Ecological Informatics 80 (2024) 102487

Contents lists available at ScienceDirect

Ecological Informatics

journal homepage: www.elsevier.com/locate/ecolinf

Impact of topographic factors on animal field pathings: Analysis and prediction of deer movement patterns

José M. Valderrama-Zafra [a,*], Miguel A. Rubio-Paramio [a], Diego Francisco Garcia-Molina [a], Jorge Manuel Mercado-Colmenero [a], Antonia Oya [b], Rafael Carrasco [c], Concepción Azorit [c,*]

[a] Department of Engineering Graphics Design and Projects, University of Jaén, Spain
[b] Department of Statistics and Operational Research, University of Jaén, Spain
[c] Department of Animal Biology, Plant Biology and Ecology, University of Jaén, Spain

ARTICLE INFO

Keywords:
Animal movement patterns
Topographical factors
Computer graphics
Wildlife management and conservation

ABSTRACT

Understanding and tracking the complexities of animal movement patterns is of paramount importance in wildlife management, conservation efforts, and the sustainable use of natural resources. An infinite number of factors influence the movement path of animals within their respective habitats, including: the structure of the habitat, the availability of resources, the presence of natural predators, social memory, the topographic attributes of the environment, etc.

Numerous studies have attempted to delineate the spatial boundaries of animal habitats by elucidating the complexities of their movement dynamics. These investigations have highlighted the profound impact of factors such as environmental topography and the presence of natural impediments and other anthropogenic structures on animal mobility, but very few have analyzed topographic factors at a fine three-dimensional spatial scale.

This research focuses on a novel methodology for identifying animal trajectories at a fine scale and evaluating the influence of topographic factors on these trajectories, specifically of deer herds in southern Spain. To understand movement patterns, transects recorded in the field due to continued use by deer are analyzed. Topographical information was obtained in two steps: first with a graphical analysis of orthophotos for the incorporation of the sufficient data set. Secondly, the veracity of this data was verified using Global Positioning System (GPS) tracking technology. The integration of data from multiple sources with Geographic Information Systems (GIS) allowed the analysis to be automated. Next a statistical linear regression model, based on both the ascent and descent lengths and the total length of the path traveled, was designed to infer the trajectories between two designated points within the study area. Using topographical variables obtained in the study environment, such as the slope, the elevation difference (cumulative vertical distance), and the 3D length of the transect paths, the influence of these variables on the movement decisions of animals within their habitat is established in order to facilitate their subsequent prediction.

Analytical tests of the trajectories have shown that the movement behavior of cervids is predictable. The results demonstrate the usefulness of the methodology presented which, by providing and collect valuable topographic information on movement and transit areas, can guide sustainable management practices for deer populations and their habitats.

1. Introduction

The study and analysis of animal movement trajectories constitutes a fundamental task in the realm of wildlife management and conservation. An array of factors governs the definition of these trajectories, intertwining with the dynamics of both the animals themselves and their habitats. Among these factors are the topographic attributes of the terrain, the resource availability within the environment, the structural composition of the habitat, the enduring influence of social memory embedded within animal communities, and the presence of natural predators. Previous research studies have established the animal habitat ranges based on the complexity of their locomotion within these domains. Among the factors that most influence habitat demarcation the most important are topographic factors, as stated by Lempidakis et al.

* Corresponding authors.
E-mail address: jmzafra@ujaen.es (J.M. Valderrama-Zafra).

https://doi.org/10.1016/j.ecoinf.2024.102487
Received 3 October 2023; Received in revised form 15 January 2024; Accepted 17 January 2024
Available online 19 January 2024

(2018), Zonneveld (1995), and Wiens and Moss (2005), since the terrain difficulties could condition the animals during their movements. Furthermore, natural obstacles, including rivers, lakes, ravines, roads, buildings, and other anthropogenic structures, exert influences upon animal locomotion, often manifesting as insurmountable barriers, as observed in the work of Panzacchi et al. (2016). Concurrently, the interplays within the purview of vegetative cover and environmental heterogeneity should be evaluated, aspects explored by Shepard et al. (2013), Masello et al. (2017) and Kauffman et al. (2021), showing their substantial roles in shaping animal movement patterns. Complementing these terrain-based investigations, certain studies pivot towards the realm of animal cognition, showing how social or individual memory influences the selection of trajectories at different spatial scales. Along these lines are the studies developed by Spencer (2012), Schlägel and Lewis (2014), Guo et al. (2019), which examine the effects of spatial memory and dynamic information in guiding the movement decisions of animals.

On the other hand, the availability of resources emerges as a crucial factor related to the movement patterns of animals. Kauffman et al. (2021) focus on resource tracking and the ecological facets, determining the mechanisms governing such patterns. Complementing this concept, Kenward et al. (2018) performed a research study on the impact of natural predators on animal movement dynamics, uncovering their role as agents of influence. In tandem, Masello et al. (2017) delve into the multifaceted aspects surrounding migration, determining the causative agents, consequences and conservation implications of large-scale animal movements.

Animal trajectories, considered within the heterogeneous landscapes they cross, expose individuals to various environmental elements that may positively or negatively impact long-term processes like reproduction and survival (Edelhoff et al., 2016). At a broader scale, emergent spatial processes and patterns are all influenced by the movement decisions of animals (Seidel et al., 2018). In the field of movement ecology, many studies have been conducted regarding the metrics of space use by individuals, e.g. home ranges, proximity/social networks, and selection functions (Cumming and Cornélis, 2012; Lele et al., 2013 and Pinter-Wollman et al., 2013).

In environments free of natural or artificial impediments, animal movements are mainly governed by fundamental needs such as food, shelter, hydration or other essential requirements (Abrahms et al., 2021; Kauffman et al., 2021). Within such contexts, the ground-level routes may offer myriad possibilities. However, the overarching principle guiding these movements appears to be the minimization of energy expenditure or movement trajectories with lower slopes and unevenness as no factor appears to supersede this objective.

Aspects such as energy consumption and its relationship with the slope (Anjitha Krishna et al., 2019), the roughness of the terrain (Korzeniowska et al., 2018) and elevation (Wangdi et al., 2019) significantly influence the behavior of their movements. In this area, other studies focused on topographic factors in order to determine the movement patterns. Shepard et al. (2013) showed the fundamental role of energy landscapes in sculpting the ecological facets of animal locomotion, while Lachica and Aguilera (2000) estimated the energetic costs associated with the locomotion of the Iberian pig based on various movement behaviors. Additionally, Lachica et al. (1997) carried out exhaustive investigations on energy expenditure over different slopes on Grenadine goats (*Capra hircus*), evaluating the impact of terrain topography on energy consumption.

In recent years the field of wildlife monitoring has undergone a profound transformation, propelled by remarkable technological advancements and data analysis techniques. Presently, the advent of cost-effective, long-lasting GPS tracking technology (Riotte-Lambert and Matthiopoulos, 2020) has ushered in a new era where data can be garnered with increased frequency and uninterrupted precision (Fernández-Rodríguez et al., 2023), thereby affording a more comprehensive quantification of animal mobility. Furthermore, there has been a notable evolution in the analysis of cervids movement trajectories, transitioning from two-dimensional (2D) to three-dimensional (3D) modeling, enhancing precision and accuracy, and optimizing wildlife management strategies, as emphasized by Valderrama-Zafra et al. (2022).

The use of these technologies, including the current GNSS devices, allows its application in the fields of ecology and biology (Garrido-Carretero et al., 2023).

There are other technologies that allow an analysis of the trajectory of animals at a fine scale. Methodologies based on camera or video camera trapping (Klasen and Steinhage, 2022) allow us to obtain even 3D trajectories at a close scale. In controlled environments, other technologies such as Bluetooth can be used (Morita et al., 2020).

As Seidel et al. (2018) exposed, there are also several special publications in the GIS community regarding quantitative movement analysis and spatial ecology (Dodge et al., 2016; Laffan et al., 2012, 2014, 2016; Skidmore et al., 2011). Despite these domain-specific reviews and broader special publications, an exposition that provides a broad overview of metrics and tools used to analyze animal movement data is still needed.

