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# Perched above the fields: density and habitat selection of wintering raptors in an intensive farmland area in northern Italy

**Diego Rastelli[1*], Lara Todeschini[2], Alessandro Pavesi[3]**

DR 0009-0001-3727-254X, LT 0009-0005-7221-5726, AP 0000-0003-0426-4794

[1] Independent Researcher, Strada Argine Interna 30, Soragna 43019 (PR)
[2] Independent Researcher, Via San Biagio 3, Treviolo 24048 (BG)
[3] AsOER - Associazione Ornitologi dell'Emilia-Romagna ODV

*corresponding author: Diego Rastelli rastellidiego01@gmail.com

**Abstract**

The wintering period represents a critical stage for avian survival and population dynamics. However, systematic monitoring during this phase remains scarce compared to the extensive research dedicated to the reproductive period and migration. To address this gap, we investigated the wintering raptor community in the *Parmigiano Reggiano* production area in the Province of Parma (northern Italy), a unique agro-ecosystem dominated by perennial forage crops, especially alfalfa *Medicago sativa*. We conducted roadside car transects during the winter of 2025/2026 to estimate the population density using distance sampling, and to assess the habitat preferences of the two most abundant species: the Common Buzzard *Buteo buteo* and the Common Kestrel *Falco tinnunculus*. Survey data indicate a high density for both species, with estimated densities of 2.61 ind./km² (95% CI: 1.63-4.18) for the Common Buzzard and 5.59 ind./km² (95% CI: 3.97-7.87) for the Common Kestrel. The Common Kestrel exhibited a strong roadside bias, requiring left-truncation to obtain unbiased estimates. Furthermore, habitat analysis showed a significant selection for forage crops by the Common Kestrel, confirming the key role of alfalfa in the agricultural matrix. We hypothesize that these densities, among the highest recorded in European lowlands, are driven by the synergy between the extensive availability of favourable habitats (i.e., forage crops) supporting high prey densities, and the increasing frequency of mild winters with no snow cover. This study establishes an important quantitative baseline for future winter monitoring, highlighting the importance of adopting distance sampling methods for effective large-scale bird surveys.

**Keywords:** alfalfa, *Buteo buteo*, distance sampling, *Falco tinnunculus*, habitat preferences, road counts, wintering raptors, roadside bias

## INTRODUCTION

Birds of prey, occupying top or near-top positions in trophic chains, serve as environmental sentinels and indicators while providing key ecosystem services (Donázar et al. 2016, O'Bryan et al. 2018). Monitoring their numbers is a fundamental tool for assessing population trends and understanding the effect of environmental changes on biodiversity (Nikolov et al. 2006). This is particularly urgent in farmland habitats, where intensification and land-use changes have driven severe declines in farmland bird populations across Europe (Donald et al. 2001, Gregory et al. 2005). However, monitoring programmes are predominantly undertaken during the reproductive period or migration, with comparatively few studies conducted during the non-breeding season. Winter counts are crucial because this season is often considered a critical period for population regulation of many species (Newton 1998). A complete understanding of the population ecology and trends requires monitoring programmes in wintering areas.

The Mediterranean basin represents a key wintering area for European raptor populations (Panuccio et al. 2019, Toffoli et al. 2025, Chiatante et al. 2026). Across Europe, wintering raptors are primarily associated with agricultural landscapes, showing a strong preference for open lowlands (Wuczyński 2005, Nikolov et al. 2006, Jankowiak et al. 2015). These habitats serve as crucial foraging grounds, where raptor presence and abundance are shaped by multiple factors such as food availability, weather conditions, habitat characteristics, migration strategies, behavioural plasticity and flight capacity (Newton 1979, Wuczyński 2003, Chiatante 2026). Food availability, specifically the density and accessibility of small mammals, is often the primary driver of winter site selection, especially for rodent specialists like the Common Kestrel *Falco tinnunculus* (Village 1990). In modern intensive agro-ecosystems, the intensification of agriculture and the land-use changes (e.g., the loss of permanent grasslands) have severely impacted raptor populations (Butet et al. 2022). Consequently, the persistence of wintering specialists strictly depends on the maintenance of specific high-quality habitats, particularly grasslands and perennial forage crops such as alfalfa *Medicago sativa*, which sustain key prey populations (Nemček 2013, Butet et al. 2022).

The Po Plain, in northern Italy, is a highly human-modified landscape characterized by intensive agriculture, typically dominated by intensive annual crops (approximately 70% of the herbaceous agricultural matrix; ISTAT 2026). However, the southeastern part of the Po Plain (i.e., the province of Parma) represents a notable exception. Here, the specific fodder requirements of the *Parmigiano Reggiano* PDO supply chain (Battini et al. 2016) drive the maintenance of a landscape mosaic dominated by perennial forage crops (approximately 70% of the herbaceous agricultural matrix; ISTAT 2026), particularly alfalfa. Concurrently,

from a climatic perspective, although the region is historically characterized by rigid winters with average minimum temperatures around 0°C (1991-2020 reference period; Arpae 2022), it has recently experienced a marked warming trend (SNPA 2025). This unique combination of high habitat suitability, ensured by the persistence of fodder crops, and favourable mild conditions sustains key wintering populations of several raptor species, including the Hen Harrier *Circus cyaneus,* Red Kite *Milvus milvus*, Common Buzzard *Buteo buteo*, Common Kestrel, Merlin *Falco columbarius*, and owls such as the Short-eared Owl *Asio flammeus* (Chiavetta 1986, Bressan & Roscelli 2013). However, systematic monitoring of wintering populations is scarce, and objective data on abundance and trends are largely lacking.

This study aims to estimate the density and the abundance of wintering raptors in the Po Plain in the Province of Parma and to evaluate the habitat preferences of the most common species, with a specific focus on the role of alfalfa and permanent grassland in supporting wintering populations. Specifically, we hypothesized that (1) alfalfa may provide a highly suitable habitat for the most common wintering species in the study area, particularly the Common Kestrel and the Common Buzzard; (2) raptor distribution may be influenced by the presence of roads, which can provide perches from which individuals can hunt, potentially increasing the attractiveness of roadside areas. Since systematic data on the entire wintering raptor community in this area were previously lacking, our study establishes an important quantitative baseline for future population trend monitoring.

