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RESEARCH

Habitat suitability and niche comparison of sympatric weasels in northwestern Italy

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Abstract

Ecological Niche Models (ENMs) are useful tools for assessing habitat suitability and niche overlap among similar species, but their application to understudied sympatric carnivores remains limited. Three weasel species coexist throughout much of Europe: stoat (*Mustela erminea*), least weasel (*Mustela nivalis*), and European polecat (*Mustela putorius*). Due to their elusive nature, however, little is known about their exact distribution and ecological niches. In this study, we collected occurrences and environmental variables to predict the habitat suitability of these species in northwestern Italy under an ensemble forecasting approach that combined machine learning and maximum entropy algorithms. Moreover, we compared their ecological niches through principal component analysis and Schoener's *D* overlap metric. A total of 112 occurrences for stoats, 95 for weasels, and 72 for polecats were obtained from a collaborative network and open-source databases. Habitat suitability for the stoat increased with distance from lowland habitats and moderate spring temperatures. For the weasel, suitability increased with distance from agricultural areas and the presence of coniferous forests. Habitat suitability for the polecat was influenced by mild temperatures, rice fields, and slope. Niche overlap analysis revealed a slight similarity between weasels and polecats (Schoener's $D=0.43$), while the stoat differed more markedly from the other species. These results suggest that climate change may threaten stoats in the Alps, while land-use change, especially intensive agriculture, likely impacts weasels and polecats. Given current data limitations, our findings also highlight the urgent need for long-term monitoring programs to inform effective conservation strategies for sympatric small mustelids.

Keywords Weasels · *Mustela* · Sympatry · Niche comparison · ENMs

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Introduction

Quantifying the ecological niche, i.e., the range of environmental conditions a species requires to survive and reproduce (Hutchinson 1957), and assessing niche overlap and divergence among species represent fundamental research areas in conservation biology (Guisan and Thuiller 2005; Broennimann et al. 2012). Identifying the key environmental factors shaping a species' niche can provide critical insights, such as (1) predicting areas where the species may maintain viable populations, (2) assessing the potential effects of environmental changes (e.g., climate and land-use alterations), and (3) informing the development of effective conservation strategies (Anderson et al. 2011; Guisan et al. 2017). Furthermore, comparing the niches of ecologically similar species may enhance our understanding of the extent of their niche overlap and divergence, thereby elucidating

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how these species may coexist within the same ecosystems (Schoener 1970; Broennimann et al. 2012).

Over the last decade, correlative Ecological Niche Models (ENMs) have been widely used for assessing habitat suitability and comparing the niches of ecologically similar carnivores (order Carnivora; e.g., Khosravi et al. 2019; Mukherjee et al. 2021; Peers et al. 2013). These models combine species occurrences with environmental variables to predict potential distribution patterns and identify the most important factor shaping them (Soberon and Peterson 2005; Guisan et al. 2017). ENMs are particularly valuable for studying elusive or rare species, such as carnivores, as they can yield reliable results even with limited occurrence data (Jeliazkov et al. 2022). However, with a few notable exceptions (Vergara et al. 2016; Schiaffini 2017; Fonda et al. 2021), ENMs have been rarely applied to explore habitat suitability and niche overlap among understudied carnivores, largely due to the challenges of collecting reliable data on these species (Jachowski et al. 2024).

Small mustelids belonging to the genus *Mustela* (hereafter referred to as weasels) are generally considered among the least-studied carnivores (Macdonald et al. 2017). Due to their small size, low population density, and elusive behavior, weasels' ecology and conservation status are currently poorly understood (Macdonald et al. 2017; Croose et al. 2018; Wright et al. 2022). Three species of weasels co-occur across much of Europe: the stoat *Mustela erminea*, the least weasel *Mustela nivalis*, and the European polecat *Mustela putorius*. In various environments, weasels—particularly the stoat and the least weasel—play a crucial role in ecosystem functioning as specialized rodent predators (Lodé 1997; King and Powell 2007; Korpela et al. 2014). However, despite their widespread distribution, small mustelids are undergoing significant declines in several European countries (Hellstedt et al. 2006; Torre et al. 2018; Croose et al. 2018; Coomber et al. 2021; Llorca et al. 2024).

In Italy, stoat, least weasel, and European polecat are currently listed as *Least Concern* on the IUCN Red List (Rondinini et al. 2022), though there are growing concerns about population declines, despite limited evidence currently available to support this trend. The stoat is considered a high-altitude specialist, typically found in the Alpine environment (Bounous et al. 1995; Martinoli et al. 2001; Boitani et al. 2003). In contrast, the polecat is more common in the lowlands throughout the Italian peninsula (Boitani et al. 2003; Marcelli et al. 2003; Rondinini et al. 2006). The least weasel has a broader distribution, ranging from lowlands to mountainous areas (Boria and Prigioni 1983; Boitani et al. 2003; Magrini et al. 2009). In northwestern Italy, a region ranging from 70 to almost 5000 m a.s.l., and characterized by high levels of biodiversity (Sindaco et al. 2008), all three weasel species coexist: the stoat in the Alps, the European polecat in the lowlands, and the least weasel in both (Sindaco and Carpegna 2010). However, crucial information regarding their ecological requirements, current distribution, and conservation status remains poor.

Recently, Cheeseman et al. (2024) examined niche shifts for three weasel species in North America, including the least weasel. ENMs have also been successfully applied to predict polecat habitat suitability in Sweden (Osinga et al. 2023) and to assess polecat roadkill distribution in Italy (Russo et al. 2020). However, regional-scale studies of habitat suitability for the least weasel and the stoat are still absent in Europe. Additionally, while Vergara et al. (2016) and Fonda et al. (2021) explored the niches of medium-sized mustelids (*Martes martes* and *M. foina*), no studies have yet investigated the niche overlap and divergence among weasel species. To address these knowledge gaps, we conducted a study aimed at investigating habitat suitability patterns and environmental niche features for three sympatric weasels (stoat, least weasel, and European polecat) in northwestern Italy, relying on ENMs and niche overlap analysis.