Laube and Purves (2011) conducted some research work with tagging animals with GPS devices and collected data of less than a second in order to investigate issues of scale, granularity and uncertainty in evaluating movement parameters. According to Seidel et al. (2018), the results of this study should be of great interest to ecologists, who typically collect fixed data much more space-time apart and then invoke a straight-line assumption about the nature of paths between any two consecutive points in their data or assume Gaussian diffusion, often relying on a Brownian bridge method to construct probable trajectories between such points (Horne et al., 2007). At present, the vast majority of studies of animal movement have been carried out using different types of tracking devices. Nevertheless, there is a problem with this technology: the data collection rate is conditioned by the duration of the power supply in the devices. Fernández-Rodríguez et al. (2023) carried out a study on the importance of pre-analysis of GPS data acquisition times in collars on ungulates, in order to optimize the interval and battery consumption without significant loss of information. This allows us to know the position of the animals at a specific moment of their movement but, depending on the species, the connection of these points does not show the detail of the animal movement. With the help of the methodology developed in this study both can be complemented, allowing us to know the details of the animal's movements through the terrain between monitoring points. At this fine scale the most influential factors in animal movement are topographical.

This detailed parameterization will also allow us to estimate energy costs based on results formulated by other authors (Lachica et al., 1997). Fine-scale estimation of movement patterns allows for more precise action in aspects of conservation and species management.

The methodology proposed in this research study focuses on analyzing at a fine scale where the animal is forced to make decisions constantly along its route. Consequently, it is essential to assess the topographic factors involved since, at this smaller scale, aside from residual vegetation the most influential factor to be considered on the animal's movement is the terrain's topography. Their movement is closely related to topographical aspects that shape their navigation and habitat selection. A second objective of the present manuscript is to validate a tracking methodology grounded in cartographic data and topographic technologies aimed at digitalizing and verifying cervid movement trajectories, recorded in the field and visible in orthophotos.

A novel approach is proposed, entailing the continued detection and analysis of transects recorded on the ground by the deer through the utilization of Geographic Information System (GIS) graphical tools, facilitated by high-resolution aerial orthophotos. This methodology affords the means to comprehensively decipher cervid movement patterns. The synergy between telemetry data and Geographic Information Systems (GIS) serves as the linchpin in automating the analysis of wildlife monitoring data, already highlighted by Ganskopp et al. (2000). Additionally, the utilization of GIS augments the visualization and interpretation of spatial information, offering an efficient approach through which to comprehend movement patterns.

The main goals of this study are:

a. Develop a clear methodology that leverages current technology to obtain fine-scale animal trajectories.
b. Know at a fine scale the movements of the animals and different parameters associated with them.
c. To be able to develop a predictive model of fine-scale animal movement based on the parameters obtained.

With this methodology we bridge the gap between the ring-monitoring and the knowledge of the animal movement at fine scale.

2. Natural area under study

Habitat management in Europe is a key requirement of the European Directives on Nature, especially for areas designated as Special Areas of Conservation (SACs) within the European Natura 2000 network. One of the priority locations designated as a SAC is the Sierra Morena Mountain range, a natural area of 2241 km^2 located in the southern Iberian Peninsula, in the province of Jaén. This site is simultaneously an important hunting area and a designated Special Area of Conservation (SAC) due to its ecological significance and conservation status. This natural site is divided into hunting estates with a wide range of sizes. Percentage-wise, the estates are grouped as follows: 55.6% have an area of 1000 ha, 26.7% have an area between 1000 ha and 2000 ha, and finally, 17.6% have an area exceeding 2000 ha (Azorit et al., 2012). Although livestock farming is practised in some areas, its primary economic activity is the hunting of species that inhabit it, such as red deer (*Cervus elaphus*) and wild boar (*Sus scrofa*) (Azorit and Moro, 2010). The population density of fallow deer (*Dama dama*) has increased significantly since the 1950s, coinciding with the introduction of specimens in some game reserves (Azorit et al., 2012), and similarly, this has occurred with the mouflon (*Ovis aries musimon*) (Azorit et al., 2020). In contrast, an isolated and threatened population of roe deer (*Capreolus capreolus*) is also present in this area (Azorit and Muñoz-Cobo, 1997). The topographical analysis conducted in this study covers an area of 270 ha within the estate of Lugar Nuevo (38°09′12,6”N, −4°03′07,4”W), with an area of over 9000 ha of the Sierra de Andujar Natural Park (see Fig. 1). This estate exhibits an ideal biologically, forestally, topographically and morphologically favorable landscape with an elevation range of 200 to 700 m above sea level. This mountainous area is covered by well-preserved Mediterranean forests, dominated by *Quercus ilex*, *Q. faginea*, and *Q. suber*, with a diverse shrub composition that hosts stable populations of several emblematic protected species: the Iberian lynx (*Lynx pardinus*), the black vulture (*Aegypius monachus*), and the Spanish imperial eagle (*Aquila adalberti*) in addition to the aforementioned species of game ungulates.

3. Material and methods

The methodology developed in this manuscript focuses on the recognition, digitization, and precise acquisition of animal trajectories using orthophoto recognition techniques and measurements with surveying instruments. This is in order to analyze the topographic