# MATERIALS AND METHODS

## Study area

The study area is located in the southeastern Po Plain, within the Province of Parma (Emilia-Romagna, Northern Italy; centroid 44° 51’ 42” N 10° 14’ 37” E; Fig. 1). Characterised by a temperate continental climate, the area covers approximately 1135 km² with elevation ranging from 15 to 199 m a.s.l. Geographically, the area is delimited to the north by the Po River and to the south by the 200 m contour line, which marks the ecological transition to the Apennine foothills. The eastern and western boundaries correspond to the administrative limits of the Province of Parma. During the study period (winter 2025-2026), December was characterized by a positive regional thermal anomaly (+2.33 °C above the 1991-2020 historical averages; Arpae 2026), with a regional mean temperature of 6.32 °C. This anomaly was driven by both minimum temperatures, which were +2.63 °C above the historical average, and maximum temperatures, which exceeded expectations by +2.05 °C. Total regional rainfall in December was 107.1 mm. In contrast, January aligned more closely with historical averages (-0.11 °C). The regional mean temperature was 3.10 °C,

with maximum temperatures below average (-0.78 °C), while minimums remained above average (+0.58 °C). Total rainfall in January was 66.7 mm (Arpae 2026). Crucially for the wintering raptor community, we recorded a complete absence of snow cover in the study area throughout the entire study period.

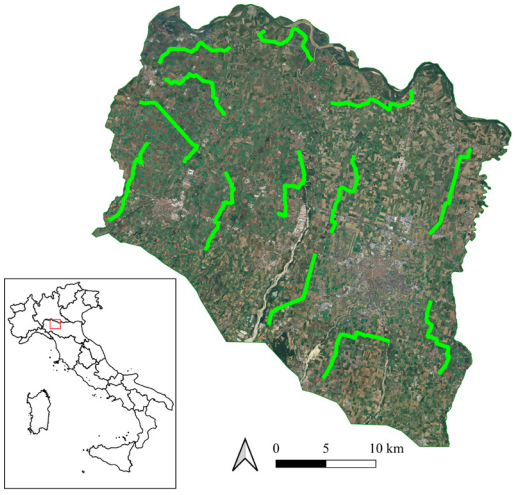


**Figure 1.** Map of the study area located in the Po Plain (northern Italy). The green lines indicate the 13 roadside transects surveyed. The inset shows the location of the study area within Italy (red rectangle).

The landscape is dominated by intensive agriculture, creating a mosaic of arable lands interspersed with synanthropic elements (Regione Emilia-Romagna 2023; Fig. 2). The area is also characterized by a dense network of drainage and irrigation canals and roads, often bordered by rows of utility poles or trees, which provide potential perching sites for raptors. Notably, land use is strongly influenced by the *Parmigiano Reggiano* PDO cheese industry, whose production specification rules do not allow silage and require that at least 75% of the forage provided to cattle must be cultivated in the area (Mantovi et al. 2015, Battini et al. 2016). According to administrative data (ISTAT 2026), forage crops cover 78.400 ha of the Province of Parma, representing 66.6% of the herbaceous agricultural matrix. Specifically, alfalfa accounts for the majority of the surface (53.200 ha; 45.2%), while the remaining part (21.4%) is constituted by permanent grasslands and pastures concentrated in the Apennine foothills. Notably, the alfalfa exceeds the total area of all main annual crops combined (39.300 ha; 33.4%). However, in our lowland study area during winter, the effective availability of forage crops is lower than these provincial statistics suggest. This difference is driven by two factors: (1) the exclusion of upland pastures, concentrated in the foothills, and (2) the crop rotation of alfalfa fields, where senescent stands and fields prepared for new spring sowing temporarily function as bare ground in winter.

## DATA COLLECTION

### Road surveys

Surveys were conducted using a line transect approach, a reliable method to count diurnal raptors, especially in open habitats and during the winter season (Fuller & Mosher 1981, Millsap et al. 1988, McClure et al. 2021). This sampling

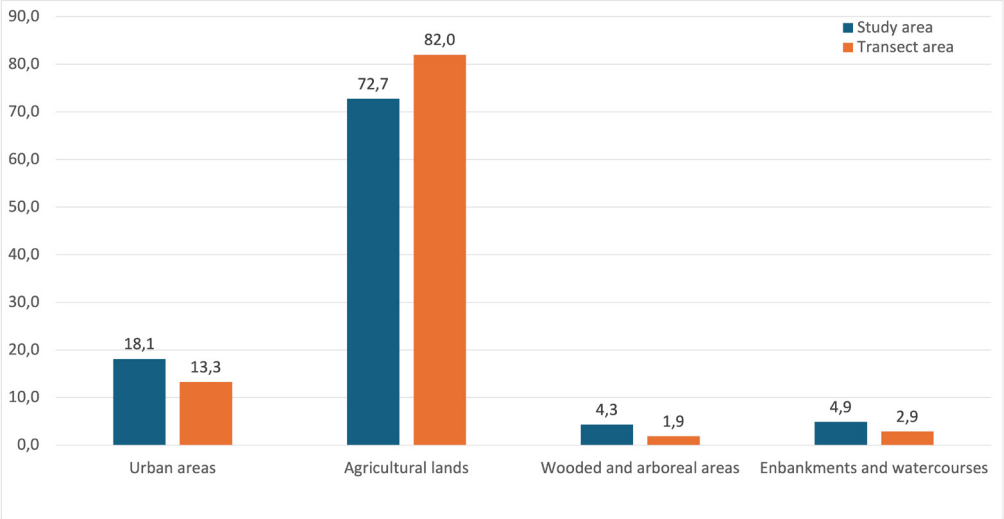


**Figure 2**. Proportions of different habitat types along the transects based on the 2020 Regional Land Use Map (Regione Emilia-Romagna, 2023). The study area is the southeastern Po Plain River included in the Province of Parma. Transect area refers to the area covered by the study transects (within a 300 m buffer on both sides of the transect).

