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Mapping risks and landscapes: conservation insights for Italian small ruminant populations

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Local livestock breeds are valuable genetic resources that support ecosystem services, cultural identity, and the sustainability of animal husbandry. However, these populations face increasing threats from intensive farming, land abandonment, and environmental risks. This study aimed to assess Italian small ruminant populations' exposure to environmental threats and distribution across different landscapes. Therefore, we integrated geolocation data of 3,712 active registered farms of 41 goat and 47 sheep breeds with publicly available data on environmental hazards, including seismic activity, landslides, floods, and projected climate change, alongside landscape characterization maps of Italy. Additionally, we evaluated extinction risks based on effective population size (Ne) and calculated biodiversity indices at the provincial level to describe small ruminant biodiversity in Italy. Our findings indicate that over a quarter of Italian small ruminant populations are at short-term risk of extinction, while nearly half face long-term threats. The two most pressing environmental concerns include seismic risk, particularly for breeds in southern Italy, and climate change projections indicating shifts to warmer and drier conditions, especially for Alpine breeds traditionally adapted to colder environments. Landscape characterization revealed that sheep farming is predominantly associated with agricultural landscapes, whereas goat farms are more frequently linked to woodlands and mountainous areas. Each breed exhibits specific environmental adaptations, underscoring their role in sustainable land management. Biodiversity analyses highlighted significant regional disparities, with high diversity in provinces such as Cuneo and Frosinone, whereas others exhibit limited breed representation. Understanding the spatial distribution of local breeds, their exposure to environmental risks, and their interactions with landscapes is essential for developing targeted conservation strategies. Integrating ecological, genetic, and spatial data allows for effective prioritization of conservation efforts to safeguard genetic diversity, support rural communities, and promote sustainable livestock farming.

KEYWORDS

biodiversity, climate change, environmental hazards, sheep, goats, local breeds, animal genetic resources

Introduction

Small ruminants are widely distributed worldwide due to their exceptional adaptability to a variety of climatic and managerial conditions and to their ability to provide valuable products even in harsh environments with minimal inputs (Clutton-Brock, 1999; Silanikove and Koluman, 2015). Italy, known for its rich agricultural heritage and diverse landscapes, has a significant small ruminant sector, accounting for approximately 10% of the total ruminant population in the country. This makes Italy one of the leading producers of sheep and goat milk, as well as renowned cheeses, in Europe (Ismea, 2022; 2023; Bionda et al., 2024). By contrast, sheep and goat meat play a minor role in Italian production, although their consumption remains strongly tied to traditional holiday celebrations such as Christmas and Easter (Ismea, 2022; 2023; Bionda et al., 2024). While the sector has been moving toward intensification and the increasing prominence of specialized breeds (Pardo and del Prado, 2020), local animal genetic resources—comprising 64 sheep breeds and 41 goat breeds—continue to play a crucial role in maintaining biodiversity and supporting sustainable agricultural systems in the Italian farming panorama (Iommelli et al., 2022; Dubeuf et al., 2023).

The interconnection between livestock and landscapes is profound, particularly for local breeds, which are often reared in extensive and traditional systems. These breeds are uniquely adapted to their environments, forming a strong interconnection with the landscape they inhabit (Hoffmann et al., 2014; FAO, 2015a; Rojas-Downing et al., 2017; Cortellari et al., 2021). The effects of grazing on landscapes, however, remain a topic of debate. On one side, husbandry practices can have detrimental consequences, especially when linked to overstocking, overgrazing, and unsustainable land management. These negative impacts include excessive defoliation, land degradation, soil erosion, and water quality deterioration, all of which threaten ecosystem stability and biodiversity (Bilotta et al., 2007; Minea et al., 2022). However, well-managed livestock grazing has been widely demonstrated to exert substantial positive effects on ecosystems. Sustainable grazing and browsing enhance plant and animal biodiversity, improve land cover, reduce the risks of firebreaks and avalanches, help control weeds and invasive species, and promote habitat connectivity (Nardone et al., 2004; Hoffmann et al., 2014). These ecosystem services are particularly significant in remote and marginal areas, which are often at risk of abandonment if not for the presence of local livestock populations, especially sheep and goats (Pardini and Nori, 2011; Primi et al., 2025).

Local breeds provide much more than ecosystem services. They are essential to the livelihoods of rural communities, serving as a primary source of income, while also being deeply embedded in cultural traditions. In many cases, these breeds have become integral parts of the landscapes themselves, reflecting a harmonious interplay between people, animals, and the environment (Hoffmann et al., 2014). If, on the one hand, this strong bond between animals and their territory has allowed local populations to adapt to harsh environmental conditions, on the other hand, it also makes them vulnerable to climate change. Rising temperatures have been extensively documented to have direct and indirect negative effects on livestock production, reproduction, and survival (FAO, 2015a; Sarangi, 2018; IPCC, 2021). However, climate change is not only causing gradual temperature increases but also leading to a rise in the frequency and intensity of extreme weather events, which further exacerbate the challenges faced by livestock and their ecosystems.

Italy, in particular, is highly susceptible to geological, hydrological, and hydraulic instability, and climate change is aggravating these issues. The probability of extreme weather-related risks in Italy has increased by 9% over the past two decades (Spano et al., 2020). The country is facing a significant rise in both droughts and episodes of heavy rainfall (Zittis, 2024). The hydrogeological characteristics of the Italian landscape, combined with climate change and other non-climatic factors such as increasing urbanization, are worsening the situation. Floods, landslides, and forest fires are common, and their risk is escalating (Gariano and Guzzetti, 2016; Cramer et al., 2018; Palagiano, 2020; ISPRA, 2021; Trigila et al., 2021). On top of this, Italy is one of the Mediterranean countries with the highest seismic risk. The most affected areas are concentrated along the Apennine mountain range, extending to Calabria and eastern Sicily, with severe consequences in terms of both human lives and economic losses (Crowley et al., 2009). These natural disasters impose significant costs, both in terms of human casualties and financial damages. The livestock sector is no exception: earthquakes, hurricanes, landslides, and floods can destroy hundreds of stables and kill thousands of animals, leading to long-term repercussions such as resource shortages and the spread of diseases (FAO, 2015b; Migliaccio et al., 2018; Ismea, 2024). Furthermore, such disasters pose a serious risk to biodiversity. This is particularly critical for local breeds, which are often small in population size and geographically concentrated (Alderson, 2009), as in the case of Italian local sheep and goat populations (Bionda et al., 2024).

In light of these considerations, this study aims to provide an overview of the environmental risks posed by extreme weather events to Italian sheep and goat populations, enabling a better understanding of the specific exposure of each breed and the development of more effective management plans. Furthermore, it analyses the landscape and territorial characteristics of the regions where these populations are reared, with the aim of fostering management strategies that valorize Italian livestock and environmental resources by promoting the sustainable coexistence of livestock farming, biodiversity conservation, and ecosystem health.

Materials and methods

Farm data

The present study included data of all the farms registered to the Italian Sheep and Goat Breeders Association (Asso.Na.Pa.)

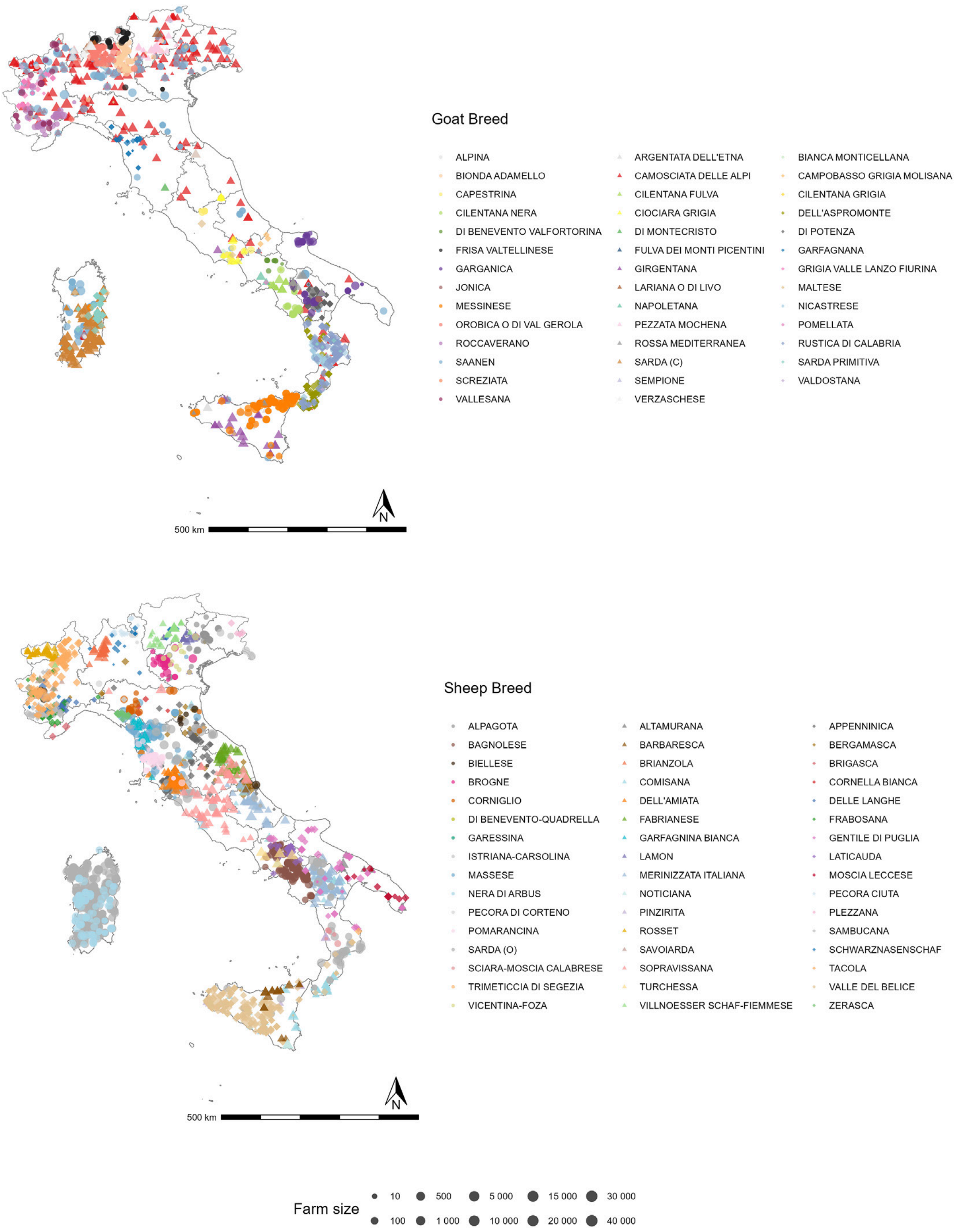

FIGURE 1
Distribution and size of Italian registered goat and sheep farms.

and operational as of 31st December 2022. Asso.Na.Pa. is the sole authorized organization in charge of managing sheep and goat herd books in Italy and keeps a record of reliable and accurate geolocation and management data for Italian sheep and goat farms and breeds. Using these data, the effective population size (Ne) was calculated for all the breeds using Wright's formula based on sex ratio (Wright, 1931).