Materials and methods

Study area

In this study, we focused on northwestern Italy (Fig. 1), specifically the administrative regions of Piedmont and Aosta Valley, covering a total area of 28,650 km^2. Elevation ranges from 70 m a.s.l. in the Po Plain (province of Alessandria) to the Mont Blanc (4,808 m a.s.l.), the highest peak in Europe. The Po River, the longest in Italy, originates in the Cottian Alps and flows through the Piedmont plains, including the region's largest city, Turin. Northwestern Italy spans three biogeographical regions: Alpine (50.5%), Continental (46.5%), and Mediterranean (3%; Roekaerts 2002). In the Alpine region, the climate is cold-temperate, with abundant precipitation, and becomes nival at high altitudes (Soldati and Marchetti 2017). The Po Plain is defined by a more continental climate, with cold, humid winters and hot, foggy summers. The Mediterranean climate, characterized by limited precipitation and higher temperatures, is found only in the southern sectors. The land cover consists mainly of agricultural areas (37.6%), both intensive and heterogeneous, in the lowlands, while forests (28.9%) and open, rocky areas (15.1%) define the Alpine environment (ISPRA 2018). Urban areas account for approximately 5% of our study area, mostly concentrated in the Po Plain. This geomorphological, climatic, and ecological diversity contributes to high levels of biodiversity, making the region a biodiversity hotspot in Italy (Sindaco et al. 2008). Specifically, Piedmont is home to the highest number of protected

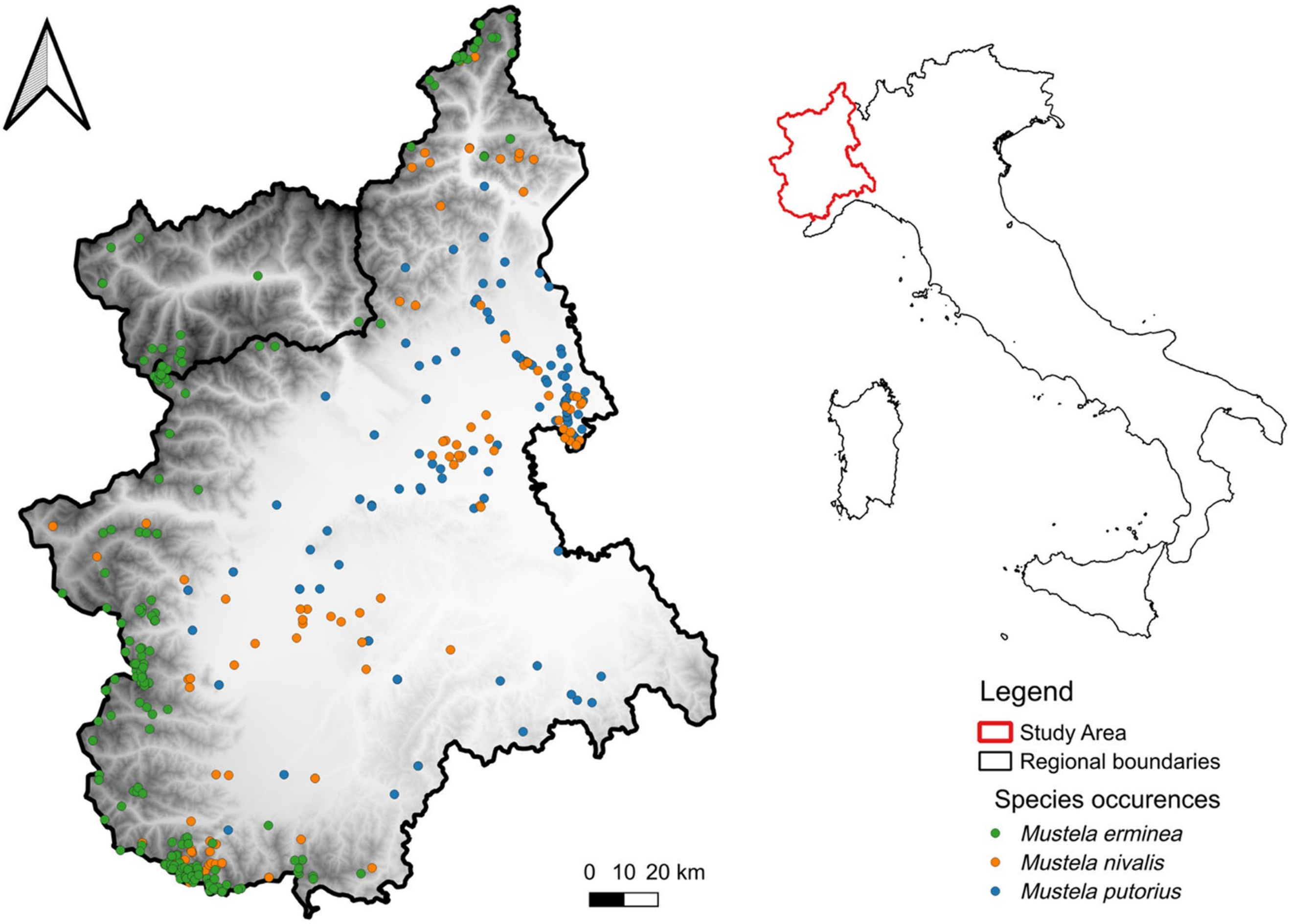

Fig. 1 Study area and occurrence distribution of weasel species in northwestern Italy. The occurrences of stoat are shown in green, those of least weasel in orange, and those of European polecat in blue. Black lines in the left map indicate regional boundaries separating Piedmont from Aosta Valley. The elevation map in the background was obtained from WorldClim (worldclim.org)

species in Italy, holding this distinction in Europe (MATTM 2018). Consequently, protected areas cover 17.2% of northwestern Italy (4,924 km^2), including two national and several regional parks.

Species occurrences

Due to the large size of the study area, it was not feasible to implement standardized surveys for small mustelids. To address this, we established a collaborative network of regions, parks, museums, other institutions, and researchers to share occurrences of the target species within the study area. Additionally, we downloaded sightings from two open-source databases: iNaturalist and the Global Biodiversity Information Facility (GBIF; 2025 https://doi.org/10.15468/dl.h7ud3v). The occurrences from both sources were primarily derived from direct observations, road kills, and camera-based surveys. We collected geo-referenced occurrences from 2000 to 2023, accompanied by photos and/or videos, to ensure accurate species identification. Each image and video was verified based on the morphological features by King and Powell (2007) and Boitani et al. (2003). The European polecat is the most easily distinguishable, due to its larger, marten-like body shape and the characteristic white facial mask contrasting with its otherwise dark fur. In comparison, the stoat is smaller, with a slender build and a distinctive black tip on its tail, whereas the least weasel is the smallest of the three and lacks the black-tipped tail, displaying a proportionally shorter, uniformly colored tail. Moreover, the boundary between the back and the belly is more distinct in the stoat, whereas in the weasel it is more irregular, sometimes with gular spots. Since the target species are quite easy to distinguish, observations made by experts, such as researchers and park rangers, were accepted without visual confirmation. On the contrary, occurrences with uncertain identification and/or location imprecision greater than 500 m were discarded. At the end of the process, we gathered 337 occurrences for the stoat, 149 for the weasel, and 123 for the polecat (Fig. 1). Although opportunistic records can provide accurate predictions of species distribution (Tiago et al. 2017), they can still be autocorrelated (Van Strien et al. 2013). To mitigate this, we used the *spThin* R package (Aiello-Lammens et al. 2015) to thin points less than 2 km apart for all species. This threshold was based on the scientific literature regarding the species' ecology (Baghli and Verhagen 2004; King and Powell 2007; Macdonald et al. 2017). After the thinning procedure, we retained 112 final occurrences for the stoat, 95 for the weasel, and 72 for the polecat.