design was adapted from Boano & Toffoli (2002) and Toffoli et al. (2025), following the McClure et al. (2021) operational standards (i.e., vehicle speed and detection conditions). Data collection covered 13 transects (mean length ± SD = 9.8 ± 0.4 km; range 9.0-10.5 km) separated by a minimum distance of 2 km. This separation ensured spatial independence and avoided double-counting, a strategy supported by the significant contraction of home ranges during the non-breeding season (Damiani et al. 2022, Walls & Kenward 2020). Specifically, winter home ranges have been estimated at only 0.35 km$^2$ (range 0.24-0.45 km$^2$) for the Common Buzzard (Weir & Picozzi 1983) and 0.75 km$^2$ (range 0.49-1.21 km$^2$) for the Common Kestrel (Damiani et al. 2022). Furthermore, as an additional precaution to minimize the risk of double-counting of individuals moving between nearby areas across different days, spatially adjacent transects were grouped and surveyed consecutively on the same day (mean number of transects per daily session ± SD = 3.3 ± 0.6). Each transect was repeated three times between December 2025 and January 2026; these replicates were pooled to achieve the recommended sample size for detection function modelling (Buckland et al. 2001), resulting in a total sampling effort of 381.8 km. Despite potential temporal non-independence due to winter site fidelity, this approach ensured model stability and was validated by testing the consistency of encounter rates across visits. Regarding data truncation, we collected observations in the 0-300 m strip, excluding data beyond

that distance. This threshold was adopted to ensure reliable distance binning and to minimize misclassification bias due to the compression of perspective at greater distances, a threshold consistent with established standards for road transects of medium-sized raptors in open landscapes (Millsap & Lefranc 1988). The surveyed strip covered an area of approximately 78 km², representing 6.8% of the total study area. Moreover, the land use along the transects is representative of the study area (Fig. 2). Observations were performed by a team of two experienced observers (driver and detector) maintaining a low driving speed (range 15-40 km/h; mean speed ± SD = 33.7 ± 5.5 km/h), consistent with the protocols recommended to maximize detection rates (McClure et al. 2021).

For each detection, we recorded the species and visually estimated the perpendicular distance from the transect line. Simultaneously, we characterized the habitat used by each individual and the type of perch employed. Habitat types were determined by direct observation in the field to ensure fine-scale accuracy compared to regional land-use maps. Habitat types were classified into five functional categories: alfalfa and permanent grasslands, winter cereals and other annual crops (including also ploughed fields and stubbles), network of watercourses and embankments (merging rivers, canals, and wetlands with their associated grassy levees and riparian vegetation), wooded and arboreal areas (including hedgerows, poplar groves, vineyards and fruit orchards), and urban areas (including farmsteads and paved roads). Perch types were categorized as: utility poles (concrete/wood), wires, trees, buildings, ground; individuals observed in flight were also recorded.

To ensure unbiased density estimates, the survey design strictly adhered to distance sampling assumptions (Buckland et al. 2015). We assumed certainty of detection on the transect line, a condition robustly met by the use of two observers in open habitats. Perpendicular distances were visually estimated by a single experienced observer to minimize inter-observer variability and grouped into four intervals (0-50, 50-100, 100-200, 200-300 m) to improve model stability. Specifically, the separation of the 0-50 m band allowed for a fine-scale assessment of the roadside effect (Meunier et al. 2000). To satisfy the assumption of random transect placement within a non-random road network, we selected secondary roads with low traffic and surveyed during central daylight hours (10:00-15:00). Finally, since target species exhibited solitary behaviour, each detection was treated as an independent observation.

## Assessment of habitat availability

To estimate the relative availability of different habitat types, we applied a random point sampling approach using QGIS 3.28 “Firenze” (QGIS Development Team 2022). We generated random points along each transect with a density of 10

points per km (total number of points = 1260) within a fixed buffer of 300 m on both sides of the transect line (matching the survey truncation distance). To ensure spatial independence and minimize autocorrelation (i.e., preventing multiple points from falling within the same crop field), we imposed a minimum distance constraint of 50 m between points. This threshold was selected to capture the fine-scale heterogeneity of the landscape, ensuring the inclusion of narrow linear elements often missed by coarse-scale maps. The habitat category corresponding to each random point was recorded through direct field inspections conducted during the survey period. This procedure ensured that the recorded availability reflected the actual agricultural landscape.

## Data analysis

The analyses were performed in the statistical software R v.4.4.1 (R Core Team 2024) with the packages *Distance* (Miller et al. 2019), *lmer* (Bates et al. 2015), *car* (Fox & Weisberg 2019) and *emmeans* (Lenth 2025).

## Density estimation and relative abundance

Distance sampling analysis was restricted to species with a sufficient sample size to robustly model the detection function (recommended minimum 60-80 observations; Buckland et al. 1993). Consequently, population density was estimated only for the two most abundant species: the Common Kestrel and the Common Buzzard. Population density was estimated using Conventional Distance Sampling (CDS; Buckland et al. 1993, Buckland et al. 2015). To ensure accurate variance estimation, the 13 transects were treated as independent spatial sampling units. Specifically, the distance data from the three temporal replicates were pooled for each line, and the cumulative survey length (i.e., transect length multiplied by the number of visits) was set as the total effort for that specific sampling unit. Consistency in encounter rates across the three survey replicates was verified using Kruskal-Wallis tests to justify data pooling. Although distance sampling represents a powerful analytical framework to account for imperfect detection (Buckland et al. 1993, Buckland et al. 2015), this method has been rarely applied to raptor density estimation to date (McClure et al. 2021), especially in Europe (with some exceptions, see Boano & Toffoli 2002, Nikolov et al. 2006, Baltag et al. 2013, Panuccio et al. 2019, Stevens et al. 2019, Toffoli et al. 2025, Chiatante et al. 2026). As recommended by Buckland et al. (1993) and Thomas et al. (2010), we tested four standard definitions for the detection function: (1) uniform key with cosine adjustments, (2) half-normal key with cosine adjustments, (3) half-normal key with Hermite polynomial adjustments, and (4) hazard-rate key with simple polynomial adjustments. The most parsimonious model was selected based on Akaike Information Criterion

(AIC; Akaike 1998). For models with similar support (ΔAIC ≤ 2), considering the principle of parsimony, the model with fewer parameters and a non-significant goodness-of-fit test was selected (Burnham & Anderson 2002, Arnold 2010). Considering that data were binned, the goodness-of-fit of the models was assessed by $\chi^2$ tests (Buckland et al. 1993, Thomas et al. 2010).

