Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Camera-trap-based density estimation and control of an introduced muntjac (Muntiacus reevesi) population in mainland Europe

Bram D'hondt

bram.dhondt@inbo.be

Research Institute for Nature and Forest (INBO)

Bert Verbist

Agency for Nature and Forests (ANB)

Jan Vercammen

Research Institute for Nature and Forest (INBO)

Lynn Pallemaerts

Research Institute for Nature and Forest (INBO)

Sara Pezzatini

Research Institute for Nature and Forest (INBO)

Tim Adriaens

Research Institute for Nature and Forest (INBO)

Jim Casaer

Research Institute for Nature and Forest (INBO)

Research Article

Keywords: Reeves' muntjac, barking deer, biological invasions, invasive alien species, IAS, Agouti

Posted Date: November 2nd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10916571/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

methods

shooting from tree stands (high seats) and car-assisted stalking. Muntjac was the second most frequently detected species, after roe deer (*Capreolus capreolus*). The REM revealed low population densities in the first two years of the study (95% confidence intervals: 3–11 individuals per km² in 2022–2023 and 3–10 per km² in 2023–2024), and a very low density in the third year (< 1 individual per km², 2024–2025). These densities are substantially lower than those reported for British populations, suggesting that the studied population is still in an early phase of invasion. The decline observed in the final year is attributed to the management interventions. Car-assisted stalking proved ten times more effective in terms of catch per unit effort than shooting from tree stands. Further research into muntjac population dynamics and the efficacy of control methods is essential to address the challenges posed by this emerging invasive species across Europe.

Introduction

Muntiacus reevesi (Ogilby, 1839) is a small deer species with evolutionary origins in southern China, where it remains widespread (Chen et al. 2024). Introduced to Europe in the late 19th century, the species has since become established, notably in Great Britain (Cooke 2019; Chapman 2022). There, it is both common and locally abundant, with reported site-scale densities of approximately 20 km^{-2} (Hemami et al. 2007), reaching up to 50 km^{-2} (Wäber et al. 2013) or even 110 km^{-2} (Cooke 2006). High muntjac numbers are considered detrimental to forest ecosystems, as browsing and fraying induce changes across vegetation layers — from the herb layer (through selective feeding that favors forest generalists over old-growth forest herbs) to the tree layer (by impeding forest regeneration). Cooke (2019) provides a comprehensive review of these ecological impacts. Especially in regions with elevated atmospheric nitrogen deposition, such as Western Europe, intensified deer herbivory has been linked to declines in threatened herb species and shrub cover (Segar et al. 2022). In studies from Great Britain, muntjac densities often exceed those of native roe deer (*Capreolus capreolus*), which can be explained by the depletion of shared resources (Hemami et al. 2004, 2005). At high densities of muntjac, Zini et al. (2023) observed a reduced fertility in roe deer, which they suggest stems from agonistic encounters. There is thus evidence that both exploitation competition and interference competition occur between muntjac and native species (Dolman and Wäber 2008).

To prevent muntjac from becoming similarly widespread in the European Union, the species has been listed as an ‘invasive alien species of Union concern’ since 2016 (EU Regulation No. 1143/2014). This legal status obliges all Member States to prevent, where possible, the establishment and spread of muntjac. Suitable habitat is widely available on the European mainland, and the species has been sporadically recorded in various Member States (Ward et al. 2021; e.g. France: Maillard et al. 2024; Germany: Schulz and Borkenhagen 2021; Austria: Schertler et al. 2024). The situation is particularly pressing in Belgium, where *M. reevesi* was first observed in 2004 but has increased rapidly since 2013

(Casaer et al. 2026; D'hondt et al. 2023). Although the species' overall distribution is largely erratic here – primarily due to escapes from captivity without subsequent spread – it is clear that *M. reevesi* has established self-sustaining populations in at least a few sites.

One of these sites, near the city of Antwerp, has been managed for several years (D'hondt et al. 2023). Nevertheless, significant knowledge gaps hinder optimal control. First, the population size remains unclear. Consequently, it is uncertain whether the density (or abundance) is comparable to that reported for established British populations or if the population is still in an early invasion stage. This knowledge is obviously crucial for defining management objectives, and particularly for assessing the feasibility of local eradication.

Second, it remains unclear which of the legally permitted control methods are most effective. Indeed, in a review on the effectiveness of ungulate population management, Barton et al. (2022) concluded that there is a significant lack of data for muntjac. Only Wäber et al. (2013) are referred to, which concluded that culling muntjac can lead to population decline, provided it is sufficiently intensive and accounts for source-sink dynamics. At a more methodological level, various techniques for managing ungulate populations have become well-established in hunting practice (e.g., the use of tree stands or thermal imaging cameras). Yet, quantitative descriptions of their deployment and success rates remain limited. This is certainly true for muntjac in Europe, where knowledge development and exchange are crucial for achieving the international objectives of the Regulation.

The use of camera traps for studying wildlife has grown significantly over the past decades, accompanied by the development of advanced analytical methods and software (Burton et al. 2015; Fisher 2023). A specific challenge is estimating the abundance of individually unidentifiable (unmarked) species —such as muntjac— and several approaches have been proposed for this purpose (Gilbert et al. 2021). One such method is the Random Encounter Model (REM), which models the encounters between moving animals and static cameras (Rowcliffe et al. 2008). In brief, given the camera's viewshed (known), the number of detections (measured), and parameters of animal movement (estimated), the number of animals in an area can be derived. Methodological studies have demonstrated the reliability of the approach (Palencia et al. 2022), as well as its applicability in relatively small areas such as hunting grounds or management units (Wohlfahrt et al. 2025). The REM method is currently widely applied, and this is facilitated by dedicated and accessible software for image and statistical processing (see below).