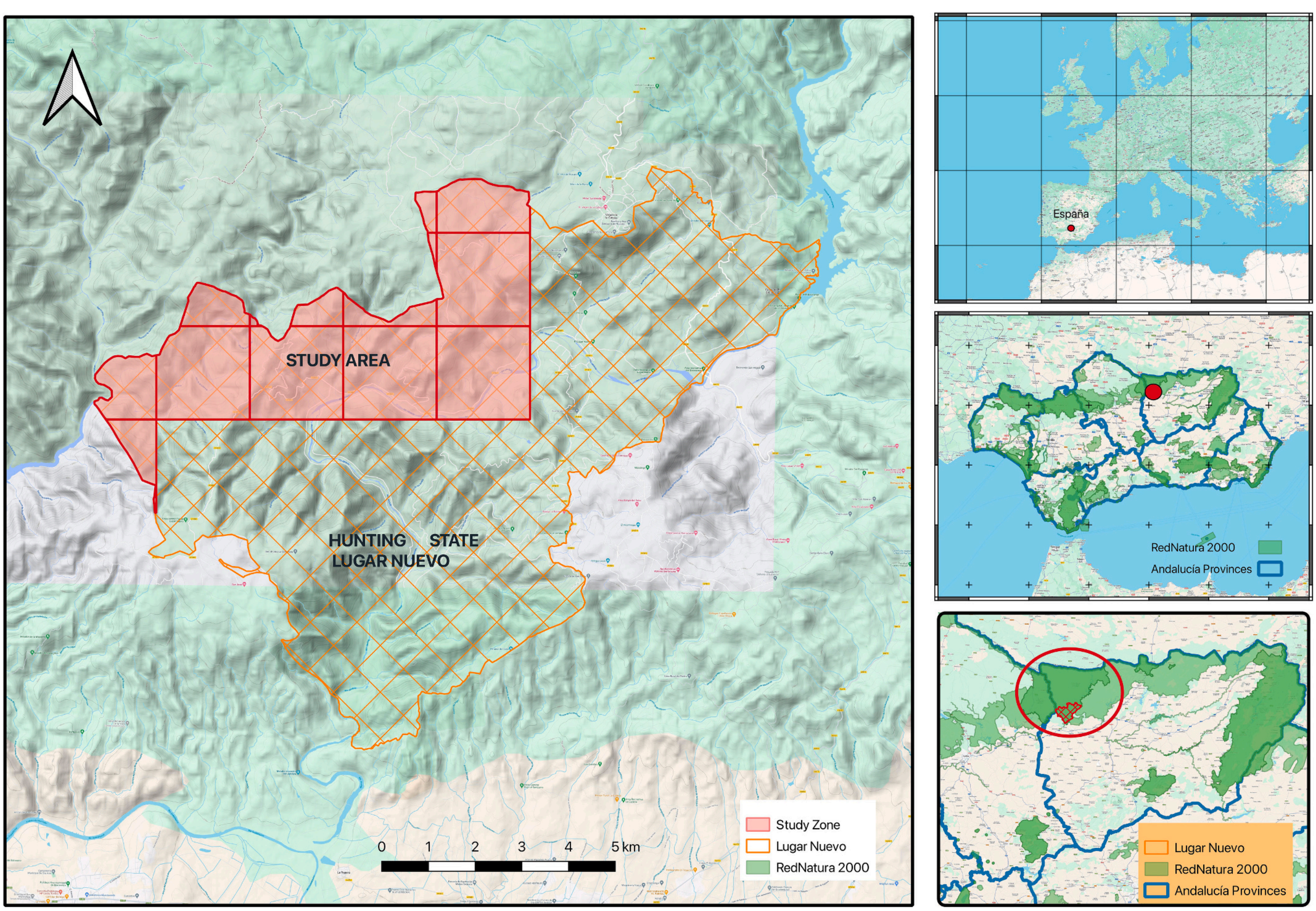

Fig. 1. Location map of the study area within the Lugar Nuevo estate (Sierra de Andújar Natural Park, Spain).

factors of the terrain that influence the movement and route selection of animals in the study area. This process will be carried out with the detection, digitation and analysis of transects recorded on the ground by the deer through the utilization of Geographic Information System (GIS) graphical tools, facilitated by high-resolution aerial orthophotos. This methodology affords the means to comprehensively decipher cervid movement patterns, which is of vital importance for understanding wildlife behavior in a specific area and for establishing movement patterns within the territory. Such information is fundamental in various fields of study, including ecology, species conservation and habitat management.

Currently, technological advances in the digital analysis of orthophotos and surveying techniques allow for the precise acquisition of up-to-date data for defining the main characteristics and properties of a terrain or natural environment. Thanks to these advancements, the methodology developed in this research work enables both the modeling of the main topographic properties and characteristics of a terrain or natural environment and the determination of the movements made by the animals that inhabit it. Accordingly, the methodology proposed in this manuscript can be grouped into three main phases: Phase 1: the analysis of the main sources for acquiring orthophotos of the study area is carried out, along with the selection of the most suitable ones for digital processing. The technical development of this operation is performed within a geographic information system using the open-source software QGIS (QGIS, edition 2023). In particular, this software allows access to an extensive repository of satellite images in order to establish the cartographic base of the study area. For instance, Bing Maps can be used as an example as well as Google maps, one of the most popular repositories incorporated within the software. However, for the present paper updated national and regional orthophotos from the web map service of PNOA (National Plan of Aerial Orthophotos) and IECA (Institute of Cartography of Andalusia) are employed. Due to their timeliness and accuracy, it was finally decided to use PNOA images (resolution of 0.5 m Pixel / 0.25 m Pixel).

For proper visual and graphical management, the study area was divided into smaller zones (see Fig. 1). In addition, these zones were traversed by sweeping from north to south using a map window at a scale of 1/600. Subsequently, at the end of each sweep the process was repeated from west to east. When certain features on the terrain were identified, they were digitized. To do this the working scale was increased, shifting to digitize the terrain cartography at a 1/300 scale in order to achieve higher precision.

Subsequently, the traces of animals identified through the orthophotos associated with the study area were digitized. Again, for this case, vector digitization was carried out within the geographic information software QGIS with precision and using an appropriate coordinate system. For the development of this digitation, the following hypotheses have been considered:

- The footprint of traces produced on slopes by rain is similar to the footprint left by animal tracks. However, the difference between the two lies in the fact that the former always follow the steepest slope line and are therefore directly discarded.
- Trails with greater distance and a higher number of tracks indicate that they are used by a larger number of animals.
- When there is a set of trajectories with parallel geometry the one that stands out the most is selected, as it is assumed to be the movement of a complete herd (see Fig. 2a).

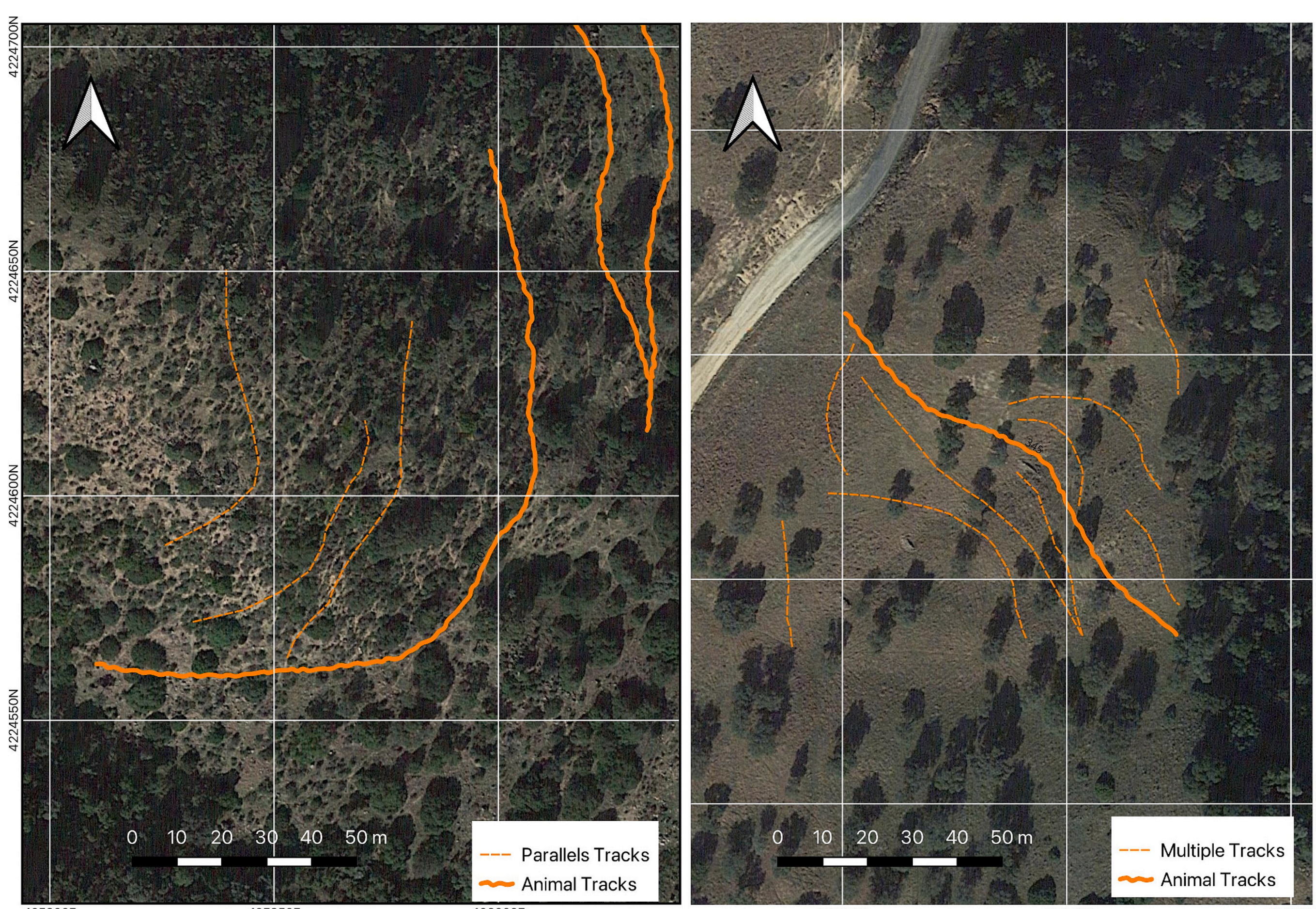

Fig. 2. A) Example of multiple parallel trajectories (The longest and most prominent ones are taken) and B) Image of a flat area with multiple trajectories.