Roadside surveys are a cost-effective method for monitoring raptors but are subject to inherent sampling biases (Millsap & Lefranc 1988, McClure et al. 2021). A critical concern is the roadside bias, where the surveyed transect does not accurately represent the land cover of the wider landscape (Harris & Haskell 2007). For diurnal raptors, this bias is often exacerbated by a behavioural attraction to roadside infrastructure (e.g. utility lines, fences, road signs) used for perching and hunting (Meunier et al. 2000) or to forage on roadkilled animals (Walls & Kenward 2020, Pavesi 2022). CDS assumes that transects are placed randomly with respect to the distribution of animals (Buckland et al. 2015). However, when density is higher near the transect line due to attractive features, density estimates derived from the full dataset may be positively biased (Marques et al. 2010). Disentangling roadside attraction from baseline detectability requires complex assumptions in line transect models (Marques et al. 2010). Therefore, we opted for a spatial exclusion approach. To estimate the density within the open agricultural matrix, we performed a secondary analysis applying left-truncation. We excluded the first distance interval (0-50 m), which contains the road and associated infrastructure (especially pylons, road signals, poles, wires), and refitted the detection functions using the remaining observations (50-300 m). This comparative approach performs a double function: it allows us to assess the potential attractive effect of road infrastructure by comparing density estimates derived from the full versus the truncated datasets, and, when such an effect is detected, it mitigates the influence of the roadside attraction zone to provide a more representative estimate of the wider landscape density. In addition to density estimation, we calculated the kilometric abundance index (KAI), expressed as the number of individuals observed per linear kilometre (ind./km). This index was computed for all the recorded species to facilitate comparisons with previous studies conducted in similar agricultural landscapes. Finally, to compare our density estimates with those reported in previous studies, we performed Z tests (Buckland et al. 2001).

## Habitat selection

Habitat selection was evaluated by comparing habitat use and availability at the population level (Manly et al. 2002). Availability was estimated by generating random points within the study area, while use was defined by the frequency of raptor observations in each habitat category. First, we performed a Pearson's

chi-square goodness-of-fit test ($\chi^2$) to determine if habitat use differed significantly from availability, testing the null hypothesis of random habitat use. Upon rejection of the null hypothesis, we calculated Manly's Selection Ratios ($w_i$) for each habitat category ($i$) using the formula $w_i = u_i / a_i$, where $u_i$ is the proportion of habitat used and $a_i$ is the proportion of habitat available. A $w_i$ value > 1 indicates a positive selection (preference), a value < 1 indicates negative selection (avoidance), and a value ≈ 1 indicates use in proportion to availability, implying no resource selection. To assess the statistical significance of selection for each habitat category, we calculated 95% simultaneous Bonferroni-corrected confidence intervals. Selection was considered statistically significant if the confidence interval for $w_i$ did not contain the value 1 (Manly et al. 2002).

## Perch use analysis

To investigate interspecific differences in perching strategies and reliance on anthropogenic infrastructure, we performed a comparative analysis between Common Kestrel and Common Buzzard. Perch types were aggregated into two main functional categories to ensure robust sample sizes: anthropogenic (utility poles, wires, buildings, road signs) and natural (trees and ground). Birds observed in flight were excluded from this analysis. We modelled the probability of using an anthropogenic perch using a Generalized Linear Mixed Model (GLMM) with a binomial error distribution and a logit link. Observations of birds perched on natural perches were coded as 0, whereas observations on anthropogenic perches were coded 1. The model included Species as a fixed effect, while Transect ID and Visit (i.e., the transect repetition number, from 1 to 3) were included as random intercepts to account for spatial and temporal non-independence. Overall significance of the fixed effect was tested using a Wald chi-square test. Predicted probabilities of anthropogenic perch use were calculated using estimated marginal means. Residual temporal autocorrelation was assessed via Autocorrelation Function (ACF). Model performance was evaluated using marginal ($R^2_m$) and conditional ($R^2_c$) coefficients of determination.

## RESULTS

During the survey, we counted 671 raptors of 5 species (Tab. 1). The mean KAI showed that Common Buzzard and Common Kestrel were the most abundant species (CB: N = 178, KAI ± SD = 0.46 ± 0.29, CK: N = 489, KAI ± SD = 1.28 ± 0.64). Both species were widely distributed across the study area, being observed on 13 transects out of 13 (100%). Notably, encounter rates remained consistent across the three replicates for both species (Kruskal-Wallis test: Common Kestrel, P = 0.598; Common Buzzard, P = 0.468), confirming the temporal stability of the

**Table 1.** Abundance and distribution of target species recorded during road transect surveys. For each species, data reported are the total number of individuals (N), the frequency of occupied transects (with percentage in parentheses), total sampling effort expressed in kilometres (km), and the kilometric abundance index (KAI) ± standard deviation (SD) expressed in individuals per kilometre (ind./km).

| Species | N | KAI ± SD | Frequency | Total Effort |
|---|---|---|---|---|
| Common Buzzard | 178 | 0.47 ± 0.29 | 13 (100%) | 381.8 |
| Common Kestrel | 489 | 1.28 ± 0.64 | 13 (100%) | 381.8 |
| Hen Harrier | 2 | 0.01 ± 0.02 | 2 (15.4%) | 381.8 |
| Red Kite | 1 | < 0.01 | 1 (7.7%) | 381.8 |
| Eurasian Sparrowhawk | 1 | < 0.01 | 1 (7.7%) | 381.8 |

wintering community during the study period. Excluding the Common Buzzard and Common Kestrel, which allowed for density estimation, abundance indices for other raptor species were generally low. The Hen Harrier (N = 2, KAI ± SD = 0.01 ± 0.02), Eurasian Sparrowhawk *Accipiter nisus* (N = 1, KAI < 0.01) and Red Kite (N = 1, KAI < 0.01) were recorded occasionally.

## Common Buzzard density

During the survey, we counted 178 Common Buzzards. Among the candidate models fitted to the data, the best detection probability function was the hazard-rate key with simple polynomial adjustments (Tab. 2; Fig. 3a). The goodness-of-fit of the model was good ($\chi^2$ = 1.424, df = 1, P = 0.233). The average probability of detection was estimated to be 0.30 ± 0.06 SE. The density was equal to 2.61 ind./km² (SE = 0.56, CV = 24.0%, 95% CI = 1.63-4.18). To assess the potential influence of roadside bias, we repeated the analysis using a left-truncated dataset (Tab. 3, exclusion of the 0-50 m band; N = 93). The resulting density estimate (2.10 ind./km², SE = 0.54, CV = 25.7%, 95% CI = 1.27-3.48) was consistent with the untruncated value, suggesting a negligible effect of roadside infrastructures on the spatial distribution of Common Buzzard.

Comparisons with other European wintering grounds (Tab. 4) showed that the estimated Buzzard density was significantly higher than the values reported for Eastern Europe and Mediterranean islands (P < 0.001), while qualitative assessments indicated it was lower than specific Greek and Central European populations.

