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Dog invasions in protected areas: A case study using camera trapping, citizen science and artificial intelligence

Santiago Gutiérrez-Zapata [a,*], Simone Santoro [a], Manuel Emilio Gegundez-Arias [a], Nuria Selva [b,c,d], Javier Calzada [a,b]

[a] Departamento de Ciencias Integradas, Facultad de Ciencias Experimentales, Universidad de Huelva, Huelva, Spain
[b] Centro de Estudios Avanzados en Física, Matemáticas y Computación, Facultad de Ciencias Experimentales, Universidad de Huelva, Huelva, Spain
[c] Institute of Nature Conservation, Polish Academy of Sciences, al. Adama Mickiewicza 33, Kraków 31-120, Poland
[d] Estación Biológica de Doñana, Consejo Superior de Investigaciones Científicas, Seville, Spain

A R T I C L E I N F O

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A B S T R A C T

Domestic dogs, *Canis familiaris*, wandering into natural habitats poses a grave threat to wildlife, increasing predation pressure and disease risk and disrupting the ecological balance within ecosystems. This study examines the presence of dogs in a European Protected Area (PA), Doñana National Park (SW Spain), where their access is strictly restricted, and explores how dog presence relates to potential access points. We utilised classifications provided by citizen science and artificial intelligence, subsequently validated by experts, to detect dogs within 5200,000 photos taken by 60 camera traps randomly deployed across the PA from October 2020 to January 2024. We discovered 33 dogs, primarily in groups of 2–5 individuals, recorded across 31 detection events at 22 camera locations. Dogs were detected ranging from 10 to 42 km^2 (Minimum Convex Polygon) within the PA. The detection probability of dogs increased by 0.22 log odds per kilometre closer to a village (corresponding to an increase from 0.5 to approximately 0.55) bordering the PA and exceeded 0.9 near it. Our data revealed three types of dogs wandering within the PA: dogs accompanying poachers, free-roaming dogs living in nearby human settlements, and stray dogs, most likely relying on the PA resources. Urgent actions are needed in Doñana as dogs pose severe threats to endangered species like the Iberian lynx *Lynx pardinus* (six adult female lynx documented killed by dogs). We recommend raising awareness among local authorities of free-roaming dogs, particularly in settlements close to PAs, where their presence should be banned. Regularly monitoring dog presence within PAs is crucial to prevent invasions and their associated impacts. Our findings underscore the importance of using camera traps and integrating artificial intelligence with citizen science to monitor invasive species effectively.

1. Introduction

In the last decades, the increase in anthropogenic activities has harmed ecosystem functioning through the loss of species and populations (Dirzo et al., 2014). Natural Protected Areas (PAs) play a crucial role in biodiversity conservation by slowing the loss and degradation of habitats, increasing their resilience, and improving the composition and structure of their communities (Barnes et al.,

* Corresponding author.
E-mail address: santiago.gutierrez@dci.uhu.es (S. Gutiérrez-Zapata).

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2023; Soares-Filho et al., 2010). Protected areas are becoming increasingly fragile due to global change. One of the drivers of global change and one of the most severe threats to PAs are invasive species, which can harm native flora and fauna, disrupt ecological processes, and reduce biodiversity (Bellard et al., 2016). Furthermore, the increasing invasion of alien species (Foxcroft et al., 2017; Ren et al., 2021) is widely recognised as one of the primary drivers leading to the loss of native species in ecosystems (Bellard et al., 2016). The spread of invasive species into PAs can significantly compromise conservation efforts' effectiveness and threaten ecosystems' long-term functioning. Therefore, monitoring and controlling their presence is critical to minimise their impact.

The domestic dog, *Canis familiaris*, is the world's most abundant and widespread domestic carnivore species, outnumbering even cats, *Felis catus*, by 1.5 times and exceeding the population of any other wild carnivorous species by at least two-fold (Clark, 2011; Gompper, 2014; Kovacs, 2015). The global biomass of dogs is equal to the combined biomass of all terrestrial mammal species (Greenspoon et al., 2023). Owned, stray, and feral dogs significantly impact animal populations when roaming freely in natural environments. Dogs pose numerous threats to wildlife, including competitive interactions (Home et al., 2018), increased mortality and predation (Merz et al., 2022), resource competition (Wierzbowska et al., 2016), local population extinctions (Lessa et al., 2016), reduction of populations of native species (Zapata-Ríos and Branch, 2018), and genetic diversity reduction due to hybridisation (Leonard et al., 2014). Furthermore, dogs pose severe risks to human health, causing injuries and fatalities through attacks on humans (Biswajeet, 2018), with a worrying increasing trend in the number of fatal dog attacks in Europe in recent years (Sarenbo and Svensson, 2021). Moreover, they transmit diseases such as the Canine Distemper Virus and Canine Parvovirus, which can result in spillover infections and significant mortality in wild carnivore populations (Almberg et al., 2010; Conrad et al., 2021; Kimpston et al., 2022; McDermott et al., 2023). For example, disease transmission by dogs is a major threat to the endangered Ethiopian wolf, *Canis simensis* (Jilo et al., 2023).

