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BRIEF REPORT

Impact of wind farm on summer spatial distribution of roe deer *Capreolus capreolus* – a UAV-based study in central Poland

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Abstract

Recent studies assessed the effects of WFs (wind farms) on terrestrial mammals, but the response of roe deer *Capreolus capreolus* to this infrastructure remains unclear. We aimed to investigate whether the spatial distribution of roe deer differs between operational wind farm area and nearby control area during summer, using a UAV-based approach that combined thermal infrared and RGB imaging. We used a DJI Matrice 300 RTK, equipped with Zenmuse H20T camera, to mark locations of roe deer in real-time during evening sessions. We performed a Nearest Neighbor Analysis and Kernel Density Estimation in QGIS. We also performed a logistic regression model of roe deer presence points and random points to verify landscape elements of roe deer distribution. Both in the WF area and in the control area, roe deer showed clustering; however, roe deer in the WF area showed this effect more strongly. In the control area, the area of KDE 50 was about 50% larger than in the WF area. The spatial distribution of roe deer in the WF area depended on distance to settlements, roads, enclaves, and forests, but for the control area, the logistic model was insignificant. The modified density of roe deer in the WF area may have multiple consequences for both the reproduction process and the overall condition of animals. Increased ambient noise could impair not only predator detection but also vocal communication between individuals, especially relevant during territorial marking. While our study did not demonstrate clear avoidance of wind turbines by roe deer, it did reveal varying distributions of this species, which may indicate an indirect effect of the wind farm.

Keywords Roe deer · Wind farm · Distribution · Summer · Drone

Introduction

As the global demand for renewable energy grows, wind farms (WFs) are expanding rapidly across diverse landscapes. Along with their associated infrastructure, they are becoming prominent landscape features worldwide (Beiter et al. 2022; Bošnjaković et al. 2022). However, this development adds to the cumulative anthropogenic pressures on ecosystems (Gillingham et al. 2015), and more recent studies assessed the effects of WFs on terrestrial mammals (Helldin et al. 2012; Klich et al. 2024; Lovich and Ennen 2011; Łopucki et al. 2017; Schöll and Nopp-Mayr 2021).

Among terrestrial mammals, roe deer (*Capreolus capreolus*) represents an interesting model for assessing WF impacts. Originally associated with early successional stages of the forest, the roe deer is now an important game species widespread across Europe and frequently found near human-altered landscapes (Lorenzini et al. 2022; Ionescu et al. 2025). Currently in Central Europe, roe deer inhabiting lowlands with scarce wood cover live mainly in open areas, in a mosaic of cultivated fields, i.e., in an environment where mostly WF are located (e.g., Kamieniarz et al. 2024; Sardaro et al. 2019). However, the response of roe deer to WFs remains unclear. An assessment of general trends across Poland has shown that hunting bags may decrease in hunting districts with increasing WFs cover (Klich et al. 2024). However, this effect was weak and its primary cause remains unknown, as other factors may have influenced the shown trend. Łopucki et al. (2017) demonstrated the negative impact of WFs as a landscape element on the frequency of tracks of this species during winter. Kim et al. (2023), based on camera traps in a forest landscape, found no negative effect of WF on roe deer occupancy. However, using the same method but over a larger area and taking into account

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many environmental covariates, a negative effect of WF was found (Kim et al. 2025). Roe deer may also exhibit physiological responses to wind farms in the form of increased levels of stress hormones (Klich et al. 2020).

Traditional wildlife monitoring methods, such as direct counts or snow tracking, are often labour-intensive and prone to error, especially in dense habitats or at night (Borkowski et al. 2011; Frederick et al. 2003; Keeping et al. 2018; Morellet et al. 2010; Takeshita et al. 2016). In this context, unmanned aerial vehicles (UAVs) have emerged as transformative tools in wildlife research, offering high-resolution, efficient, and low-disturbance data collection (Christie et al. 2016). UAV-mounted sensors can cover large areas quickly, overcoming terrain accessibility issues and reducing the need for ground-based disturbance. They have already proven useful in studying a wide range of species (e.g., Corcoran et al. 2019; Maeda et al. 2021; Sardà-Palomera et al. 2017; Scarpa and Piña 2019), particularly in open or semi-open habitats but their role in forest ecosystems is growing (Franke et al., 2012; Kays et al. 2019; Witczuk et al. 2018; Zhang et al. 2020).

