Can bear corridors support mammalian biodiversity? A case study on the Central Italian Apennines

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Abstract:
Ecological corridors are essential for maintaining ecosystem functionality, as they facilitate the movement of species between protected areas. In the Central Italian Apennines, five corridors have been identified to enhance habitat connectivity for the critically endangered Marsican brown bear (*Ursus arctos marsicanus*). This study focuses on two of these corridors to investigate their support of other mammal species populations. We collected data from camera traps over four months, and applied a Random Encounter Model to estimate the population densities of eight meso- and macro-mammal species. We compared the densities we estimated with those reported in the literature for different locations across Europe. The results indicated higher-than-average densities for several species compared to published data, especially for ungulates. These findings underscore the broader importance of Marsican bear corridors, providing important habitats for several mammal species. This type of analysis can be replicated in the same area at different times, or in other coexistence corridors for large carnivores, to support management strategies. Effective management of these corridors, with a focus on reducing human disturbance and improving habitat connectivity, will be critical for the long-term survival of both the Marsican bear and its coexisting species.

Keywords: wildlife management, ecological corridors, camera-traps, REM, density estimation.

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Short title
The density of mammals in a study area of Central Apennines

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Introduction

Protected areas (PAs) are the cornerstone of biodiversity conservation (Watson et al. 2014), and have increased rapidly in their global extent, now covering around 16% of the Earth's land surface (UNEP-WCMC & IUCN, 2024). PAs have been effective at preventing the extinction of several species, and nowadays the populations of many threatened mammal species rely almost entirely on these sites, while threats such as habitat loss, degradation and fragmentation affect unprotected parts of their distribution ranges (Pacifici et al. 2020). Yet, even effectively managed PAs might not be sufficient to preserve species with high spatial requirements, thus maintaining ecological connectivity between PAs is essential (Hilty et al. 2020). This is the rationale behind the inclusion of ecological corridors within the 2030 EU Biodiversity Strategy "*Legally protect a minimum of 30% of the EU's land areas and 30% of the EU sea area and integrate ecological corridors*" (EC 2024). This strategy requires extending conservation intervention beyond PAs, also focussing on the restoration and maintenance of habitat corridors between isolated reserves (Fahrig 2003, Pacifici et al. 2020, EC 2022).

Ecological corridors can increase the persistence of species with large spatial requirements, by allowing migration and dispersal, and they can also help to reduce species' mortality by facilitating the avoidance of predation and human disturbance (Curcic and Djurdjic 2013). They became a key element of conservation and management strategies for endangered mammal species, as they can mitigate the impact of habitat loss and fragmentation and they can increase the resilience of PAs networks (Mateo-Sánchez et al. 2014, McGuire et al. 2016). However, the ecological value of a corridor is species-specific, as corridors intended for one species may not work for other species with different habitat preferences and movement patterns (Merenlender et al. 2022). The vast majority of ecological corridors are designed for charismatic and endangered species, which have high conservation support from stakeholders and citizens (Keeley et al. 2019). Yet, these areas might also provide important co-benefits for several other species co-occurring with the focal species for which the corridor was designed, especially if the former have lower spatial requirements than the latter (Wang et al. 2018).

The Marsican brown bear (*Ursus arctos marsicanus*) is a subspecies of the brown bear (*Ursus arctos*) and an endemism of the Central Italian Apennines (Ciucci and Boitani 2008). This subspecies is geographically isolated from other bear populations, and represents one of the most endangered mammal in Europe, facing severe risk of extinction due to very small population size (Ciucci and Boitani 2008, Ciucci et al. 2015, Gervasi and Ciucci 2018). While the population is almost entirely confined within the Abruzzo, Lazio, and Molise National Park (ALMNP), five corridor areas of suitable habitat have been identified by stakeholders and conservationists to enhance the connectivity towards critical areas in between PAs (Carotenuto et al. 2014, Ciucci et al. 2016, Ciucci et al. 2017, Maiorano et al. 2019). These corridors are now the focus of conservation, restoration and rewilding activities from a group of local NGOs, with the main goal of facilitating bear recolonization of its former range by reducing the mortality causes outside protected area (Cipollone et al. 2024).

In addition to the Marsican brown bear, the Central Apennines host other charismatic mammal species (Loy et al. 2019), including endemic subspecies such as the Apennine chamois (*Rupicapra pyrenaica ornata*) and the Apennine wolf (*Canis lupus italicus*), and other species such as the red deer (*Cervus elaphus*), the roe deer (*Capreolus capreolus*) and the porcupine (*Hystrix cristata*). As all these species co-occur with the Marsican brown bear, they can in principle benefit from the management of bear ecological corridors, because several causes of mortality and disturbance operate in a similar way among species. Indeed, it is possible that these corridors act simultaneously as connectivity areas for facilitating bear movement and as suitable habitats able to support meta-populations of other mammal species with lower spatial requirements (Thornton et al. 2016). Despite the high ecological value of these corridor areas, wildlife populations living within them are understudied. Except for the Marsican brown bear, most wildlife monitoring is restricted to PAs, with data often unavailable or only traceable in unpublished reports.

Here, we aim to estimate the population density of meso- and macro-mammal species within two Marsican bear corridors in the Central Apennines, an information that is particularly underexplored in the existing literature. In particular, we aim to provide a baseline estimate of population density intended to be replicated over time and space, and comparable estimates of these species' densities within these corridors. Our goal is to determine if corridors delineated and managed to enhance the safe movements of the Marsican bear population also serve as ecologically valuable habitats for other mammal species, thereby having a high conservation value for them. We deployed camera traps to detect the images of meso- and macro-mammal species with smaller spatial requirements than the brown bear. Based on data collected, we focus on eight species: European badger (*Meles meles*), hare (*Lepus spp.*), porcupine, red deer, red fox (*Vulpes vulpes*), roe deer, wild boar (*Sus scrofa*), and wildcat (*Felis silvestris silvestris*). To estimate population densities for each species, we used the Random Encounter Model (REM; Rowcliffe et al. 2008), one of the most used and robust methods to estimate population density of unmarked populations of different species (Palencia et al. 2022a).

Materials and Methods

Study area

Our study area is located in the Central Apennines (Italy) and includes two ecological corridors designed to enhance the connectivity for the Marsican bear population (Fig. 1). The two corridors connect the Abruzzo, Lazio and Molise National Park (ALMNP) with the Sirente Velino Regional Park (Corridor 1) and with the Majella National Park (Corridor 2). These are part of a set of five corridors identified for the National action plan for the Marsican brown bear protection (PATOM - Piano d'Azione nazionale per la Tutela dell'Orso Marsicano: VV.AA, 2011 by Ciucci et al. (2016). Along their extent, the corridors intersect or include additional reserves that contribute to the regional ecological network, including the Monte Genzana Alto Gizio Natural Reserve (~3,160 ha), the Gole del Sagittario Natural Reserve (~450 ha), and the Lago di San Domenico Natural Reserve (~60 ha). The two corridors together cover an area of approximately 265 km^2, with Corridor 1 extending for around 75 km^2 and Corridor 2 extending for around 190 km^2. Corridor 1 is dominated by grassland (49%), followed by tree cover (36.5%) and a notable proportion of cropland (8.5%), while elevation ranges from 472 to 1637 m asl. Instead, Corridor 2 is dominated by tree cover (68%) and grassland (28.6%), with no significant cropland, and elevation ranging from 449 to 2199 m asl. The climate is temperate Mediterranean continental, with frequent snowfalls, cold winters and hot summers, with a temperature ranging between 24°C and 35°C during the sampling period (Fratianni and Acquaotta 2017).