To effectively manage the presence of invasive species in PAs, it is necessary to implement regular monitoring and surveillance systems. Camera trap devices, equipped with motion sensors, capture images and videos, enabling monitoring of animals at large scales both regionally and temporally (Kays et al., 2009). While traditionally used for native wildlife, camera traps are increasingly applied to detect and monitor invasive species (Yen et al., 2019). The massive volume of photos generated by camera trapping can overwhelm managers, mainly when dealing with large datasets or studying multiple species simultaneously and when invasive species, still uncommon in the area, must be identified (Fegraus et al., 2011; Swanson et al., 2015). Solutions for photo classification involve the use of citizen science (Green et al., 2020; Hsing et al., 2022) and artificial intelligence tools such as convolutional neural networks (Norouzzadeh et al., 2018; Tuia et al., 2022). Citizen science projects enlist volunteers to label camera trap images, enhancing data processing efficiency by rapidly and accurately identifying species captured (Swanson et al., 2016; Townsend et al., 2021). On the other hand, convolutional neural networks demonstrate high efficiency in classifying photo-trapping images due to their ability to learn and recognise species within images (Brodrick et al., 2019; Norouzzadeh et al., 2018). Moreover, citizen science can aid in training artificial intelligence, facilitating the acquisition of reliable, near real-time information on invasive species presence (Aota et al., 2021; Green et al., 2020).

In this study, we investigated dog invasion in one of Europe's most important PA, Doñana National Park, in Southwestern Spain, which provides crucial habitat for numerous endangered species within the European Union's protected area network (Natura 2000). We used camera traps and a combination of citizen science and convolutional neural network technology for image classification. We aimed to (1) assess the extent and magnitude of dog presence in the PA and (2) determine how nearby human settlements, roads and habitats affect the occurrence of dogs in the PA. Additionally, we examined the dogs in the images in detail for collar presence, health status, grouping behaviour, and whether people accompanied them. We hypothesised that dogs' presence would be more likely close to the PA boundaries, particularly with settlements.

2. Methods

2.1. Study area

The Doñana National Park, situated at the mouth of the Guadalquivir River Basin in SW Spain, is a PA of outstanding importance in Europe. Doñana is a protected site under the European Union's Natura 2000 network, with dual designations as a Special Protection Area and a Special Area of Conservation. It is a UNESCO Biosphere Reserve, a RAMSAR site, and a UNESCO World Heritage Site. Agriculture and hunting are banned in the Park, while activities related to tourism, cattle breeding, and shell fishing are permitted. However, they are subject to regulations and restrictions that ensure their compatibility with the conservation of ecosystems. People's entrance to the Park is restricted and only allowed at specially designated visitor centres or on guided tours. Pets, including dogs, are not permitted within the Park boundaries under any circumstances. During the last decades, climate warming and intensive agriculture in its surroundings have seriously endangered Doñana National Park by exacerbating wildfire risks, altering habitats, causing habitat loss, water pollution, and changes in hydrological patterns (Navedo et al., 2022).

The PA predominantly consists of (1) marshland habitats spanning 28,000 ha, dominated by species such as bulrushes (*Bolboschoenus maritimus* and *Schoenoplectus litoralis*), glasswort (*Arthrocnemum macrostachyum*), and common woodrush (*Juncus subulatus*); (2) 7000 ha of beaches and dunes that support stone pine forests (*Pinus pinea*) and juniper bushes (*Juniperus macrocarpa*): and, (3) Mediterranean scrublands, covering 19,200 ha, characterised by a dense thicket of *Halimium halimifolium*, heathers (*Erica sp.*), and gorses (*Ulex sp.*), interspersed with scattered trees such as cork oaks (*Quercus suber*), junipers (*Juniperus phoenicea*), and wild olive trees (*Olea europaea*).The scrubland presents a patchy, diverse landscape, while the marshland remains flooded for part of the year (Serrano Martín et al., 2006). The medium and large mammal community includes three species of ungulates (red deer, *Cervus elaphus*; fallow deer, *Dama dama*; and wild boar, *Sus scrofa*), five species of carnivores (Iberian lynx, *Lynx pardinus*; red fox, *Vulpes vulpes*; European badger, *Meles meles*; Egyptian mongoose, *Herpestes ichneumon*; and genet, *Genetta genetta*), and two species of lagomorphs (Iberian hare, *Lepus granatensis*; and European rabbit, *Oryctolagus cuniculus*). Additionally, cattle and horses are allowed in the Park. The study was conducted in all habitats except marshlands or flooded areas (Fig. 1).

The protected area (PA) is currently uninhabited, with only two settlements near its borders. El Rocío is a traditional village with an area of approximately 1.8 km^2 and a population of about 1500 residents. Its economy relies on agriculture, livestock, and the renowned pilgrimage, which attracts nearly one million participants who cross the Doñana National Park with caravans and horses during spring. Matalascañas is a coastal town primarily depending on beach tourism. It covers an area of about 3.9 km^2 and has a population ranging from 2500 residents in the off-season to up to 100,000 during the summer. In Andalusia, there is an average of 0.26 microchipped dogs per inhabitant (Regional Government of Andalusia, 2023a), translating to an estimated 390 dogs in El Rocío and between 649 and 25,973 in Matalascañas during winter and summer, respectively. However, because microchipping is still uncommon in Spain and there are no estimates for stray or feral dogs, the number of dogs in these settlements is likely higher than official statistics. Additionally, dog management practices probably differ between El Rocío and Matalascañas, with residents of the former more likely to allow their dogs to roam freely.