- In the study area, trajectories generated in flat regions or with minimal slope will not be considered in the methodology's development. These flat regions are used by animals for grazing and furthermore they are not involved in significant movement between two points of interest, so we are left with the most outstanding that goes to the forest. (see Fig. 2b).
- It is worth noting that in damp areas near streams or riverbeds it is easier to identify tracks because the footprints are more clearly visible on the ground. On the other hand, in areas with more vegetation or grass distinguishing tracks is not as straightforward, although this does not imply that animals do not traverse these regions.
- In rocky areas it is not possible to detect complete animal trajectories as their passage does not leave tracks on the rocks.
- In general, the trajectories of animal movements are interrupted by the following natural obstacles: continuous or intermittent water bodies, the entry or exit of wooded or forested areas, the passage through rocky terrain, and lastly, the presence of a road or motorized passage.

The digitization of animal tracks, as proposed, provides crucial information for understanding wildlife movement patterns and their influence on the ecosystem. Fig. 3 illustrates a real example of an animal trajectory in a region of the study area. As can be seen, it is evident that the animals typically move in single file, maintaining the trail typology that has been digitized in this phase of the study.

Subsequently, for the generation of resulting animal trajectories over the digital cartographic information of the study area, friction layers are employed. The definition of these friction layers is carried out using a high-precision Digital Terrain Model (DTM) generated from Lidar data of the MDT05 (0.25 to 0.50 m/cell) with a density of 0.5 point/m^2 and altimetric accuracy (RMSE Z: Root-Mean Square Error in Z component) better than 40 cm, available from the Spanish National Geographic Institute (IGN). Subsequently, slope (in degrees) was derived from the DTM (Digital Terrain Model). All calculations were performed using QGIS. Consequently, the digital animal trajectories generated exhibit a precision analogous to that established for the DTM.

These trajectories were enriched with attributes calculated digitally from friction layers generated in the QGIS geographic information system. The attributes that ultimately comprise the database of the resulting animal trajectories are as follows:

- ID: Unique numerical identifier of the trajectory.
- Climb: Cumulative ascending distances on the trajectory (inferred from the elevation layer).
- Descent: Cumulative descending distances on the trajectory (inferred from the elevation layer).
- Maxelevation: Maximum elevation on the trajectory (inferred from the elevation layer).
- Minelevation: Minimum elevation on the trajectory (inferred from the elevation layer).
- MaxSlope: Maximum slope on the trajectory (inferred from the slope layer).
- MinSlope: Minimum slope on the trajectory (inferred from the slope layer).
- Length2D: Projected length on the horizontal plane of the trajectory.
- Length3D: Three-dimensional spatial length of the trajectory (inferred from the elevation layer).

Phase 2: to verify that the digital modeling of tracks and animal trajectories defined is valid, a field verification is conducted. Phase 2 involves the precise field layout of an estimated percentage of routes to check for correspondence with physical reality. In other words, based on the resulting digital animal trajectories, and using corrections from the Andalusian Positioning Network (RAP), a real and on-site verification is carried out using a GPS measurement device. The field equipment used is the Trimble Geoexplorer Geo7x, a dual-frequency GNSS receiver and antenna with Trimble R-Track technology. It achieves centimeter-level accuracy with differential corrections (horizontal accuracy of 10 mm + 1 ppm RMS and vertical accuracy of 15 mm + 1 ppm RMS).

After completing the process of digitizing the animal trajectories and the experimental verification of them in the region of land under study a model is generated, based on the topographic variables of the trajectories obtained from the digitization of the terrain, to generate digital trajectories of analogous animals from two points on the terrain under study. To this end, it is proposed to establish, based on the results obtained, a linear regression analysis, using the numerical calculation software (Matlab R21, 2021), which allows modeling the relationship between the main topographic parameters of the digital trajectories of animals. All of this in order to generate, from any two points on the terrain under study, digital trajectories of animals similar to those previously obtained.

Finally, Fig. 4 depicts the flowchart of the methodology developed for the recognition and digitization of animal paths across the study

Fig. 3. Panoramic images with movements of cervids.

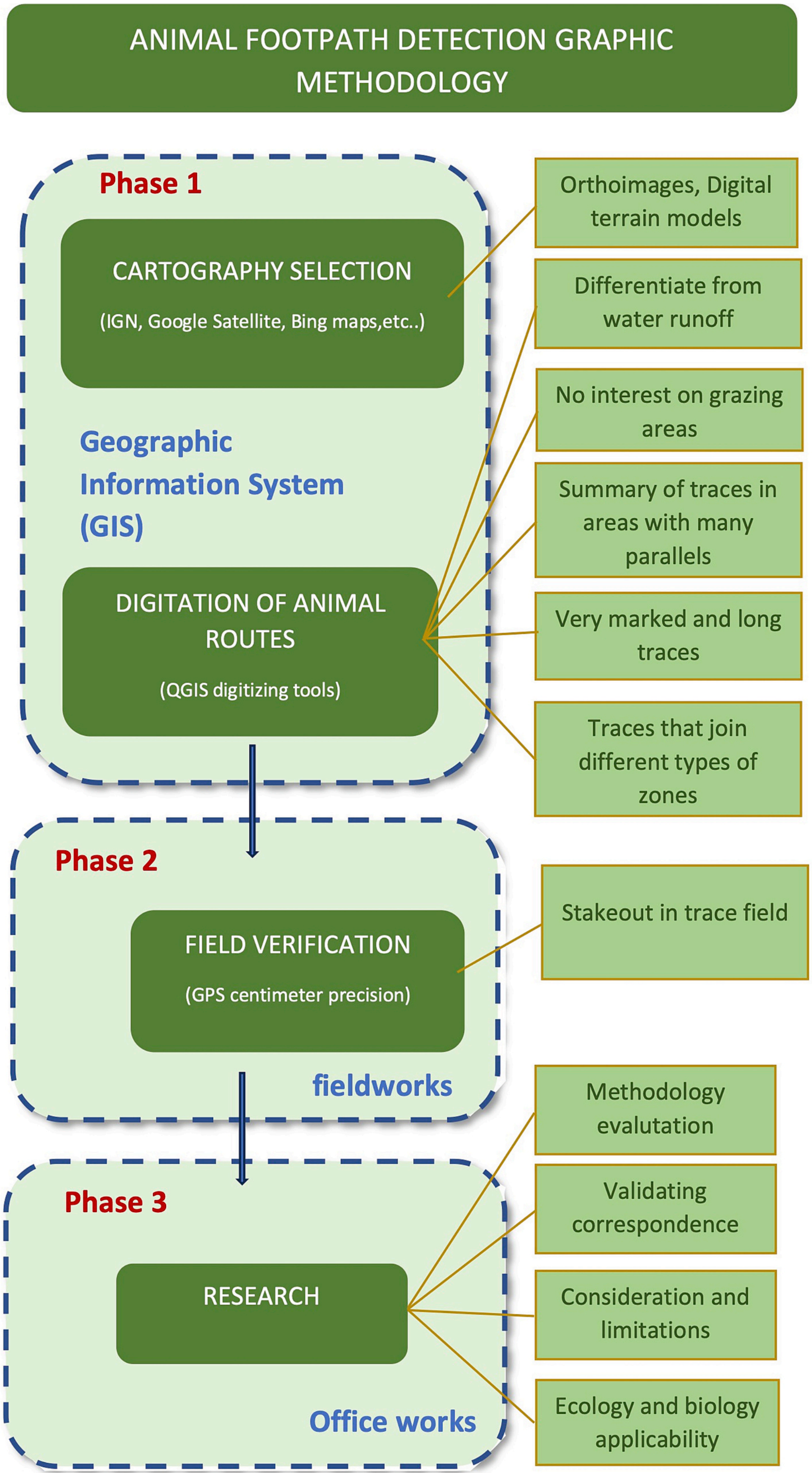

Fig. 4. Flowchart of the methodology developed Field/office WORK.

area, without the need for tagging or monitoring the animals.