Table 1 Name, description, resolution, and source of all variables included in the ENMs, separated into three categories

Variable	Description	Resolution	Source
Geomorphology			
Slope	Rate of change of elevation (from DEM)	10 m^2	Worlclim: worldclim.org
Climate			
Mean daily mean air temperatures of the wettest quarter (bio8)	The wettest quarter of the year is determined (to the nearest month)	1 km^2	CHELSA: chelsa-climate.org
Mean daily mean air temperatures of the driest quarter (bio9)	The driest quarter of the year is determined (to the nearest month)	1 km^2	CHELSA: chelsa-climate.org
Mean monthly precipitation amount of the coldest quarter (bio19)	The coldest quarter of the year is determined (to the nearest month)	1 km^2	CHELSA: chelsa-climate.org
Land use			
Coniferous forests	Euclidean distance from coniferous forests pixels	10 m^2	SINAnet: groupware.sinanet.isprambiente.it
Deciduous forests	Euclidean distance from deciduous forests pixels	10 m^2	SINAnet: groupware.sinanet.isprambiente.it
Grasslands and pastures	Euclidean distance from grasslands and pastures pixels	10 m^2	SINAnet: groupware.sinanet.isprambiente.it
Heterogeneous agricultural areas	Euclidean distance from heterogeneous agricultural areas pixels	10 m^2	SINAnet: groupware.sinanet.isprambiente.it
Rice fields	Euclidean distance from water bodies pixels	10 m^2	SINAnet: groupware.sinanet.isprambiente.it

Environmental predictors

We considered the 19 bioclimatic variables from the CHELSA database - version 1.2 (Karger et al. 2017). Additionally, we included Elevation, Slope, and Aspect (the latter two were derived from the elevation map, and were calculated in degrees and radians respectively) from WorldClim 2 (Fick and Hijmans 2017). We also considered 12 land use categories (ISPRA 2018): Artificial surfaces, Coniferous forests, Deciduous forests, Grasslands and pastures, Heterogeneous agricultural areas, Intensive agricultural areas, Mixed forests, Rice fields, Rocky areas with little or no vegetation, Shrubs and or pioneer vegetation, Vineyards and fruit trees, and Water bodies. Specifically, each category was transformed from categorical to continuous by calculating the Euclidean distance from each pixel (Jamwal et al. 2022). Before calculating geomorphological variables and Euclidean distances from land use categories, all the variables were projected into UTM 32 N coordinate system. All the predictors were clipped to our study area and rasterized at a spatial resolution of approximately 1 km. The variables were further checked for multicollinearity by calculating the variance inflation factor (VIF), with a threshold of 5 (Zuur et al. 2009). From the non-correlated variables, we retained a final set of 9 predictors known to adequately describe the habitat characteristics of our target species (King and Powell 2007; Macdonald et al. 2017; Osinga et al. 2023; Cheeseman et al. 2024): 1 geomorphology, 3 climate, and 5 land-use variables (Table 1).

Ecological niche models

We applied an ensemble forecasting approach to calibrate ENMs using the *biomod2* R package (Thuiller et al. 2009). Specifically, we used three modelling algorithms: Generalized Boosted Models (GBM), Random Forest (RF), and Maxent. For each species, 10,000 background points were generated and geographically distributed within the study area according to the density of the occurrence data, ensuring a higher concentration of background points in areas with denser presence data (Syfert et al. 2013; Roy-Dufresne et al. 2019; Mondanaro et al. 2021). The models were calibrated on 80% of the data (training set) and evaluated on the remaining 20% (validation set), with the procedure repeated ten times. To evaluate the predictive performance, each model was assessed by measuring the area under the receiver operating characteristic curve (AUC; Hanley and McNeil 1982) and the true skill statistic (TSS; Allouche et al. 2006). Model averaging was performed by weighting each model prediction by its AUC and averaging the results (Marmion et al. 2009). Statistical significance of AUC values achieved by the ensemble models was assessed by applying the null model approach proposed by Raes and ter Steege (2007) and refined by Bohl et al. (2019), considering 99 replicates. We projected the ENMs for each species onto the study area, generating continuous habitat suitability predictions. The relative importance of predictors for each species was computed using the functionalities provided by the *biomod2* package within the ensemble model (Thuiller et al. 2009).

Niche overlap analyses and classification models

To compare weasel niches, we implemented the analytical framework developed by Broennimann et al. (2012). This approach utilizes Principal Component Analysis (PCA) to partition the environmental space defined by species data encompassing all the environmental conditions associated with both occurrence and background points. The densities of occurrences and background environments were then normalized by dividing them by the maximum number of occurrences within any cell of the environmental space and by the number of sites sharing the most common environment respectively (Broennimann et al. 2012). To quantify niche overlap between species, we calculated Schoener's *D* index over the density grid in the environmental space generated by the previous procedure. This index ranges from 0 to 1, with 0 indicating no niche overlap and 1 indicating complete overlap (Schoener 1970). Niche overlap analyses were conducted using the *ecospat* R package (Di Cola et al. 2017). We identified the most critical environmental predictors differentiating non-overlapping niche segments for each species, by implementing three Random Forest classification models (RF; Breiman 2001): (1) *M. erminea* versus *M. nivalis*; (2) *M. erminea* versus *M. putorius*; (3) *M. nivalis* versus *M. putorius*. For each model, the environmental variables associated with each non-overlapping niche portion of the PCA environmental space were used as covariates (Di Febbraro et al. 2023). Classification performance was assessed by quantifying the out-of-bag accuracy rate, while the contribution of each variable was calculated as the mean decrease in this accuracy (Liaw and Wiener 2002). Lastly, two spider plots were generated from the RF classification model results to highlight the differences in variable importance between pairs of species: the first plot shows the importance of each variable for the first species compared to the second, while the second plot depicts the reverse pattern. All the analyses were conducted using the *ecospat* (Di Cola et al. 2017) and *randomForest* (Liaw and Wiener 2002) R packages.

Results

The ENMs of the target species (Fig. 2) exhibited fair-to-good predictive performance. The stoat showed the highest accuracy, with a mean AUC of 0.839 (SD = ±0.023; $p < 0.01$) and a mean TSS of 0.567 (±0.058). The least weasel had a mean AUC of 0.712 (±0.009; $p < 0.01$) and a mean TSS of 0.379 (±0.015), while the polecat reported a mean of 0.742 (±0.037; $p < 0.01$) and a mean TSS of 0.43 (±0.061).