The western boundary of the PA is a 15-kilometre road that connects both settlements and is delimited by a 2 m high single-twist steel mesh fence. The fence runs along the Park boundary, also in its limit with Matalascañas. Wildlife has restricted access to the PA from the south and east by the Atlantic Ocean, the Guadalquivir River, and the marshlands, at least during the winter and spring months when the wetland is flooded (Fig. 1). Despite the road being fenced off and the marsh flooded half the year, dogs can move through if the fence is damaged or the marsh is dry or partially flooded.

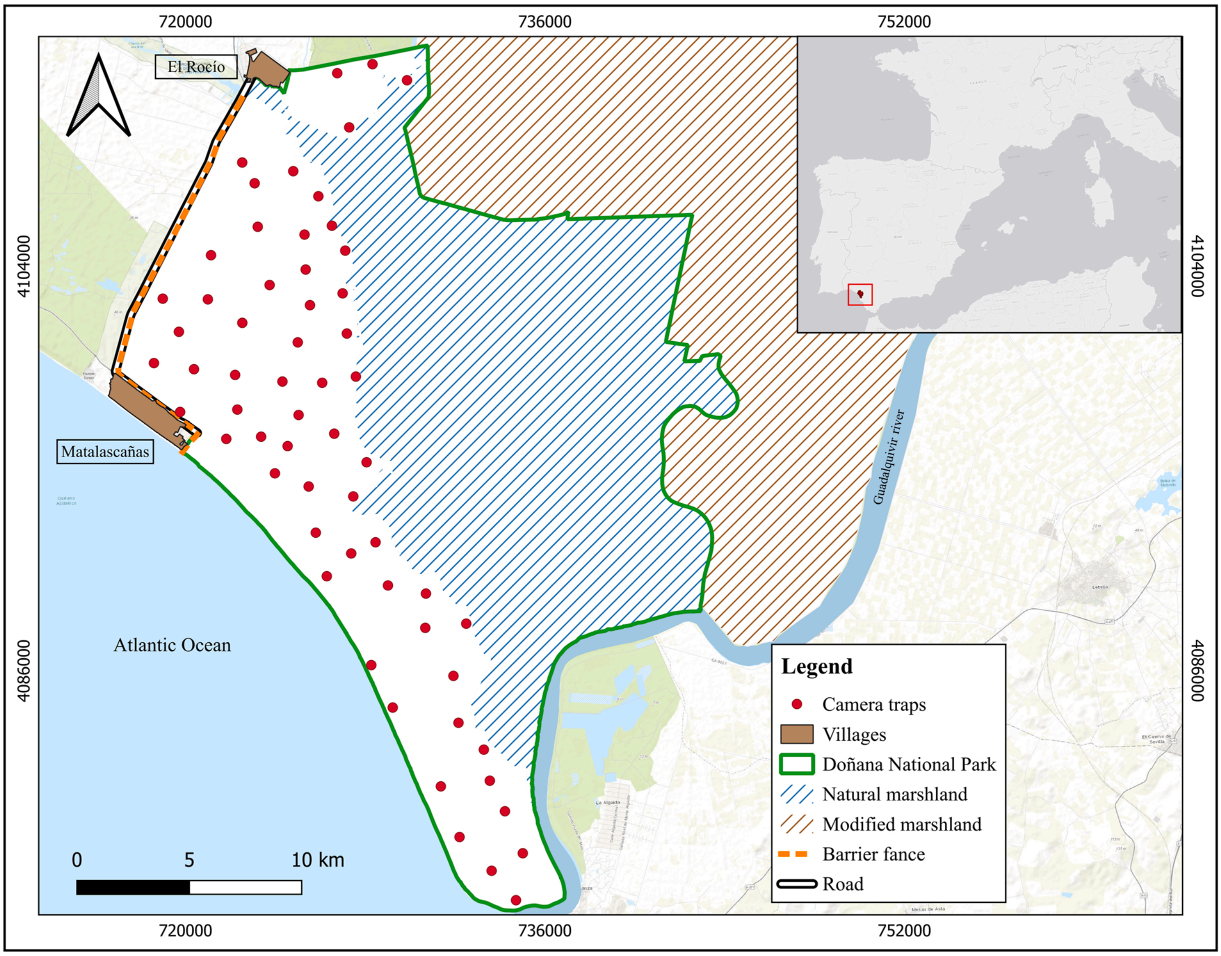

Fig. 1. Doñana National Park (limits as a green line), showing the study area (the non-flood zone in white) and the camera trap locations (red dots; n = 60). Nearby settlements are indicated in brown. The Atlantic Ocean bounds the study area to the southwest and the Guadalquivir River and its marshlands to the east, preventing or hindering wildlife access from those directions. Additionally, a single-twist steel mesh fence (orange dotted line), 2 feet high, isolates the road between the two settlements and prevents wildlife from entering the Park from the west.