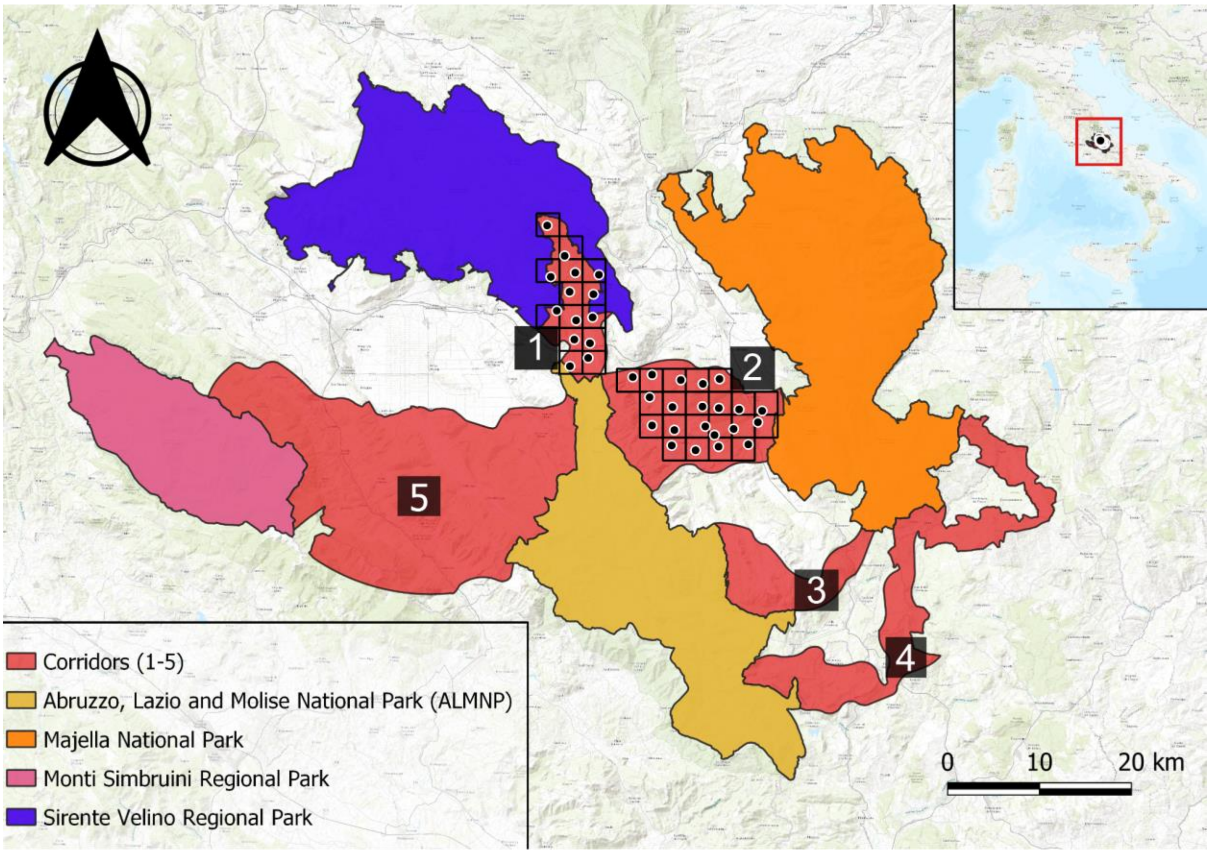

Figure 1: *Map of the five corridor areas identified in the Central Apennines. The corridors (in red, marked with numbers) connect four protected areas (other coloured polygons). The study area, covering Corridor 1 and Corridor 2, is divided into 34 2.5 km grid cells, each including a camera trap (black points).*

Data collection

We placed 34 camera traps from 19/04/2023 to 20/11/2023, for a total of 215 days. We selected this period to avoid winter season, when mammals are less active and snow and frost would have made access to many camera trap locations difficult or impossible. We deployed 14 camera traps in Corridor 1 and 20 in Corridor 2, using a random sampling and following a grid with cells of 2.5 km side. The camera traps were deployed as close as possible to the centroid of each cell, with a maximum distance from the centroid of 200 metres. Camera traps were placed on trees at a height ranging from 0.5 m to 1.7 m, and facing north orientation, to avoid direct exposure to the sun. We used Browning Patriot (BTC-PATRIOT-FHD) camera-traps with the following settings: trail mode (i.e., picture mode); capture delay of 1 seconds; multi shot set on 3 shots; image resolution of 3840 x 2160 (Ultra HD); night exposure on "mid-range" for confined spaces and "long-range" for open spaces. Checks were made regularly every three weeks for each camera trap, to control the status of the batteries and SD cards. During the sampling period, two camera traps were stolen, and replaced approximately 100 metres away from their original locations.

Based on a minimum number of encounters threshold >20 (Rowcliffe et al. 2008) and thus on the possibility to derive the needed parameters for the application of REM, we decided to estimate the density of 8 species of meso- and macro-mammals: European badger, hare, porcupine, red deer, red fox, roe deer, wild boar, wildcat. Since it was not possible to distinguish the European hare (*Lepus europaeus*) from the Apennine hare (*Lepus corsicanus*) in the images, we refer to the hare as *Lepus spp*. We decided to not consider the wolf it in our analysis, because the home range of a wolf pack is much larger than our study area and a different sampling design would have been needed to estimate wolf density (Ciucci et al. 1997, Mancinelli et al. 2018).

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Data processing

We processed camera trap data to calculate density estimates via the REM, a model that operates with unmarked animals and estimates their population density in a given area (Rowcliffe et al. 2008). The model treats animals like ideal gas particles and estimates density within the collective detection viewsheds of a camera array. REM has been proven to be a reliable method for estimating wildlife population density in a wide range of situations and scenarios, when using appropriate methods to estimate parameters and appropriate sampling designs (Palencia et al. 2022). It is also effective for monitoring more than one species using the same survey design, because for its application it is not needed for the animals to have a high detection probability (Rowcliffe et al. 2008). We estimated densities for each corridor separately, and for the entire study area (Corridor 1 + Corridor 2).