Habitat suitability for the stoat was primarily shaped by distance from rice fields, intermediate proximity to deciduous forests (as shown by a hump-shaped curve), a strong association with grasslands and pastures, and moderate wettest-quarter conditions (Table 2). Specifically, the most suitable areas for the species were located far from lowlands, close to Alpine habitats, and under non-extreme

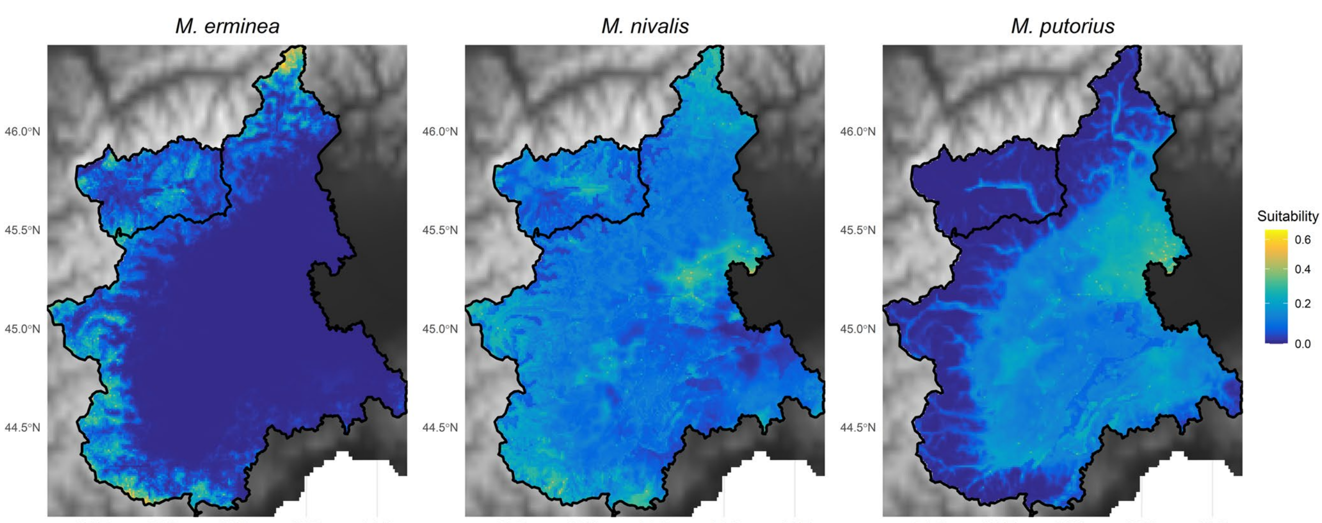

Fig. 2 Estimated habitat suitability for sympatric weasel species in northwestern Italy. Habitat suitability is visually represented using a color gradient, with yellow indicating areas of higher suitability, green indicating areas of intermediate suitability, and blue indicating areas of lower suitability

Table 2 Environmental predictors and their percent contribution to the overall model prediction for each species. In bold are reported the most important variables for each species (percent contribution > 5)

Variable	Percent contribution		
	M. erminea	*M. nivalis*	*M. putorius*
Coniferous forests	4.92	**9.04**	1.95
Deciduous forests	**5.95**	3.79	0.65
Grasslands and pastures	**5.91**	3.77	0.26
Heterogeneous agricultural areas	3.81	**10.6**	0.54
Mean temperature of the driest quarter	1.66	**5.79**	2.96
Mean temperature of the wettest quarter	**6.24**	4.77	**25.42**
Precipitation of the coldest quarter	3.40	1.08	2.72
Rice fields	**14.87**	**8.10**	**6.25**
Slope	3.23	3.00	**9.22**

temperatures (Fig. 3a). For the least weasel, habitat suitability increased with distance from heterogeneous agricultural areas and rice fields, and it was positively associated with coniferous forests (Table 2; Fig. 3b). Polecat suitability increased with rising temperatures, decreasing slope, and proximity to rice fields (Table 2; Fig. 3c).

The niche overlap analyses revealed only a moderate overlap between the least weasel and the polecat (Shoeners's $D = 0.43$), a low overlap between the weasel and the stoat ($D = 0.22$), and a negligible overlap between the stoat and the polecat ($D = 0.01$). The polecat's niche was almost entirely contained within that of the least weasel, which exhibited the broadest niche breadth among the three species (Fig. 4).

Two spider plots were generated from the Random Forest analysis to highlight the differences in variable importance between pairs of species (Fig. 5). The stoat exhibited the greatest differences from the other species, being more influenced by temperature variables, while lowland habitats (rice fields, heterogeneous agricultural areas, deciduous forests) were more relevant for polecats and weasels (Fig. 5). Rice fields and slope were the main variables distinguishing the least weasel and polecat, both more important for the latter; other variables displayed some fluctuations but were largely overlapping across the species (Fig. 5).

Discussion

We used occurrence data for three sympatric *Mustela* species (the stoat, the least weasel, and the European polecat) to model their habitat suitability and assess niche overlap in northwestern Italy.

Our models predicted that habitat suitability for the polecat is highest in lowland areas, while the stoat appears to be confined to the Alps. The least weasel exhibits a more widespread distribution, ranging from the Po plain to the mountains. These findings align with the distribution patterns described for Piedmont by Sindaco and Carpegna (2010). In their study, they found the stoat exclusively in the Alpine region, particularly concentrated in the Maritime Alps; the least weasel in the lowlands and, less frequently, in mountain forests; and the polecat in rice fields and some Alpine valleys. Similarly, our data identified a hotspot for the polecat in the rice fields of central-western Piedmont, which are notoriously valuable wetland surrogates in a landscape dominated by intensive agriculture (Fasola and Ruiz 1996; Ranghetti et al. 2018), while some natural or naturalized wetlands still persist in the area (ISPRA 2018). Few records came from mountainous areas, consistent with previous findings of polecats at medium altitudes (Salvador subm.; Virgós 2003; Weber 1987). As for the stoat, only a few scattered high-altitude areas in the Alps were identified as suitable. Lowlands habitats, primarily along the River Po and close to rice fields, were deemed suitable for the least weasel, which also showed good habitat suitability in mountainous areas. This dual distribution could reflect the presence of two subspecies of the least weasel in northwestern Italy: *M. nivalis nivalis*, which turns white for winter as an adaptation to snowy high-altitude habitats, and *M. nivalis vulgaris*, which inhabits the lowlands and does not exhibit winter molting (King and Powell 2007; Mills et al. 2018). Niche overlap analysis supports this hypothesis, revealing moderate overlap between the least weasel (possibly the *vulgaris* subspecies) and the polecat, and between the least weasel (possibly the *nivalis* subspecies) and the stoat. Conversely, the stoat and polecat show a negligible niche overlap.