Given this context, we aimed to investigate whether the spatial distribution of roe deer differs between operational wind farm area and nearby control area during summer, using a UAV-based approach that combined thermal infrared and RGB imaging. By comparing patterns of roe deer occurrence across these landscapes, we tested the hypothesis that wind farm areas show a less random or more structured distribution, potentially reflecting avoidance behavior or altered habitat use.

Materials and methods

Study area

The study was conducted in central Poland near the town of Iłża at a wind farm (WF) site (51°10′17″N, 21°11′36″E) and a nearby control site about 2 km east (51°09′05″N, 21°15′55″E). The WF site comprises 32 Vestas 90 wind turbines (2 MW capacity, 80–95 m hub height, 90 m rotor diameter), constructed in 2013–2014 (27 turbines), with five turbines added in 2024. It covers an area of 20.45 km comprised of cultivated agricultural land and occasional shrubs. The dominant crops in the area include cereals, corn, and rapeseed. The control site covers an area of 19.59 km^2 of comparable land use and habitat structure. Both the wind farm and control site are bordered by local and regional roads, forest patches, and rural settlements. These sites were selected due to their comparable habitat characteristics, land use, and established roe deer populations.

Data collection

Surveys were conducted between 28 May and 2 July 2025, coinciding with the period when roe deer are no longer grouped in winter herds. By this time, males have typically established and begun defending their territories, resulting in a more stable and predictable spatial distribution that is favorable for monitoring.

We used a DJI Matrice 300 RTK UAV, equipped with Zenmuse H20T with thermal infrared radiometric camera (TIR) and a wide and zoom RGB camera. Sensors were gimbal-mounted and manually adjustable during flight. This dual-sensor configuration allowed real-time thermal detection and visual confirmation, crucial in dense vegetation where TIR's resolution and penetrative power are limited. TIR detects animal heat signatures, making it especially valuable for monitoring nocturnal or crepuscular species like roe deer. While TIR is effective at initial detection, it often lacks the resolution needed for species identification, especially in multi-species habitats or when animals are partially obscured (Boonstra et al. 1994; Goodenough et al. 2018; Virtue et al. 2023; Witczuk et al. 2018). In contrast, RGB imagery provides critical detail for accurate identification but struggles with camouflage and poor lighting. Multisensor systems that integrate both TIR and RGB cameras are therefore considered more effective, with TIR aiding detection and RGB supporting identification (Chrétien et al. 2016; Delisle et al. 2023; Franke et al., 2012; Kays et al. 2019; Millette et al. 2011).

Operating UAVs on wind farms introduces unique environmental and technical challenges. Before each transect on WF, turbine locations were cross-checked with databases, routes were planned in Google Earth, and field verification identified unlisted turbines. Flight paths followed parallel "lawnmower" or "zigzag" patterns with minimal overlap (Online Resource 1), maintaining a 30 m buffer from the maximum rotor blade reach to account for wind drift and GPS errors. Connection stability and system alerts were closely monitored. The HOME POINT was set to ensure safe emergency returns; if not possible, the "HOOVER" function was used. Fully charged batteries were used for each mission. The drone was flown at a constant speed of 3 m/s and an altitude of 75 m above ground level (AGL). Each flight lasted approximately 30–40 min (per battery set), with full survey missions lasting up to 2.5 h. All surveys were started about two hours before dusk to maximize thermal contrast, align with roe deer activity patterns, and ensure adequate RGB visibility for species and sex identification. Flights were avoided during rain, strong winds, or intense sun. On sunny days, flights were delayed to reduce surface reflectance, especially from bare ground, which could mask animal heat signatures. To test detection quality, UAV operators first checked their own thermal signatures from ~150 m to calibrate their observations according to the atmospheric conditions. Thermal imagery was manually monitored by the operator in real-time, with RGB used when hot surfaces interfered. Camera angles were adjusted mid-flight to improve detection. At approximately every 100 m, the UAV was paused to hover and scan for targets. If visibility was poor or identification was uncertain, the route was paused, and the drone was manually redirected for closer inspection of the area. Our surveys ended before the peak of the rut.

Flight sessions were rescheduled or split across days when weather or battery issues prevented full transect coverage. To avoid double-counting, detections within 200 m across consecutive days that matched in appearance (e.g., adult male or female with offspring) were assumed to be the same individual, and the second detection was removed. In total, eleven evening sessions were performed, six sessions were completed in the WF site and five in the control site. Following confirmed detections, a pinpoint was manually set on the drone controller. These georeferenced pinpoints were subsequently exported to QGIS for spatial analysis.