The densities are estimated based on different parameters (Fig. 2), which can be measured directly from the camera trap pictures, without the need of auxiliary data (Caravaggi et al. 2016, Hofmeester et al. 2017). Parameters estimated include: day range (i.e., the average distance travelled by an individual during the day, estimated as the product of speed –average travel speed while active– and activity rate –proportion of day that the population spent active), the camera traps' effective detection zone (EDZ; i.e., the area effectively monitored by cameras, defined by the effective detection radius – EDR– and the effective detection angle –EDA), and trapping rates (i.e., the number of independent encounters per unit time, in particular the number of encounters occurred at least 30 minutes from each other over the collective time in which the camera traps were operative) (Rowcliffe et al. 2008). To account for heterogeneity in detection distances across different camera trap models, we estimated EDR and EDA by extracting the distance and the angle from camera traps of each encounter, and then by using distance sampling models to find the threshold value at which the expected number missed within is equal to the expected number detected beyond (Rowcliffe et al. 2011; more details in Appendix SI). All the parameters were measured by using data from Corridor 1 and Corridor 2 separately when estimating densities of each corridor, while we considered all the images together in calculating densities of the entire study area (Corridor 1 + Corridor 2) (Appendix SI, Table S2).

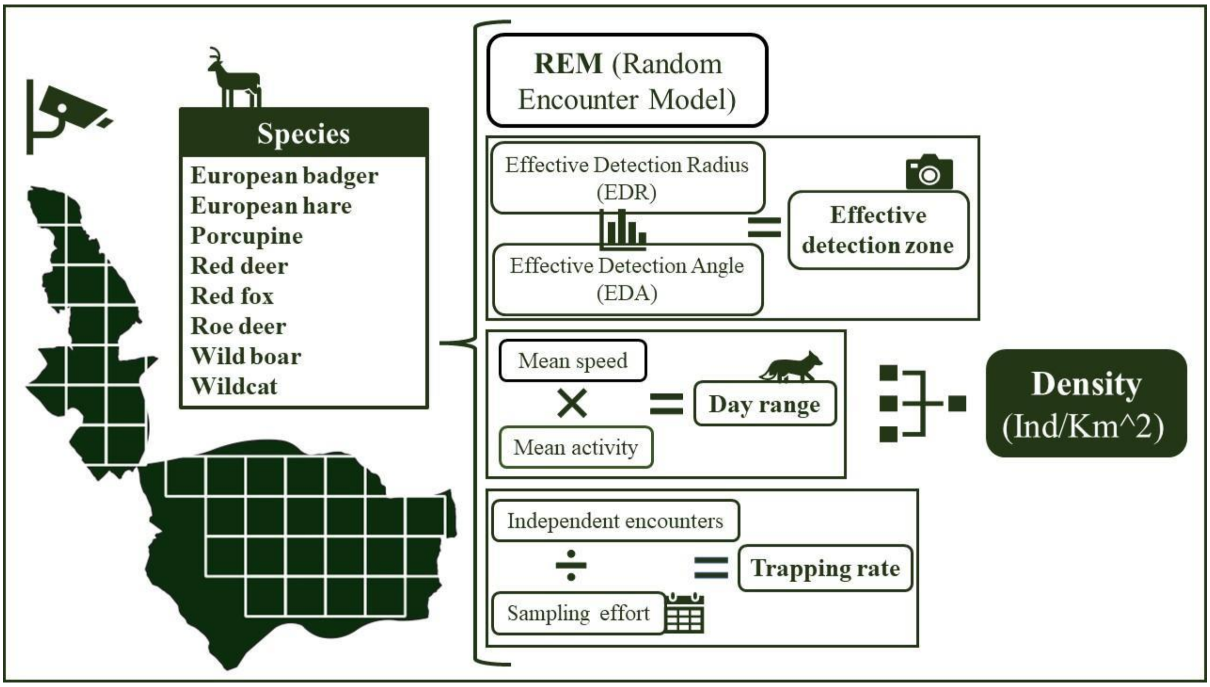

Figure 2: *Framework of the application of the Random Encounter Model (REM) to estimate the density of the eight mammal species analysed, in the study area.*

Random Encounter Model application

We applied REM following Palencia (2022b) to estimate the density of each species (*D*), using the formula:

$$D = \frac{y}{t}\frac{\pi}{vr(2+\alpha)} \qquad [1]$$

where *y* is the number of independent encounters, *t* is total camera survey effort (in days), *v* is the average distance travelled by an individual during a day (i.e., day range, expressed in km/day), and *r* and *α* are the radius (metres) and angle (degrees) of the camera traps detection zone, respectively. For the wild boar, which is a highly gregarious species, most independent encounters included groups rather than solitary individuals. As a result, applying the standard REM formula directly yields an estimate of group density rather than individual density (Rowcliffe et al. 2008). To adjust this, we multiplied *D* by the average group size observed in our dataset ($\bar{s}$ = 3.31 individuals), according to the following formula:

$$Di = D \times \bar{s} \qquad [2]$$

Where *Di* is the individual density, *D* is the group density estimated using the REM, and $\bar{s}$ is the average number of individuals per group.

We also represented the trapping rates estimated for each species in each grid cell.

To allow interpretation of our results, we gathered available information on species density from the literature. Previous studies have demonstrated that REM results are comparable to those obtained through other methods when all the parameters (i.e., day range, detection zone and encounter rate) are estimated accurately (e.g., Palencia et al. 2022a; Santini et al. 2018). We selected references published from the year 2000 onwards and referring to population densities estimated in Europe, giving priority to those estimated in Italy, whenever available. Since it was not possible to consider only densities estimated with the camera trap method, we took into consideration studies that used different methodologies. We collected 29 studies that reported population estimates in Europe for recent years (year 2000 and onwards). Among these, five were literature reviews that reported several density estimates (Smith et al. 2005, Melis et al. 2009, Lara-Romero et al. 2012, Mattioli et al. 2014). We found a total of 9 studies that used camera traps to estimate densities, two of which used REM. One of them is a collection of 19 works using REM to calculate the density of wild boars in different European areas (ENETWILD-consortium et al. 2022). Except for the Abruzzo Lazio and Molise National Park (ALMNP) for which we densities of red deer and roe deer were estimated using the pellet count method (Latini 2019) and the Monte Genzana reserve for which we found red deer estimates from individual recognition by camera trapping (Fabrizio et al. 2012), we have not found density data within the nearby PAs.

Covariates extraction and comparison between corridors

We also compared density estimated across corridors. We extracted the values (i.e., mean, median, and standard deviation) of different environmental covariates within each corridor, to highlight the main environmental differences between the two areas and therefore better explain the differences in the density results we obtained. We considered the following covariates: land-cover (i.e., tree cover, shrubland, grassland, cropland, built up) measured as the percentage values of the classes surface coverage within corridors, fractal dimension index (dimensionless), elevation (m), slope, distance from primary roads (m), distance from settlements (m), livestock density measures as livestock units per hectare (LSU/ha).