The distance from typically lowland habitats, such as rice fields and deciduous forests, was a key determinant of stoat distribution in northwestern Italy. The linear, negative relationship with rice fields likely reflects their remoteness from suitable high-altitude areas, whereas the hump-shaped relationship with deciduous forests corresponds to their greater prevalence near the mountain foothills. Although the American ermine *Mustela richardsonii* (formerly considered a subspecies of the stoat; Colella et al. 2021) is known to be strongly associated with forests, as demonstrated by both ENMs (Cheeseman et al. 2024) and occupancy studies (Evans and Mortelliti 2022), the stoat in Europe is traditionally associated with open habitats (Erlinge 1977; Pounds 1981; Debrot 1984). In the Italian Alps, the stoat is considered an Alpine specialist, closely linked to rocky areas and Alpine meadows above the tree line (Bounous et al. 1995; Martinoli et al. 2001; Boitani et al. 2003). This pattern is further supported by our models, which show positive associations with grasslands and pastures—good proxies for Alpine prairies—as well as with moderate values of the

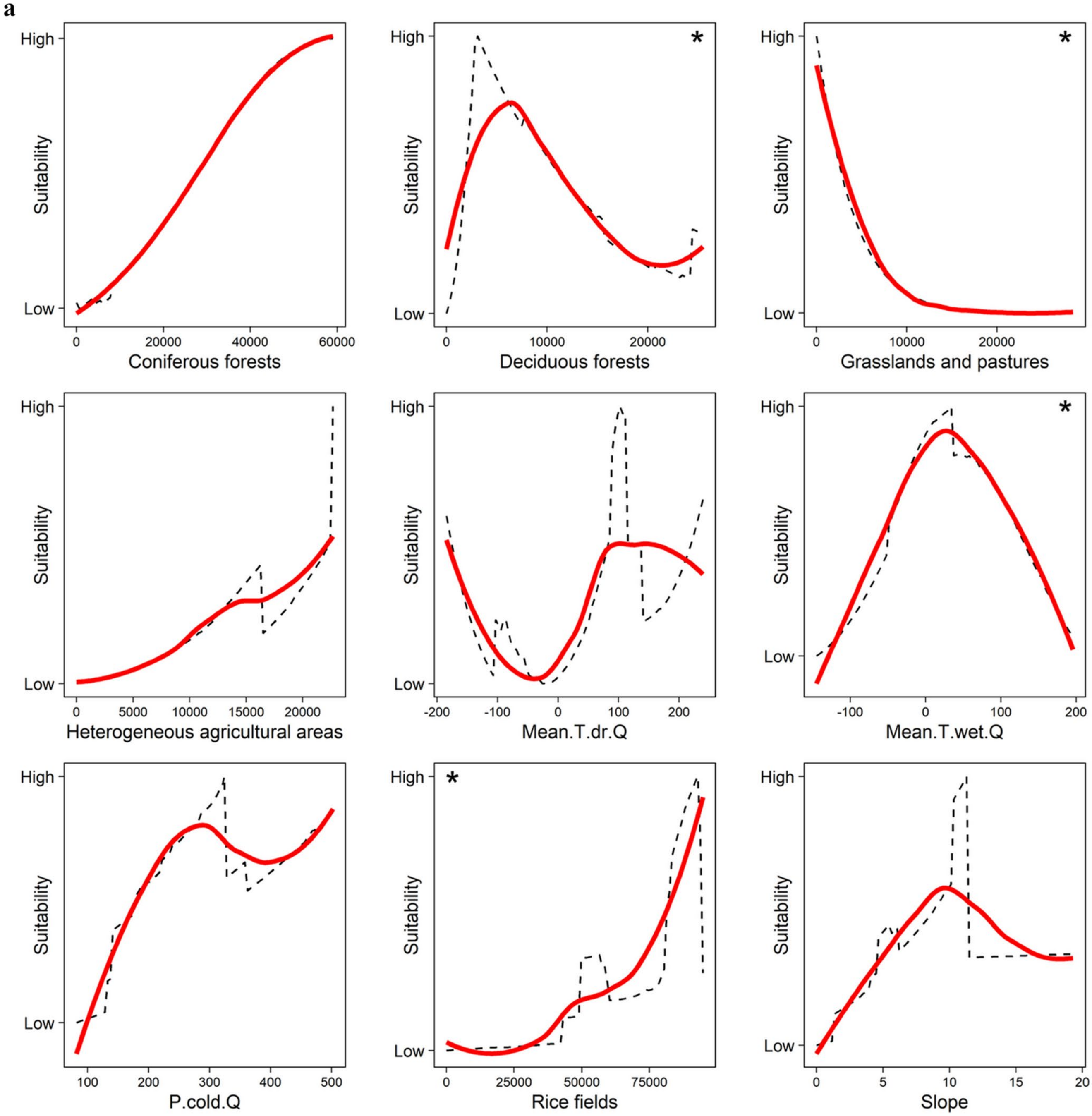

Fig. 3 Response curves for the (**a**) stoat, (**b**) the least weasel, and (**c**) the European polecat showing the relationship between habitat suitability and environmental predictors as predicted by the ENMs. The variables that most strongly influence their distribution (percent contribution > 5) are marked with an asterisk (*). Land-use variables are measured as Euclidean distance from each land-use polygon. Response curves were smoothed using a loess function

mean temperature of the wettest quarter, which corresponds to spring in northwestern Italy (ARPA Piemonte 2020), as extreme temperatures can strongly affect prey abundance at high altitudes (Billman et al. 2021; Chirichella et al. 2022). Random Forest analysis indicated that stoats differed most from other species, with temperature variables generally being the most influential, confirming the species' strong link to climatic factors (e.g., potential vulnerability to camouflage mismatch under climate change; Otte et al. 2024).