**Table 2.** Conventional distance sampling models computed to estimate the density of wintering Common Buzzards and Common Kestrels in the Po Plain within the Province of Parma using the full dataset (0-300m). We show the model used (key + series adjustment), the AIC and its Δ versus the lowest, the coefficient of variation of the density (CV), and the average estimated detection probability ($P_a$). Selected models used for density estimation are in bold.

| Model | AIC | ΔAIC | CV (%) | Pa (Mean ± SE) |
|---|---|---|---|---|
| Common Buzzard | | | | |
| **Hazard rate simple polynomial** | 447.54 | 0.00 | 24.0 | 0.30 ± 0.06 |
| Uniform cosine | 449.15 | 1.62 | 18.2 | 0.34 ± 0.04 |
| Half normal cosine | 469.73 | 22.19 | 15.6 | 0.46 ± 0.05 |
| Half normal Hermite polynomial | 469.73 | 22.19 | 15.6 | 0.46 ± 0.05 |
| Common Kestrel | | | | |
| **Hazard rate simple polynomial** | 959.66 | 0.00 | 15.1 | 0.23 ± 0.02 |
| Half normal cosine | 963.53 | 3.88 | 13.6 | 0.23 ± 0.01 |
| Uniform cosine | 989.87 | 30.22 | 14.0 | 0.29 ± 0.02 |
| Half normal Hermite polynomial | 1044.24 | 84.59 | 14.2 | 0.30 ± 0.02 |

**Table 3.** Conventional distance sampling models computed to estimate the density of wintering Common Buzzards and Common Kestrels in the Po Plain within the Province of Parma using the truncated dataset (50-300m). We show the model used (key and series adjustment), the AIC and its Δ versus the lowest, the coefficient of variation of the density (CV), and the average estimated detection probability ($P_a$). Selected models used for density estimation are in bold.

| Model | AIC | ΔAIC | CV (%) | Pa (Mean ± SE) |
|---|---|---|---|---|
| Common Buzzard | | | | |
| **Half normal cosine** | 199.76 | 0.00 | 25.7 | 0.25 ± 0.05 |
| Hazard rate simple polynomial | 200.73 | 0.97 | NA | NA |
| Uniform cosine | 200.72 | 2.78 | 25.6 | 0.38 ± 0.08 |
| Half normal Hermite polynomial | 205.77 | 6.02 | 18.7 | 0.48 ± 0.05 |
| Common Kestrel | | | | |
| **Half normal cosine** | 321.41 | 0.00 | 17.1 | 0.16 ± 0.02 |
| Hazard rate simple polynomial | 321.56 | 0.15 | NA | NA |
| Uniform cosine | 332.11 | 10.70 | 17.4 | 0.29 ± 0.04 |
| Half normal Hermite polynomial | 337.04 | 14.63 | 14.2 | 0.30 ± 0.02 |

NA: Model failed to fit the shape of the truncated data, resulting in unreliable parameters (CV>1000%)

## Common Kestrel density

During the survey, we counted 489 Common Kestrels. Among the candidate models fitted to the data, the best detection probability function was the hazard-rate key with simple polynomial adjustments (Tab. 2; Fig. 3b). The goodness-of-fit of the model was good ($\chi^2$ = 0.410, df = 1, P = 0.522). The average probability of detection was estimated to be 0.23 ± 0.02 SE. The density was equal to 9.49 ind./km² (SE: 1.43, CV = 15.1%, 95% CI = 6.96-12.93). To assess the potential influence of roadside bias, we repeated the analysis using a left-truncated dataset (Tab. 3; exclusion of the 0-50 m band; N = 175).

The truncated model yielded a markedly lower density estimate of 5.59 ind./km² (SE = 0.96, CV = 17.1%, 95% CI = 3.97-7.87). The substantial difference (-41.1%) between the full and the truncated estimates suggests a strong aggregative response of the Common Kestrel to roadside infrastructures. For the Common Kestrel, the estimated density was significantly higher than the values reported in other Italian and Mediterranean areas (P < 0.001; Tab. 2).

## Habitat selection

The analysis of habitat selection, based on 1260 random points characterizing the landscape availability contrasted with 178 use points for the Common Buzzard and 489 points for the Common Kestrel, revealed that habitat use differed significantly from availability for both species (Tab. 5). The Common Kestrel exhibited a non-random habitat selection ($\chi^2$ = 198.62, df = 4, P < 0.001). Most individuals were recorded in agricultural land (78.7% of observations). Within this category, alfalfa and permanent grassland hosted the highest abundance (55.4%), and were significantly selected ($w^i$ = 1.64, 95% CI = 1.40-1.88), whereas annual crops were significantly avoided (23.3%, $w^i$ = 0.52, 95% CI = 0.40-0.64). Wooded and arboreal areas showed a relatively high selection ratio ($w^i$ = 2.35), although the selection was not statistically significant due to wide confidence intervals. However, the strongest positive selection was recorded for the embankments and watercourses ($w^i$ = 2.85, 95% CI = 1.41-4.29), while urban areas were highly avoided ($w^i$ = 0.41, 95% CI = 0.08-0.21, Fig. 4a).

Similarly, the Common Buzzard showed a non-random habitat distribution ($\chi^2$= 189.58, df = 4, P < 0.001) and it was predominantly associated with agricultural land (72.9% of individuals). The Common Buzzard used alfalfa and permanent grasslands in proportion to their availability (41.8%, $w_i$ = 1.24, 95% CI = 0.93-1.54), while annual crops were significantly avoided (31.1%, $w_i$ = 0.70, 95% CI = 0.48-0.90). Wooded and arboreal areas were used neutrally due to the wide confidence intervals, despite the high selection value ($w_i$ = 3.84, 95% CI = 0.53-7.15). Finally, positive selection was recorded for embankments and watercourses ($w_i$ = 4.32, 95% CI = 1.81-6.83), whereas urban areas were significantly

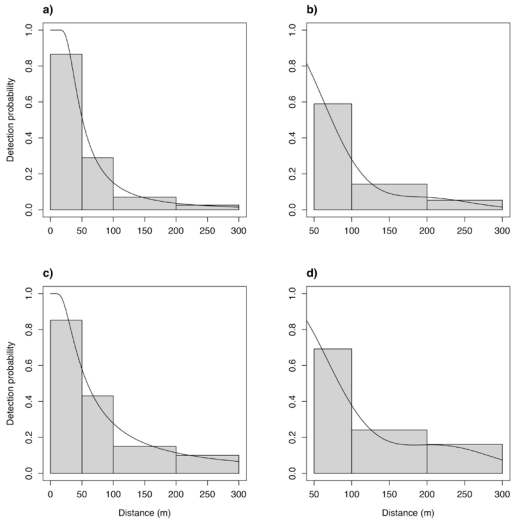


**Figure 3.** Detection function modelled to estimate the density of Common Kestrel and Common Buzzard. The upper panels show the models for the Common Kestrel using the full dataset (0-300 m; a) and the left-truncated dataset (50-300 m; b). The lower panels show the models for the Common Buzzard using the full dataset (0-300 m; c) and the left-truncated dataset (50-300 m; d). Data are grouped into intervals (bars), and the solid line represents the fitted detection function.