Agricultural activity during flights was minimal. At each site, a single working tractor was observed, and occasional passersby were seen driving or cycling along dirt roads between fields. No hunting activity was detected, and human presence did not appear to influence animal behavior. Before each session, the surrounding area was monitored using optical and thermal binoculars to verify whether the launch of drone raids would scare away any nearby animals. Flying a drone had no significant impact on the animals, though a few roe deer showed brief signs of disturbance without fleeing far, which allowed them to avoid recounting. Surveys excluded areas directly adjacent to buildings, fenced or forested areas.

Data analysis

The geographic coordinates of the roe deer (from the pinpoints) and wind turbines (from GPS) were converted into vector layers. Furthermore, vector data for four land cover types (forests, settlements, enclaves, and roads) were downloaded from the Topographic Objects Database (BDOT10k) from Geoportal (https://www.geoportal.gov.pl). All lands cape elements were verified on the ground after the flight sessions. If necessary, corrections were made to individual ground cover layers. We included only adults in the analysis because fawns were strongly associated with the presence of mothers, hard to detect in vegetation because of their small size, and being hidden most of the time. Within the surveyed areas, the same number of random points was generated as the number of roe deer detected, separately for the WF area and the control area. Next, using the NNJoin plugin in QGIS, the distances of each roe deer and random point from the forests, buildings, and wind turbine (only for the WF site) were calculated. Based on the data obtained, a statistical analysis of roe deer distribution in both areas was performed. A logistic regression model was implemented using IBM SPSS software, with the dependent variable being the actual presence of roe deer, designated as 1, and a random point, designated as 0. We performed two separate regressions: for the WF area and for the control area. In both regression models, the covariates were: (a) distance to forest (forest complexes), (b) distance to settlements, (c) distance to natural enclaves (patches of trees and shrubs in a mosaic of fields, in the vicinity of watercourses, and near villages - excluding trees and shrubs directly adjacent to buildings), (d) distance to roads (including paved and dirt roads), and for the WF area, the fifth variable was the distance from wind turbines. We also performed a Nearest Neighbor Analysis in QGIS to present differences in roe deer distribution in both areas. Finally, we calculated kernel density estimation KDE for 95% points (KDE95) and 50% points (KDE50) in QGIS.

Results

In the WF area, the presence of 104 adults (f=62, m=39, NN=3) and 5 fawns was recorded. The low number of detected fawns suggests imperfect detectability, indicating that some individuals, potentially including adults, may have been missed. Therefore, the results are presented as minimum density estimates; in the WF area, this yields a minimum density of 5.33 roe deer/km². In the control area, the presence of 116 adults (f=82, m=34) and 7 fawns was recorded, which indicates a minimum density of 6.28 ind./km. Both in the WF area and in the control area, roe deer showed clustering; however, roe deer in the WF area showed this effect more strongly (Nearest Neighbor Index was 0.643 for WF area and 0.759 for control area; Z-Score was −6.96 for WF area and −4.96 for control area). Both KDE 95 and KDE 50 in the WF area were located primarily in the southern part of the study area. In the control area, both KDE 50 and KDE 95 were distributed relatively evenly throughout the study area (Fig. 1). The area of KDE 95 was similar in both study areas (KDE 95% = 9.02 km^2 for WF area and 10.9 km^2 for control area), but in the control area, the area of KDE 50 was about 50% larger than in the WF area (KDE 50% = 1.99 km^2 for WF area and 2.92 km^2 for control area).

Distance to turbines was not significant and was finally excluded from the model to present similar variables for both models, the WF and the control area. The logistic regression model for the WF area was significant ($Chi^2=31.795$,