We utilized recent advancements in camera trap image processing to estimate the density of a wild muntjac population in Belgium (Antwerp). Additionally, we describe and compare the two methods used to control this population, i.e. culling from tree stands (high seats) and car-assisted stalking, with the aim of evaluating their effectiveness.

Material and methods

Study area

The study was conducted in Park Vordenstein (51°15'45"N, 4°29'37"E), a government-owned, public woodland park spanning about 140 hectares and encompassing diverse habitats. Roughly 60% of the park is covered by broad-leaved and mixed forests (primarily oak, birch, beech; pine), with an understorey dominated by *Rhododendron* spp., bramble (*Rubus* spp.) and bracken (*Pteridium aquilinum*). While the park is open to the public and heavily frequented during the day, it is closed at night, and dogs are prohibited. The park is partially fenced and includes a shallow moat, but these do not present a fundamental barrier to wildlife movement.

Muntjac have been observed in Park Vordenstein since 2013, and are known to originate from a private estate a few kilometres away (Deflem et al. 2022, 2025). A camera trap survey conducted from 2020 to 2022 confirmed the presence of muntjac and documented the species' typical behavior (D'hondt et al. 2023). However, these exploratory data did not allow for density estimation, prompting the initiation of a new campaign.

Camera-trapping

We deployed 16 cameras (Reconyx, HyperFire 2) from early winter to late spring over three consecutive years: 2022–2023 (December-May), 2023–2024 (November-May), and 2024–2025 (November-May). Hereafter, we refer to these periods as the first, second, and third year, respectively. Camera positions were restricted to the forested areas of the park and were based on randomized allocations (but see below). Positions remained fixed across years (Fig. 1). Cameras were mounted on trees at approximately 50 cm height and oriented northward to minimize lens flare. They were configured to capture still images (not videos) in bursts of ten for as long as movement was detected.

All images were uploaded to the online system Agouti (www.agouti.eu/; Casaer et al. 2019). Following the system's standard procedure, consecutive image bursts captured in quick succession (i.e., within 2 minutes) were grouped into a single sequence. Each sequence was then manually reviewed, and the observed species and their counts were recorded. For muntjac, additional observations such as sex and behavior were noted.

To estimate movement parameters from the camera trap images, a calibration step was performed during each camera deployment (including interim readouts), following the photogrammetry protocol of the ENETWILD-consortium et al. (2023). During this process, the operator was recorded by the camera at approximately 15 random positions while holding a pole marked with fixed intervals (20, 60, 80, 100 cm). In the subsequent annotation phase using Agouti, intervals on the pole were indicated for each unique recorded pole position. This allows the protocol to determine the distance from the camera to the ground level for every pixel in the image. By additionally marking the pixel where a muntjac's foot touches the ground on all suitable images within a sequence, the movement parameters required for the model can be estimated (e.g. speed).

In addition to the full analysis (using all cameras), we repeated the analysis multiple times, each time excluding a different camera. This sensitivity analysis allows us to understand the effect of individual cameras on the density estimation results.

For data processing, we extensively used functions from the *tidyverse* R package (v2.0.0, Wickham et al. 2019). For analyses, we employed several packages dedicated to camera trap data, including *camtrapdp* (v0.6.0.9000, Desmet et al. 2026) and *camtrapDensity* (v0.1.16, Rowcliffe 2026), the latter of which also interacts with *camtraptor* (v0.28.0, Oldoni et al. 2026).

Muntjac control

During the study period, management of muntjac in Park Vordenstein employed two methods: shooting from tree stands (high seats), and ground-level stalking involving the use of a car. High-seat shooting was conducted from fixed positions, typically involving multiple shooters simultaneaously (mode: 4 shooters, maximum: 7). Car-assisted stalking entailed patrolling the park by car along gravel roads and forest tracks. When an animal was spotted, the shooter would discreetly exit the vehicle to organize the cull, sometimes requiring a brief approach on foot. These operations were conducted by a single shooter but always included a driver and occasionally additional spotters. For consistency, only the time spent by shooters is reported here.

In both methods, hand-held thermal imaging devices were used to locate animals, though current legislation prohibits the use of thermal riflescopes. Shooting therefore required artificial light when necessary. No attractans were used. Throughout the campaign, shooters received interim updates from camera trap readouts on the presence of muntjac. Most operations were conducted in the evening or at night, as this aligned with park closure and coincided with periods of slightly higher muntjac activity (D'hondt et al. 2023).

Results

Animal detections

The cameras recorded 5,710 image sequences in which 35 taxa were identified (excluding humans and dogs). The most frequently detected species were roe deer (66% of sequences), muntjac (15%), wood pigeon (*Columba palumbus*, 6%), red fox (*Vulpes vulpes*, 5%), and red squirrel (*Sciurus vulgaris*, 3%). Muntjac were recorded in 415, 309, and 119 sequences across the three respective study years. In the vast majority of cases, muntjac were observed solitarily (1 animal: 84.8%; 2 animals: 14.6%; 3 animals: 0.6%). Both adult males, adult females, and juveniles were observed. Muntjac were detected on 15 of the 16 cameras (Fig. 1).

All species observations, including photographs, have been included in the species occurrence dataset of D'hondt et al. (2026).

Muntjac control

Between September 2022 and September 2025, a total of 430 person-hours were dedicated to muntjac control (Fig. 2, Table 1). Of the 77 organized sessions, roughly half involved shooting from tree stands (43 sessions; 56%), while the rest involved car-assisted stalking (34 sessions; 44%). Most sessions took place in the evening (64 sessions; 83%), with only a few conducted in the morning (13 sessions).

Table 1
Effort spent on muntjac control at Park Vordenstein. The total effort are person-hours (shooters only). The three periods run from Sep' 1 to Aug' 31.