Among the most important environmental predictors for the least weasel were heterogeneous agricultural areas and rice fields. Historically, the least weasel has always been linked to traditional agricultural landscapes, characterized by a diverse mosaic of fields, meadows, and hedges, both in Europe

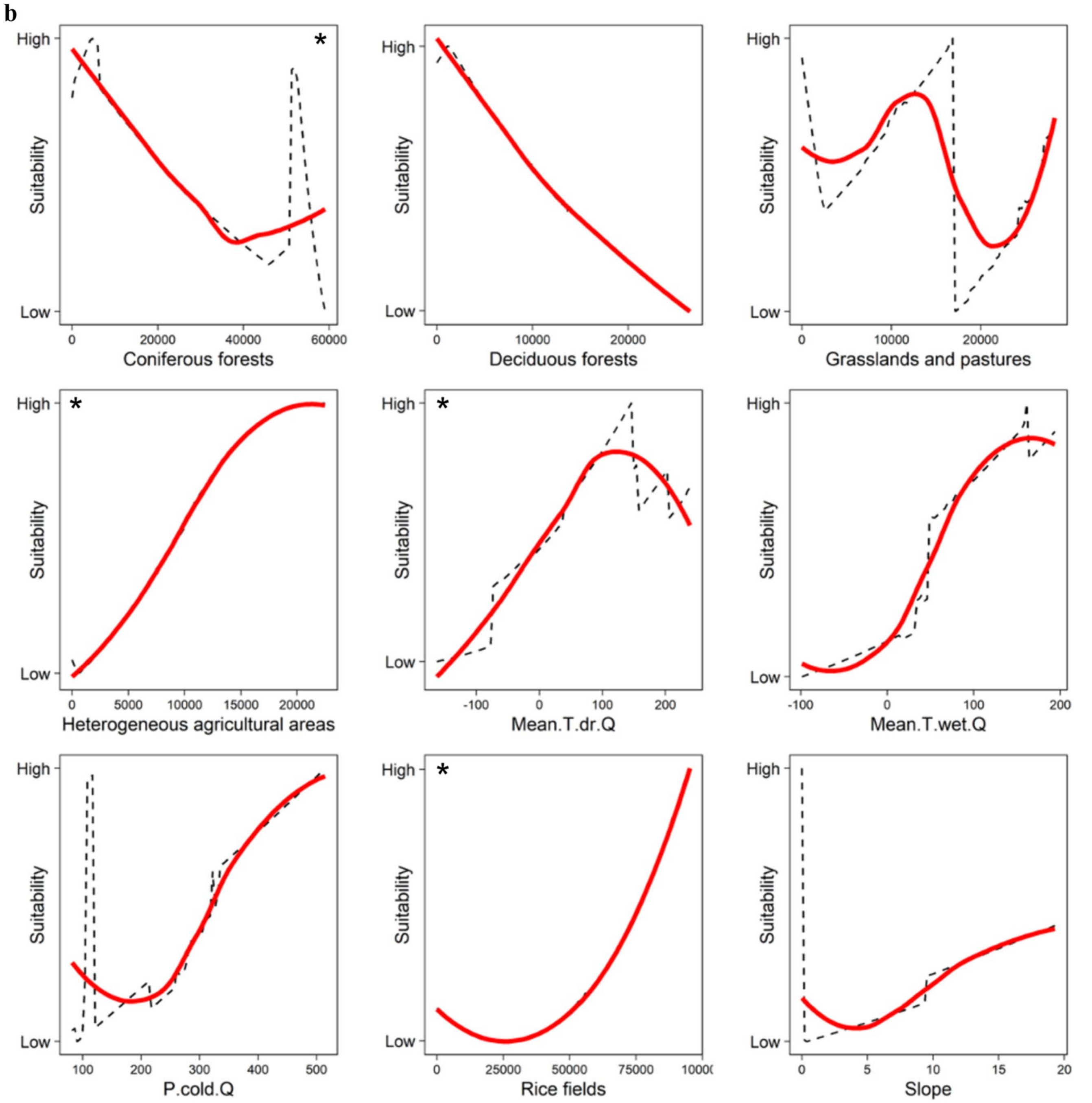

Fig. 3 (continued)

(Macdonald et al. 2004; Zub et al. 2008) and Italy (Boria and Prigioni 1983; Magrini et al. 2009). However, intensive agriculture is known to disrupt such agrosystems, making them less suitable for rodents (Gentili et al. 2014; Balestrieri et al. 2019) and mustelids (Marneweck et al. 2021; Wright et al. 2022). The loss of hedges and meadows, combined with the widespread use of rodenticides, is a major threat to weasels' conservation (Sainsbury et al. 2018). Consequently, habitats once considered suitable for the least weasels in northwestern Italy, such as heterogeneous agricultural areas and, to a lesser extent, rice fields (Sindaco and Carpegna 2010), now appear avoided. Conversely, the least weasel showed a positive relationship with coniferous forests: the initial part of the curve likely reflects its ubiquitous distribution, particularly in mountainous areas where coniferous forests dominate, whereas the latter part indicates higher suitability at greater distances from coniferous forests, corresponding to its presence in lowland habitats (ISPRA 2018). Finally, its association with