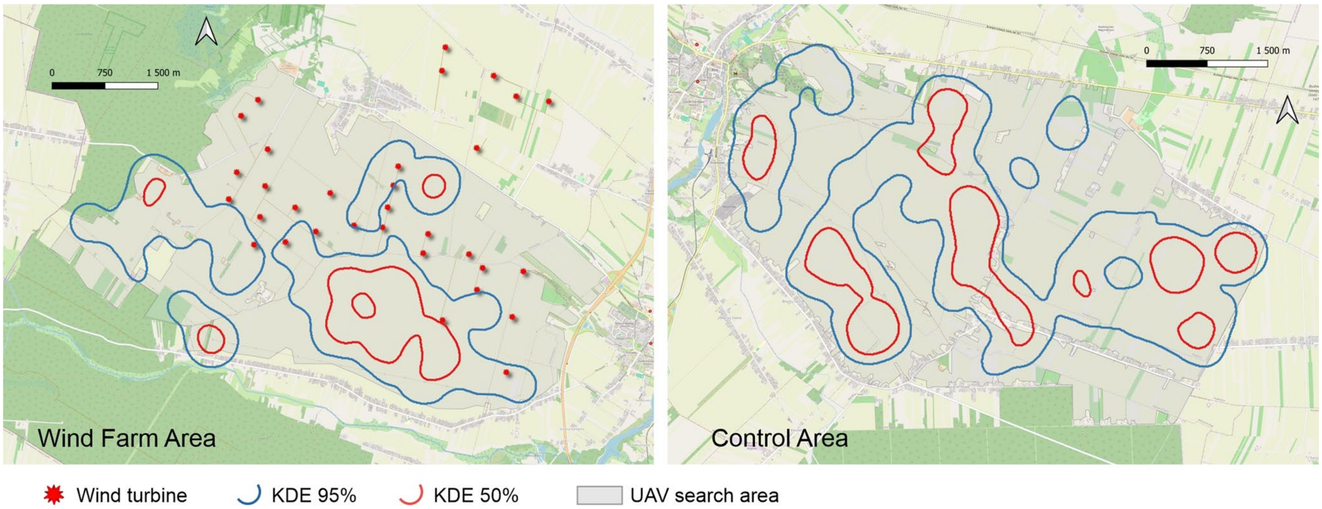

Fig. 1 Distribution areas for roe deer expressed by kernel density estimation of 95% (KDE 95) and 50% points (KDE 50) in the WF area and the control area

Table 1 Effects of landscape elements on roe deer distribution in the WF and control areas in logistic regression models (B – beta coefficient, SE – standard error of the coefficient, Wald – Wald chi^2 test of significance, *p* – p-value of Wald chi^2 test, exp (B) – odds ratio, Lower/Upper 95% CI − 95% confidence intervals for an odds ratio, * significant predictors)

Source	B	SE	Wald	*p*	Exp (B)	Lower 95% CI	Upper 95% CI
Model for WF Area							
Constant	0.123	0.408	0.90	0.764	1.130		
Forest	−0.687	0.281	6.001	0.014*	0.503	0.290	0.872
Settlements	1.228	0.496	6.751	0.009*	3.267	1.372	9.587
Enclaves	−1.943	0.678	8.210	0.004*	0.143	0.038	0.541
Roads	3.444	0.972	12.540	<0.001	31.304	4.654	210.563
Model for Control Area							
Constant	0.072	0.463	0.024	0.877	1.074		
Forest	−0.155	0.174	0.802	0.371	0.856	0.609	1.203
Settlements	−0.119	0.638	0.035	0.852	0.888	0.254	3.102
Enclaves	−0.438	0.576	0.578	0.447	0.645	0.209	1.996
Roads	2.535	1.066	5.657	0.017*	12.601	1.562	101.906

$p < 0.001$), and it showed 67.3% of correctly classified cases. The spatial distribution of roe deer was significantly different from random, and all analyzed factors (except for distance to turbines) were influencing it (Table 1). A negative effect of settlements and roads was observed, but the effect of roads was more pronounced (Exp (B) = 31.304 for roads and Exp (B) = 3.267 for settlements). In both cases, the uncertainty of the estimate was high because the 95% confidence intervals had a wide range (Table 1). A positive impact of the forest and natural enclaves was observed, but enclaves presented much higher impact on roe deer distribution (Exp (B) = 0.503 for forest and Exp (B) = 0.143 for natural enclaves).

The logistic regression model for the control area was not significant (Chi^2 = 7.188, $p = 0.126$), and only 56.5% of cases were correctly classified. Although the beta coefficients of detecting roe deer with distance to forests and enclaves were similar to those in the WF area (negative for both), they were not significant (Table 1). The settlements, unlike in the WF area, although not significant, showed a positive effect on the distribution of roe deer. Only distance to roads was significant and negatively affected roe deer distribution (Table 1).