We extracted land-cover variables from the European Space Agency (ESA) World Cover portal (Zanaga et al. 2022). The original raster has a resolution of 10 m, and we resampled it at a resolution of 30 m to be consistent with other covariates. Fractal dimension index is a fragmentation metric that is based on the area and perimeter of the patch and describes its complexity. It was extracted using the LecoS plugin on Qgis (3.22.12-Białowieża, 2022; Jung 2016) from the tree cover raster, thus quantifying the fragmentation of forest habitats. To calculate the statistics for the elevation and the slope, we downloaded the Digital Elevation Model DEM GLO-30 (Fahrland et al. 2022) for central Italy from the Nasa Earth Observing System Data and Information System (EOSDIS) and we then calculated the zonal statistics using Qgis Processing tools. Using Qgis, we calculated the Euclidean distance of each camera trap to the nearest village. To calculate the distances of each camera trap from the primary roads, we used the roads' shapefile downloaded from "OpenstreetMap" (Curran et al. 2013). We calculated the livestock density in Corridor 1 and Corridor 2 using the dataset of Dragonetti et al. (2025).

Results

Estimating model parameters

We collected a total of 3,942 pictures of 15 species of wild mammals, including 3,379 pictures of our 8 study species (Table S1). We found high variability in the estimate of day range among species – i.e., the average distance that animals travel in a day – with values ranging from 5.91 km/day (SE = 0.89) for the European hare to 16.21 km/day (SE = 1.49) for the red fox (Table S2). The trapping rate (i.e., the number of independent encounters over time) varied widely in the study area, both among species and between the two corridors (Fig. 3, Table S3). The porcupine and the wildcat were not detected in several cells and showed the lowest trapping rates (mean = 0.02 ± 0.05 encounters per day for porcupine; mean = 0.01± 0.02 for wildcat). Conversely, the red deer and roe deer were detected in all cells and showed the highest trapping rates (mean = 0.21 ± 0.22 and mean = 0.21 ± 0.16, respectively). The wild boar was also detected in the entire study area except two cells of corridor 2, with a mean trapping rate = 0.08 ± 0.12, and showing high values in some locations (i.e., 0.50 in “Marsicana” and 0.47 in “Anversa”). The red fox showed trapping rates greater than 0 in all the cells of corridor 1 but not in all cells of corridor 2, with a mean of 0.10 ± 0.11 in the whole study area. Notably, the porcupine was only detected in three locations of Corridor 2: "Anversa" (0.27), "Lago di San Domenico" (0.05) and "Valle Santa Margherita" (0.04).

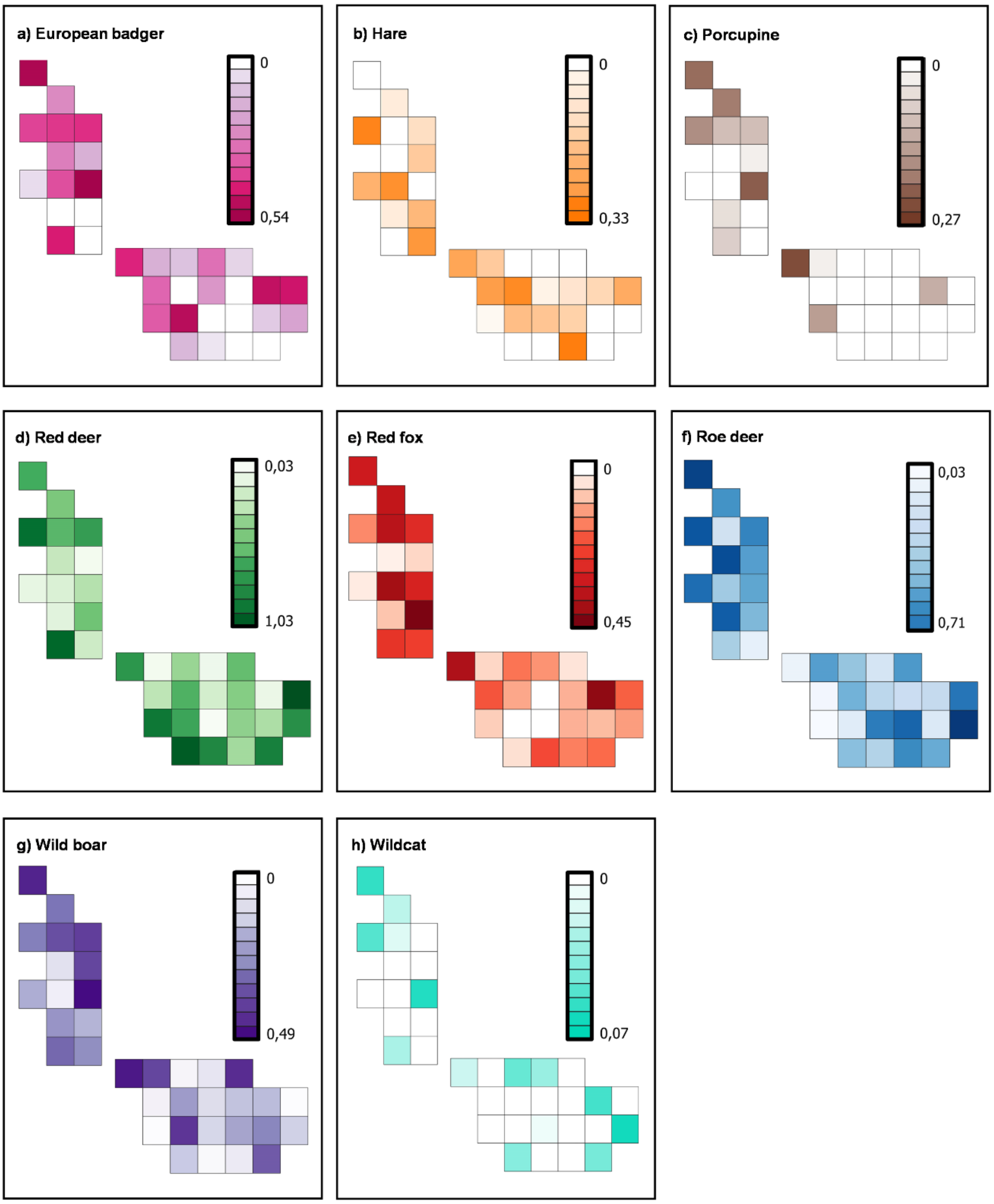

Figure 3: *Trapping rates of each camera trap location of the study area, for each of the eight species of meso- and macro-mammals analysed (panels a-h). Trapping rates were obtained from the number of independent encounters divided by survey effort (i.e., the operating time of camera traps expressed in days).*

Species density estimates

The wild boar showed the highest density in the overall study area (7.22 ± 1.75 ind./km^2), followed by the roe deer (3.41 ± 0.70 ind./km^2) and the hare (3.39 ± 0.86 ind./km^2; Table 1). Instead, the wildcat and the red fox were the species with the lowest densities (0.43 ± 0.17 ind./km^2 and 1.27 ± 0.27 ind./km^2, respectively). For the wildcat, reliable estimates could only be obtained for the entire study area, due to an insufficient number of images for each separate corridor. To aid interpretation of our results, we compared the population densities estimated in our study area with those found in the literature (Table 1, Table S4).