Method	Measure	2022-'23	2023-'24	2024-'25	all
Shooting from tree stands	Nr. of sessions	19	20	4	43
	Total effort (hours)	112	129	13	255
	Effort per session (hours)	5.9	6.5	3.3	5.9
	Muntjac shot	2	3	0	5
	Effort per muntjac shot (hours)	56.2	43.1	.	50.9
Car-assisted stalking	Nr. of sessions	6	15	13	34
	Total effort (hours)	19	95	60	175
	Effort per session (hours)	3.2	6.4	4.6	5.1
	Muntjac shot	5	9	5	19
	Effort per muntjac shot (hours)	3.9	10.6	12.0	9.2

During this period, 24 muntjac were shot: 11 males and 13 females. All animals were shot during evening sessions, and after sunset. The median time between sunset and a successful shot was 3.3 hours (min. 0.3 hours, max. 9 hours).

In each of the three years, more animals were shot while stalking than from high seats. Additionally, the time investment per animal shot during stalking was approximately one-tenth of that required for shooting from high seats (Table 1).

Density

As shown in Table 2, the parameter estimates of the Random Encounter Model are highly consistent for the first and second years but differ significantly in the third year. Specifically, cameras V06, V16, and V23 were found to be influential for the results of years 1, 2, and 3, respectively. This is evident from the

sensitivity analysis, as illustrated in Fig. 3 (for two parameters) and Fig. 1 in the Supplementary Information (for the other five). Notably, the parameters related to speed differed at these cameras (active speed, overall speed, activity level).

Table 2
Output from the Random Encounter Model (estimate and 95% confidence interval). The three periods run from Nov'/Dec' to May (see text).

Parameter	**2022-'23**			**2023-'24**			**2024-'25**		
	est.	**l.c.l.**	**u.c.l.**	**est.**	**l.c.l.**	**u.c.l.**	**est.**	**l.c.l.**	**u.c.l.**
Radius (m)	6,39	5,93	6,86	6,02	5,48	6,56	7,85	6,82	8,88
Angle (°)	41,47	36,69	46,25	40,00	34,05	45,94	31,86	27,02	36,71
Active speed (km/h)	0,66	0,55	0,77	0,45	0,36	0,54	1,19	0,91	1,46
Activity level	0,36	0,31	0,41	0,45	0,37	0,53	0,55	0,41	0,68
Overall speed (km/day)	5,69	4,48	6,90	4,87	3,62	6,11	15,61	10,27	20,95
Trap rate (n/day)	0,19	0,10	0,30	0,13	0,06	0,23	0,04	0,01	0,11
Density (n/km²)	5,99	3,40	10,55	5,20	2,59	10,43	0,44	0,14	1,39

After a thorough examination of the data, we conclude that these differences are reliable. Camera V06 was located in the center of the park in a forest clearing surrounded by dense undergrowth and proved to be the most visited camera during the first year (21% of the image sequences with muntjac). It was a preferred spot for calm, relatively 'slow-moving' behaviors such as grazing and social interaction. Indeed, 22% of the sequences at this camera showed more than one muntjac, a higher proportion than the overall figure above (Fisher's Exact Test: odds ratio = 1.62, P = 0.09; representing weak evidence [Muff et al. 2022]). The same elements applied to V16 during the second year. At that time, it was the most frequented camera (32% of the image sequences with muntjac), disproportionately often by more than one animal (29% of the sequences at this camera; odds ratio = 2.35, P < 0.01; i.e., very strong evidence). In the third year, however, few or no muntjac were observed at these cameras (zero and four sequences at V06 and V16, respectively). Instead, V23 became the most visited camera, with 63% of the sequences with muntjac. This camera was positioned at the edge of the park in an open forest area between a walking path and a road —a location better described as a 'corridor' from a wildlife perspective. This resulted in solitary animals, consistent with the general figure (only 12% of sequences with more than one animal; odds ratio = 0.76, P = 0.61), and more 'fast-moving' behavior (i.e., walking or running).

As the ultimate variable of interest, the resulting density of muntjac in Park Vordenstein was estimated at 5.99 animals per km² for the first year, 5.20 animals per km² for the second year, and 0.44 animals per km² for the third year (Table 2, Fig. 3).

Discussion

Overall density – To our knowledge, this is the first study to estimate the density of a European *M. reevesi* population using the Random Encounter Model. Maillard et al. (2024) estimated the density of a French population using a different method, whereas Nakashima et al. (2026) applied REM-like methods to a Japanese population. Previous estimates of *M. reevesi* densities from British populations relied on direct counts, faecal pellet counts, or distance sampling (Hemami et al. 2005, 2007; Wäber et al. 2013; see Cooke 2006 for a additional methods). Comparisons between these methods have shown that estimates can vary substantially even within a single site, making their accuracy difficult to assess. Nonetheless, these studies consistently report densities on the order of tens of muntjac per km^2. While the accuracy of our estimates also remains uncertain, the densities observed at Park Vordenstein are clearly substantially lower. The relative proportion of species detections suggests that muntjac are less abundant than roe deer. However, we assume that, ultimately, similar densities to those in Great Britain could be achieved in Park Vordenstein. The habitat is considered highly favorable, and the genetic diversity of this specific population is known to be comparable to that of British populations (Deflem et al. 2025). We therefore conclude that the population is currently in an early invasive stage.

Muntjac have been observed annually in the area since 2013 (Casaer et al. 2026), and several plausible processes may have suppressed rapid population growth, including interference competition with roe deer (Zini et al. 2023), predation by foxes (Cooke 2019; D'hondt et al. 2023), human disturbance (recreation and maintenance works), urban mortality (e.g., road collisions, though reports are scarce), and emigration (to suitable sites elsewhere). Additionally, earlier control efforts may have contributed to the relatively low density, although the number of animals shot has always remained limited compared to the current campaign.