4. Results and discussion

The application of the methodology of graphic recognition of animal tracks using orthophotos has yielded significant and revealing results on the behavior of wildlife in the study area. Its application and use is simple and requires basic training. Specifically, this research work has allowed the digitization of a total of 413 sampled trajectories (see Fig. 5), covering approximately 53 km of animal movements. There are studies that use automatic trajectory detection techniques in the field (Sahani and Ghosh, 2021), which would help in our proposal, but the size of the animal footprint of the trajectory makes its application difficult.

This methodology provides a detailed, close-up view of the animal's movement, while the monitoring of tagged animals gives us a broader view due to data collection times, currently limited by technology. Monitored tracking of animals allows us to determine their habitats, large movements and migratory movements, etc. The methodology presented here allows us to delve into the detail of these movements at a much closer scale, and we understand that at this scale, topography is the determining factor in animal movement.

Table 1 is generated as the first result obtained on the data associated

Table 1
Statistical summary values in digitized trajectories 3D of animals.

	Track Length [m]	Max. Slope [°]	Min. Slope [°]	Max. Height [m]	Min. Height [m]
Mean	127.9	27.2	13.8	384.2	369.5
Median	99	27.7	13.7	382.7	360.1
Std. Deviation	97	6.6	7.8	90.6	92.3
Minimum	13.4	7.2	0.3	228.6	225.1
Maximum	834.1	45.9	31.8	630.6	622.3
Geographic area	–	68.0	–	644.2	224.5

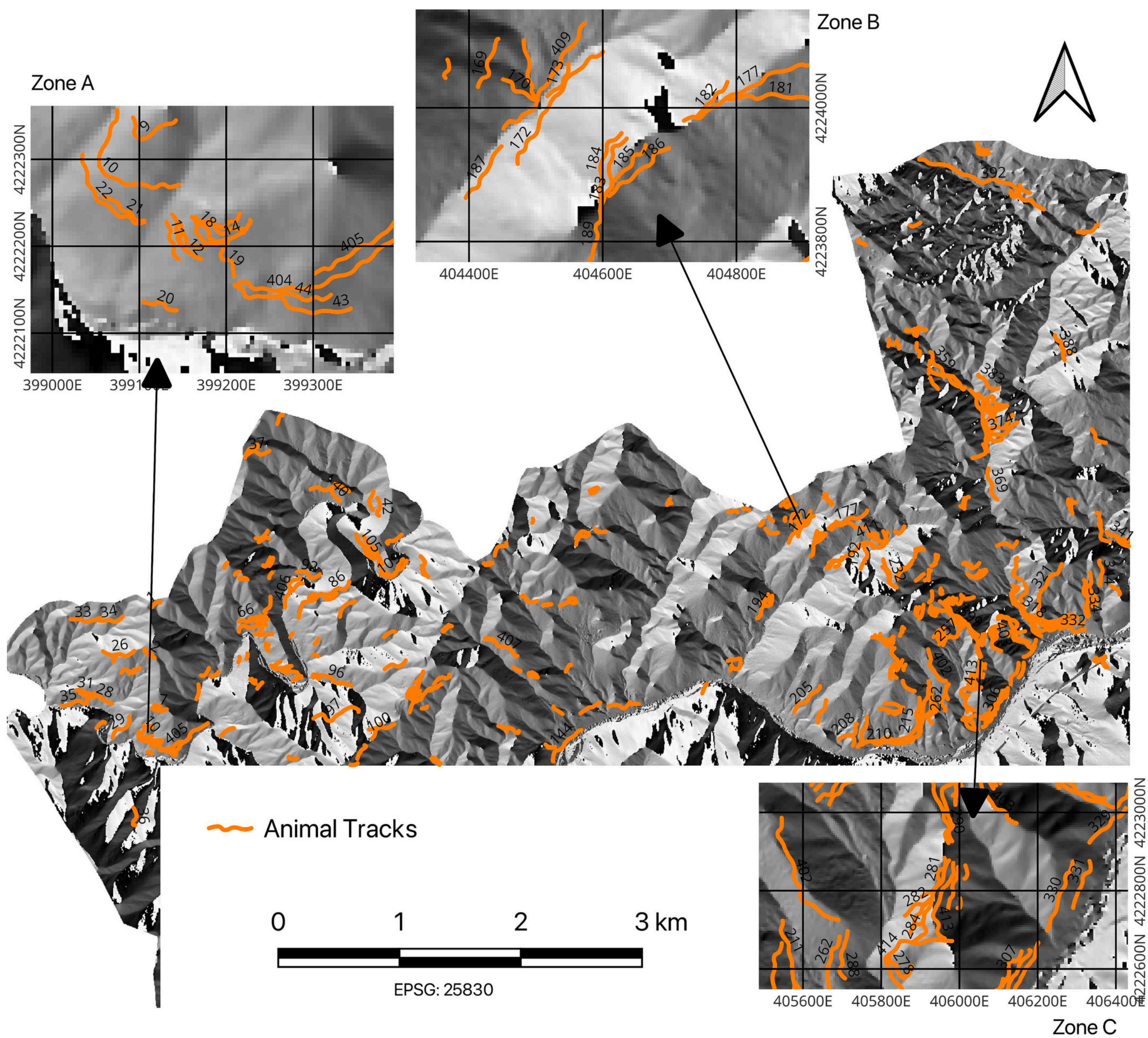

Fig. 5. Graphical representation of the resulting digital animal trajectories.

with each trajectory generated from the different friction layers (DTM and Slopes). It shows the mean values and other statistical parameters of trajectory length, maximum slope, minimum slope, maximum height and minimum height compared to the general values of the geographical area. This is already providing us with a close-scale description of the movement habits of these animals, such as the fact that the animals move taking full advantage of the high-altitude region of the study area, as the elevations of the trajectories range from 224 to 645 m. However, taking the slope parameter as a reference, the animals prefer to travel on roads with a lower slope, between 0° and 32°, with terrain slope values ranging between 0° and 68°.

In addition, the graphical description of animal movement is obtained at a detailed scale (see Fig. 5), so that the location of animal movement throughout the study area can be verified quickly and directly. This digital process helps to reduce the time and costs associated with monitoring a species. Evidently, traditional methods of marking and tracking animals not only do not conflict with this methodology, since underlying issues such as obtaining the spatio-temporal direction of movement of the specimen, limitations in the digitization of trajectories referred to problems with rocky or wooded areas, or the problem of areas where orthophotos do not present the necessary resolution for their use, or do not exist at all, but rather complement it.

In this context, the tools developed by Calenge et al. (2009) for discerning and analyzing animal behavior through GPS trajectories can be valuable to understanding the detailed information obtained in the graphical description of the movement. Similarly, Fernández-Rodríguez et al. (2023) on the data acquisition interval in GNSS collars highlights the importance of temporal accuracy in animal tracking, a crucial aspect when verifying and validating digital trajectories.

In order to validate the methodology, some of the trajectories sampled were reconsidered in the field with the idea of verifying that what was recognized graphically were not other geographic features, but animal tracks. The results obtained from the field work show that the digital trajectories of the animals obtained coincide significantly with the real trajectories in the given place (see Fig. 6). As for the level of coincidence, it may vary slightly, given that some time has elapsed between obtaining the orthophotography and conducting the field review and the animal herds may have slightly varied their pace at some points.

At this point, the findings of Morita et al. (2020) on individual differences in animal trajectories can be incorporated, which could explain the variations observed in the level of agreement between digital and real trajectories. In addition, the work of Marshall et al. (2022) on the 3D measurement of animal behavior could contribute to the discussion, as field validation could also benefit from advanced 3D measurement tools for assessing the accuracy of digital trajectories in natural and occlusive contexts. We understand that the degree of approximation is adequate to what is intended to be demonstrated, which is to say that what is appreciated in the orthophoto coincides with the reality on the ground in terms of animal passage through the area. This statement is reinforced by the information provided by Klasen and Steinhage (2022) on how the use of camera-based monitoring systems can avoid common problems in traditional tracking, thus supporting the reliability of the proposed methodology.