The dataset included 1,349 goat farms, rearing a total of 124,524 animals across 41 populations. Concerning sheep, 2,363 farms were investigated, hosting 315,204 heads belonging to 47 populations (Figure 1). All the breeds studied were Italian local populations, except for the Saanen goat, which originated in Switzerland but is widely bred in Italy. For the purposes of this study, Camosciata delle Alpi and Saanen goats, along with Sarda sheep, will be considered specialized breeds, as they undergo genetic selection and are typically raised in intensive or semi-intensive production systems. A more detailed description of these data is provided in Bionda et al. (2024); Supplementary Table S1.

After retrieving the GPS coordinates for each farm, a circular buffer with a 10-km diameter around their exact location was calculated with ArcGIS Pro Desktop 3.0.2's *Buffer* tool to account for their physical extension and the fact that typically sheep and goats graze in the areas around the farm. This same extension has already been used in other studies, such as Bertolini et al. (2018).

Environmental data

Natural hazards

Maps (in .shp file format) and data related to flood and landslide risks were made publicly available by the Italian Institute for Environmental Protection and Research (ISPRA) (ISPRA, 2021; Trigila et al., 2021). The classification of landslide hazard zones (attention zone – AA, moderate hazard – P1, medium hazard – P2, high hazard – P3, and very high hazard – P4) was based on four categories, considering both the probability of occurrence and the magnitude of the landslide events, which were evaluated using events' speed and geometric severity by adapting the procedure developed by the Swiss Federal Office for the Environment (Supplementary Figure S1A). The flood hazard classification follows the definitions outlined in D.Lgs. 49/2010, identifying three scenarios: low hazard (P1, low probability of flood events or extreme scenarios), medium hazard (P2, recurrence interval between 100 and 200 years), and high hazard (P3, recurrence interval between 20 and 50 years) (Supplementary Figure S1B).

The classification of seismic zones (updated in April 2023) was retrieved from data published by the Italian Civil Protection Department (Supplementary Figure S1C). Data were provided as a table listing all Italian municipalities with their respective classification. Using this table, we created a polygon shapefile representing seismic risk. Seismic classification in Italy is defined by four main zones based on the territory's acceleration on rigid ground (ag) with a probability of exceeding equal to 10% in 50 years: High seismicity (Zone 1, $ag > 0.25$ g), Medium-high seismicity (Zone 2, $0.15 \text{ g} < ag \leq 0.25$ g), Medium-low seismicity (Zone 3, $0.05 \text{ g} < ag \leq 0.15$ g), and Low seismicity (Zone 4, $ag \leq 0.05$ g).

Data on present (1980–2016) and projected future (2071–2,100) Köppen-Geiger climate classifications (Supplementary Figure S2, definitions in Supplementary Table S5) were obtained as raster files at a 1-km resolution from Beck et al. (2018). This classification system defines five main climate classes, further subdivided into 30 subtypes based on seasonal temperature and precipitation patterns. Future climate projections were derived using the anomaly method, incorporating 32 climate models under the RCP8.5 scenario (Beck et al., 2018). The climate classes present, or expected to be present, in Italy are:

- Dry – Semi-arid steppe – hot (BSh): Low annual precipitation, hot summers.
- Dry – Semi-arid steppe – cold (BSk): Low annual precipitation, cold winters.
- Dry – Arid desert – cold (BWk): Very low precipitation, cold winters.
- Temperate – No dry season – hot summer (Cfa): Hot and humid summers, cool-to-mild winters.
- Temperate – No dry season – warm summer (Cfb): Cool summers and mild winters, relatively narrow annual temperature range and few extremes of temperature.
- Temperate – Dry summer – hot summer (Csa): Hot and dry summers, mild and wet winters.
- Temperate – Dry summer – warm summer (Csb): Warm and dry summers, mild and wet winters.
- Continental – No dry season – warm summer (Dfb): Four distinct seasons with large seasonal temperature differences, having cold winters and warm-to-hot summers.
- Continental – No dry season – cold summer (Dfc): Long and cold winters, short warm-to-cool summers.
- Continental – Dry summer – warm summer (Dsb): Extreme seasonal changes with cold or very cold and wet winters and warm and dry summers.
- Continental – Dry summer – cold summer (Dsc): Cool and dry summers, long and cold winters.
- Polar – Ice cap (EF): Perennial ice cover, extremely cold year-round.

A more detailed definition for all the classes is provided in Supplementary Table S5.

Landscape characterisation

Italian socio-ecological landscape characterization data were retrieved from ISPRA, including physiographic types, ecosystems, land cover, land use, and naturalistic-cultural value. The physiographic types map (.shp format, 1: 250,000 scale) (Amadei et al., 2000) identifies landscape units with homogeneous litho-morphological and land cover characteristics, as well as a specific geographic connotation (Supplementary Figure S3A). Therefore, characterizing the physiographic context of small ruminant breeding ranges can help in understanding how litho-morphological and land-cover conditions shaped and shape adaptation and management strategies; indeed, historically, small ruminants have been mainly raised in marginal areas where other activities were not feasible. The Authors of this map grouped these landscape units into seven main categories: low plain, hilly, tabular hills, mountainous, tabular mountains, depressed landscapes in mountainous areas, and landscapes characterized by singularity. The complete description of all the categories can be found in Annex 1 of APAT (2003).

The 2018 map of Italian ecosystems (Supplementary Figure S3B) and 2021 maps of land cover and land use (raster files with a 10x10 m resolution) (Supplementary Figure S3C, D, respectively), were retrieved from the ISPRA website (ISPRA, 2025). These maps, reported to have been generated by combining data from the Copernicus Land Monitoring Service (2018) with the Italian National Map of Soil Take (2021) from ISPRA (SNPA, 2024), provide distinct but interconnected information. According to Directive 2007/2/EC, land cover refers to the "physical and biological cover of the earth's surface, including artificial surfaces, agricultural areas, forests, (semi-)natural areas, wetlands, and water bodies." Following the definition of the same Directive, land use describes the actual biophysical status of the territory "according to its current and future planned functional dimension or socio-economic purpose." A more detailed definition for land use and land cover categories has been translated and adapted from Munafò (2023) and reported in Supplementary Tables S9, S10, respectively. The Ecosystem Map of Italy is based on land cover and potential natural vegetation data and identifies 84 ecosystem types grouped into 11 main categories, which we used for our analyses (Blasi et al., 2017). In the context of the present study, each of these spatial layers provides a different perspective on the landscape: land cover informs about the actual physical and biological surface—such as vegetation type or bare ground—that livestock are directly exposed to and interact with; land use captures the functional dimension of the territory, reflecting how humans manage or intend to manage the land (e.g., for agriculture, forestry, or settlements), thus offering insights into anthropogenic pressures and livestock farming systems; and the ecosystem classification, by integrating land cover with potential natural vegetation, provides a more holistic ecological framework that reflects the broader biotic and abiotic characteristics of the territory.

ISPRA also provided a shapefile on the naturalistic-cultural value (NCv) of the Italian territory, which was calculated for each physiographic unit (Supplementary Figure S4A). This index integrates a cultural score given by the presence of cultural and environmental goods, such as protected areas and parks, and the number of PDO and PGI enogastronomic products, with a naturalistic evaluation based on the landscape type and variability and the anthropic impact (Capogrossi et al., 2017). Assessing NCv in breeding ranges can provide information about the influence of small ruminant breeding on the development of landscapes of high environmental and cultural significance: indeed, many PDO and PGI products, included in the cultural evaluation, originate from local breeds and represent a tangible link between biodiversity, gastronomy, and cultural identity. In addition, in areas with particularly high NCv, careful planning is needed to ensure harmonious coexistence between breeding activities and the preservation of natural ecosystems.

Additionally, we included data from the Red List of Ecosystems in Italy (Zavattero et al., 2023), classified according to the International Union for Conservation of Nature (IUCN) criteria for ecosystem collapse risk assessment (Supplementary Figure S1B). These criteria consider reductions in geographic distribution, restricted distribution, degradation of the abiotic environment, and disruptions in biotic processes or interactions. A comprehensive description of all ecosystems (from the aforementioned Map of Italian Ecosystems) and their risk status can be found here in Annex C3 of Zavattero et al. (2023). Relating breed distribution to ecosystems at different collapse risk levels allows evaluation of the reciprocal relationship between livestock and their habitats. Breeds can be vulnerable to habitat degradation, but they can also influence ecosystem condition—negatively through overgrazing or habitat alteration, or positively by providing ecosystem services such as vegetation management, biodiversity maintenance, and fire prevention.