2.2. Field study and image data collection

Data collection took place from October 2020 to January 2024. We used the *Create random points* tool in ArcGIS Pro™ 3.1 to randomly place 38 non-glow camera traps (Browning: Dark OPS Pro DCL, Dark HD Pro X) within the non-flood zone of the protected area (PA) between October 2020 and June 2022. Starting in January 2023, we increased the number of cameras to 60, following a random design. The minimum separation between neighbouring cameras was 1 km. The cameras were installed on a stake 50 cm above the ground and programmed to take three images per burst with a one-second time-lapse between consecutive bursts. Over the study period, we collected 5193,371 images.

2.3. Dog detection and identification

The project was authorised by the General Directorate of Natural Environment, Biodiversity and Protected Spaces of the Regional Government of Andalusia, Spain. The necessary permits were issued by the authorities of the National Park. Out of the total number of images collected, we collated image data of detected dogs by the camera traps following two complementary approaches:

(i) Citizen science: we created a project on the Zooniverse platform (https://www.zooniverse.org/projects/aicensusuhu/iberian-camera-trap-project). For each event —defined as a sequence of consecutive photos from the same camera trap taken within 2.5 minutes of each other— a maximum of five randomised photos (n = 1309,377) were uploaded to the platform. We asked participants to classify them into predetermined categories, including the livestock species (horses and cows) and all the medium and large-size wild mammals of the PA. Volunteers in the citizen science project were not formally trained to classify species. Instead, we provided them with a field guide, reference images, and warnings about similar species to assist with classification. Initially, dogs were not included in the predetermined categories because we did not expect to have them in the photos. However, after volunteers first noticed dogs in the photos and alerted us, we requested that they notify us each time they spotted one.

(ii) Artificial intelligence: we developed a convolutional neural network classification model using the EfficientNet-B5 architecture for optimal performance and resource efficiency (Tan and Le, 2019). We trained the model to classify 18 distinct classes: 12 mammal species (including domestic dogs), four taxonomic groups, and empty images and human classes. The training utilised a dataset of 390,208 images for training and 7200 for validation, with 400 samples evenly distributed across all classes. We employed transfer learning techniques, leveraging pre-trained weights from the ImageNet dataset, which expedited learning and convergence (Pan and Yang, 2010; Russakovsky et al., 2015; Torrey and Shavlik, 2009). Additionally, we employed data augmentation methods to bolster the model's robustness (Shorten and Khoshgoftaar, 2019). To rectify class imbalances, particularly in the minority class (dog class), we randomly sampled 1160 images per class at each training epoch.

After obtaining image classifications from both sources, we conducted expert verification (by JC, SS, and SGZ) to confirm the presence of dogs in the images. From the photos, we extracted the date and time of the event and the number of dogs in the pack. We identified each dog based on morphological characteristics and tagging devices like collars. We also examined the images for visual indicators of each dog's apparent health status, such as severe thinness indicating malnutrition, mange spots on the coat, or wounds. Additionally, we observed whether the dogs were accompanied by people and the behavioural responses of other species, such as fleeing, captured within five minutes before and after the dogs were detected. Based on Van't Woudt (1990), we categorised dogs into three groups: 1) free-roaming dogs, animals with an owner in nearby settlements but free to roam freely; 2) stray dogs, which have no home or owner and depend on both the natural environment and human settlements for food and shelter; and 3) feral dogs, which survive and breed in the wild without any human assistance.

2.4. Statistical analyses

We utilised generalised linear models (GLMs) with a binomial family to assess whether the presence of dogs was influenced by the minimum distance of each camera site to the possible access points: the bordering settlements (Matalascañas and El Rocío), the road and the marshland. We did not model temporal variation due to insufficient data on this gradient.

Our analysis used the presence or absence of dogs at each camera location as the response variable. "Presence" indicated dog detection during the study period (between October 2020 and January 2024), while "absence" meant no detection. We evaluated species presence or absence at the detection event level, defining a new detection event as two photos of dogs taken at least 30 minutes apart (Monterroso et al., 2014). The sole predictor in the GLM was the minimum distance from each camera site to four potential access points: the two settlements (El Rocío and Matalascañas), the marshland, and the road. Records of dogs accompanied by humans (n = 2) were excluded. We used the *simulate Residuals* function in package DHARMa (Harting, 2022) to assess model assumptions, particularly variance homogeneity and normality, by comparing simulated and observed residuals. Using an information-theoretic approach, we evaluated the association between dog detection and distances to potential access points (Burnham and Anderson, 2002), comparing each model's AICc (Akaike Information Criterion adjusted for small sample size) with the lowest value.

We utilised the timestamp of the first image from each dog detection event to estimate diel activity patterns using nonparametric Kernel density plots (Ridout and Linkie, 2009). We initially intended to consider only events with a separation of more than 30 minutes (Meek et al., 2014); however, we never observed multiple events involving dogs in a single day at any camera location. Since daylight hours vary considerably throughout the year in the study area, we applied a double-anchor transformation to our detections to link the activity to average sunrise and sunset times (Vazquez et al., 2019) using the *activity* package (Rowcliffe, 2023).

Furthermore, we used the convex hull polygon (the polygon of the minimum perimeter that contains all observations of an individual dog), applying the *st_convex_hull* function from the *sf* package (Pebesma, 2018) to estimate the minimum surface area over which each dog has been roaming when the same individual was recorded in three or more sites (two dogs were detected in four sites and one in seven sites). All analyses were conducted in R (version 4.3.3, R Core Team 2024). The R code is available in a public repository.