Finally, after validating the digital process of generating trajectories for the movement of the animals, it is important to evaluate how the topographic factors of the terrain influence or condition the selection of

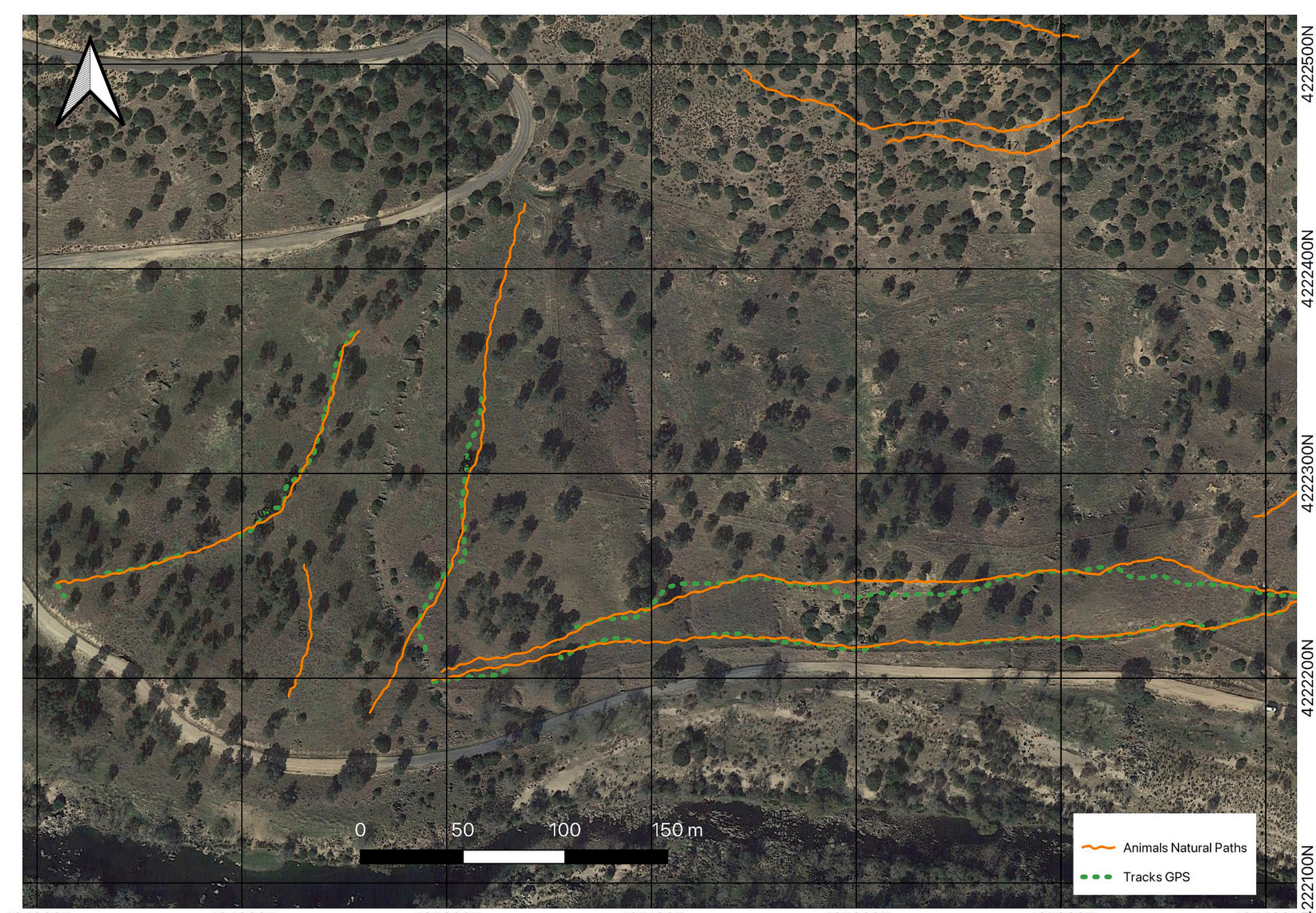

Fig. 6. Comparison of GPS field paths with digitized paths.

travel routes for the animals. For this purpose, based on the topographic parameters obtained from the digital terrain model in each of the resulting digital trajectories of the animals, a linear regression model is applied in order to analyze the relationship between the dependent variable Ascent+Descents and the 3D length (L3D). In particular, the slope estimated in the model is equal to 0.2272 and this coefficient is significantly different from zero (p-value <0.01). In terms of goodness of fit, the fitted model explains >90% of the total variability of Ascent + Descent. Fig. 7 shows the scatter plot together with the fitted regression line.

Similar to the authors' contribution based on location points predicting spatial distributions of species (Zaniewski et al., 2002), we based our predictions on 3D trail trajectories and linear regression relating topographic terrain parameters and were able to predict the location of preferred routes for deer in the study area. To evaluate the fitted model, a set of possible alternative digital trajectories were programmed from two points in the study area, as shown in Fig. 8, with their corresponding topographic parameters. Based on the estimated equation derived from the linear regression model, the best-fit trajectory was selected.

This adjusted model, based on the analysis of topographic parameters of the terrain, has been evaluated and validated for each of the resulting digital trajectories in the study area. Additionally, it provides valuable information to promote the conservation of the natural habitat of the species and their main travel routes, as well as the possibility of implementing assistance or preservation mechanisms for the species and generating new potential natural corridors for them. Furthermore, it helps to reduce the time and costs associated with maintenance tasks related to animal specimens, improving the sustainability of these operations and creating a less invasive and safer environment for the animals.

As shown in Fig. 8, the adjusted model has been evaluated and validated using information from a specific set of previously analyzed digital trajectories. In this way, different alternative trajectories are generated from any two points within the study area (see Fig. 8), and by considering the information on their associated topographic parameters, it is determined which one is very close to the actual trajectory of the animal. As can be seen in Fig. 8, the selection of the predicted trajectory resulting from the linear regression model closely resembles the actual trajectory. It should be noted that this validation has been successfully verified for each digital trajectory generated.

The topographic factors that determine the movement of animals, in the absence of other natural or artificial impediments, are mainly the accumulated slope along the route and the total length. It does not appear that the absolute altitude of the road plays an important role. Based on the different animal trajectories obtained through digitization compared to different random alternatives for moving from one point to another (see Fig. 8), the factors described above have been analyzed. In many cases, the path followed by the animal was found to have the best cumulative slope and the shortest distance. In other cases, the animal improves the slope, but one of the alternatives is more advantageous in terms of distance, or vice versa (in 54% of the cases). In cases where the route chosen by the animal does not have the best parameters, it is very close to them. In the latter case, we understand that some factor may have influenced the selection of the route, which, logically was not considered in the random alternatives.

5. Conclusions

The results obtained fully support the proposed methodology, which uses cutting-edge technologies such as Geographic Information Systems (GIS), high-resolution orthophotos and GNSS devices to verify movement trajectories. This methodology stands out for its versatility and applicability across various terrains and habitats, which makes it a valuable tool for both scientific research and wildlife conservation management. It is shown as a complement, on a closer scale, to the monitoring of animals with tracking devices, improving their limitations, such as the lack of visibility in certain areas or under certain morphological characteristics of the terrain, where some location points obtained with monitoring can help to complete or connect certain routes. In addition, monitored tracking would help to determine the spatio-temporal variable of the animal's movement, that is, with the proposed methodology we have the trace of the route, but we do not