Livestock biodiversity indices

To assess biodiversity in terms of Italian local populations of sheep and goats, we utilized farm geolocation and size data at the provincial level to compute various biodiversity indices. Although typically used for wild species, these indices can also be well-suited to describe livestock distribution. Specifically, we calculated the Shannon Diversity Index (H'), the Inverse Simpson Index (1/D), and the Gini-Simpson Index (1 - D) (Shannon, 1948; Simpson, 1949; Jost, 2006) using the vegan package in R (Oksanen et al., 2025).

The Shannon's Diversity Index (H′) quantifies both breed diversity and evenness, while the Gini-Simpson Index, which ranges from 0 to 1, represents the probability that two randomly selected individuals belong to different breeds. The Inverse Simpson Index (1/D) provides an estimate of the "effective number of breeds" within a given area, meaning the number of equally abundant breeds that would generate the same diversity level as observed.

Additionally, we derived Pielou's Evenness Index (EH) from the Shannon's Diversity Index, calculated as the ratio between H′ and log (Richness), where Richness corresponds to the total number of recognized breeds in Italy. This index, which ranges from 0 to 1, quantifies the uniformity of breed distribution across farms (Pielou, 1966).

To evaluate whether differences in these indices could be related to the size of the provinces, we also calculated corrected index values by dividing each by the logarithm of the respective province area. In addition, the Spearman correlation between the indices and the total province area was assessed using the *cor.test* function from the stats package.

Data analysis

For each farm, we calculated the percentage of its buffer area covered by different hazard or landscape classes. When environmental data were in shapefile format (landslide hazard, flood hazard, seismic risk, physiographic types, and naturalistic-cultural values), we used ArcGIS Pro's *Tabulate intersection* tool, whereas for raster maps we applied the *exact_extract* function from the exactextractr package (Baston, 2024) in R (version 4.4.1 for all the analyses performed in this study). Data were then summarized by breed and species.

Figures representing the environmental maps were generated using sf and ggspatial packages for shapefile maps (Pebesma, 2018; Dunnington, 2023) and the raster and tidyterra packages for raster files (Hernangómez, 2023; Hijmans, 2025).

A principal component analysis (PCA) was performed with summary indices for provinces and breeds using *prcomp* function and plotted using a modified version of *ggbiplot* function from ggbiplot R package (Vu and Friendly, 2024). In the context of this study, PCA was used to explore patterns of variation among breeds and provinces based on multiple environmental risk and demographic indicators. This method is particularly effective for summarizing and visualizing complex datasets, such as the one that includes both geographically explicit variables—e.g., seismic and hydrogeological risk, climate change projections, and ecosystem vulnerability—and non-geographical variables, such as Ne and biodiversity indices. PCA helps identify the linear combinations of these variables—interpreted as composite measures of exposure to different risks—that best explain the distribution of breeds or provinces in the multivariate space. This approach not only highlights the variables contributing most to the observed variation, but also allows the identification of breeds or areas facing simultaneous threats, which may not be apparent when considering each risk factor in isolation, and/or that, sharing similar risk profiles, might benefit from similarly designed interventions.

For both goat and sheep breeds, the following variables were included: effective population size (Ne), the percentage of area with high or very high naturalistic-cultural value (NCv), the percentage of area with ecosystem risk classified as vulnerable or higher, the percentage of area in seismic zones 1 or 2, the percentage of area with landslide hazard classified as P3 or P4, the percentage of area with medium or high flood hazard, and the percentage of farms predicted to experience a shift in Köppen-Geiger climate classification. The Sarda sheep breed was excluded due to its exceptionally high Ne value. In the PCA, all variables were expressed as percentages except for Ne, which was measured as an absolute count. To prevent the different numerical range of Ne from disproportionately influencing the principal components, we applied a log transformation and then scaled Ne. Percentage-based variables were left unscaled because they all had a possible range of 0–1, making them directly comparable without the need for further scaling. Moreover, standardizing them would have artificially increased the weight of variables with a lower observed range, whereas, by maintaining their original scale, we preserved the relative impact of each risk factor while ensuring a meaningful interpretation of environmental risk and landscape characterization.

At the province level, the PCA included Gini-Simpson index for Italian domestic small ruminant populations, the percentage of the province classified as having high or very high NCv, the proportion of the province in seismic zones 1 or 2, the percentage of land with medium to high flood hazard, the percentage of the territory classified as P3 or P4 for landslide risk, the proportion of ecosystems considered vulnerable or at higher risk, and the percentage of the province expected to experience a shift in Köppen-Geiger climate classification. Since the possible range of all the variables was 0–1, they were not scaled. Conducting analyses at the provincial level—alongside those focused on breeds—allows us to extend our considerations beyond the current distribution of small ruminant farms. This broader territorial perspective facilitates the identification of areas where other species might be affected or where shifts in livestock distribution may occur in the near future. Moreover, it aligns with the scale at which many policy decisions are made, as interventions are often planned and implemented at the level of provinces or regions rather than for specific breeds alone.

The same datasets used for the PCA were also analyzed using hierarchical clustering to identify groups of breeds or provinces with similar characteristics. We applied the *hclust* function from the stats package, using the "ward.D2" method. The optimal number of clusters was determined with the silhouette method, as implemented in *fviz_nbclust* from the factoextra package (Kassambara and Mundt, 2020), complemented by a visual inspection of the dendrogram. In addition, a heatmap showing the mean values of each variable for each group was generated using pheatmap (Kolde, 2019).

Results

Effective population size

The computation of Ne revealed that among goat breeds (median = 123, IQR = 29–500), 15 (36%) have a value below 50, indicating a short-term risk of extinction, while 16 (38%) fall within the 50–500 range, suggesting a long-term risk of extinction. For three goat populations, the estimated Ne was 0: the Alpina (an ancient population that likely gave rise to most of the breeds reared in the Alpine region), the Fulva dei Monti Picentini (originating from Campania, once considered extinct and recently rediscovered), and the Screziata (a dairy breed from

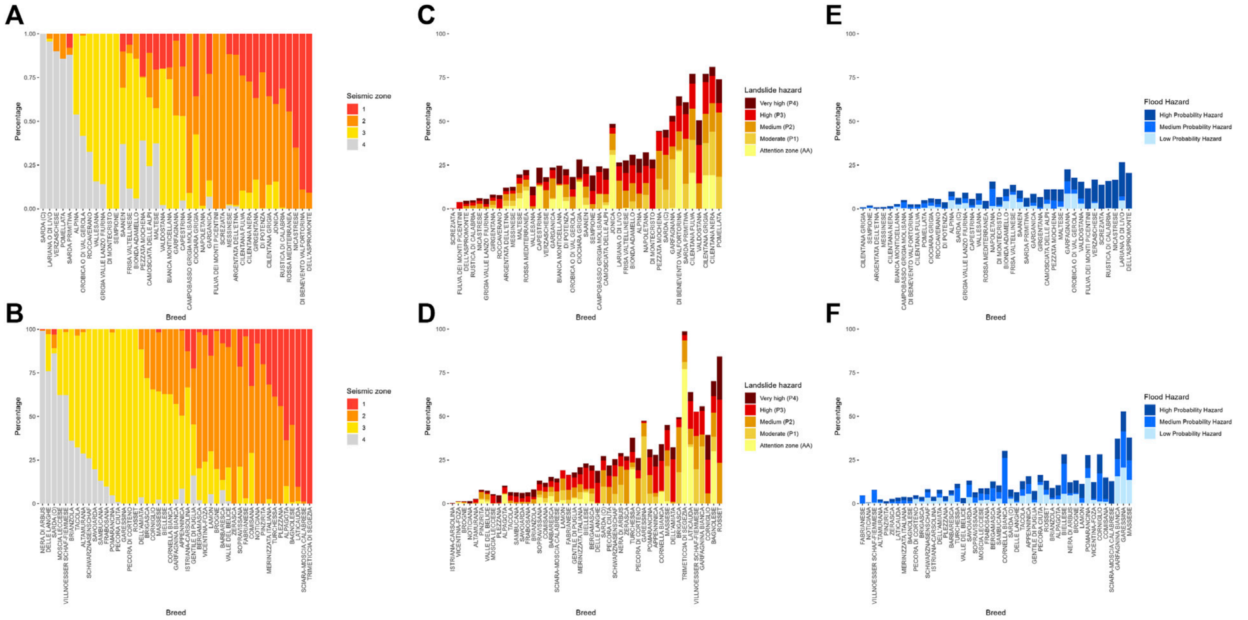

FIGURE 2
Percentage of small ruminant farm area located in different seismic zones [**(A,B)** for goat and sheep populations, respectively], landslide hazard areas [**(C,D)** for goat and sheep populations, respectively], and flood hazard areas [**(E,F)** for goat and sheep populations, respectively]. Breeds have been ordered according to their weighted hazard score.

the Campania region, believed to be related to the Napoletana breed and African goats, named for its characteristic speckled coat) (Bigi and Zanon, 2020).The situation for sheep populations (median = 226, IQR = 117–656) is only slightly better, with 9 (18%) breeds having a Ne below 50 and 25 (51%) falling between 100 and 500. For three populations, Ne was estimated at 0: the Garessina (a Piedmontese population subjected to extensive crossbreeding with both Italian and Merino breeds), the Pinzirita (an ancient Sicilian breed possibly of Asian origin, adapted to harsh mountainous environments), and the Trimeticcia di Segezia (a synthetic meat breed recently developed through crosses of Gentile di Puglia × Ile de France × Württemberg) (Bigi and Zanon, 2020). Ne estimation for all the breeds is reported in Supplementary Table S1.

Natural hazards

Seismic risk

A significant portion of small ruminant farms is located in areas with high seismic risk (seismic zones 1 or 2), affecting 45% of goat and 40% of sheep farms. However, risk exposure varies by breed (Figures 2A,B; Supplementary Table S2). Nineteen goat breeds (e.g., Dell'Aspromonte, Di Benevento, Nicastrese) and 18 sheep breeds (e.g., Trimeticcia di Segezia, Sciara-Moscia Calabrese, Laticauda) have more than 75% of their breeding range in high-risk seismic areas. Most of these breeds are concentrated in Calabria. In contrast, Sarda and Lariana goats, along with Nera di Arbus and Delle Langhe sheep, are located in zones with minimal seismic risk.