**Table 4.** Comparisons of winter densities (ind/km²) for the Common Buzzard and the Common Kestrel between the present study (Parma, southeastern Po Plain) and other European regions. Statistical comparisons were performed using Z-tests to evaluate differences between our estimates and literature data. The reported Z-score represents the standardized difference, while the P-value indicates the statistical significance of this difference.

| Species | Area | Density (ind/km²) | Z-score | P-value | Reference |
|---|---|---|---|---|---|
| **Common Buzzard** | | | | | |
| | Parma | 2.61 | | | Current study |
| | Piedmont | 0.45-2.21 | - | - | Toffoli et al. 2025 |
| | Sicily | 0.36 | 3.57 | <0.001 | Panuccio et al. 2019 |
| | Crete | 0.91 | 2.67 | 0.007 | Panuccio et al. 2019 |
| | Bulgaria | 0.34 | 3.60 | <0.001 | Nikolov et al. 2006 |
| | Romania | 0.33-0.54 | 4.35 | <0.001 | Baltag et al. 2013 |
| | Poland | 2.12 | - | - | Wuczyński 2003 |
| | Western Grece | 3.89 | - | - | Chiatante et al. 2026 |
| **Common Kestrel** | | | | | |
| | Parma | 5.59 | | | Current study |
| | Piedmont | 0.44 | 5.35 | <0.001 | Toffoli et al. 2025 |
| | Sicily | 0.75 | 5.01 | <0.001 | Panuccio et al. 2019 |
| | Crete | 0.10 | 5.72 | <0.001 | Panuccio et al. 2019 |

Z-scores and P-values are reported only for studies where variance estimates (i.e., standard errors) were available in the original publication, allowing for statistical testing. Dashes (-) indicate studies where original data presentation mathematically precluded the calculation of Z-tests. In these cases, comparisons remain qualitative.

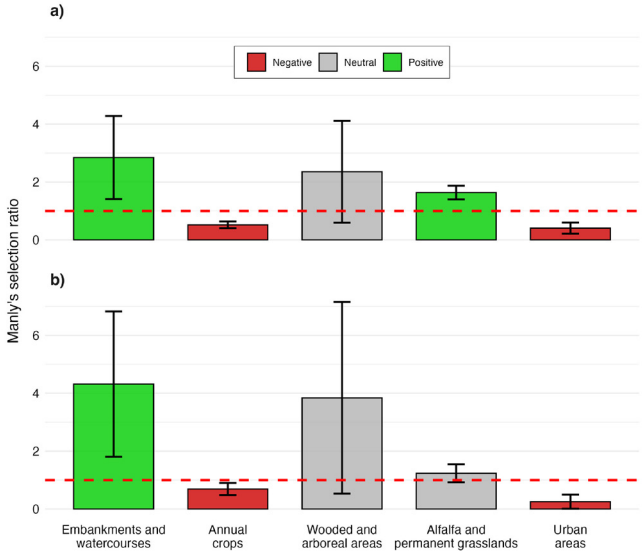


**Figure 4.** Habitat selection of Common Kestrel (a) and Common Buzzard (b) wintering in the agricultural landscape in the Province of Parma. Bars represent Manly's standardized selection ratios ($w_i$) for each habitat category. The horizontal dashed red line ($w_i = 1$) indicates habitat use in proportion to availability. Error bars represent 95% simultaneous Bonferroni-corrected confidence intervals. Green bars indicate significant positive selection (preference), red bars indicate significant negative selection (avoidance), and grey bars indicate use proportional to availability (neutral selection).

**Table 5.** Habitat selection analysis for wintering Common Kestrel and Common Buzzard in the study area. For each habitat category, observed use (%) and landscape availability (%) are reported. Habitat preference is described by Manly's standardized selection ratio ($w_i$) with its 95% Bonferroni-corrected confidence interval (95% CI). The selection status indicates whether the habitat is significantly selected (+), avoided (-), or used in proportion to availability (=).

| Species | Habitat | Use (%) | Available (%) | $w_i$ | 95% CI | Selection |
|---|---|---|---|---|---|---|
| **Common Kestrel** | | | | | | |
| | Embankments and watercourse | 10.4 | 3.7 | 2.84 | 1.41 - 4.28 | + |
| | Annual crops | 23.3 | 44.8 | 0.52 | 0.40 - 0.64 | - |
| | Wooded and arboreal areas | 4.5 | 1.9 | 2.35 | 0.68 - 4.11 | = |
| | Alfalfa and permanent grasslands | 55.4 | 33.7 | 1.64 | 1.40 - 1.88 | + |
| | Urban areas | 6.3 | 15.9 | 0.41 | 0.21 - 0.60 | - |
| **Common Buzzard** | | | | | | |
| | Embankments and watercourse | 15.8 | 3.7 | 4.32 | 1.81 - 6.83 | + |
| | Annual crops | 31.1 | 44.8 | 0.69 | 0.48 - 0.89 | - |
| | Wooded and arboreal areas | 7.3 | 1.9 | 3.84 | 0.53 - 7.15 | = |
| | Alfalfa and permanent grasslands | 41.8 | 33.7 | 1.24 | 0.93 - 1.54 | = |
| | Urban areas | 4.0 | 15.9 | 0.25 | 0.01 - 0.50 | - |

avoided ($w_i$ = 0.25, 95% CI = 0.01-0.50, Fig. 4b).