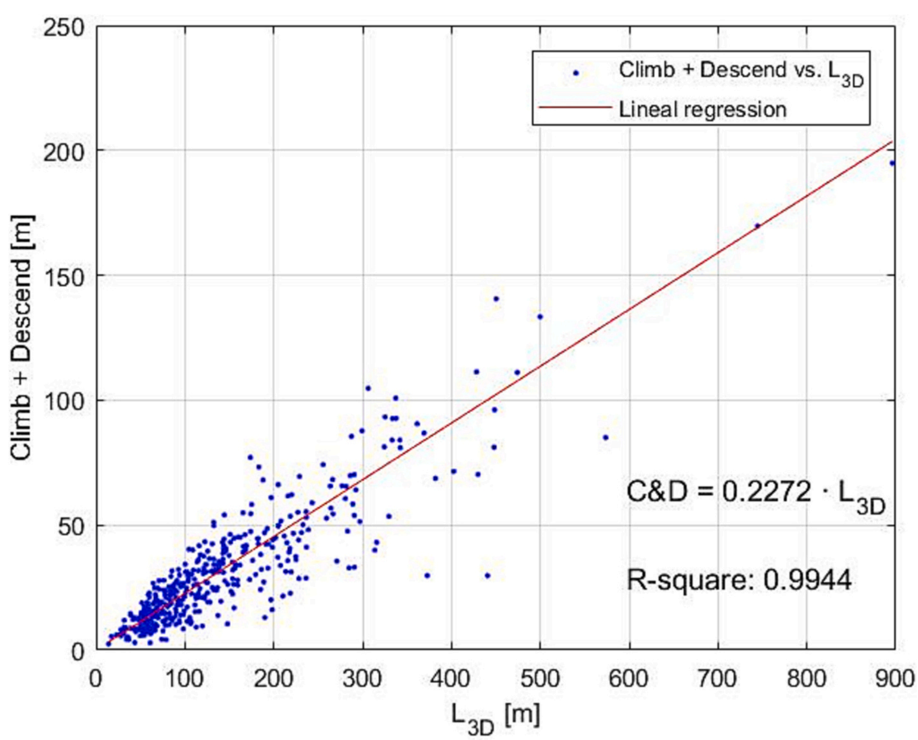

Fig. 7. Representation of the linear regression generated for the analysis of the topographic factors of the area under study.

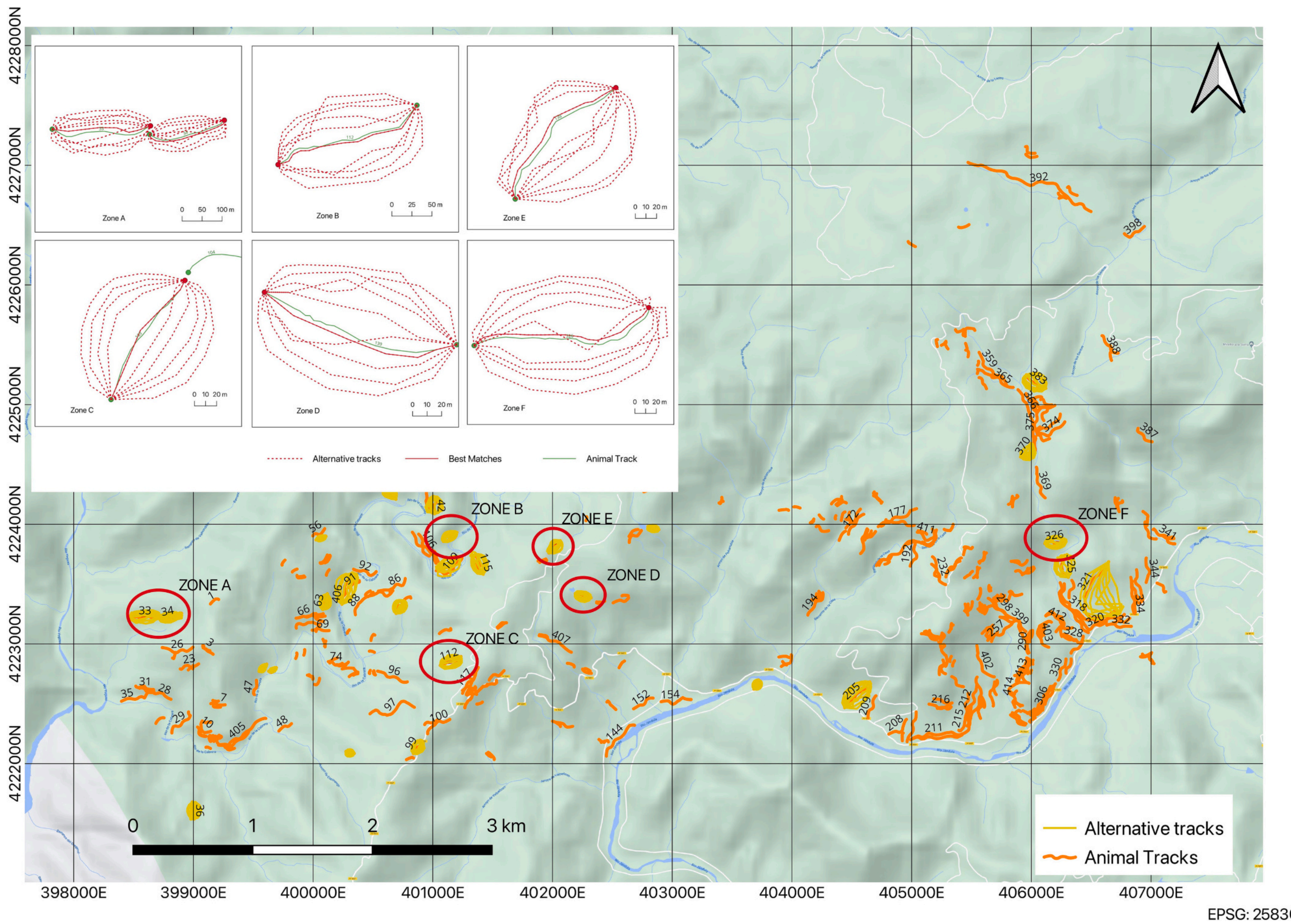

Fig. 8. Graphical digital representation of the resulting animal trajectories.

know the direction of movement, whereas if it is complemented with traditional techniques this variable can be determined. On the other hand, with traditional techniques we do not know the close-scale detail of the animal's movement, but rather the exact location at a certain moment. With our methodology, we can determine in detail which are the preferred routes to connect these acquired points with traditional species monitoring technologies and what topographic factors influence them.

The methodology developed here has been validated and verified through field work. Through precise measurement with GPS surveying techniques, it has been verified that each of the digital trajectories generated using GIS tools adjust to the real trajectories taken by the animals over the area under study.

This methodology feeds the knowledge of the geographical parameters in which animals move and expands the understanding of cervids movements, contributing significantly to decision-making in wildlife conservation strategies and providing a solid basis for the sustainable management of cervids populations and their habitats.

Analytical tests of the trajectories have shown that the movement behavior of cervids is predictable. The results demonstrate the usefulness of the methodology presented which, by providing and recounting valuable topographic information on movement and transit areas, can guide sustainable management practices for deer populations and their habitats.

CRediT authorship contribution statement

José M. Valderrama-Zafra: Writing – review & editing, Writing – original draft, Validation, Software, Resources, Methodology, Formal analysis, Conceptualization. **Miguel A. Rubio-Paramio:** Supervision, Methodology. **Diego Francisco Garcia-Molina:** Writing – review & editing, Validation, Supervision, Methodology. **Jorge Manuel Mercado-Colmenero:** Methodology, Formal analysis, Data curation. **Antonia Oya:** Formal analysis, Data curation. **Rafael Carrasco:** Resources. **Concepción Azorit:** Writing – review & editing, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

Acknowledgments

This study was carried out with the financial support of the 'Consejería de Innovación Ciencia y Empresa', 'Junta de Andalucía', the autonomous agency of 'Parques Nacionales', 'Ministerio de Medio Ambiente, Medio Rural y Marino', Spain, and the 'European Regional Development Fund' (FEDER), PAIDI RNM175 "Biodiversity and Sustainable Development" Research Group, Junta de Andalucía, Spain, as well as the project PID2022-1426610B-I00 from the Ministerio de Ciencia e Innovación, Spain. Thanks to José Manuel Valderrama Sánchez for his help in Python routines in QGIS.

References

Abrahms, B., Aikens, E.O., Armstrong, J.B., Deacy, W.W., Kauffman, M.J., Merkle, J.A., 2021. Emerging perspectives on resource tracking and animal movement ecology. In Trends Ecol. Evol. 36 (4), 308–320. https://doi.org/10.1016/j.tree.2020.10.018.