Discussion

The research conducted at the Iłża WF site revealed an effect of roe deer being distributed spatially differently than in the control area, which was partially confirmed by indices and logistic regression. Roe deer were concentrated primarily in the southern part of the WF area, causing increased roe deer density in part of the area and low density in the remaining WF area. This pattern appears to be associated with the avoidance of settlements and roads and the need to locate closer to forests and natural enclaves. Although no significant correlation was found between roe deer distribution and wind turbines, an indirect effect of the wind farm as a landscape element is possible. This is indicated by the lack of an effect of three of the four land cover elements in the control area, where roe deer avoided roads but showed no tendency to avoid settlements or to stay closer to forests or natural enclaves.

If the differences shown are true, they may have multiple consequences for both the reproduction process and the overall condition of animals. Increased animal density and consequently augmented interactions can cause elevated stress, especially in the context of competition for females, since roe deer males occupy and defend territory during the summer irrespective of habitat quality or female distribution (Johansson et al. 1995; Vanpé et al. 2009). The observed spatial compression in Iłża WF results in locally elevated densities, increasing encounters, and competition during the summer period. Furthermore, a high density of roe deer in a reduced area could exacerbate density-dependent effects, previously shown to influence antler size (Vanpé et al. 2007), reproductive success (Vanpé et al. 2009), and other life-history traits (Body et al. 2011; Bonenfant et al. 2009; Douhard et al. 2013; Kjellander et al. 2004; Pettorelli et al. 2002; Vincent et al. 1995). Elevated densities can also facilitate pathogen transmission and may lead to increased agricultural crop damage and a higher frequency of traffic collisions involving roe deer.

As highlighted by Kjellander et al. (2006), density-dependent effects are typically shaped by interactions between population density and habitat quality (see also Sinclair 2003). In this context, however, the high density observed near the WF does not reflect a favorable habitat but rather avoidance of the wind farm area. This is indicated by the greater sensitivity of roe deer to anthropogenic elements (roads, settlements) and the clear proximity to natural shelters (forests, natural enclaves). The distance of the roe deer from the turbines ranged from 30 m to almost 2 km. About half of roe deer in WF area (54 individuals) were located less than 700 m from the turbines, the distance considered for human settlements and with possible impact on animals (e.g. Łopucki et al. 2017). The presence of roe deer in the vicinity of turbines exposes them to noise pollution (Shannon et al. 2016), as increased noise can impair roe deer's hearing not only in terms of safety from predators and hunters, but also in the context of vocally marking occupied territory. Wind turbines emit both high- and low-frequency sounds, with the latter traveling long distances (Van Kamp and Van Den Berg 2021). Increased ambient noise could impair not only predator detection but also vocal communication between individuals, especially relevant during territorial marking. Roe deer males vocally mark their territories by emitting loud barks (Reby et al. 1999), which may be drowned out by turbine noise, potentially reducing the effectiveness of this behavior and impairing their ability to deter rivals. This acoustic masking could interfere with the reproductive process by weakening the signaling mechanisms that underpin territory defense and mate attraction. This may also apply to altered communication between females and their fawns.

Wind farms may also shape animal responses via the infrastructure and activities associated with their operation (Qin et al. 2025). The construction and maintenance of turbines require access roads and service infrastructure, which increase human activity, traffic, and habitat fragmentation in previously less-disturbed areas. These changes can elevate disturbance levels and alter roe deer movement, space use, and habitat selection, potentially contributing to the spatial compression observed at the WF site.

The applied UAV dual-sensor configuration (TIR and RGB) proved effective in practice. The drone did not appear to disturb the animals, which facilitated accurate counting of adult roe deer. However, we acknowledge limitations of this approach, as detectability could be reduced in areas with dense vegetation cover. Fawn detection was particularly low due to their small size and tendency to hide. While the method performs well for animals of roe deer size, it may be insufficient for reliably detecting smaller individuals or species in densely vegetated habitats.

While our study did not demonstrate clear avoidance of wind turbines by roe deer, it did reveal varying distributions of this species, which may indicate an indirect effect of the wind farm. We hypothesize that turbine noise may increase roe deer sensitivity to threats, as indicated by the different distribution effects of roe deer in the WF and control areas. Therefore, it seems justified to request further research on a larger number of wind farms, which could confirm the demonstrated relations or, if necessary, correct our theoretical considerations regarding the impact of wind farms on the spatial distribution of roe deer and the subsequent consequences associated with it.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10344-026-02060-4.

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

Declarations

Competing interests The authors declare no competing interests.

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