We found that all the densities we estimated were comparable to the data collected from the literature. While important for results interpretation, it is important to clarify that this is not a formal comparison of densities inside *vs* outside corridors, as the study design behind different estimates was not the same (see Discussion).

Comparison between the two corridors and covariates extraction

The analysis of environmental covariates revealed that Corridor 1 is, on average, more cultivated, more built, more densely grazed and less forested than Corridor 2. The fractal dimension index (i.e., fragmentation of forested habitats) was also higher in Corridor 1. Corridor 2, on average, showed a higher altitude and slope. Additionally, the camera traps in Corridor 1 were generally closer to primary roads than those in Corridor 2, but almost at the same distance from the nearest village (Fig. S2).

These environmental differences between the two corridors are also reflected in different estimates of population density for several species (Table 1, Fig. S3). In Corridor 1, species with the highest density included the wild boar (14.21 ± 4.64 ind./km^2), the badger (4.73 ± 2.05 ind./km^2) and the roe deer (4.67 ± 1.47 ind./km^2). In Corridor 2, species with the highest density included the hare (3.60 ± 2.96 ind./km^2), the red deer (3.36± 1.50 ind./km^2) and the roe deer (2.94 ± 0.68 ind./km^2). We found

Corridor 1 showing higher densities than Corridor 2 for all species except the hare (that however showed similar estimate across corridors). Some of the most notable examples were the wild boar (14.21 $\pm$ 4.64 ind./km^2 in Corridor 1 *vs* 1.69 $\pm$ 0.71 ind./km^2 in Corridor 2), the badger (4.73 $\pm$ 2.05 ind./km^2 in Corridor 1 *vs* 1.03 $\pm$ 0.34 ind./km^2 in Corridor 2) and the red fox (2.65 $\pm$ 0.63 ind./km^2 in Corridor 1 *vs* 0.49 $\pm$ 0.14 ind./km^2 in Corridor 2). For the wildcat, data were not sufficient to estimate the densities for the two corridors separately.

Table 1. *Density estimates and standard errors (S.E.) derived from the application of Random Encounter Model (REM), for eight species of meso- and macro-mammals. Densities of all species are reported separately for Corridor 1, Corridor 2, and for the whole study area, with the exception of the wildcat (Felis silvestris silvestris) which could only be reported for the whole area. The last column refers to the other densities found from the literature.*

Species	**Corridor 1 (ind./km^2)**	**Corridor 2 (ind./km^2)**	**Corridor 1+2 (ind./km^2)**	**Literature values (ind./km^2)**
European badger (*Meles meles*)	4.73 ± 2.05	1.03 ± 0.34	1.83 ± 0.82	Min: 0.26 Max: 3.81 Median: 0.85
Hare (*Lepus spp*)	3.22 ± 1.58	3.60 ± 2.96	3.39 ± 0.86	Min: 0.0023 Max: 82 Median: 9.15
Porcupine (*Hystix cristata*)	1.84 ± 0.68	1.08 ± 0.67	1.40 ± 0.47	Min: 0.44 Max: 0.49 Median: 0.46
Red deer (*Cervus elaphus*)	3.36±1.50	2.71 ± 0.99	3.16 ± 0.92	Min: 1.72 Max: 8.5 Median: 2.85
Red fox (*Vulpes vulpes*)	2.65 ± 0.63	0.49 ± 0.14	1.27 ± 0.27	Min: 0.21 Max: 4.4 Median: 0.66
Roe deer (*Capreolus capreolus*)	4.67 ± 1.47	2.94 ± 0.68	3.41 ± 0.70	Min: 0.11 Max: 53.8 Median: 15.45
Wild boar (*Sus scrofa*)	14.21 ± 4.64	1.69 ± 0.71	7.22 ± 1.75	Min: 0.35 Max: 47 Median: 6.54
Wildcat (*Felis silvestris silvestris*)	*NA*	*NA*	0.43 ± 0.17	Min: 0.069 Max: 1.36 Median: 0.33

Discussion

We estimated the densities of eight meso- and macro-mammal species in two areas of the Central Apennines managed as connectivity corridors for the Marsican bear by local administration and NGOs (Ciucci et al. 2016, Maiorano et al. 2019, Cipollone et al. 2024). Our results on mammal density constitute important knowledge, since this information is especially scarce in our study area and, overall, in the Central Apennines. We estimated densities both at the individual corridor level and for the entire study area, and we compared these with density values from other European areas, to contextualize and validate our results, and to identify species with existing population data from nearby protected areas. We found that the densities we estimated are on average higher than those found in the literature, suggesting that these bear corridors host areas of high ecological value for several other mammal species.

The comparison between the two corridor areas allowed us to understand which environmental conditions could favour the presence of the species analysed. Corridor 1 showed higher density values than Corridor 2 for almost all species. Species that showed the greatest differences between corridors were the European badger, the red fox, the wild boar and the roe deer. The greater presence of badgers in Corridor 1 than in Corridor 2 is certainly something to further investigate, as this species is known to prefer forested environments rather than shrubland and grassland or cultivated fields, which are more present in Corridor 1 (Rosalino et al. 2008, Chiatante et al. 2017). Species such as foxes and wild boars could benefit from the more widespread (albeit not intense) anthropic presence in Corridor 1, being high generalists. Conversely, the roe deer could benefit from mosaic spaces with a high ecotone index characterised by the continuous alternation of open environments with herbaceous vegetation and broad-leaved woods, typical of Corridor 1. Corridor 1 showed a slightly higher grazing pressure than Corridor 2, placing it within the category of semi-natural habitats shaped by extensive grazing (Dragonetti et al. 2025). These habitats play a key role in maintaining open landscapes and supporting biodiversity, particularly species that thrive in ecotonal and transitional zones. This is consistent with the higher forest fragmentation observed in the area, as grazing helps prevent woodland encroachment (Falcucci et al. 2007; Ponzetta et al. 2010). In addition, the lower altitude and slope of Corridor 1 could favour most of the species analysed, as they are not strictly mountainous or alpine species.

The three species of ungulates (i.e., roe deer, red deer, wild boar) showed the highest densities and the highest trapping rates. This is consistent with the trend of the last few years in Italy, which sees these species expanding their ranges and increasing their population numbers (Rondinini et al. 2022). Italian ungulates are mostly represented by opportunistic and generalist species. As they can adapt to several ecological conditions, they have exploited the massive abandonment of mountains and hills by humans in the last decades in the internal areas of Italy which facilitated the expansion of the woodlands (Acevedo et al. 2011, Falcucci et al. 2007, Valente et al. 2020). While we could not obtain a reliable density estimate of the wildcat in each corridor, but just for the whole area, Corridor 2 showed higher trapping rates than Corridor 1 which seem to indicate higher suitability (Fig. 3). However, a more extensive camera trapping design would be required to validate this hypothesis.

A potential limitation of our estimates concerns the selected sampling period (19 April – 20 November), which excludes the winter season. This may have led to seasonally biased species activity rates and detection probabilities. However, the REM framework is designed to account for such variation: a lower trapping rate due to reduced activity should be balanced by a correspondingly shorter day range, resulting in broadly consistent density estimates.