Methodology – The Random Encounter Model requires cameras to be placed at random positions relative to animal movement (Rowcliffe et al. 2008). We paid considerable attention to this, for example by rejecting suggestions to lure muntjac for control purposes or requests to use salt licks for roe deer. For the camera positions, we used computer-based randomization. However, we must acknowledge that four positions were inherited from the preceding exploratory survey (2020–2022), where they had been placed in locations pre-identified as suitable for muntjac (quiet, open forest clearings; D'hondt et al. 2023). Position V06, mentioned above, was one of these locations. We thereby note that the combination of calm and non-solitary behavior on cameras at tranquil sites means that the animals' slow movements become replicated in parameterization. We thus acknowledge that some sampling bias has been introduced, and the estimated densities should therefore be considered more likely over- than underestimated (Palencia et al. 2022). However, the decision to retain these positions was driven by the need for continuity in monitoring these sub-sites and the necessity to at least confirm the presence of muntjac — as a minimal input for the control efforts. Indeed, particularly in light of potentially very low densities, succesful control was deemed a priority, given the imposed obligations. In general, we evaluate the REM protocol as suitable for muntjac: the animals appear to be consistently on the move (making parameterization straightforward) and are solitary (avoiding issues related to group size;

Rowcliffe et al. 2008). However, proper execution of the REM model does require a minimum number of sequences (Palencia and Barroso 2024) and, consequently, a certain minimum abundance (Robertson et al. 2026).

Density trend – During the study period, we observed a decline in muntjac density in the winter of 2025. This is suggested by the reduced number of observations (strongly linked to the 'disappearance' of muntjac from the favorable locations V06 and V16), the lower estimated density (Table 2), and the reduced harvest and increased effort per animal (Table 1). We attribute this decline to the control efforts. It is unlikely that muntjac simply relocated to areas outside the cameras' range, as car-assisted stalking —which implicitly serves as a form of area-wide monitoring— also yielded fewer sightings. The fact that most animals were recorded at the edge of the area during the third year may indicate that the core of the area was effectively free of muntjac at the end of the campaign.

Control methods - Our data suggest that car-assisted stalking is more effective than high-seat shooting for culling muntjac, with a catch per unit effort (CPUE) approximately five times higher. Of course, a vehicle covers a larger area, though we suspect its movement may help avoid alarming animals, and its noise may help mask the preparatory steps for shooting. We therefore recommend stalking as the preferred method but acknowledge that high-seat shooting still has its merits —for example, when the area cannot be traversed by car, the whereabouts of animals are well known, a large group of shooters is mobilized, or experience is limited. Indeed, stalking by vehicle does carry higher safety risks, as the considerations to shoot or not are constantly changing. Particularly in highly urbanized settings such as ours, car-assisted stalking may not be straightforward. Our experience shows it can be applied safely, but we advise applying it only under professional supervision.

Landscape-level control – Based on our experiences, we hypothesize that local eradication of muntjac is possible. However, we refrain from making such estimates at a regional scale. There is reason to believe that, in the absence of management, Park Vordenstein has the potential to function as a 'source' population, but with sustained control, it could be transformed into a 'sink'. The park is currently being monitored as such, while car-assisted stalking is now also being implemented in other sites across the region. We consider a better understanding of source-sink dynamics to be crucial (Wäber et al. 2013), in addition to two specific challenges that determine the efficacy of control. The first is establishing an effective rapid-response system that can quickly address muntjac detections across a wide range of areas, many of which are private. This requires public involvement (Pocock et al. 2024) as well as continuous engagement by authorities. The second challenge is detecting muntjac at very low densities, typical of the invasive front, where cameras may be inadequate. A notable innovation in this regard is the use of airDNA, which is still highly experimental but has already detected muntjac (Clare et al. 2022). A more developed, implementable, and thus promising approach is acoustic detection, which targets muntjac barking calls and can provide the complete coverage of an area (Robertson et al. 2026).

Outro – M. reevesi currently has a limited distribution on the European mainland. Given the international obligations to prevent further spread (EU Regulation No. 1143/2014), it is essential to better understand

the species' population status and widely share this knowledge. Despite over a decade of presence, we found the density of muntjac in a Belgian population to be low, suggesting an early invasive stage. Notably, Maillard et al. (2024) also reported a very low density in a French population, suggesting that conditions for muntjac control in Western Europe may still be favorable. Methodologically, we found car-assisted stalking at night to be an effective control measure. Thus, we hope to have contributed to the evidence base for the management of this invasive species (Barton et al. 2022).

Declarations

Supplementary Information

(Supplementary information is included as a separate document.)

Funding

This study utilized infrastructure funded by the Research Foundation - Flanders (FWO), as part of Belgium's contribution to LifeWatch.

Data availability

The observations of all species (including pictures) have been published as species distribution data on the Global Biodiversity Information Facility (GBIF.org; https://doi.org/10.15468/GN87D6). Any other data will be made available on reasonable request.

Ethics approval

This study supported an existing control campaign, which was conducted in accordance with Flemish, Belgian, and European policies on invasive alien species. No animals were captured, handled, or killed for scientific purposes. Formal ethical approval was therefore not required.

Competing interests

The authors declare no competing interests.

Author Contribution

This study was conceptualized by BD, BV, and JC. JV, LP, and SP contributed as investigators and managed operational resources. BD led the data curation, formal analysis, and writing. JC supervised the methodology and software usage, while general supervision was provided by TA.