## Perch use

We restricted the analysis of perch use to the two most abundant species: the Common Buzzard and the Common Kestrel. We analysed perch selection for 548 individuals (excluding birds in flight). Although anthropogenic structures (i.e., wires, poles, pylons, road signs) were the primary perches for both species (accounting for 73.8% of the used perches for the Kestrel and 62% for the Buzzard), the GLMM confirmed that the Common Kestrel used them significantly more than the Common Buzzard ($\chi^2$ = 7.26 , P = 0.007). Based on the model the estimated probability of using an anthropogenic

perch was 74.4% (95% CI = 68.7-79.4%) for the Common Kestrel, compared to 62.7% (95% CI = 53.8-70.8%) for the Common Buzzard ($R^2_m$ = 0.018, $R^2_c$ = 0.038, Fig. 5). The inclusion of Transect ID ($\sigma^2$ = 0.050) and Visit ($\sigma^2$ = 0.018) as random effects accounted for spatial and temporal dependencies, with negligible residual autocorrelation (maximum ACF peak at Lag 1 = 0.110, followed by an immediate decay to zero). The low variance of these random effects indicates that this interspecific difference remained consistent throughout the study.

## DISCUSSION

This study provides the first density detection-corrected estimates for the complete wintering raptor community in the agricultural landscape in the Province of Parma, derived from roadside distance sampling. As emphasized by McClure et al. (2021), the adoption of standardized protocols that account for imperfect detection is critical for rigorous raptor monitoring. Unlike simple encounter rates (e.g., kilometric abundance index), which are sensitive to visibility biases and observer variability (Anderson 2001, Rosenstock et al. 2002), density estimates derived from distance sampling (Buckland et al. 2015) allow for robust and direct comparisons across different regions and time periods (McClure et al. 2021). In this context, the density estimates obtained, place the southeastern Po Plain among the most important wintering grounds in Europe. For the Common Buzzard, our density estimate (2.61 ind./km$^2$) exceeds those reported in North-West Po Plain (0.45-2.21 ind./km$^2$; Toffoli et al. 2025), and is substantially higher than those observed in other European contexts (comparisons performed using Z tests), such as in Eastern Europe (0.34 ind./km$^2$ in Bulgaria and 0.33-0.54 ind./km$^2$ in Romania; Nikolov et al. 2006, Baltag et al. 2013) and in the Mediterranean Islands (0.36 ind./km$^2$ in Sicily and 0.91 ind./km$^2$ in Crete; Panuccio et al. 2019). Instead, our results align with the high abundance recorded in Central Europe (2.12 ind./km$^2$ in Poland; Wuczyński 2003), and are lower than the exceptional concentrations found in the protected Mediterranean wetlands of western Greece (3.89 ind./km$^2$; Chiatante et al. 2026). Even more striking is the result for the Common Kestrel, whose density in our study area (5.59 ind./km$^2$) stands in sharp contrast to the significantly lower densities reported in other Italian landscapes (0.75 ind./km$^2$ in Sicily and 0.44 ind./km$^2$ in Piedmont; Panuccio et al. 2019, Toffoli et al. 2025). Since Common Kestrel wintering density is known to be strictly regulated by resource availability (Village 1990), such exceptional concentrations suggest that the local agricultural matrix provides highly suitable foraging habitats.

A critical finding of our study is the quantification of the roadside bias, a well-known but often neglected issue in raptor surveys (Meunier et al. 2000). While roads provide convenient transects, they often act as attractive areas for specif-

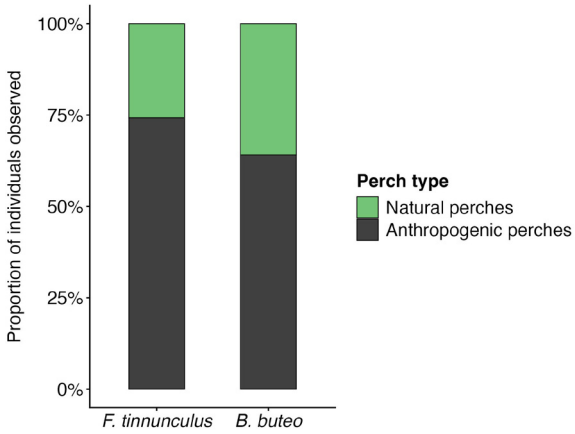


**Figure 5.** Proportional use of anthropogenic versus natural perches by Common Kestrel (*F. tinnunculus*) and Common Buzzard (*B. buteo*). Anthropogenic perches include pylons, wires, and poles; natural perches include trees and ground. The difference between species is significant ($P < 0.01$, GLMM).

ic raptors, potentially leading to inflated density estimates if not properly corrected (Meunier et al. 2000). Our analysis revealed a difference between the two target species. The Common Kestrel exhibited a strong positive bias towards the roadside strip. Without the application of left-truncation (i.e., excluding observations within the first band of 0-50 m), the density estimate would have been overestimated by approximately 40%. This phenomenon aligns perfectly with the hypothesis of Meunier et al. (2000), who described how roadside verges and associated infrastructures attract certain raptors (i.e., Common Kestrel and Black Kite *Milvus migrans*). Our data on perch selection strongly support this mechanism: most Common Kestrels (73.8%; Fig. 5) were detected on artificial structures, primarily power lines and poles running parallel to the road network. This heavy reliance on roadside perches for hunting concentrates individuals along the transect line, violating the assumption of random distribution required by standard census plots. Consequently, the adoption of distance sampling with left-truncation was mandatory to filter out this effect and obtain a more representative density for the open agricultural matrix. In contrast, the Common Buzzard showed a negligible roadside bias, with detection probabilities remaining stable across

distance bands. This suggests a more uniform spatial distribution, likely due to a different hunting strategy or perch selection that includes trees and ground positions scattered throughout the fields (Fig. 5), rather than being strictly tethered to roadside infrastructure. These results underscore that simple encounter rates (e.g. KAI) calculated from roads may be reliable for some species, such as the Common Buzzard, but are heavily biased for others, such as the Common Kestrel, unless the availability of perches is standardised or highly comparable across the surveyed areas. This reinforces the need for correction protocols that account for both species-specific behaviours and environmental features.