Hydrogeological hazard

Landslide hazard

The analysis of landslide hazard revealed that seven goat breeds (Figure 2C), including Pomellata, Cilentana, and Valdostana, and four sheep breeds (Figure 2D), such as Rosset, Bagnolese, Corniglio, and Garfagnina Bianca, have over one-third of their breeding range in moderate to high landslide risk zones (P2-P4 areas). Values for all zones and breeds are reported in Supplementary Table S3.

Flood hazard

Flooding is a relatively low concern, especially for goat farms, as few farms are located in high-risk flood zones. Specifically, only nine farms had more than half of their buffer area located within high-probability hazard zones, while 41 farms—all raising sheep of different breeds—were located within high- or medium-probability hazard zones. However, when considering the entire breeding range, some breeds face higher risk levels, including Dell'Aspromonte and Lariana goats, as well as Massese, Garessina, and Garfagnina Bianca sheep, with nearly 50% of

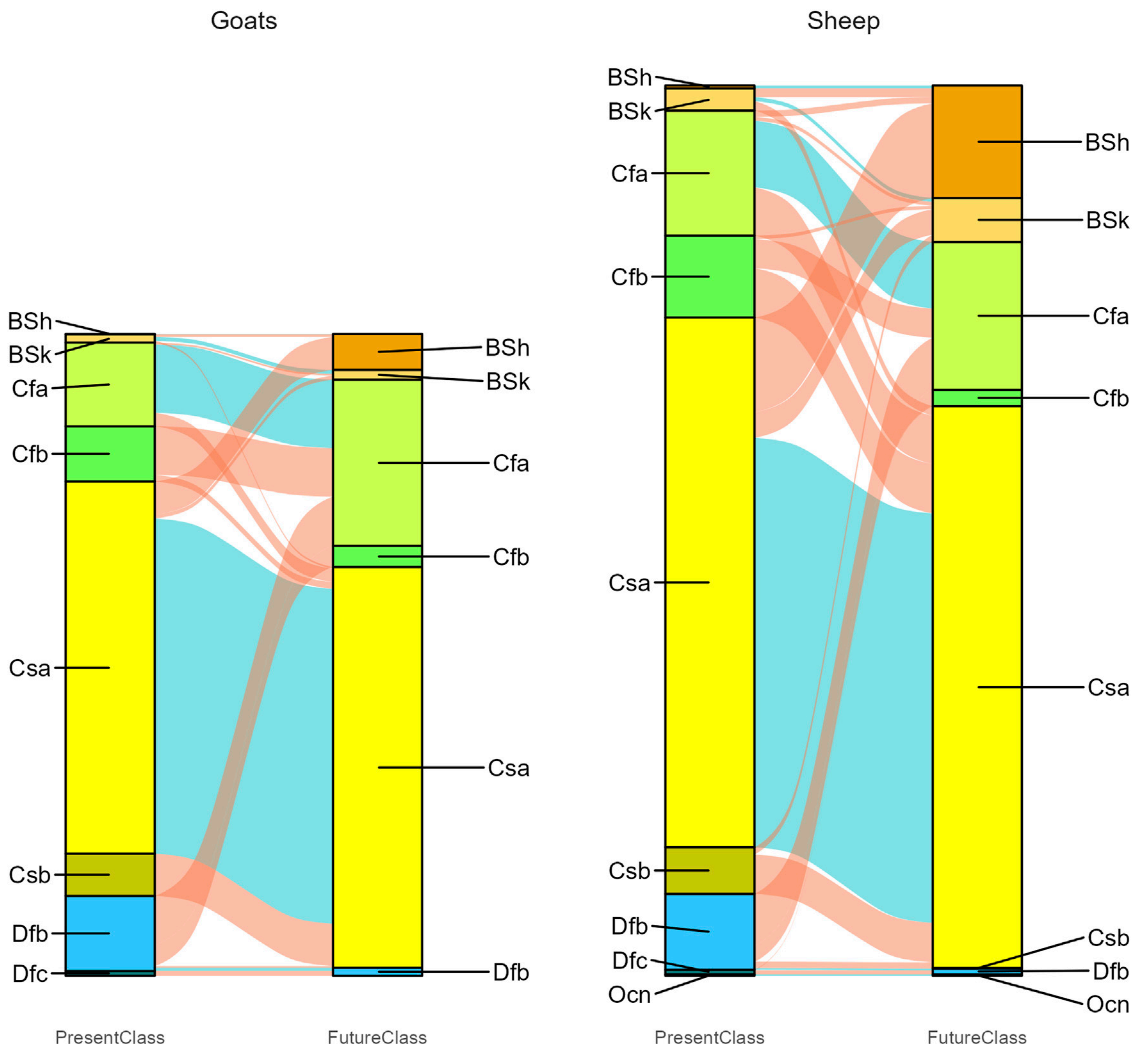

FIGURE 3
Alluvial plot of expected switching in Köpper-Geiger climate class for goat and sheep farms.

their territory at risk of flooding (Figures 2E,F; Supplementary Table S4).

Present and projected future climate classification

Currently, 47% ± 32% of goat farms' area covers Csa Koppen-Geiger climate class, followed by Csb (14% ± 17%) and Dfb (12% ± 18%). Sheep farms are similarly distributed, with 57% ± 44% in Csa and 13% ± 30% in Cfa (Supplementary Table S5).

Projected climate changes indicate that 45% of sheep farms and 36% of goat farms will shift to warmer and/or drier climate zones (Figure 3). Almost all the farms currently in the coldest climate classes are expected to change their class (72% if considering Cf- and Df-classes, 97% if considering only Df-classes). For example, we observed that Dfb and Dfc farms will shift to Cfa and Dfb classes, Cfb farms will shift to Csa or Cfa, and Csb farms will transition to Csa. Moreover, many farms (17%) currently in Csa will move into Bsk or Bsh classes.

For 18 goat and 27 sheep breeds, over half of their farms are likely to undergo climate classification changes, including, for example, all Verzaschese goat and Pecora di Corteno farms, which for the most will shift from Dfb to Cfb class.

Landscape characterization

Ecosystems

Small ruminant farms in Italy are primarily situated in Agricultural areas and Forest and woodland ecosystems. However, there are clear differences between sheep and goat farms (Figures 4A,B, respectively; Supplementary Table S6). Agricultural areas are more prevalent among sheep farms

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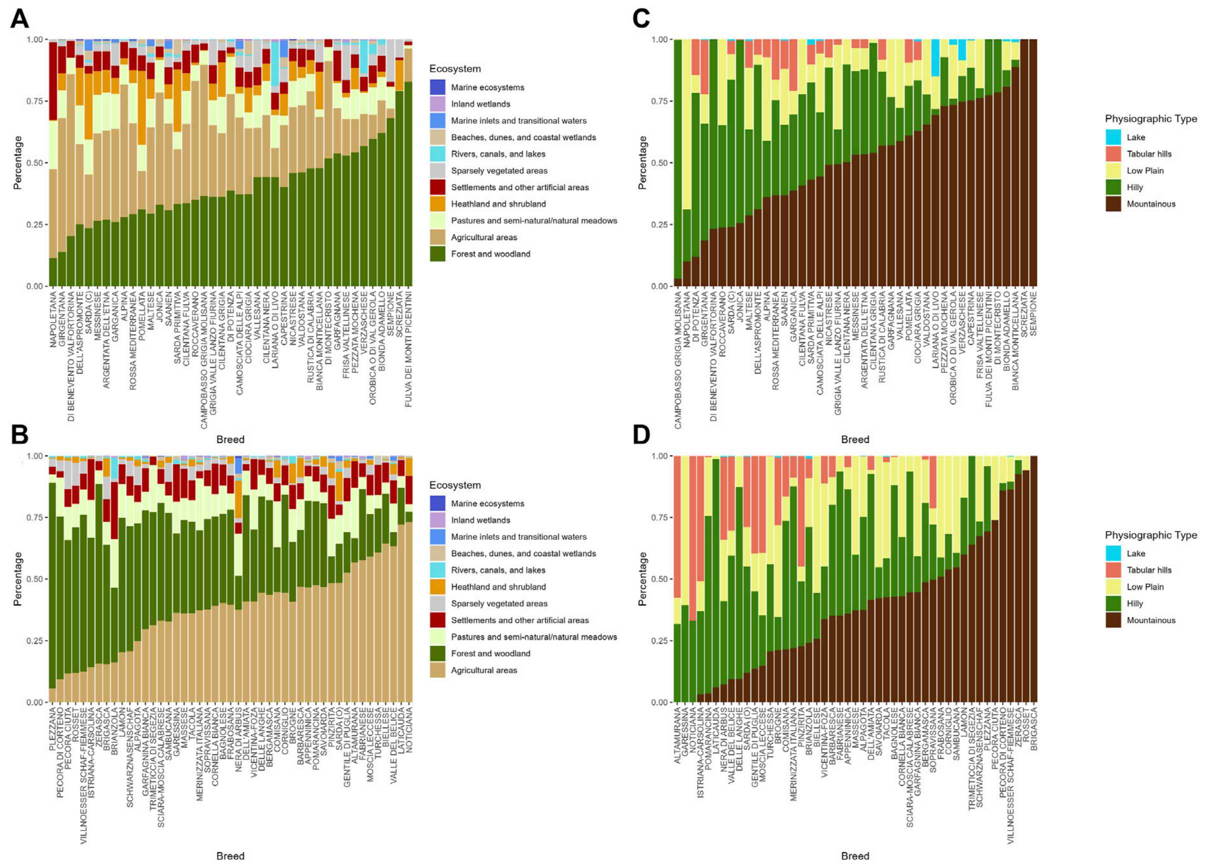

FIGURE 4
Percentage of small ruminant farm area covered by different ecosystems [**(A,B)** for goat and sheep populations, respectively] and main categories of physiographic type [**(C,D)** for goat and sheep populations, respectively]. Breeds have been ordered according to the percentage of the most represented category of the species; categories have been ordered according to their percentage at the species level.