Acknowledgement

We are grateful to the volunteers, colleagues, internship and thesis students who assisted with image processing and preliminary analyses, notably Gerrit Huybreghts, Matthias Neeckx, Wannes Dermout, Marco Morbidelli, and Martijn Bollen. We also extend our thanks to Wouter Huygens, Patrick Engels, and all members of the Fauna Management Unit at the Agency for Nature and Forest for their contributions to the muntjac management campaigns.

References

1. Barton O, Gresham A, Healey JR, Cordes LS, Shannon G (2022) The effects of population management on wild ungulates: A systematic map of evidence for UK species. PLoS ONE 17:e0267385. https://doi.org/10.1371/journal.pone.0267385
2. Burton AC, Neilson E, Moreira D, Ladle A, Steenweg R, Fisher JT, Bayne E, Boutin S (2015) Wildlife camera trapping: A review and recommendations for linking surveys to ecological processes. J Appl Ecol 52:675–685. https://doi.org/10.1111/1365-2664.12432
3. Casaer J, Milotic T, Liefting Y, Desmet P, Jansen P (2019) Agouti: A platform for processing and archiving of camera trap images. Biodivers Inf Sci Stand 3:e46690. https://doi.org/10.3897/biss.3.46690
4. Casaer J, Devisscher S, Adriaens T, Brosens D, Desmet P, Reyserhove L (2026) Invasive species - Chinese muntjac (*Muntiacus reevesi*) in Flanders, Belgium. GBIF.org (dataset). Accessed 2 September 2026. https://doi.org/10.15468/SR8BN2
5. Chapman NG (2022) Reeves' muntjac *Muntiacus reevesi* (Ogilby, 1839). In: Corlatti L, Zachos FE (eds) Handbook of the mammals of Europe: Terrestrial Cetartiodactyla, 1st edn. Springer Nature, Switzerland, pp 29–50. https://doi.org/10.1007/978-3-030-24475-0_18
6. Chen G, Sun Z, Shi W, Wang H, Shi G, Hu Y, Fan H, Wu Q, Zhang B (2024) Climatic fluctuations, geographic features, and evolutionary forces: Shaping high genomic diversity and local adaptation in *Muntiacus reevesi*. Divers Distrib 30:e13904. https://doi.org/10.1111/ddi.13904
7. Clare EL, Economou CK, Bennett FJ, Dyer CE, Adams K, McRobie B, Drinkwater R, Littlefair JE (2022) Measuring biodiversity from DNA in the air. Curr Biol 32:693–700e5. https://doi.org/10.1016/j.cub.2021.11.064
8. Cooke AS (2019) Muntjac and water deer: natural history, environmental impact and management. Pelagic publishing, Exeter
9. Cooke AS (2006) Monitoring muntjac deer *Muntiacus reevesi* and their impacts in Monks Wood National Nature Reserve, vol 681. English Nature Research Reports, p 173
10. Deflem I, D'hondt B, De Corte Z, Mouton C, Van Breusegem A, Neyrinck S, Adriaens T, Mergaey J (2022) Een genetische studie van Chinese muntjak in Vlaanderen. Research Institute for Nature and Forest, Brussels. https://doi.org/10.21436/inbor.84191641

11. Deflem I, D'hondt B, Mouton C, Van Breusegem A, Neyrinck S, Adriaens T, Mergeay J (2025) Een genetische studie van Chinese muntjak in Vlaanderen - een update (2025). Research Institute for Nature and Forest, Brussels. https://doi.org/10.21436/inbor.128499361
12. Desmet P, Govaert S, Huybrechts P, Oldoni D (2026) Camtrapdp: Read and manipulate camera trap data packages. R package version 0.6.0.9000. https://github.com/inbo/camtrapdp
13. D'hondt B, Engels P, Verbist B, Vercammen J, Huygens W, Adriaens T, Casaer J (2023) Monitoring of a population of Reeves' muntjac in the context of eradication (Flanders, Belgium). Lutra 66:105–121
14. D'hondt B, Casaer J, Vercammen J, Pallemaerts L, Adriaens T, Desmet P, Govaert S (2026) MUNTJAC_ANTWERP - Camera trap observations of Chinese muntjac in forested areas near Antwerp (Belgium). GBIF.org (dataset). Accessed 2 September 2026. https://doi.org/10.15468/GN87D6
15. Dolman PM, Wäber K (2008) Ecosystem and competition impacts of introduced deer. Wildl Res 35:202–214. https://doi.org/10.1071/WR07114
16. ENETWILD-consortium et al (2023) Wild ungulate density data generated by camera trapping in 37 European areas: first output of the European Observatory of Wildlife (EOW). https://doi.org/10.2903/sp.efsa.2023.EN-7892. EFSA Supporting Publications 20
17. Fisher JT (2023) Camera trapping in ecology: A new section for wildlife research. Ecol Evol 13:e9925. https://doi.org/10.1002/ece3.9925
18. Gilbert NA, Clare JDJ, Stenglein JL, Zuckerberg B (2021) Abundance estimation of unmarked animals based on camera-trap data. Conserv Biol 35:88–100. https://doi.org/10.1111/cobi.13517
19. Hemami MR, Watkinson AR, Dolman PM (2004) Habitat selection by sympatric muntjac (*Muntiacus reevesi*) and roe deer (*Capreolus capreolus*) in a lowland commercial pine forest. Ecol Manage 194:49–60. https://doi.org/10.1016/j.foreco.2004.01.049
20. Hemami M-R, Watkinson AR, Dolman PM (2005) Population densities and habitat associations of introduced muntjac *Muntiacus reevesi* and native roe deer *Capreolus capreolus* in a lowland pine forest. Ecol Manage 215:224–238. https://doi.org/10.1016/j.foreco.2005.05.013
21. Hemami MR, Watkinson AR, Gill RMA, Dolman PM (2007) Estimating abundance of introduced Chinese muntjac *Muntiacus reevesi* and native roe deer *Capreolus capreolus* using portable thermal imaging equipment. Mamm Rev 37:246–254. https://doi.org/10.1111/j.1365-2907.2007.00110.x
22. Maillard J-F, Bonhotal H, Terlin M, Pisanu B, Hurel P (2024) Current distribution of the Reeves' muntjac *Muntiacus reevesi* (Ogilby, 1839) in France. Mammalia 88:547–553. https://doi.org/10.1515/mammalia-2024-0022
23. Muff S, Nilsen EB, O'Hara RB, Nater CR (2022) Rewriting results sections in the language of evidence. Trends Ecol Evol 37:203–210. https://doi.org/10.1016/j.tree.2021.10.009
24. Nakashima Y, Yajima G, Matsuoka R (2026) Reducing data processing effort in camera trap density estimation: Extending the REST model by explicitly modelling animal detection processes. Methods Ecol Evol 17:850–862. https://doi.org/10.1111/2041-210x.70248