3. Results

We identified 31 detection events of dogs (Fig. 2a) across 22 camera-trap sites, with up to five individuals found at single sites throughout the study period (Fig. 2b). The occurrence of dogs in the PA varied throughout the sampling period. The number of dog detection events varied monthly from 0 to 8 (Appendix – Fig. A1). The highest number of individual dogs detected in a single year was nineteen. Notably, over half (51.7 %) of the detections involved dogs in packs of 2–5 individuals. We identified thirty-three adult dogs: eighteen were uncollared, and fifteen were collared.

On two occasions, we observed dogs accompanied by humans. One case involved five poachers (identified by unmistakable signs of hunting activity) and a pack of five hounds (Fig. 3a), while the other involved a man just walking his dog without obvious signs of poaching intentions. We also noticed one malnourished dog (Fig. 3e) and two dogs wearing sophisticated GPS collars, bells and other devices, which are common among hound pack dogs (Fig. 3b). In one case, camera traps documented a red deer fleeing from a dog (Fig. 3c-d).

The number of individual recaptures for the same dog ranged from 0 to 8. The longest time between detections of the same dog inside the PA was 272 days. We estimated the minimum roaming areas for three dogs recaptured in at least three camera traps as 9.6 km^2, 11.4 km^2, and 41.6 km^2, respectively (Appendix – Fig. A2).

According to AIC_c, the top model linked detection probability to the distance to one of the two bordering settlements (El Rocío), explaining 34.4 % of the deviance and showing an Akaike weight close to 1. In contrast, the proximity to the other access points (Matalascañas, marshland and the road) did not receive comparable AIC_c support (Table 1).

We found that dog detection probability increased with proximity to the El Rocío, the traditional village ($\beta = -0.22$, $P < 0.01$; Fig. 4). The predicted probability of detecting a dog in one of our camera traps during the study period was notably high, reaching 0.78 or higher when the distance from El Rocío was less than five km (the farthest point in the PA is approximately 40 km away from this village).

Regarding their activity pattern, dogs are more active within the PA during the day (≈ 08:00 – 17:00) than at night (≈ 19:00 – 05:00). Activity shows two peaks: one in the morning and another in the afternoon, with the morning peak being more pronounced (Fig. 5).

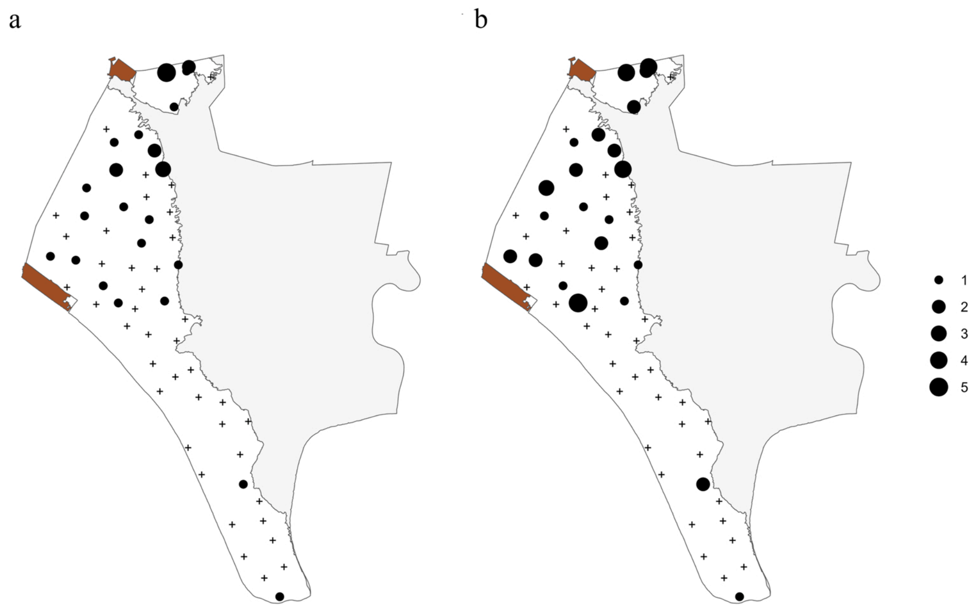

Fig. 2. Number of dogs' detection events in Doñana National Park (A) and individuals (B) captured at each camera-trap site over the study period. The size of the black dots indicates the number of events or individuals, while the crosses represent camera-trap sites without dog records.