(39% ± 17%) compared to goat farms (30% ± 15%), while Forest and woodland dominate in goat farming (42% ± 16% vs. 37% ± 18% in sheep). Both species also rely on Pastures and semi-natural/natural meadows, which comprise approximately 11% of the farmed area.

Regional variations further distinguish these ecosystems. Agricultural areas are most significant in sheep farms located in central (42% ± 24%), southern Italy (47% ± 24%), and the Islands (54% ± 24%), whereas Forest and woodland ecosystem plays a crucial role in northern Italy and, for goats, also in central Italy. Heathland and shrubland are particularly relevant in Sardinian and Sicilian farms (11% for sheep, 18% for goats) and are notably represented in the Pomellata goat breed.

The farms rearing the two specialized goat breeds, Camosciata delle Alpi and Saanen, present two distinct patterns of ecosystem characterization: farms in southern Italy and the Islands are predominantly in Agricultural areas, while those in northern and central Italy are mainly in Forest and woodland regions. The Sarda sheep, predominantly located in Sardinia, is primarily associated with Agricultural areas across its distribution.

Physiographic types

Mountainous terrain is the dominant physiographic type for small ruminant farms, especially for goats (52% ± 24% vs. 38% ± 27% for sheep). Hilly areas also support a substantial portion of both sheep (31% ± 22%) and goat farms (30% ± 22%).

Among breeds (Figures 4C,D; Supplementary Table S7), 21 out of 41 goat breeds and 13 out of 47 sheep breeds are found in regions that are at least 50% mountainous. Notable exceptions among goats include Campobasso Grigio Molisana, predominantly located in hilly regions, and Napoletana, which is mainly found in low plains. For sheep, the Altamurana, Noticiana, and Istriana-Carsolina breeding ranges also cover tabular hills.

Land cover and land use

Analysis of land cover data revealed that both sheep and goat farms are mostly found in areas covered by broad-leaved trees

(37% ± 13% and 42% ± 13%, respectively) (Supplementary Figures S5A,B; Supplementary Table S8). For sheep farms, periodic herbaceous vegetation is the second most common land cover type (23% ± 13%), whereas goat farms are more often associated with permanent herbaceous vegetation (16% ± 5%). A notable exception is observed in north-eastern goat farms, where needle-leaved tree cover dominates (38% ± 27%). This is particularly evident for Frisa Valtellinese, Sempione, and Pezzata Mochena goat breeds, as well as some sheep breeds such as the Pecora di Corteno and the Fiemmese.

Forestry is the predominant land use for Italian small ruminant farms, accounting for 39% ± 23% of goat and 29% ± 24% of sheep farms' extension (Supplementary Figures S5C,D, respectively; Supplementary Table S9). Arable land is also significant for sheep, particularly in central-southern Italy and the islands. Several goat breeds, including Pomellata, Sarda Primitiva, and Sarda, are associated with non-economic land uses, whereas some sheep breeds, such as Pinzirita and Moscia Leccese, are found on permanent crops or other agricultural land uses.

Naturalistic-cultural value (NCv)

On average, goat farms are located in regions with higher NCv than sheep farms. Specifically, 23% ± 19% of goat farms are in high or very high NCv areas, compared to 11% ± 13% for sheep farms.

Marked regional differences emerge, with the highest NCv values recorded for goat farms in the north-east, followed by those in southern Italy and the Islands. Conversely, Sardinian and Sicilian sheep farms have the lowest NCv. Among breeds, Brigasca and Pecora di Corteno sheep, along with Screziata and Cilentana goats, exhibit the highest NCv, whereas Noticiana and Valle del Belice sheep, as well as Campobasso Grigia Molisana and Alpina goats, have the lowest values (Supplementary Figures S6A,B; Supplementary Table S10).

Ecosystem collapse risk

Most of the farms (52% ± 21% sheep, 40% ± 19% goats) are on agricultural lands not considered at risk. However, about 42% and 55% of sheep and goat farm territory, respectively, extends on near threatened or more vulnerable regions.

Among the farms in most endangered locations, we found the north-eastern goat farms (about 70% in nearly threatened or vulnerable ecosystems), whereas goat farms located in Sicily and Sardinia are for 19% ± 14% in endangered ecosystems and 32% ± 22% in vulnerable ecosystems. Among sheep, northern farms are more often found in nearly threatened and vulnerable areas. At a breed level, particular attention should be paid to the Screziata, Pomellata, and Lariana goats as well as Plezzana sheep, which are largely present in endangered and vulnerable areas (Supplementary Figures S6C,D; Supplementary Table S11).

Among specialized breeds, over 70% of Sarda sheep farms are in agricultural lands. However, it is to be noted that the two north-western Sarda farms are located for 26% ± 9% of their extension in endangered areas and that the numerous Sarda farms on the islands are for 11% ± 14% on endangered ecosystems and 18% ± 16% on vulnerable ecosystems. Both the Saanen and the Camosciata delle Alpi breeds show variable risk levels, with approximately 40%–50% of farms in at least nearly threatened ecosystems, except in Sicily and Sardinia, where 79% of farms are on agricultural lands.

Provincial biodiversity indices

Biodiversity indices describing small ruminant breed diversity were calculated for each Italian province (Figure 5). The highest Shannon Diversity Index (H′) values were observed in Cuneo (1.86), Frosinone (1.76), and Ravenna (1.69), which also exhibit the highest Gini-Simpson Index (1-D = 0.81, 0.81, and 0.79, respectively) and Inverse Simpson Index (1/D = 5.27, 5.21, and 4.80, respectively). Notably, Cuneo harbors 16 breeds, especially represented by Delle Langhe, Sambucana, and Frabosana sheep, whereas both Frosinone and Ravenna host eight breeds. However, the highest species richness was recorded in Turin (17 breeds), although the population is largely dominated by Frabosana (20%) and Tacola sheep (56%), with only a limited number of breeds such as Alpina, Bionda dell'Adamello, and Maltese goats.

Conversely, Chieti, Imperia, Modena, Pesaro-Urbino, Piacenza, Rovigo, and Venice each support only one breed. Excluding these provinces, the lowest diversity values were found in L'Aquila (H' = 0.06, 1-D = 0.02, 1/D = 1.02) and Trapani (H' = 0.07, 1-D = 0.02, 1/D = 1.02). Both provinces maintain four breeds, yet their populations are overwhelmingly dominated by a single breed: Merinizzata Italiana sheep in L'Aquila and Valle del Belice sheep in Trapani.

We also assessed whether these indices were correlated with province area using Spearman correlation. We found a correlation of 0.23 for both 1/D and 1–D ($p = 0.0239$), and 0.26 for H' ($p = 0.0102$). After correcting the indices using the logarithm of area, all provinces previously described maintained their relative rankings across all indices, with the exception of the adjusted 1–D index. In this case, Ravenna, Como (originally in fourth position based on unadjusted values), and Frosinone showed higher values, while Cuneo followed in fourth position. At a broader geographic scale (Table 1), southern Italy exhibits the highest small ruminant biodiversity (H' = 2.65, 1-D = 0.91, 1/D = 10.57), with 45 populations raised in the region. In contrast, the lowest diversity indices were found in the islands (H' = 1.39, 1-D = 0.59, 1/D = 2.43), despite hosting the largest total number of registered small ruminants (over 14,500 individuals). This low biodiversity can be attributed to

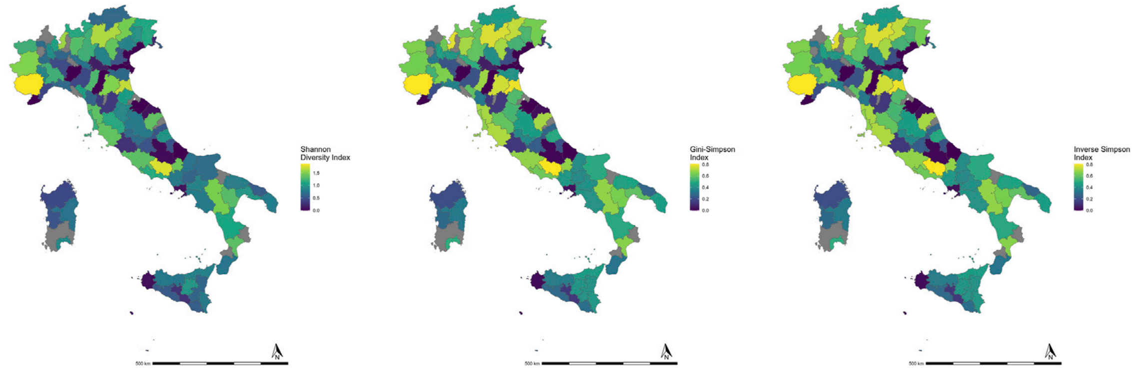

FIGURE 5
Shannon Diversity Index, Gini-Simpson Index, and Inverse Simpson Index indicating domestic small ruminant biodiversity at the province level in Italy. Higher values indicate greater biodiversity.

TABLE 1 Livestock biodiversity indices calculated at the macroregional level in Italy for sheep and goat populations.

Macroregion	Shannon diversity index	Gini-Simpson index	Inverse Simpson index	Pielou's evenness index	Richness
Northwestern Italy	2.56	0.89	8.71	0.57	29
Northeastern Italy	2.49	0.88	8.49	0.56	29
Central Italy	2.30	0.86	7.31	0.51	31
Southern Italy	2.65	0.91	10.57	0.59	45
Islands	1.39	0.59	2.43	0.31	21

both the lowest breed richness (21 breeds) and the predominance of Sarda sheep, which account for 62% of the total population.