Density estimates for individual species

We found our estimates aligning with, or even exceeding, previously reported values in the literature for almost all species (see Appendix SII for additional discussion). We decided to compare our results with densities estimated with other methods when REM estimates were not available, as unbiased densities are obtained when REM parameters are calculated accurately (Palencia et al. 2022a; Santini et al. 2018). By comparing our values with other estimates reported in the literature we aimed to place our findings within a broader range of known population densities, assess their reliability, and identify which species have been studied in nearby protected areas.

For the European badger, our estimated density (1.83 ± 0.82 ind./km^2) was higher than average but still comparable to other European studies that employed camera traps (Lara-Romero et al. 2012). Although Italy lacks comprehensive data on badger populations, one study in the river Po plain using camera traps reported lower densities (0.93–1.4 ind./km^2) in hilly regions (Balestrieri et al. 2016).

Regarding the hare, we estimated a density of 3.39 ± 0.86 ind./km^2, which is on the lower end compared to other European estimates (5.6 ind./ km^2 to 82 ind./ km^2) (Smith et al. 2005), even if most of these studies used old methods, such as transect counts or spotlight surveys. The only other study conducted in Italy (Genghini and Capizzi 2005) reported much lower hare densities (0.0027 ± 0.0007 ind./km^2).

For porcupines, our density estimate (1.40 ± 0.47 ind./km^2) was higher than most reported in the literature (e.g., 0.49 ind./km^2 in Lombardy - Palencia et al. 2024). This difference is likely due to our study area being located within the core range of the species, whereas Lombardy is probably still at the periphery of the porcupine's current distribution. The species is currently undergoing a range expansion, facilitated by habitat changes such as global warming and agricultural abandonment (Mori et al. 2021).

Results for ungulates were mixed. Our red deer density (3.16 ± 0.92 ind./km^2) closely matched previous estimates for central Italy and aligned with estimates from the ALMNP, where a pellet count survey recorded a density of 3.8 ind./km^2 (Latini 2019). We also found estimates from the Monte Genzana Alto Gizio Reserve, where individual recognition through camera trapping led to an estimated density of 1.3–2.5 ind./km^2 (Fabrizio et al. 2012). In contrast, roe deer density in our study (3.41 ± 0.70 ind./km^2) fell within the medium-to-low range of European estimates (0.11 – 53.80 ind./km^2) (Melis et al. 2009). Lower roe deer densities are expected in areas such as our study site, where high predator presence tend to limit roe deer populations. In contrast, areas with no predators, such as Ticino National Park, report much higher densities (30.7 ind./km^2 - De Pasquale et al. 2019). Comparing our estimate with a regional one, we found an average density of roe deer of 0.5 ind./km^2 (95% CI = 0.4-0.6) within the ALMNP (Latini 2019), calculated with the pellet count method, with higher densities recorded in the peripheral layers, close to our study area (0.94 ind./km^2, 95% CI= 0.22- 8.15).

For wild boar, our estimated density (7.34 ± 1.78 ind./km^2) was consistent with other studies that adopted REM (from 0.35 ind./km^2 in Croatia to 15.25 ind./km^2 in Italy: ENETWILD-consortium et al. 2022). Due to their high reproductive rate, migratory behaviour, and adaptability to various habitats, wild boar have a density that is notoriously difficult to estimate accurately (ENETWILD-consortium et al. 2018). However, the high trapping rate of wild boars in our study suggested a genuinely high density in the area, in line with European trends, where wild boar numbers have steadily increased in the last decades (Massei et al. 2015). Wild boars are highly adaptable compared to other ungulates, being omnivorous and modifying their diet based on locally available resources, showing high reproductive rates, and the ability to adapt in a wide range of habitats, from forests to agricultural areas (Colomer et al. 2024).

Our density estimate of the red fox (1.27 ± 0.27 ind./km^2) was on the higher end compared to other European studies (e.g., 0.23-1.62 ind./km^2 in the Mediterranean area - Jimenez et al. 2019). We found Corridor 1 had more than twice the fox density of Corridor 2, likely due to its greater degree of human presence and lower elevation. Red foxes, being highly adaptable and able to live in human-dominated landscapes, benefit from such conditions (Alexandre et al. 2020).

For the wildcat, we estimated a density of 0.43 ± 0.17 ind./km^2, consistent with previous European studies that used camera traps. For example, Anile et al. (2014) found similar densities (0.32–1.36 ind./km^2) in Sicily using different methods, including REM. Other studies in mountainous regions (Maronde et al. 2020, Fonda et al. 2022) reported comparable densities (0.26 and 0.35 ind./km^2) using camera traps.

Management and research implications

Our work demonstrated that ecological corridors defined for the Marsican bear host high densities of several other mammal species, highlighting the crucial role that these areas play in supporting mammalian biodiversity in the Central Apennines. Albeit not formally comparable due to different analytical protocols, REM densities of the ungulates (roe deer, red deer and wild boar) were similar to the ones found in literature. In particular, the densities of red deer and roe deer were close to the ones in the nearby PAs, further emphasizing their conservation value and the importance of dedicated management strategies. A focus of future studies could be a formal comparative study in nearby PAs using the same methods we deployed in corridor areas, that we were unable to conduct due to strict park protection policies, difficulties in availability of data and the significantly larger sampling effort required. In this sense, our results provide an important baseline to enable comparative studies. Similarly, the protocol presented here should be replicated regularly in the same study area, to allow for the detection of trends in densities and the investigation of correlations between management activities that have recently started in the corridors to enhance bear conservation and the density of non-target species (Cipollone et al. 2024). Analyses similar to those we presented here can support management in other co-existence corridors and for other large carnivores. This could be the case, for example, of the Iberian Peninsula, where two separate brown bear populations live in the Cantabrian Mountains and the Pyrenees, coexisting with human activities (Pérez et al. 2010, Méndez et al. 2014). Our analysis also highlighted marked differences between the two corridors, with Corridor 1 showing higher densities for almost all species. This finding is particularly relevant for land management, as it suggests that many species can benefit from certain forms of human activity, such as extensive agriculture and traditional pasture, when carried out in a non-intensive way (Halada et al. 2011; Schieltz & Rubenstein 2016).

We found that the porcupine and the ungulates are present with particularly high densities in the bear corridors. Human-wildlife conflict, due to the frequent use by these species of agricultural lands for foraging, increases tensions with local communities. In this sense, it is essential to monitor the population development of those species over an extended time (White and Ward 2010), while the installation of electric fences, already recommended for mitigating bear-human conflicts in the LIFE project “Bear-Smart Corridors” (Cipollone et al. 2024), could be effective in preventing also damages from porcupines. Moreover, compensation schemes and community engagement initiatives could foster coexistence, reducing the negative impacts of wildlife on human livelihoods while promoting the ecological benefit of maintaining healthy mammal populations.