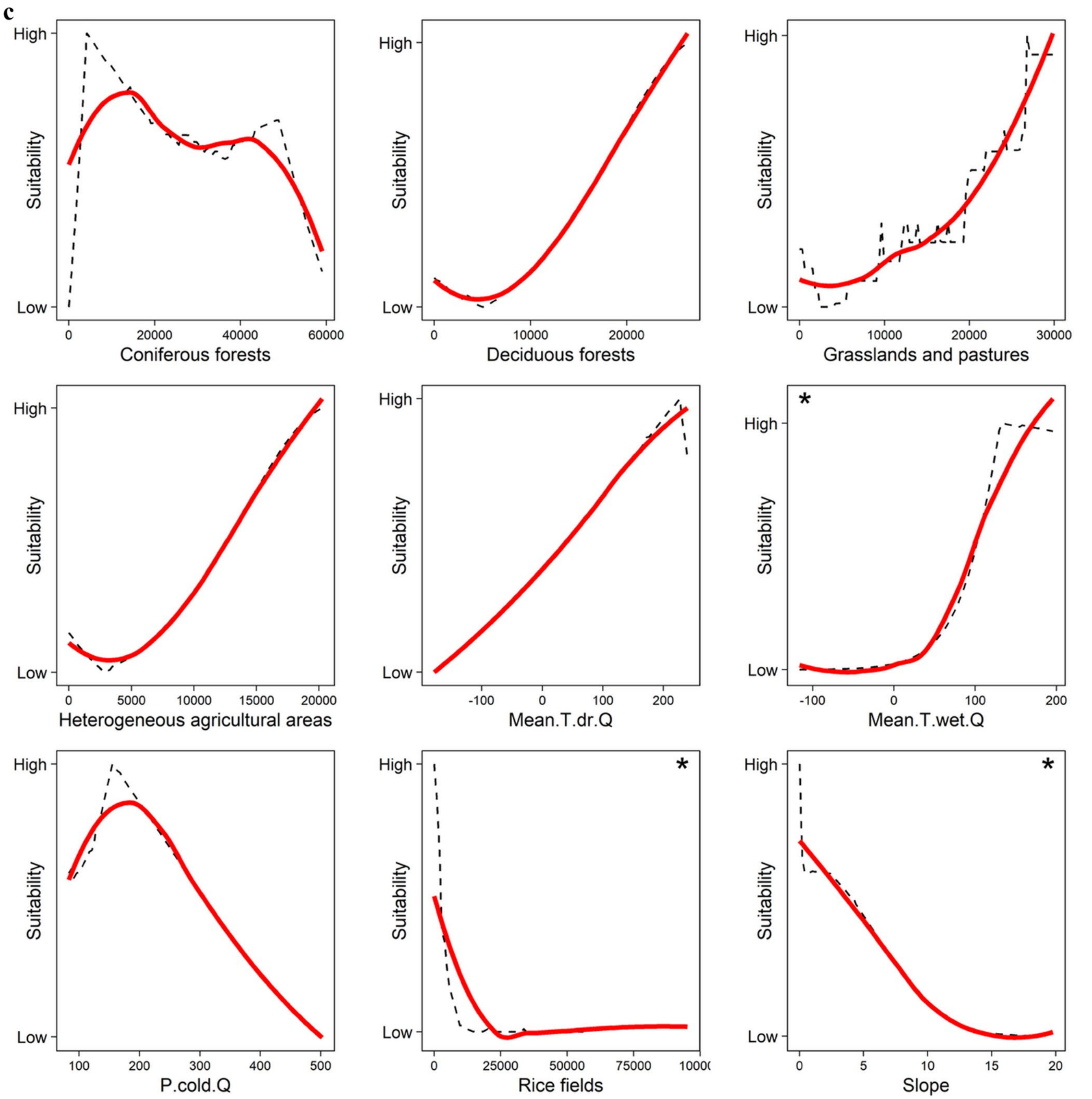

Fig. 3 (continued)

medium-to-high temperatures during the driest quarter (i.e., winter in northwestern Italy; ARPA Piemonte 2020) likely reflects higher prey availability during periods of elevated mortality (King and Powell 2007).

For the polecat, distribution was primarily influenced by the mean temperature of the wettest quarter, slope, and the presence of rice fields. Specifically, suitability increased with the mean temperature of the wettest quarter, as warmer spring temperatures likely enhance food resources when young polecats are born (Blandford 1987; Lodé 1997). This variable emerged as the most important driver of the species' distribution in the region, highlighting the polecat's reliance on abundant prey during critical life stages. The positive association with rice fields indicates that these habitats remain suitable, despite widespread habitat loss and rodenticide use, while areas closer to mountains—particularly mountain forests—also appear suitable. Both habitat types likely still support abundant prey for polecats, such as

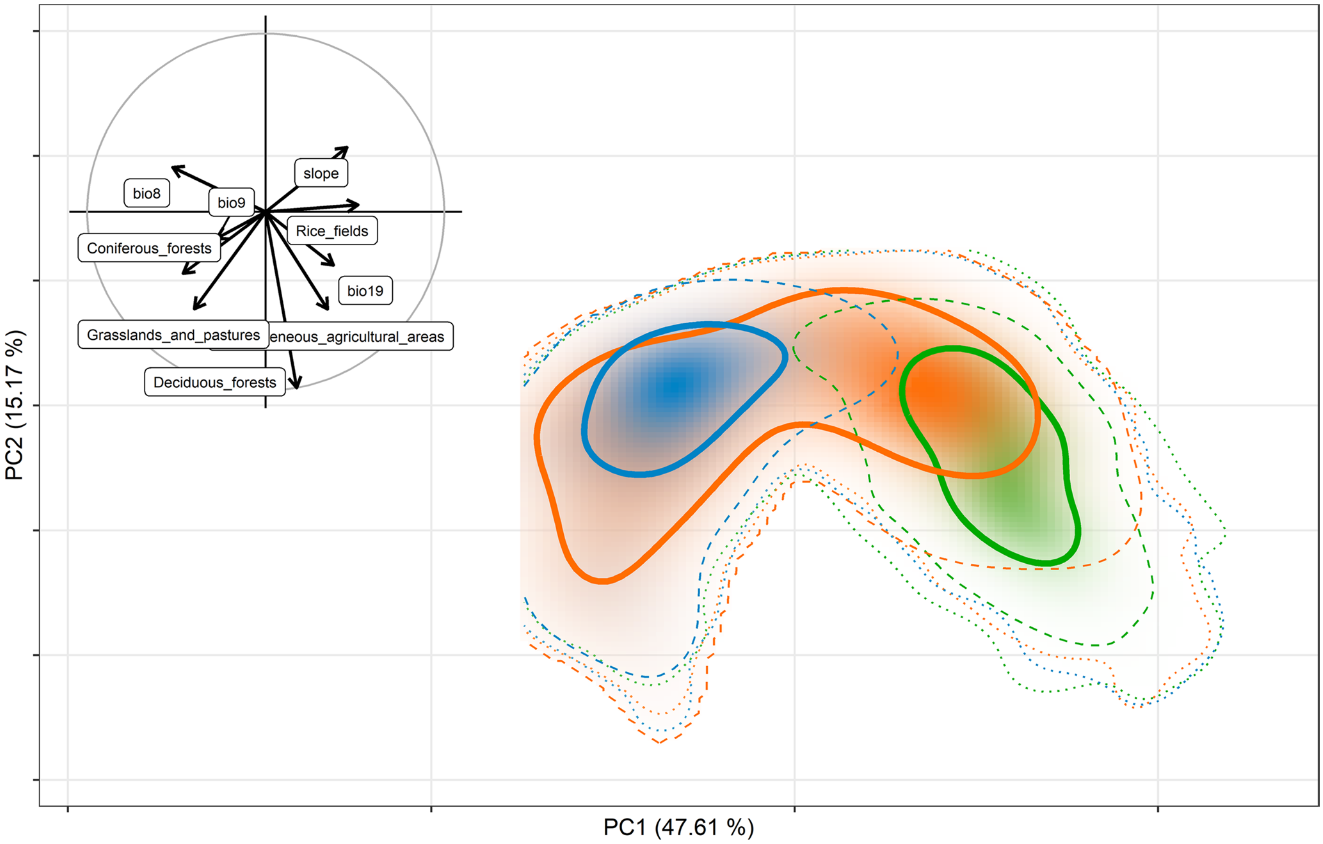

Fig. 4 Principal Component Analysis (PCA) showing overlapping and non-overlapping niche portions between sympatric weasel species. The stoat is shown in green, the least weasel in orange, and the European polecat in blue