Principal component and clustering analyses

By breed

A PCA describing sheep and goat breeds was performed including variables related to their effective population size (Ne), as well as the naturalistic-cultural value, environmental and ecosystemic risks, and projected climate change of their breeding range. In the PCA for goat breeds, the percentage of the breeding range located in seismic zones 1 or 2 is the primary driver of PC1 (eigenvalue = 0.87), which explains 44% of total variance, followed by the percentage of farms expected to experience a climate classification shift (−0.44). PC2 (explained variance = 23%) primarily reflects climate change (0.78) but also accounts for seismic risk (0.41) and Ne (−0.42), which has the greatest influence on PC3 (−0.85), which explains 14% of variance. Given the high correlation with geographically-explicit variables, as expected, in the PC1-PC2 plot (Figure 6A), breeds appear clustered by geographic location: Southern Italian and Sicilian breeds, which are highly exposed to seismic risk, are positioned on the right; Central Italian and Sardinian breeds are at the bottom; and Northern breeds, mainly affected by future climate change, are on the left. Of particular interest are the breeds located in the top-right quadrant, such as the Screziata, the Fulva dei Monti Picentini, and the Campobasso Grigia Molisana, as these populations have a low Ne and inhabit areas exposed to both seismic risk and climate change. Further insights can be gained from the PC1-PC3 plot (Figure 6B): breeds with a very small effective population size are positioned at the top, with those more affected by climate change than seismic risk on the left, and *vice versa* on the right.

Hierarchical clustering analysis indicated three as the optimal number of clusters; however, since four groups were clearly distinguishable in the dendrogram, we analysed them in more detail (Figures 6C,D). The grouping largely reflected geographical distribution and partially overlapped with the PCA results. Group 1 mainly comprises breeds from Sardinia and central Italy, characterized by moderate-to-low environmental risk—except for the moderate-to-high landslide hazard—and located in ecosystems with high collapse risk but low NCv. Group 2, which includes most of the southern and Sicilian breeds, is associated with highly valued areas and high Ne, yet faced high seismic risk. Group 3 contains the vast majority of northern breeds—excluding Alpina and

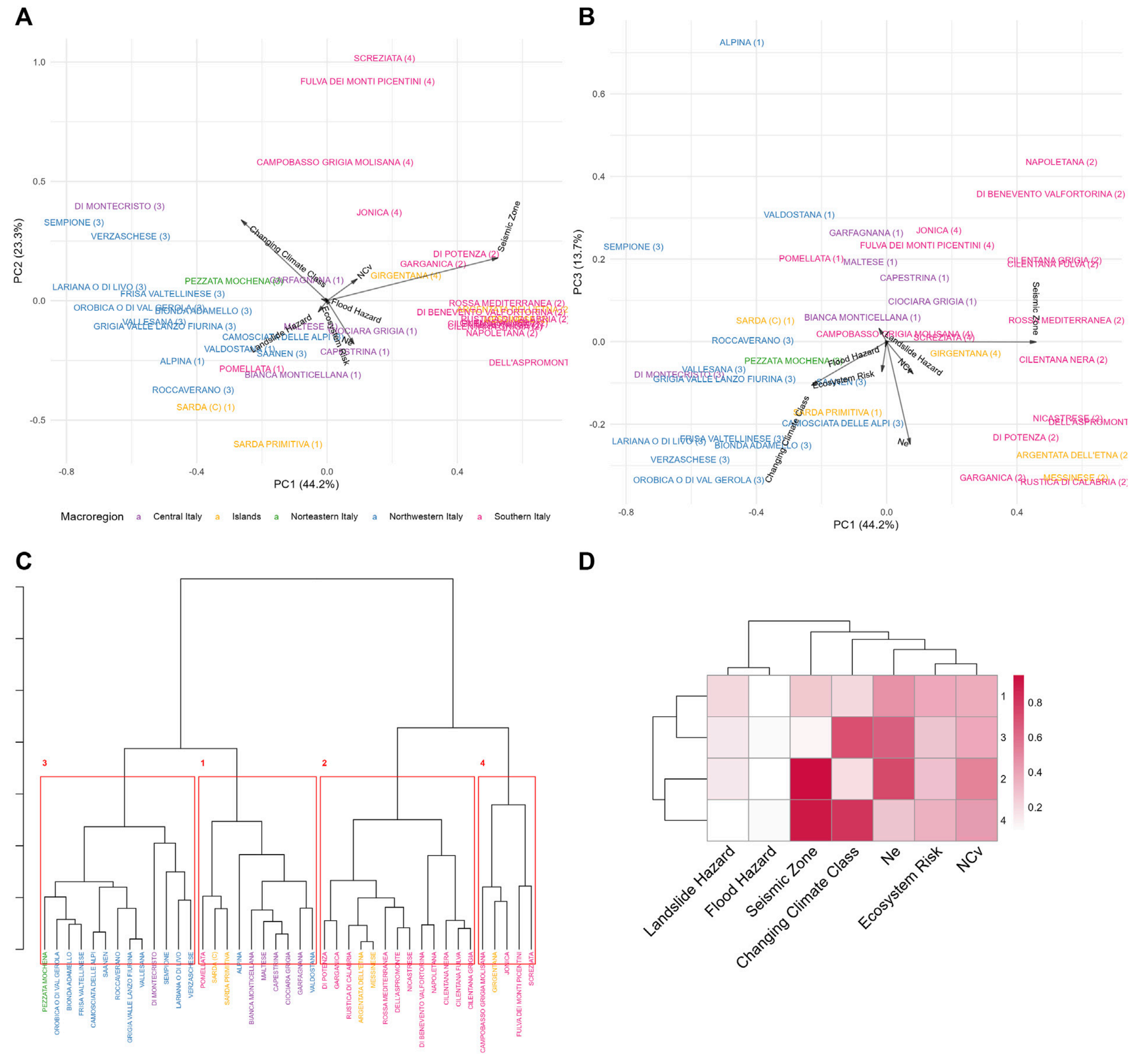

FIGURE 6
Principal component analysis [PCA; **(A,B)**] and hierarchical clustering **(C,D)** of goat breeds. Breed names are coloured according to their macroregion of origin. In the PCA, the number in parentheses indicates the cluster shown in **(C,D)**. According to the silhouette method, the optimal number of clusters is three, corresponding to groups 4, 2, and 3 + 1. In the heatmap **(D)**, the average value of all variables is reported for each analysed cluster.

Valdostana—as well as the Di Montecristo population; this group is mainly characterized by the highest flood hazard, high exposure to climate change, and low seismic risk, with other parameters at average levels. Finally, Group 4 includes four breeds from southern Italy plus the Girgentana goat, all of which are exposed to extinction risk due to low Ne, climate change, and seismic hazard.

For sheep breeds, PC1 (explained variance = 47%) is mainly driven by seismic risk (eigenvalue = −0.95), with high-risk breeds positioned on the left of the plot. PC2 (explained variance = 23%) primarily identifies breeds expected to undergo future shifts in Köppen-Geiger climate classification (−0.89) while also incorporating Ne (−0.36). In the PC1-PC2 plot (Figure 7A), populations exposed to both risks cluster in the bottom-left quadrant, including, for example, the Plezzana and Noticiana. When analyzing PC1 and PC3 (Figure 7B)—where PC3 explains 13% of variance and is mainly associated with Ne (0.91) and, to a lesser extent, expected climate change (−0.39)—breeds in the bottom-left quadrant, such as the Pinzirita, the Trimeticcia di

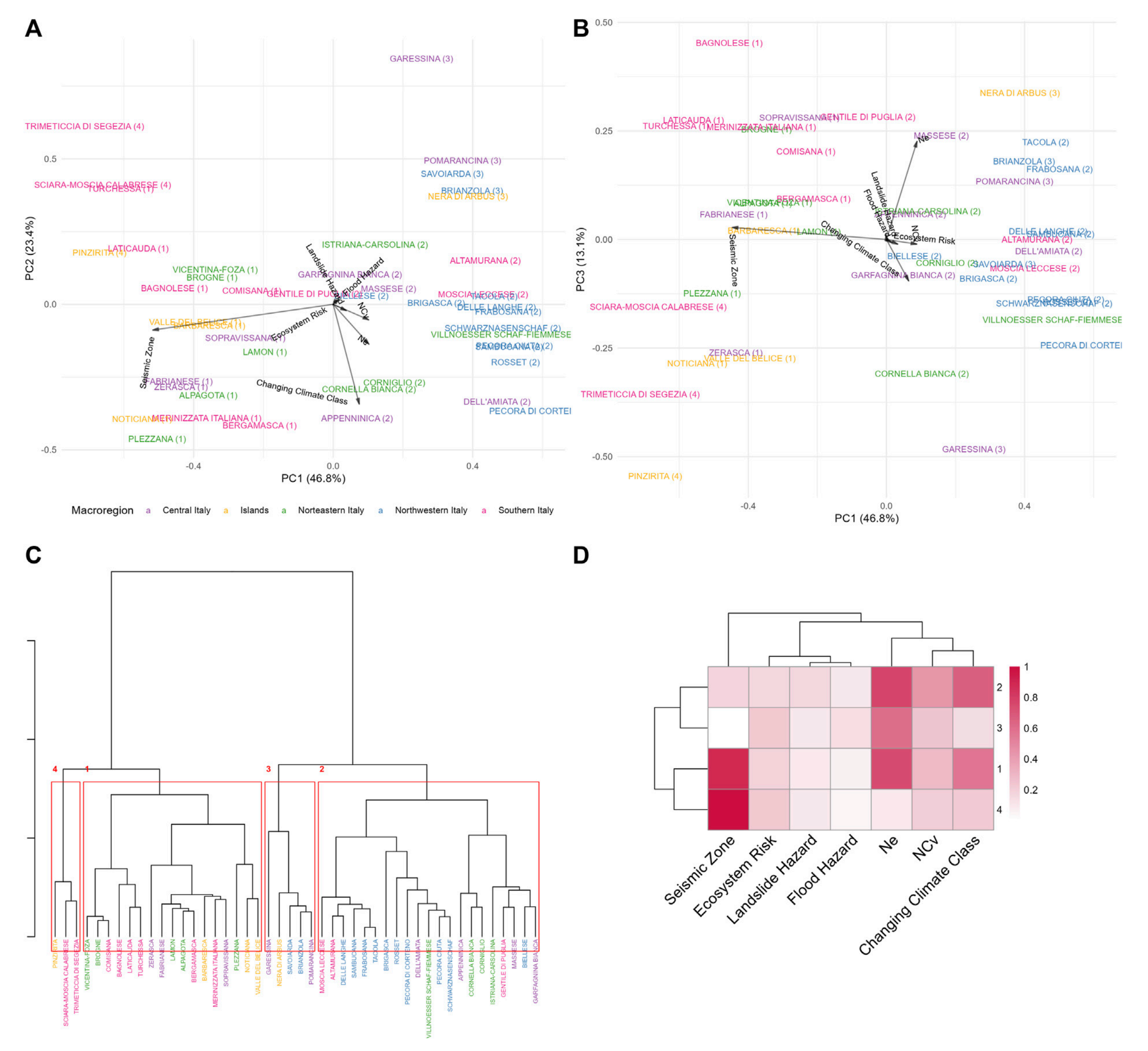

FIGURE 7
Principal component analysis [PCA; **(A,B)**] and hierarchical clustering **(C,D)** of sheep breeds. Breed names are coloured according to their macroregion of origin. In the PCA, the number in parentheses indicates the cluster shown in **(C,D)**. According to the silhouette method, the optimal number of clusters is two, corresponding to groups 1 + 3 and 4 + 2. In the heatmap **(D)**, the average value of all variables is reported for each analysed cluster.