25. Oldoni D, Desmet P, Huybrechts P, Bollen M, Nussbaumer R, Onkelinx T, Casaer J, Pallemaerts L, Mullens N (2026) Camtraptor: Read, explore and visualize camera trap data packages. R package version 0.28.0. https://github.com/inbo/camtraptor
26. Palencia P, Barroso P, Vicente J, Hofmeester TR, Ferreres J, Acevedo P (2022) Random encounter model is a reliable method for estimating population density of multiple species using camera traps. Remote Sens Ecol Conserv 8:670–682. https://doi.org/10.1002/rse2.269
27. Palencia P, Barroso P (2024) How many sequences should I track when applying the random encounter model to camera trap data? J Zool 324:155–162. https://doi.org/10.1111/jzo.13204
28. Pocock MJO, Adriaens T, Bertolino S, Eschen R, Essl F, Hulme PE, Jeschke JM, Roy HE, Teixeira H, De Groot M (2024) Citizen science is a vital partnership for invasive alien species management and research. iScience 27:108623. https://doi.org/10.1016/j.isci.2023.108623
29. Robertson P, Bishara-Robertson M, Woodburn M, Sanderson R (2026) Evaluating automated acoustic monitoring for the invasive reeve's muntjac deer (*Muntiacus reevesi*): detecting presence, absence and survey design. Biol Invasions 28:168. https://doi.org/10.1007/s10530-026-03890-8
30. Rowcliffe JM, Field J, Turvey ST, Carbone C (2008) Estimating animal density using camera traps without the need for individual recognition. J Appl Ecol 45:1228–1236. https://doi.org/10.1111/j.1365-2664.2008.01473.x
31. Rowcliffe M (2026) CamtrapDensity: Density estimation functions for camtrapDP data. R package version 0.1.16. https://github.com/MarcusRowcliffe/camtrapDensity
32. Schertler A, Tedeschi L, Essl F (2024) Reeves' muntjac *Muntiacus reveesi* (Ogilby, 1839) in Austria. Bioinvasions Rec 13:685–695. https://doi.org/10.3391/bir.2024.13.3.10
33. Schulz B, Borkenhagen P (2021) Muntjaks (*Muntiacus reevesi*) in Schleswig-Holstein – Beginn einer Invasion, erfolgreiche Bekämpfung oder beides ein bisschen? Faunistisch-Ökologische Mitteilungen 10:83–92. https://doi.org/10.38072/2699-7762/p12
34. Segar J, Pereira HM, Baeten L, Bernhardt-Römermann M, De Frenne P, Fernández N, Gilliam FS, Lenoir J, Ortmann-Ajkai A, Verheyen K, Waller D, Teleki B, Brunet J, Chudomelová M, Decocq G, Dirnböck T, Hédl R, Heinken T, Jaroszewicz B, Kopecký M, Macek M, Máliš F, Naaf T, Orczewska A, Reczynska K, Schmidt W, Šebesta J, Stachurska-Swakoń A, Standovár T, Swierkosz K, Vild O, Wulf M, Staude IR (2022) Divergent roles of herbivory in eutrophying forests. Nat Commun 13:7837. https://doi.org/10.1038/s41467-022-35282-6
35. Wäber K, Spencer J, Dolman PM (2013) Achieving landscape-scale deer management for biodiversity conservation: The need to consider sources and sinks. J Wildl Manage 77:726–736. https://doi.org/10.1002/jwmg.530
36. Ward AI, Richardson S, Mergeay J (2021) Reeves' muntjac populations continue to grow and spread across Great Britain and are invading continental Europe. Eur J Wildl Res 67:34. https://doi.org/10.1007/s10344-021-01478-2
37. Wickham H, Averick M, Bryan J, Chang W, McGowan L, François R, Grolemund G, Hayes A, Henry L, Hester J, Kuhn M, Pedersen T, Miller E, Bache S, Müller K, Ooms J, Robinson D, Seidel D, Spinu V,

Takahashi K, Vaughan D, Wilke C, Woo K, Yutani H (2019) Welcome to the tidyverse. J Open Source Softw 4:1686. https://doi.org/10.21105/joss.01686

38. Wohlfahrt S, Balkenhol N, Edelhoff H, Anderwald P, Signer J, Leitner H, Klück P, Schueler S, Langmaier M, Kohlross H, Hackländer K (2025) Exploring the use of REM in compact hunting grounds comparing site specific to average parameters. Eur J Wildl Res 71:34. https://doi.org/10.1007/s10344-025-01913-8
39. Zini V, Wäber K, Dolman PM (2023) Relative influence of inter- and intraspecific competition in an ungulate assemblage modified by introduced species. J Mammal 104:879–891. https://doi.org/10.1093/jmammal/gyad030