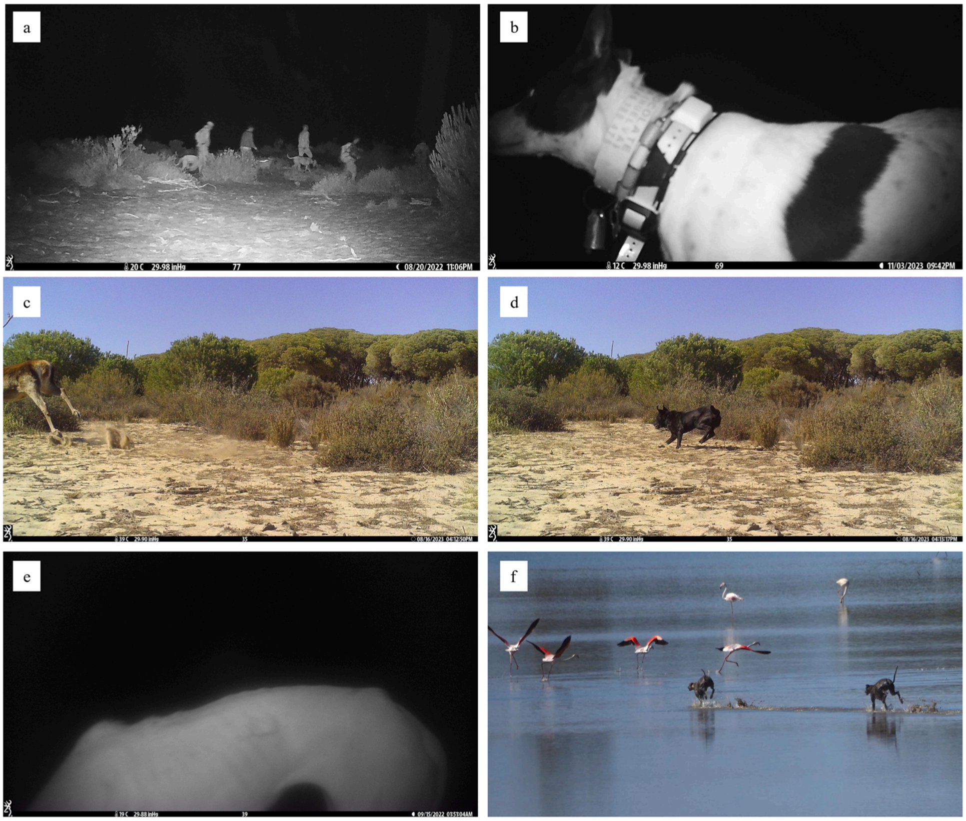

Fig. 3. Dogs within Doñana National Park: (a) a pack of dogs accompanying poachers; (b) a tracking hound wearing devices used for hunting; (c) and (d) successive snapshots showing a dog chasing an adult red deer; (e) a dog exhibiting signs of malnutrition; and (f) dogs entering the protected area via the marshes during low water levels, and pursuing a group of flamingos. All photographs were obtained using the camera traps set in this investigation, except for 5 f (photo credit: Ko Dieleman, 01/03/2023).

Table 1
Model selection for the generalised linear model analysis of dog presence depending on one of the following predictors: minimum distance to El Rocío (*dist_rocio*), minimum distance to Matalascañas (*dist_matalascañas*), distance to the nearest settlement, either El Rocío or Matalascañas (*dist_settlement*), distance to the marshes (*dist_marshes*), and distance to the road (*dist_road*). Notation: *K*, number of parameters; AIC_c, AIC for small sample size; ΔAIC_c, AIC_c difference with the best model; w_i, Akaike weights.

Model	K	Deviance	AIC_c	ΔAIC_c	w_i
Presence ~ dist_rocio	2	62.26	66.44	0	0.99
Presence ~ dist_road	2	94.96	80.56	14.11	0
Presence ~ dist_settlement	2	79.5	83.68	17.24	0
Presence ~ dist_marshes	2	94.66	98.84	32.4	0
Presence ~ dist_matalascañas	2	76.38	99.14	32.7	0

4. Discussion

This study employed artificial intelligence and citizen science classification of camera trap photos to reveal domestic dog invasion patterns in Doñana National Park, one of Europe's most significant protected areas. Our approach has proven effective in identifying key patterns and access points for dog invasions, highlighting El Rocío, the traditional village, as the primary source of these incursions. In contrast, the influx from Matalascañas, the coastal town, was minimal. The number of dogs entering the PA does not correlate with the number of owned dogs in these settlements, reflecting differing dog management practices between the two areas. More than half of the dogs were observed in packs of 2–5 individuals, with their presence in the PA being extensive both spatially and temporally, covering territories up to 41.6 km^2 and detection periods extending up to nine months. Targeted strategies are urgently needed to protect protected areas from domestic dog invasions. Integrating artificial intelligence and citizen science classification of camera trap photos can raise public awareness of these invasions and inform evidence-based conservation and control measures.

Our findings highlight an urgent conservation issue: the growing global dog population poses significant risks to biodiversity and protected areas (PAs) (Abdulkarim et al., 2021; Doherty et al., 2017). Dogs threaten biodiversity conservation worldwide,

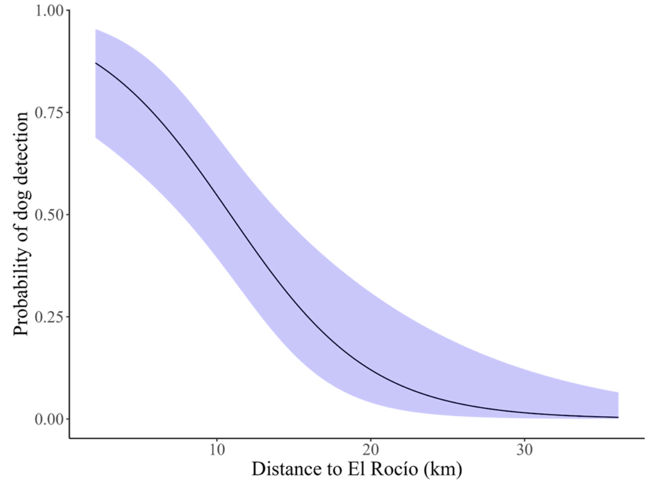

Fig. 4. Trend in the probability of dog detection relative to the distance to El Rocío, a traditional village adjacent to Doñana National Park. The dark line represents the mean probability, and the shaded bands indicate the 95 % confidence intervals.

