et al (2018) indicate that it may be difficult for *remote farms* to find sufficient livestock for the summer period because of difficulties in access. This can cause understocking of pastures, leading to bush encroachment and loss of biodiversity (Bühlmann et al 2014; Pauler et al 2022). To prevent understocking, accessibility could be enhanced, for example, through investment in transport infrastructure or by subsidizing livestock transportation to remote farms.

The results by Gueydon (2012), Blättler et al (2013), and Raaflaub et al (2013) for Swiss and German alpine farms showed that labor input per NSU decreases as herd size increases, whereby farms with high numbers of NSUs generate above-average income per working hour. This implies that the smaller farm types we identified, especially *small private cattle farms,* may be comparatively less competitive. Stronger policy support tailored to their size may be needed for these farms if the goal is to preserve traditional small-scale farming, which is commonly family owned.

The average size of *sheep farms* (30.88 NSU) corresponds to roughly 200 sheep, which Eiselen (2012) showed to be too small for herd protection measures to be established and for farming to be economically viable. However, herd protection measures are increasingly important because of the risk of predation from rising wolf populations (Mink et al 2023). Although direct payments for herding are increasing with each policy reform (Federal Statistical Office 2022), these farms could profit from merging of farms or collective farming, utilizing economies of scale, which may also help retain qualified and motivated workers when farms are collectively well managed.

In future research, we will apply the typology to empirically investigate the economic and environmental performance of the 6 alpine farm types, and to analyze their resilience and the challenges they face. This includes full cost accounting for each farm type, investigating the challenges to long-term farm employment through a comprehensive survey, and assessing the resilience of alpine farming. The typology could also be the basis for establishing distinct zones for alpine farms with varying production difficulties to account for differences in production costs, similar to the approach used for farms operating year-round in lower-lying mountain regions of Switzerland and Austria. Based on these investigations, exploring which specific policy and farm optimization measures suit each farm type can support sustainable and resilient alpine farming.

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Supplemental material

APPENDIX S1 A typology of Swiss alpine summer farms: cluster analysis documentation.

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