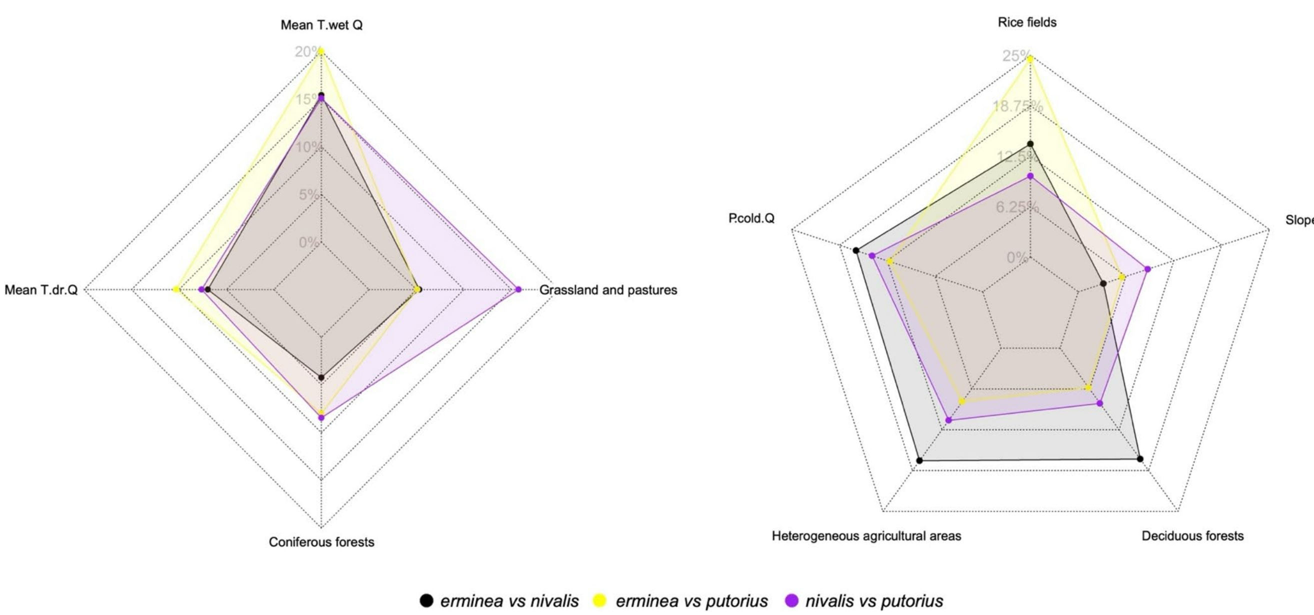

Fig. 5 Variable importance values as emerged from RF classification models quantifying the relative contribution of each predictor in driving niche differentiation between species pairs in environmental space. The left spider plot displays predictors with higher average values in the first species of each pair, while the right plot displays those with higher values in the second species

amphibians and rodents (Prigioni and Marinis 1995; Lodé 1997). Nearly two decades ago, Sindaco and Carpegna (2010) reported similar results, suggesting a potential recovery of the polecat in Piedmont. Although a recent study in Sweden indicated that polecats avoid forests (Osinga et al. 2023), our findings are consistent with observations from more comparable landscapes in Spain (Salvador subm.;Virgós 2003). Both the polecat and the least weasel showed a stronger association with lowland habitats than the stoat, with rice fields and slope being particularly more important for the polecat than for the least weasel. However, as the polecat's ecological niche is largely nested within that of the least weasel, this comparison may not fully capture differences in habitat preferences between the two species.

Overall, the relatively low number of records suggests that none of these species is likely to be common in the study area. Nevertheless, as our dataset is based on presence records collected opportunistically rather than through systematic monitoring, it does not permit reliable inferences about their actual population abundance. Small mustelids are notoriously elusive species, primarily due to their secretive behavior, scarce visible field signs, and naturally low population densities (Macdonald et al. 2017). Additionally, they are often reported as 'camera-shy', which makes monitoring them through trail cameras particularly challenging (Jachowski et al. 2024). Indeed, most of our occurrences were derived from casual sightings and roadkill reports. However, the scarcity of data may also reflect a population decline, as similar trends have been observed for weasels in North America (Cheeseman et al. 2024; Jachowski et al. 2021), Europe (Coomber et al. 2021; Llorca et al. 2024), and Africa (Hayder et al. 2023). Globally, the primary threats to mustelid conservation include overexploitation, land-use change, and the spread of invasive species (Marneweck et al. 2021; Wright et al. 2022). In northwestern Italy, however, all weasel species are protected under national and regional legislation, and the polecat is listed in Annex V of the EU Habitats Directive. This likely excludes overexploitation as a significant threat, although poaching still occurs in some Alpine areas (Deflorian et al. 2018).

As highlighted by the strong association of the stoat with the Alpine habitats, and the least weasel and polecat with agricultural landscapes, climate change and intensive agriculture emerge as potential threats to these species respectively. The limited suitable habitat for the stoat, combined with the higher rate of climate change in the Alpine region (Gobiet et al. 2014), necessitates further urgent investigation. On the other hand, understanding the relationship between the least weasel, which is reportedly experiencing a 'silent extinction' in lowlands (Llorca et al. 2024), and agricultural practices is crucial for assessing its actual extinction risk. Finally, it is necessary to clarify the polecat's distribution trend, as it is declining in several countries (Croose et al. 2018) but expanding in other areas due to the effects of climate and land-use changes (Osinga et al. 2023). For these reasons, long-term monitoring programs, involving specific tools for small mustelids such as the 'Mostela' for stoats and weasels (Mos and Hofmeester 2020; Granata et al. 2025) and the 'Polecam' for polecats (Hofmeester et al. 2024), are vital for understanding the current and future distribution of small mustelids in Europe. Implementing such approaches will be essential to assess population trends, clarify conservation status, and anticipate future changes under climate and land-use pressures.

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Author contributions M.G., M.D.F., and S.B. conceptualized and designed the study. M.G., F.D.P., R.B., L.M., L.M., and M.R. collected the data in the field and/or through database queries. M.G. and F.D.P. checked the data and finalized the datasets. F.D.P., A.M.B., and M.D.F. developed the environmental predictors and ran the models. M.G. wrote the initial draft of the manuscript. All authors provided critical feedback to the drafts and gave final approval for publication.

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Data availability Open-access data used in this study are publicly available through iNaturalist and the Global Biodiversity Information Facility (GBIF). Additional data collected from protected areas and other institutions are not publicly available, as weasel species are protected under both Italian and European legislation. In particular, the European polecat is listed in Annex V of the EU Habitats Directive (92/43/EEC). These restricted data can be provided by the corresponding author upon reasonable request, subject to the data-sharing policies and agreements of the involved institutions.

Declarations

Competing interests The authors declare no competing interests.

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