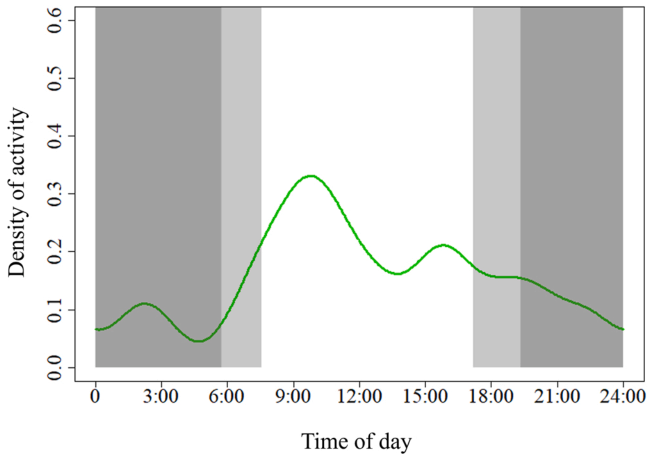

Fig. 5. Diel activity pattern (density estimates of the daily activity patterns) of domestic dogs within Doñana National Park, as inferred from camera traps. The activity pattern is presented in average anchored time. The light grey zones indicate the range of sunrise and sunset variation across the year, while the white and dark grey zones indicate the daylight and the night periods, respectively.

underscoring the need for enhanced monitoring and management efforts to address these challenges effectively (Hughes and Macdonald, 2013; Weston et al., 2014). Doherty et al. (2017) revealed domestic dogs have caused 11 vertebrate extinctions and threaten 188 endangered species globally. Moreover, they found that living in a PA does not guarantee safety for vulnerable species. This may be the case in Doñana National Park, of crucial importance for the endangered Iberian lynx, *Lynx pardinus* (López-Parra et al., 2012), a species sensible both to dog predation (Agencia EFE, 2018, 2023) and disease transmission (Millán et al., 2009). There have been six documented instances of lynx fatalities due to dog attacks in the Doñana area, with all cases concentrated in the proximity of El Rocío, the village our study identified as the primary source of dog invasions in the Park. Of the six lynx killed by dogs, all were adult females, which is particularly concerning given their critical role in population viability and persistence. Two were killed while defending their kittens, and one died of canine distemper (J. Salcedo, personal communication)

To mitigate the negative effects of dogs in protected areas, it is crucial to address the deficiencies in legislation regarding free-ranging dog management and responsible ownership (Lambertucci et al., 2024). A few rules for responsible pet ownership are beginning to be established in European and national animal rights legislation. For example, the Spanish law for the protection of the rights and welfare of domestic animals (Ley 7/2023, de 28 de marzo, 2023) expressly prohibits dog abandonment and leaving animals loose or in a condition to cause damage in public places, particularly National Parks or other PAs where they can harm the natural environment. Furthermore, dog owners are legally accountable for any environmental damage they produce. At the European level, the European Commission's new proposal for rules on the welfare of dogs and cats and their traceability (European Commission, 2023) is less specific, stating only that dog sellers must inform customers about responsible ownership, which includes the owner's responsibility to prevent threats that the dog may pose to the environment. As is appropriate, animal rights legislation focuses on the well-being of companion animals rather than the impact they may have on biodiversity and ecosystems if abandoned and become invasive in the environment. Conversely, stray and feral dogs, which lack owners and where responsible pet ownership is not possible, should be considered invasive alien species and managed according to the relevant legislation (e.g., European Union, 2014).

Management plans for Natura 2000 sites must address potential dog invasions, an often overlooked conservation issue. Our findings indicate that unwanted species access to protected areas is critical in spreading invasive species (Guerra et al., 2018). Our study identified the primary source of dogs entering the Park and indicated a hotspot of occurrence that could help rangers identify entry points, which is crucial for designing mitigation measures. Existing pet ownership regulations within and near protected areas should be strictly enforced, with fines or penalties for violations to deter irresponsible behaviour. Managers should clearly communicate prohibited activities to the public, as the lack of accessible and transparent information affects awareness of the problem (Zamora-Nasca and Lambertucci, 2023). Clear regulations and education programmes help raise awareness among local communities about the negative impact of unleashed dogs on natural ecosystems. Management strategies require an effective detection system, such as the one proposed in this study. Additionally, fencing sensitive areas and establishing regular dog vaccination campaigns in neighbouring areas are crucial to mitigate the impact and potential disease transmission to wildlife.