Figures

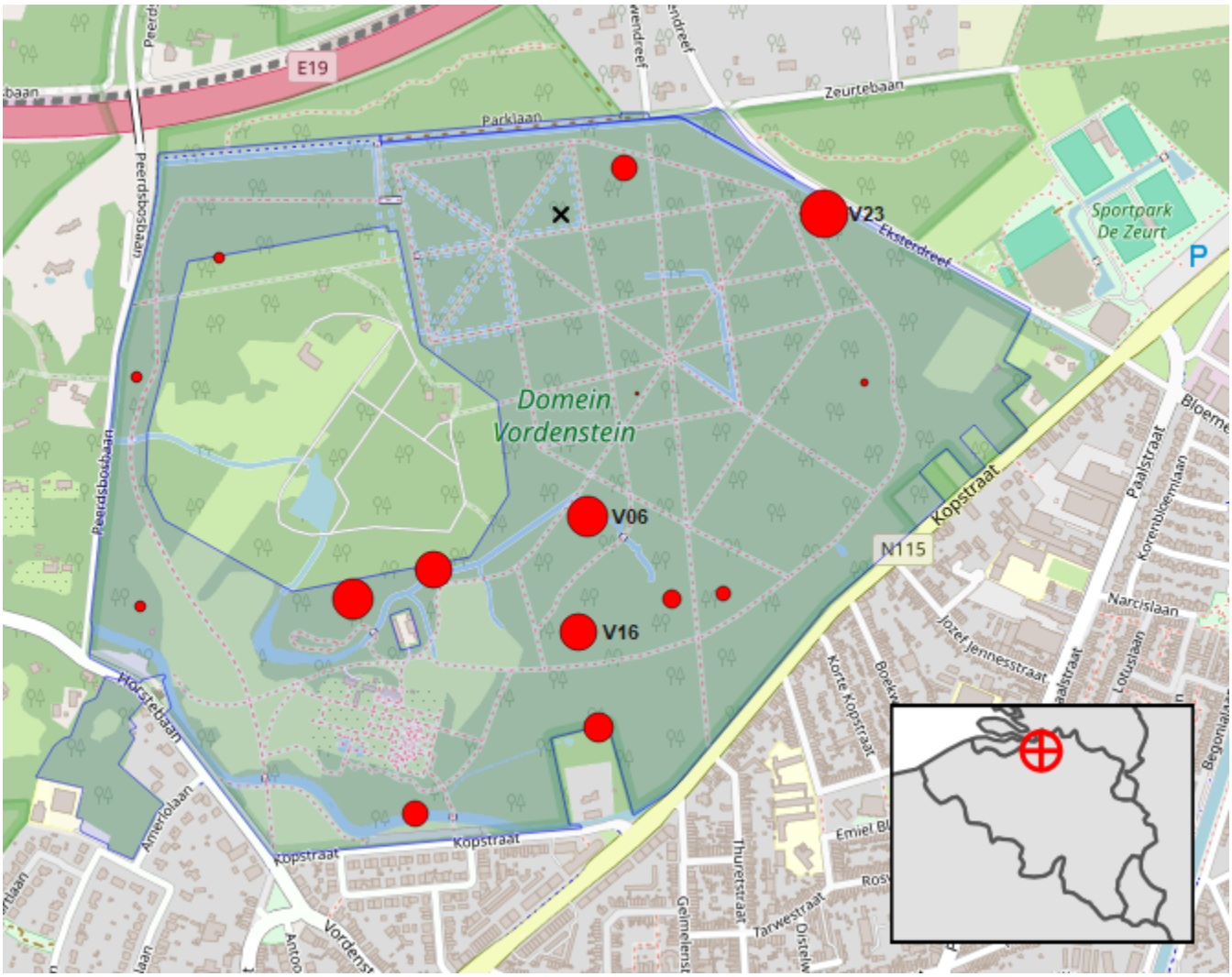


Figure 1

Park Vordenstein, showing the locations of the camera traps. The size of the circles is proportional to the number of muntjac observations (a cross if none). The blue zone represents the area available for the

study, while the inset maps the study site's location within Belgium. Cameras mentioned in the text are labeled. (Background: https://www.osm.org/)