Segezia, and the Noticiana, warrant special attention, they being small in size and exposed to significant seismic risk.

Hierarchical clustering identified two main subgroups of sheep breeds: the first comprises breeds with low Ne, located in areas with low NCv but high risk of ecosystem collapse and exposure to seismic hazards; the second includes breeds inhabiting areas with high NCv, exposed to flood and landslide hazards. However, each of these groups could be further divided, obtaining four clusters corresponding closely to the quadrants of the PC1–PC2 plot. Group 1 comprises breeds that do not show extreme values for any parameter but tend to occur in areas with moderate-to-high seismic risk and exposure to climate change. Group 2, mainly consisting of northern breeds, shows high exposure to landslide hazard and climate change, and occupies breeding ranges with high NCv but low ecosystem collapse risk. Group 3 includes a small number of breeds that stand out for their high exposure to flood hazard. Group 4 contains only three breeds (Pinzirita, Sciara-Moscia Calabrese, and Trimeticcia di Segezia) with extremely low Ne, reared in areas with moderate-to-high seismic risk (Figures 7C,D).

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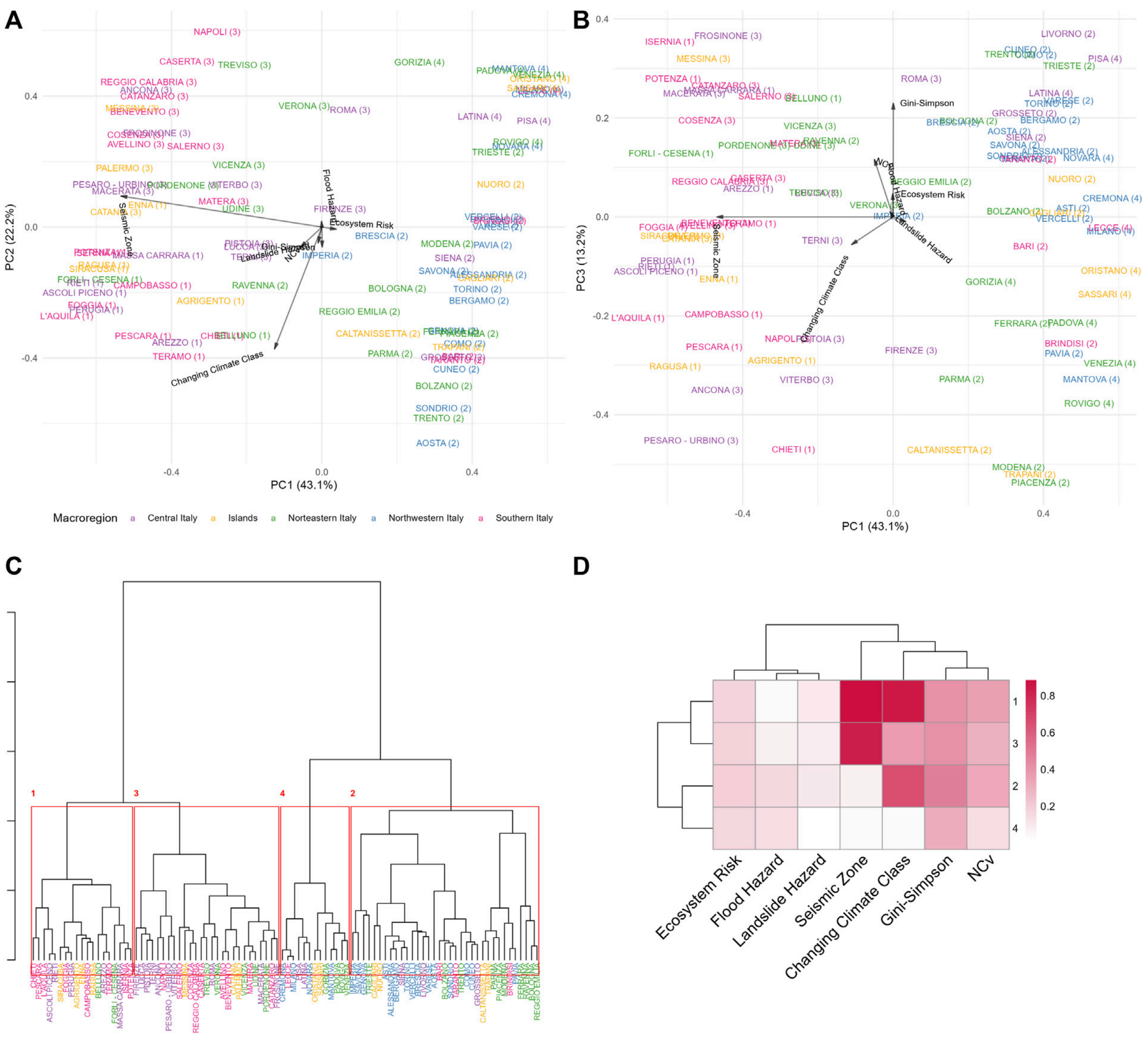

FIGURE 8
Principal component analysis [PCA; **(A,B)**] and hierarchical clustering **(C,D)** at the province level. Province names are coloured according to the macroregion where they are located. In the PCA, the number in parentheses indicates the cluster shown in **(C,D)**. In the heatmap **(D)**, the average value of all variables is reported for each analysed cluster.

By province

A PCA was also conducted at the province level using key biodiversity indices, NCv, environmental risk factors, and projected climate change.

PC1, explaining 43% of the total variance, is primarily associated with seismic risk (eigenvalue = −0.97), while PC2, explaining 22% of variance, is mostly driven by the proportion of the territory expected to undergo climate change (−0.94). As a result, provinces in the bottom-left quadrant of the PC1-PC2 plot (Figure 8A), such as those in Abruzzo, are exposed to both of these risks. PC3 (explained variance = 13%) is mainly influenced by the livestock biodiversity Gini-Simpson index and NCv (eigenvalues: 0.86 and 0.43, respectively), highlighting provinces with high small ruminant biodiversity and elevated NCv values in the upper section of the PC1-PC3 plot (Figure 8B). Notably, provinces located in the top-left quadrant of this plot warrant particular attention, as they serve as important biodiversity reservoirs while also facing significant earthquake risk.

When applied to provinces, hierarchical clustering distinguished four main groups, consistent with the PC1–PC2 quadrants (Figures 8C,D). Group 1 comprises provinces with low flood and landslide hazard but high seismic risk and strong exposure to climate change, combined with moderate-to-high NCv and small ruminant biodiversity. Group 2, predominantly in northern provinces, faces the highest exposure to flood and landslide hazard as well as ecosystem collapse risk, and is also highly subjected to climate change; these provinces also show high livestock biodiversity indices and moderate-to-high NCv, warranting particular attention for conservation. Group 3 is mainly composed of central-southern provinces with average values for most variables but high seismic risk. Lastly, Group 4 includes provinces with the lowest NCv and Gini–Simpson index, and only moderate flood hazard exposure.

Discussion

Understanding the distribution of local livestock populations and the environmental conditions in which they are raised, including the specific threats they face, is a fundamental step in developing targeted management and conservation strategies (FAO, 2015a). Our results show that many Italian small ruminant populations are exposed to multiple and overlapping threats: a significant number have small census and effective population sizes, placing them at high risk of extinction due to reduced genetic variability. This vulnerability is often compounded by their location in areas subject to high environmental risk or projected to undergo substantial climatic shifts. Local populations are deeply connected to the landscapes they inhabit, often marginal, ecologically fragile, or culturally distinctive areas shaped by traditional livestock farming (Oldenbroek, 2007; Hall, 2019). Conservation planning must therefore consider not only the genetic viability of these populations, but also the preservation of the environmental characteristics of the landscapes in which they have evolved. To this end, we characterized the landscape types associated with small ruminant farming across Italy, shedding light on the complex relationships between livestock, land use, and ecosystem function. Integrating genetic, ecological, and spatial information allows for a more comprehensive understanding of which populations are most at risk and highlights the interdependence between livestock biodiversity, landscape conservation, and rural sustainability.

Taking a closer look at these aspects, one widely used indicator of a population's long-term viability is the effective population size (Ne). When Ne falls below critical thresholds, genetic drift and inbreeding accumulate, reducing adaptive potential and increasing susceptibility to diseases, reproductive issues, and environmental changes, ultimately heightening the risk of extinction (Frankham, 2005; Kristensen et al., 2015). According to the commonly adopted 50/500 rule (Franklin, 1980), over a quarter of Italian small ruminant breeds, including over a third of goat breeds, are at short-term risk of extinction (Ne lower than 50), with six presenting Ne equal to 0, and almost half are at long-term risk (Ne between 50 and 500). These findings highlight the urgent need for systematic genetic monitoring, dedicated genomic studies, and targeted conservation efforts. Strategies such as ex-situ conservation programs (e.g., cryobanks) and sustainable breeding programs should be prioritized to maintain genetic diversity at safe levels. In this context, some national projects have been implemented to advance conservation efforts and conduct genomic characterization of most local sheep and goat populations. Continuous genomic monitoring is essential for developing effective strategies that preserve breed originality while preventing excessive genetic erosion.