Regularly monitoring their presence is a crucial step to halt the increasing dog invasion in many protected areas. Camera trapping offers several benefits compared to other monitoring techniques, such as track detection. Our findings partially align with Soto and Palomares (2015), who studied the presence of dogs in the same PA by footprint censuses 15 years ago. They did not detect dog tracks at significant distances from human settlements, suggesting owned free-roaming dogs making forays in the Park. Furthermore, they suggested that the dogs entering the Park were not feral, as they found only isolated tracks, which contradicts the typical behaviour of feral dogs forming packs (Daniels and Bekoff, 1989; Green and Gipson, 1994). Our study recorded dogs all over the PA, often in packs and without identification collars, indicating that some may be stray or feral. However, we failed to photograph dog cubs for this study, and a dog breeding population has never been documented in the National Park annual reports (Regional Government of Andalusia, 2023b). Thus, there are probably no fully feral breeding dogs in the Doñana National Park at present. The differences with the study by Soto and Palomares (2015) may be partly due to our more effective sampling protocol, which covered a larger sampling area for a longer time, thus improving detection and providing more precise information than track surveys. Other benefits of our sampling protocol include more effective and timely species detection and information on activity patterns and behaviour (such as dogs in packs or solitary) and conditions (such as health status and presence of humans).

Understanding dogs' entry dynamics into PAs is crucial for implementing effective control measures and mitigating potential conflicts between dogs and wildlife. Moreover, using camera traps has proven a powerful tool for engaging citizen science efforts and raising public awareness of dog invasions in PAs. It is important to note that current data collection involves manual processes conducted at regular intervals (e.g., battery replacement and monthly SD card retrieval). As Santoro et al. (2022) suggested, a potential advancement would be the deployment of wireless cameras on PAs capable of transmitting images instantly via GSM to a server. The server would then utilise an AI network to classify the images and deliver real-time alerts to managers of target species, such as invasive or of particular conservation concerns. Additionally, integrating camera traps with solar panels as an alternative energy source has proven to be a promising option for achieving energy independence (Barros et al., 2024). Indeed, as wireless camera traps become increasingly advanced and affordable, there is growing potential for real-time monitoring initiatives within the Natura 2000 network (Kissling et al., 2024).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data and the R code to reproduce this analysis can be found on the following GitHub repository: https://github.com/SantiagoGutierrezZ/Dog-invasions-in-Protected-Areas.git

dataDogsInvasions (Original data) (GitHub)

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Appendix

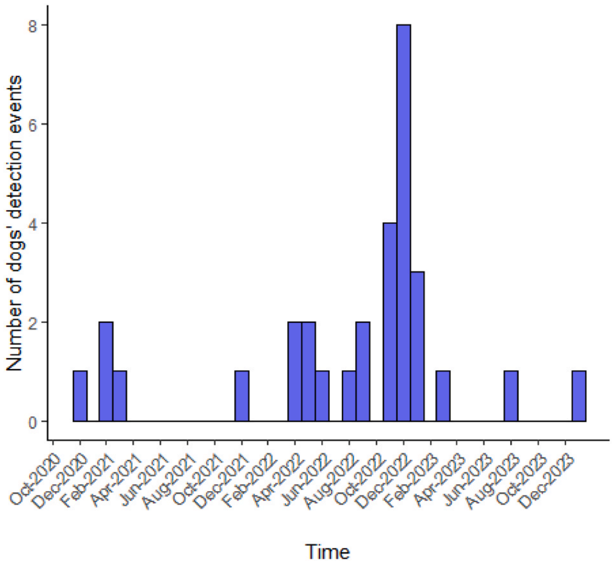

Figure A1. Temporal distribution of dogs' detection events in Doñana National Park. Between October 2020 and June 2022, we randomly place 38 non-glow camera traps. Starting in January 2023, we increased the number of cameras to 60, also randomly deployed. The minimum separation of neighboring cameras was 1 km. Images are considered to belong to different events if they are separated by a minimum of 30 minutes. One detection was recorded in 2020, four detections in 2021, twenty-two detections in 2022, and one detection in 2024. Seasonally, the detections were distributed as follows: fifteen in autumn, seven in winter, five in spring, and four in summer.

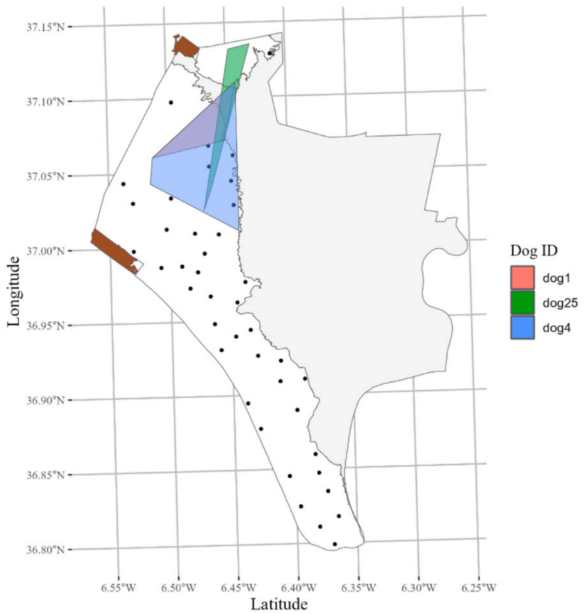

Figure A2. Roaming areas of dogs within the Doñana National Park. Convex hull polygon (the polygon of minimum perimeter that contains all individual dog observations). Minimum convex polygon was estimated for the individuals captured in at least three camera traps: dog1 = 11.4 km^2, dog25 = 9.6 km^2 and dog4 = 41.6 km^2.

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