Since bear corridors are of great importance for the entire community of meso- and macro-mammals, management strategies should focus on maintaining and enhancing their ecological connectivity, facilitating species movement and dispersal beyond PAs (Fahrig 2003, Pacifici et al. 2020). This is in line with the Kunming-Montreal Global Biodiversity Framework and the EU Biodiversity Strategy both of which emphasize the need for ecological corridors to connect fragmented habitats (EC 2022). Likewise, this goal is in line with the 2030 EU Biodiversity Strategy and the Italian National Strategy for Biodiversity 2030, which stress the importance of integrating ecological corridors to link isolated PAs (EC 2020, MASE 2023). Thus, the management of these corridors must reduce human-induced pressures, for instance by mitigating road impact with strict regulation of vehicular access on dirt roads and critical areas during sensitive periods for the bears such as the mating season (Ciucci et al. 2016). Wildlife mortality due to road accidents along main roads can be limited by measures such as road signals and awareness campaigns implemented in projects like LIFE "Strade", which are crucial in Central Apennine corridors (Giovacchini and Fabrizio 2022; Valfrè and Cipollone 2016).

Our findings imply that conservation actions intended for enhancing habitat connectivity for the Marsican brown bear could also be effective for other species in the area, thereby having an “umbrella” effect. These actions will ensure the long-term survival of the Marsican bear and other mammal species that rely on these critical habitats (either for movement and survival).

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Authors' contributions

Chiara Dragonetti, Moreno Di Marco, Jan-Niklas Trej and Piero Visconti conceived the ideas and designed the methodology; Chiara Dragonetti, Jan-Niklas Trej and Niccolò Ceci collected the data; Niccolò Ceci, Chiara Dragonetti, Jan-Niklas Trej and Stefan Von Kempis analysed the data and performed the Random Encounter Model; all authors contributed to the writing, reviewing, editing and finalising of the manuscript.

Competing interests

The authors declare that they have no competing interests.

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Data availability

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Figures captions

Figure 1: *Map of the five corridor areas identified in the Central Apennines. The corridors (in red, marked with numbers) connect four protected areas (other coloured polygons). The study area, covering Corridor 1 and Corridor 2, is divided into 34 2.5 km grid cells, each including a camera trap (black points).*

Figure 2: *Framework of the application of the Random Encounter Model (REM) to estimate the density of the eight mammal species analysed in the study area.*

Figure 3: *Trapping rates of each camera trap location of the study area, for each of the eight species of meso- and macro-mammals analysed (panels a-h). Trapping rates were obtained from the number of independent encounters divided by survey effort (i.e., the operating time of camera traps expressed in days).*

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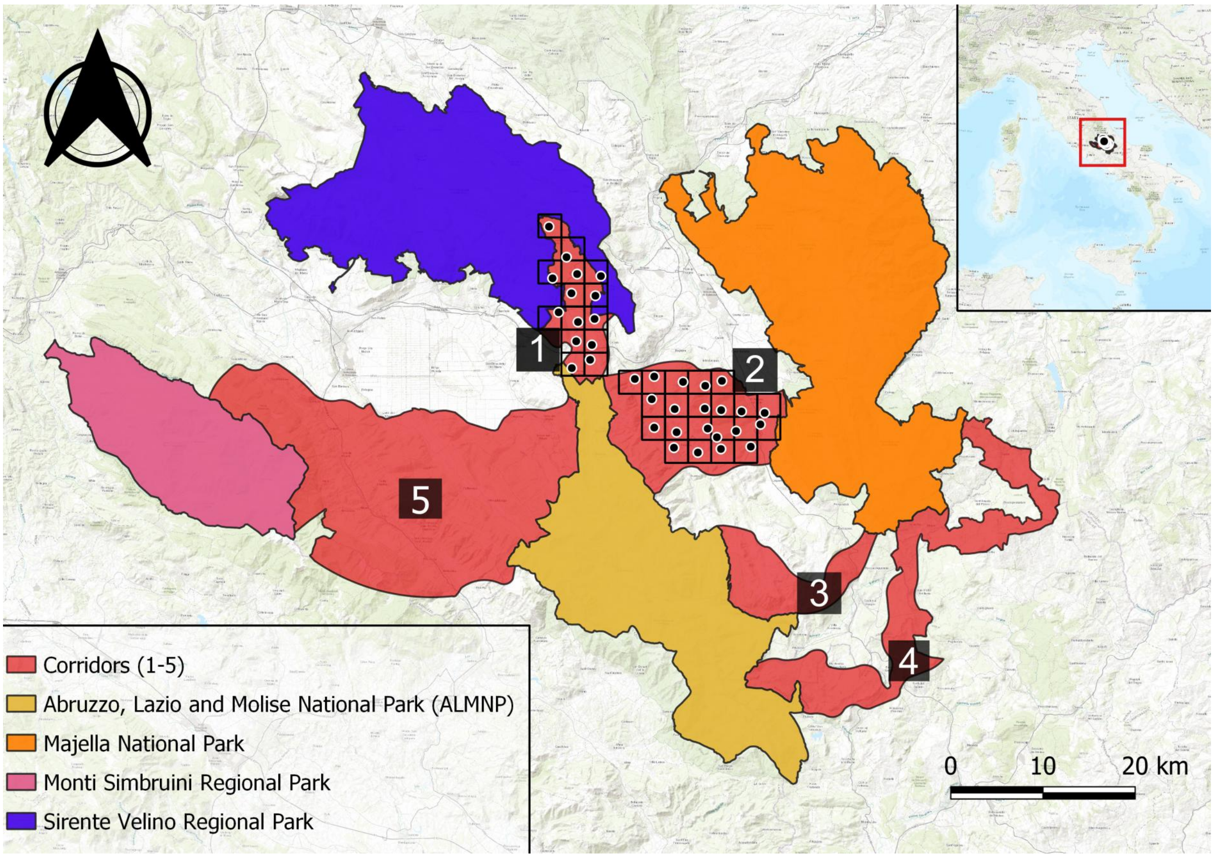

Map of the five corridor areas identified in the Central Apennines. The corridors (in red, marked with numbers) connect four protected areas (other coloured polygons). The study area, covering Corridor 1 and Corridor 2, is divided into 34 2.5 km grid cells, each including a camera trap (black points).