Comparison with historical data further highlights the significance of our findings, particularly for the Common Buzzard. Ravasini (1995), monitoring this species in Parma between 1980 and 1995, reported wintering densities of 0.6-1.2 ind./km², describing a negative correlation with the presence of snow cover. Our current estimate for the Common Buzzard (2.61 ind./km²) is more than double these historical maxima. This increase likely results from the synergy of methodological and ecological factors. Methodologically, historical estimates derived from uncorrected counts often underestimate true abundance compared to distance sampling. Ecologically, the observed density is likely driven by the synergy between the favourable climate conditions and the increase of lowland breeding pairs. Specifically, the warming trend recorded in Italy (SNPA 2025), leading to the virtual disappearance of prolonged snow cover during our study period, has likely removed a critical limiting factor. Indeed, snow cover prevents access to small mammals, and its absence makes this resource constantly accessible throughout the winter. Moreover, regarding the demographic increment of the Common Buzzard, long-term monitoring in the neighbouring Lombardy region (1992-2016) documented a mean annual increase of +3.5% specifically in the lowland (Bani et al. 2016). This climatic and demographic facilitation interacts with the unique *Parmigiano Reggiano* agro-ecosystem, creating optimal conditions for the Common Kestrel as well. Although historical density benchmarks are lacking for this falcon in the area, its exceptional current density clearly points to a super-abundance of resources. It is worth noting that, in the Parma area, high densities of Common Kestrels are observed even during the breeding season (Casagrande et al. 2008), and the species co-occurs with other raptors such as the Red-footed Falcon *Falco vespertinus* (Calabrese et al. 2020) and Lesser Kestrels *Falco naumanni* (Roscelli & Ravasini 2009). The production specifications for the *Parmigiano Reggiano* PDO (Mantovi et al. 2015, Battini et al. 2016) necessitate the widespread cultivation of alfalfa and permanent grassland. Consequently, this area represents a prime example of the agroecosystems dominated by herbaceous crops identified as fundamental for multi-taxa conservation across Italy (Dalpasso et al. 2025), and

specifically in sustaining farmland biodiversity within the Po Plain (Assandri et al. 2023). From a functional perspective, unlike annual crops where regular deep tillage suppresses vole densities (Jacob 2003), alfalfa is a poly-annual crop that maintains soil stability. This lack of disturbance preserves burrow systems and maintains significantly higher vole densities compared to cereal crops (Jareño et al. 2015, Rodríguez-Pastor et al. 2016). This mechanism explains the habitat preferences observed in other European contexts, such as in Slovakia, where Nemček (2013) confirmed that both Common Kestrels and Common Buzzards actively select alfalfa while avoiding annual crops and ploughed fields. However, a fundamental difference distinguishes our system. In Nemček's study area, alfalfa covered only a small fraction of the landscape and winter conditions were severe, while in our study area, alfalfa constitutes an important portion of the agricultural matrix. Furthermore, since snow cover is known to drastically reduce prey accessibility by offering a subnivean refuge for voles (Sonerud 1986), the lack of snow in the Po Plain maximizes hunting efficiency. Thus, the synergy between prey persistence (ensured by widespread alfalfa) and high accessibility (due to snow absence) explains the unprecedented densities recorded.

Our analysis of habitat selection provides empirical support for this ecological interpretation. For the Common Kestrel, the significant avoidance of annual crops ($w_i$ = 0.52) contrasts with the positive selection of alfalfa and permanent grassland ($w_i$ = 1.64), confirming that the latter acts as the fundamental carrying matrix supporting the bulk of the population. Similarly, the Common Buzzard showed an avoidance of annual crops ($w_i$ = 0.69), but the use of alfalfa and permanent grassland, although statistically neutral, exhibited a positive tendency ($w_i$ = 1.24). Both species converged in showing the strongest positive selection for the network of embankments and watercourses ($w_i$ > 2.8). These linear features, despite covering a marginal fraction of the landscape (3.7%), function as vital hunting infrastructures within the flat plain. They offer a dual advantage: structural support (trees for perching) and permanent grassy margins where prey remains accessible even when adjacent fields are managed or flooded. From an agronomic perspective, the high abundance of raptors may offer an important ecosystem service. Indeed, the Common Kestrel is recognised as a biological control agent against small mammal outbreaks and insects (Paz-Luna et al. 2013, Montoya et al. 2021). By naturally regulating rodent populations harmful to agriculture, high densities of wintering raptors can reduce the use of chemical products that cause severe detrimental effects on biodiversity (Montoya et al. 2021, Akinsorotan et al. 2023).

Finally, we acknowledge two methodological constraints in our study. First, regarding the spatial sampling, prioritizing a higher number of independent, single-visit transects would have been the optimal design to maximize spatial cover-

age. However, this approach was unfeasible due to the highly fragmented study area and the strict requirement for continuous, slow-traffic roads separated by at least 2 km. Consequently, our reliance on repeated surveys of the same 13 transects introduces a degree of temporal non-independence, given the strong site fidelity of wintering raptors. While pooling these observations was necessary to achieve the minimum sample size required for robust detection function modelling, this trade-off was justified by the high consistency in encounter rates across replicates. Nonetheless, we acknowledge that this design limits our ability to fully capture the broader spatial variance of the study area. To address this gap, future studies aiming to capture broader spatial variance should consider expanding the geographical scope (e.g., at a multi-province or regional scale) to accommodate a wider network of independent transects. Second, the perpendicular distances were estimated visually rather than using a laser rangefinder. While this introduces a degree of estimation error, mitigating this bias by grouping distances into wider intervals offers a highly practical and standardized methodological framework. Although this binning strategy results in fewer intervals, potentially reducing the power of goodness-of-fit tests, it prevents the introduction of false precision.

To date, our study identifies the agricultural landscape in the Province of Parma as one of the wintering hotspots of European importance for some species of diurnal raptors. The abundance is primarily driven by the specific management of the *Parmigiano Reggiano* supply chain. The widespread persistence of alfalfa and permanent grassland creates a stable habitat that, unlike intensive annual crops, sustains high biodiversity levels even within a highly anthropized matrix. From a methodological perspective, this work underscores the urgency of shifting from simple encounter rates (e.g., KAI) to standardized detection-corrected protocols. We demonstrated that for species attracted to infrastructure, such as the Common Kestrel, traditional road counts can lead to significant overestimations if roadside bias is not explicitly modelled and corrected. Roadside distance sampling proved to be a highly cost-effective and time-efficient technique, requiring limited resources while providing robust density estimates comparable across different regions and periods. Therefore, we strongly encourage the replication of this protocol in other Italian and European agricultural contexts. A standardized monitoring network is necessary to accurately track raptor population trends and disentangle the complex effects of environmental changes and land-use intensification on raptors.

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