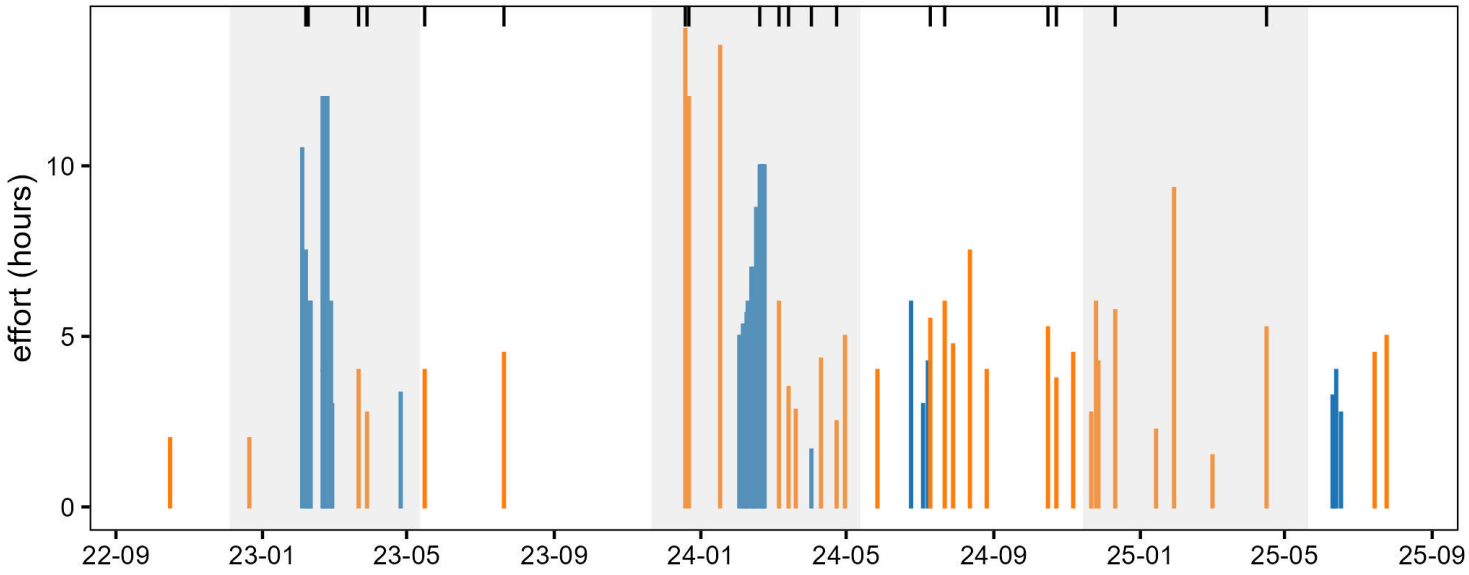


Figure 2

Overview of the daily effort invested in muntjac control in Park Vordenstein, measured in person-hours (September 2022 to August 2025). Blue bars represent shooting from tree stands, while orange bars indicate shooting by car-assisted stalking. Grey bands denote the periods when camera traps were operational. Black ticks along the top indicate muntjac shot

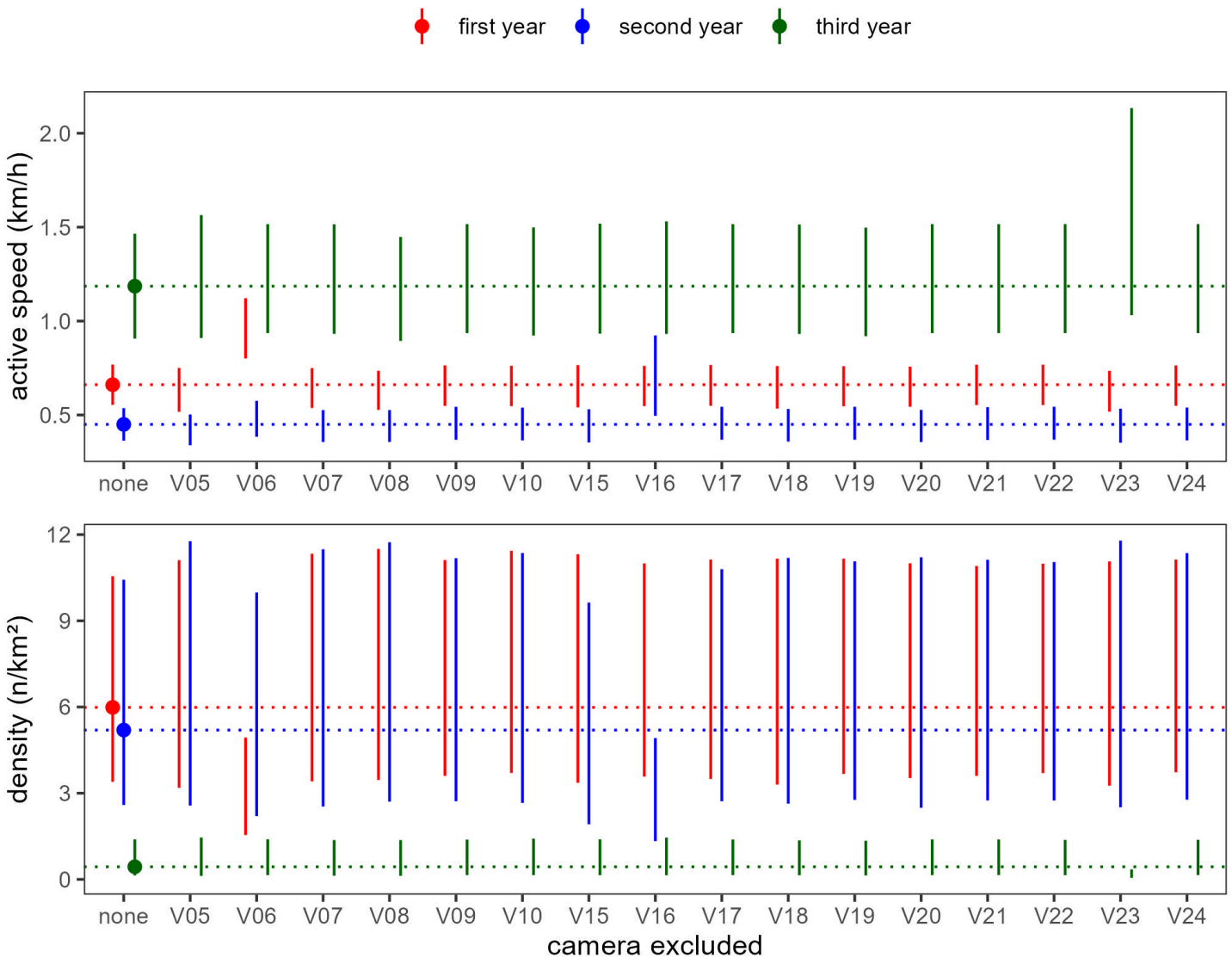


Figure 3

Output of the Random Encounter Model when individual cameras are excluded from the analysis (sensitivity analysis). Upper panel: 'active speed' parameter; lower panel: 'density' parameter. The line segments represent the 95% confidence intervals. The horizontal lines indicate the central estimates from the analysis including all cameras ('none' excluded, cf.Table 2)

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- DhondtSIv260902.docx