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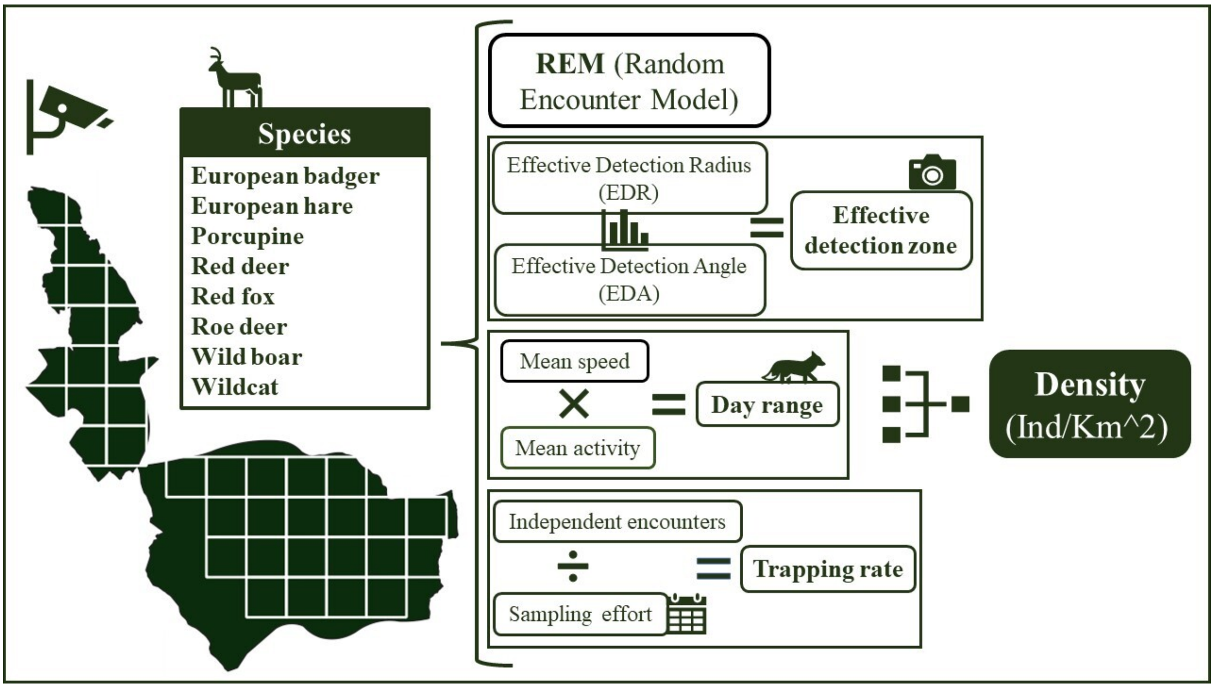

Framework of the application of the Random Encounter Model (REM) to estimate the density of the eight mammal species analysed in the study area.

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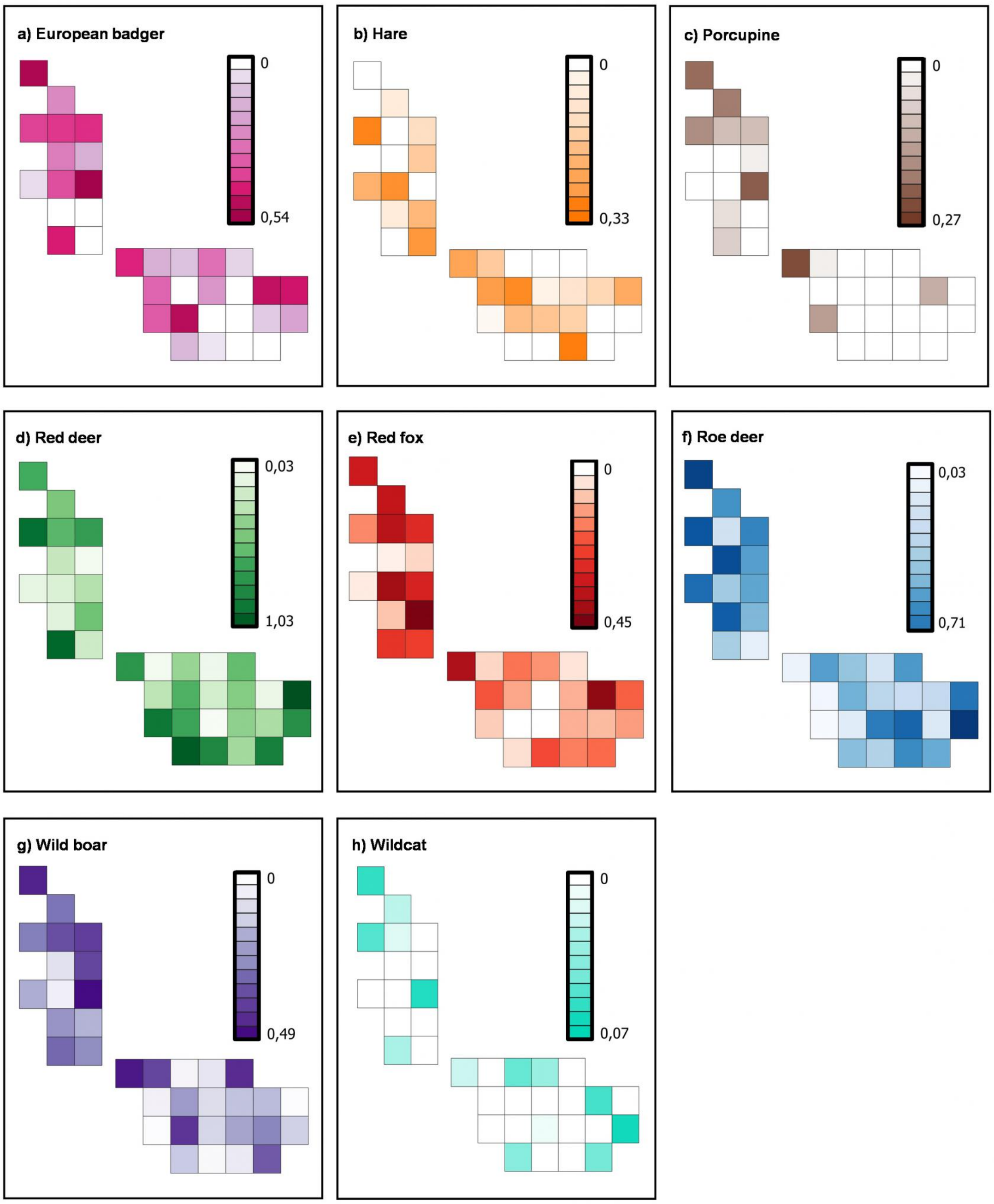

Trapping rates of each camera trap location of the study area, for each of the eight species of meso- and macro-mammals analysed (panels a-h). Trapping rates were obtained from the number of independent encounters divided by survey effort (i.e., the operating time of camera traps expressed in days).

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Manuscript body

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Figures

Figure 1 - Download source file (12.92 MB)
Map of the five corridor areas identified in the Central Apennines. The corridors (in red, marked with numbers) connect four protected areas (other coloured polygons). The study area, covering Corridor 1 and Corridor 2, is divided into 34 2.5 km grid cells, each including a camera trap (black points).

Figure 2 - Download source file (151.46 kB)
Framework of the application of the Random Encounter Model (REM) to estimate the density of the eight mammal species analysed in the study area.

Figure 3 - Download source file (309.9 kB)
Trapping rates of each camera trap location of the study area, for each of the eight species of meso- and macro-mammals analysed (panels a-h). Trapping rates were obtained from the number of independent encounters divided by survey effort (i.e., the operating time of camera traps expressed in days).

Supplementary Online Material

File 1 - Download source file (505.78 kB)

File 2 - Download source file (5.33 MB)
Main text track change (FOR REVIEWERS ONLY)