Natural hazards further compound these risks, not only by threatening livestock populations but also by damaging infrastructure, thus limiting farmers' ability to sustain their breeding programs (FAO, 2015b; Migliaccio et al., 2018; OECD/FAO, 2021). Recognizing these challenges, the FAO and UNDRR developed the Sendai Framework subindicator C2, which measures direct agricultural losses due to disasters. Analyses across 82 countries show a rising trend in such losses, with floods being the most frequent events, while droughts cause the greatest economic impact (FAO, 2023). However, as noted by FAO, the current data landscape remains fragmented—datasets often have missing information, lack sectoral specificity, and differ in event classification and data collection standards (FAO, 2023). For example, a published database on disaster impacts in Italy (2005–2021) includes only qualitative information on damages to production, structures, and infrastructure (Pontrandolfi et al., 2025). Other sources, such as individual event reports, are similarly inconsistent and difficult to compare (Heath et al., 1999; Inchaisri et al., 2013; FAO, 2023). Moreover, current estimates rarely account for indirect effects or cross-sectoral interactions—such as disruptions to feed supply from crop losses, degradation of grazing land, or rural depopulation—which profoundly affect livestock systems (Heath et al., 1999; Lubroth et al., 2017). Critically, no reliable data are available on losses in animal genetic resources or livestock biodiversity. To address this gap, we integrated breed-specific livestock distribution data with spatial layers of environmental risk, providing a baseline to estimate breed exposure to extreme events and support mitigation planning. Our analyses highlight that a considerable number of small ruminant farms are situated in high seismic risk zones, particularly in southern Italy, exposing breeds exclusively raised in these areas—such as Dell'Aspromonte, Trimeticcia di Segezia, and Laticauda—to potential disruptions. Seismic activity in Italy has already caused significant agricultural losses. For example, after the 2009 L'Aquila earthquake, livestock farms in the region declined by 11% (from over 2,000 farms, mostly small-scale cattle and sheep operations). In 2012, earthquakes in Emilia-Romagna caused even greater economic damage, affecting around 13,000 farms, predominantly involved in cattle and swine production (CENSIS, 2013). According to our data, landslides also pose a significant threat, with several goat and sheep breeds having a substantial portion of their distribution area at moderate to high risk. Although flood risk is generally lower, certain breeds, including Massese and Garfagnina Bianca sheep, face notable exposure. The 2023 floods and landslides in Emilia-Romagna illustrate the potential magnitude of such events, with total damages estimated at €912 million, including €18.5 million from livestock losses alone (Emilia Romagna and Cons, 2023).

These environmental risks necessitate targeted disaster preparedness plans, including the identification of emergency relocation areas and the development of resilient farm structures (OECD/FAO, 2021).

Climate change represents an additional threat to livestock populations, both indirectly, by increasing the intensity and frequency of extreme weather events, and directly, by impacting feed production, disease and parasite diffusion, and modifying the environmental conditions to which populations have adapted, often exacerbating the challenges animals must cope with (FAO, 2015a; 2015c; Sarangi, 2018; OECD/FAO, 2021). According to our analyses, climate change projections indicate that many farms will shift to warmer and/or drier climate classes, particularly affecting breeds traditionally adapted to colder environments, such as those in the Alpine region. These shifts may necessitate adjustments in management strategies to ensure breed viability, including selective breeding for heat tolerance, improved water and feeding management practices, and the building of suitable shelters to mitigate heat stress (Nienaber and Hahn, 2007; Al-Dawood, 2017; Pardo and del Prado, 2020; OECD/FAO, 2021).

Beyond environmental risks, the interaction between livestock and surrounding landscapes plays a critical role in biodiversity conservation. Small ruminant populations, especially those reared in extensive or semi-extensive systems, are closely tied to their ecosystems, both influencing and being influenced by them (FAO, 2016). Beyond conservation, genotype by environment interactions (G×E) are also increasingly recognized as major drivers of livestock welfare, resilience, and productivity, which should be accounted for when developing effective and sustainable breeding programs. This underscores the importance of accurately characterizing the full spectrum of environmental drivers that can modulate the expression of genetic potential, influence the detection of G×E, and ultimately determine the success of selection strategies across diverse production contexts (Silva Neto et al., 2024; Kgabo Mashamaite et al., 2025). Our landscape characterization analysis showed that while agricultural areas dominate sheep farming, goat farms are more frequently associated with woodlands and mountainous terrains, particularly in northern and central Italy. However, what emerged is that each breed is typically reared in, and likely adapted to, specific environmental and landscape conditions, including land cover, ecosystem type, and physiographic features. Local breeds are generally considered adapted to their native environments, but such environments encompass far more than just climatic variables, which are often the sole focus of adaptive studies. In reality, they also include a complex array of biological and abiotic components—such as soil type, vegetation, and habitat structure—that are rarely considered but may play an important role in shaping adaptive traits (Leroy et al., 2016; Karimi et al., 2018; Lozano-Jaramillo et al., 2019). The variability observed in landscape characteristics among breeds underscores their ability to persist in diverse and sometimes challenging environments, suggesting broader ecological adaptation than typically acknowledged. The distribution of these breeds across regions with different naturalistic-cultural values and varying ecosystem vulnerability further highlights the complexity of the interaction between livestock and their environment. Understanding the spatial distribution of these animals, particularly within vulnerable habitats, can provide insight into the potential impacts of environmental degradation on breeds that rely heavily on natural resources under extensive management systems (Hoffmann, 2010). In fragile ecosystems, traditional breeds may have developed genetic adaptations that allow them to thrive under harsh climatic conditions and limited resources, contributing to the sustainability of local agroecosystems. On the other hand, knowing that a breed is primarily reared in vulnerable habitats suggests that a disruption or degradation of these ecosystems could have severe consequences for its long-term viability and persistence (Hoffmann, 2010; FAO, 2011; Dibari et al., 2021). At the same time, livestock presence can influence these landscapes either by supporting biodiversity through traditional and well-managed pastoralism or posing environmental risks when overgrazing or habitat degradation occurs. Understanding these spatial dynamics is crucial, as improper grazing and farm management can disrupt ecosystems, whereas well-managed livestock can contribute positively to biodiversity and ecosystem sustainability (Nardone et al., 2004; Bilotta et al., 2007; Hoffmann et al., 2014; Minea et al., 2022). Indicators such as ecosystem collapse risk and naturalistic-cultural value are thus useful not only for understanding breed-environment relationships but also for informing landscape-level decisions. Indeed, finding a balance between animal husbandry and ecosystems can enhance the beneficial impact of livestock on marginal areas, contributing to habitat conservation and soil preservation while supporting the conservation of livestock biodiversity.

In this context, we also analyzed small ruminant biodiversity across Italian provinces, identifying where local populations are more present and/or valorized and where there might be room for improvement. Provinces such as Cuneo, Frosinone, and Ravenna exhibit the highest small ruminant genetic resources, hosting a broad range of breeds that contribute to the overall biodiversity of the national livestock sector. However, other provinces, including Chieti, Imperia, and Piacenza, support only a single breed, demonstrating a marked imbalance in genetic diversity. In some cases, provinces with multiple breeds show low diversity indices due to dominance by a single population, as observed in L'Aquila and Trapani. Such disparities underscore the need for improved registration of local breeds and the official recognition of unregistered populations to ensure their conservation and sustainable use. Many traditional breeds, indeed remain underrepresented in official databases, limiting their access to conservation funding and breeding programs. While these biodiversity indices are commonly used in ecology to assess multispecies diversity within communities, they are equally well suited for evaluating the distribution and abundance of livestock populations, which should be recognized as a valuable component of local biodiversity. Moreover, integrating our results with biodiversity indices of other livestock and wild species could contribute to comprehensive evaluations of the Italian natural landscape. Such measures would support the development of policies that both safeguard genetic diversity and enhance the sustainable management of rural ecosystems, ensuring that livestock farming continues to be a valuable component of environmental stewardship.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

AB: formal analysis, investigation, methodology, software, visualization, writing-original draft, writing-review and editing; AN: investigation, writing-review and editing; SG: investigation, writing-review and editing; PC: conceptualization, supervision, project administration, writing-review and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontierspartnerships.org/articles/10.3389/past.2025.14997/full#supplementary-material.

SUPPLEMENTARY FIGURE S1
Italian maps of landslide hazard **(A)**, flood hazard **(B)**, and seismic zones **(C)**.

SUPPLEMENTARY FIGURE S2
Present and projected future Köppen-Geiger climate classification of Italy.

SUPPLEMENTARY FIGURE S3
Italian maps of physiographic types **(A)**, ecosystems **(B)**, land cover **(C)**, and land use **(D)**.

SUPPLEMENTARY FIGURE S4
Italian maps of naturalistic-cultural values **(A)** and red list ecosystems **(B)**.

SUPPLEMENTARY FIGURE S5
Percentage of small ruminant farm area covered by different land cover [**(A,B)** for goat and sheep populations, respectively] and land use [**(C,D)** for goat and sheep populations, respectively]. Breeds have been ordered according to the percentage of the most represented category of the species; categories have been ordered according to their percentage at the species level.

SUPPLEMENTARY FIGURE S6
Percentage of small ruminant farm area covered by naturalistic-cultural value [**(A,B)** for goat and sheep populations, respectively] and ecosystem risk status [**(C,D)** for goat and sheep populations, respectively]. Breeds have been ordered according to the weighted score of naturalistic-cultural value or ecosystem vulnerability.

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