Anjitha Krishna, P.R., Lalitha, R., Shanmugasundaram, K., 2019. Assessment of topographical factor (LS-factor) estimation procedures in a gently sloping terrain. J. Indian Soc. Remote Sens. 47, 1031–1039. https://doi.org/10.1007/s12524-019-00953-3.

Azorit, C., Moro, J., 2010. Jabalí (*Sus scrofa*, Linnaeus, 1758)., en: Monografias INIA: Serie medioambiental No 2–2010, Ungulados silvestres de España: Biología y tecnologías reproductivas para su conservación y aprovechamiento cinegético, pp. 215–240.

Azorit, C., Muñoz-Cobo, J., 1997. Distribución y abundancia del corzo (*Capreolus capreolus* L. 1758) en la provincia de Jaén, Doñana. Acta Vertebrata 24 (1–2), 181–190.

Azorit, C., Oya, A., Tellado, S., Carrasco, R., Moro, J., 2012. Mandibular osteomyelitis in red deer (*Cervus elaphus hispanicus*) and fallow deer (*Dama dama*): occurrence and associated factors in free-living populations in southern Spain. J. Wildl. Dis. 48 (1), 77–86. https://doi.org/10.7589/0090-3558-48.1.77.

Azorit, C., Tenorio, M.J., Casinos, A., Montoya, A.J.L., López-Fuster, M.J., Barbosa, O.R., 2020. Searching for indicators of age, sex and population in European mouflon mandibles. Hystrix 31 (1), 1–10. https://doi.org/10.4404/hystrix-00197-2019.

Calenge, C., Dray, S., Royer-Carenzi, M., 2009. The concept of animals' trajectories from a data analysis perspective. Eco. Inform. 4 (1), 34–41. https://doi.org/10.1016/j.ecoinf.2008.10.002.

Cumming, G.S., Cornélis, D., 2012. Quantitative comparison and selection of home range metrics for telemetry data. Divers. Distrib. 18, 1057–1065. https://doi.org/10.1111/j.1472-4642.2012.00908.x.

Dodge, S., Weibel, R., Ahearn, S., Buchin, M., Miller, J., 2016. Analysis of movement data. Int. J. Geogr. Inf. Sci. 30 (5), 825–834. https://doi.org/10.1080/13658816.2015.1132424.

Edelhoff, H., Signer, J., Balkenhol, N., 2016. Path segmentation for beginners: an overview of current methods for detecting changes in animal movement patterns. Mov. Ecol. 4, 21. https://doi.org/10.1186/s40462-016-0086-5.

Fernández-Rodríguez, P., Carrasco, R., Moro, J., Garrido-Carretero, M.S., Azorit, C., 2023. Working with GNSS collar data. The importance of pre-analysis when setting the sampling interval. Eco. Inform. 77, 102219 https://doi.org/10.1016/J.ECOINF.2023.102219.

Ganskopp, D., Cruz, R., Johnson, D.E., 2000. Least-effort pathways?: a GIS analysis of livestock trails in rugged terrain. Appl. Anim. Behav. Sci. 68 (3), 179–190. https://doi.org/10.1016/S0168-1591(00)00101-5.

Garrido-Carretero, M.S., Azorit, C., de Lacy-Pérez de los Cobos, M.C., Valderrama-Zafra, J.M., Carrasco, R., Gil-Cruz, A.J., 2023. Improving the precision and accuracy of wildlife monitoring with multi-constellation, multi-frequency GNSS collars. J. Wildl. Manag. 87 (4) https://doi.org/10.1002/jwmg.22378.

Guo, Du, Ma, Huo, Peng., 2019. A model for animal home range estimation based on the active learning method. ISPRS Int. J. Geo Inf. 8 (11), 490. https://doi.org/10.3390/ijgi8110490.

Horne, J.S., et al., 2007. Analyzing animal movements using Brownian bridges. Ecology 88 (9), 2354–2363. https://doi.org/10.1890/06-0957.1.

Kauffman, M.J., Aikens, E.O., Esmaeili, S., Kaczensky, P., Middleton, A., Monteith, K.L., Morrison, T.A., Mueller, T., Sawyer, H., Goheen, J.R., 2021. Causes, consequences, and conservation of ungulate migration. In: Annual Review of Ecology, Evolution, and Systematics, Vol. 52. https://doi.org/10.1146/annurev-ecolsys-012021-011516.

Kenward, R.E., Arraut, E.M., Robertson, P.A., Walls, S.S., Casey, N.M., Aebischer, N.J., 2018. Resource-area-dependence analysis: inferring animal resource needs from homerange and mapping data. PLoS One 13 (10). https://doi.org/10.1371/journal.pone.0206354.

Klasen, M., Steinhage, V., 2022. Wildlife 3D multi-object tracking. Eco. Inform. 71, 101790 https://doi.org/10.1016/J.ECOINF.2022.101790.

Korzeniowska, K., Pfeifer, N., Landtwing, S., 2018. Mapping gullies, dunes, lava fields, and landslides via surface roughness. Geomorphology 301, 53–67. https://doi.org/10.1016/j.geomorph.2017.10.011.

Lachica, M., Aguilera, J.F., 2000. Estimation of the energy costs of locomotion in the Iberian pig (Sus mediterraneus). Br. J. Nutr. 83 (1), 35–41. https://doi.org/10.1017/s0007114500000064.

Lachica, M., Prieto, C., Aguilera, J.F., 1997. Los costes energéticos de caminar sobre el nivel y sobre pendientes negativas y positivas en la cabra Granadina (Capra hircus). Fr. J. Nutr. 77 (1), 73–81. https://doi.org/10.1017/s0007114500002890.

Laffan, S.W., Skidmore, A.K., Franklin, J., 2012. Geospatial analysis of species, biodiversity and landscapes: introduction to the second special issue on spatial ecology. Int. J. Geogr. Inf. Sci. 26 (11), 2003–2007. https://doi.org/10.1080/13658816.2012.721557.

Laffan, S.W., Skidmore, A.K., Franklin, J., 2014. Species Distribution and Diversity, Habitat Selection and Connectivity: Introduction to the Third Special Issue on Spatial Ecology.

Laffan, S.W., Skidmore, A.K., Franklin, J., 2016. Space, time, connectivity and conflict in biological landscapes: the fourth special issue on spatial ecology. Int. J. Geogr. Inf. Sci. 30 (1), 1–4. https://doi.org/10.1080/13658816.2015.1090001.

Laube, P., Purves, R.S., 2011. How fast is a cow? Cross-scale analysis of movement data. Trans. GIS 15 (3), 401–418. https://doi.org/10.1111/j.1467-9671.2011.01256.x.

Lele, S.R., et al., 2013. Selection, use, choice and occupancy: clarifying concepts in resource selection studies. J. Anim. Ecol. 82 (6), 1183–1191. https://doi.org/10.1111/1365-2656.12141.

Lempidakis, E., Wilson, R.P., Luckman, A., Metcalfe, R.S., 2018. What can knowledge of the energy landscape tell us about animal movement trajectories and space use? A case study with humans. J. Theor. Biol. 457, 101–111. https://doi.org/10.1016/j.jtbi.2018.08.024.

Marshall, J.D., Li, T., Wu, J.H., Dunn, T.W., 2022. Leaving flatland: advances in 3D behavioral measurement. Curr. Opin. Neurobiol. 73, 102522 https://doi.org/10.1016/j.conb.2022.02.002.

Masello, J.F., Kato, A., Sommerfeld, J., Mattern, T., Quillfeldt, P., 2017. How animals distribute themselves in space: variable energy landscapes. Front. Zool. 14 (1) https://doi.org/10.1186/s12983-017-0219-8.

Matlab R21, 2021. Natick. The MathWorks Inc, Massachusetts. https://es.mathworks.com/.

Morita, T., Toyoda, A., Aisu, S., Kaneko, A., Suda-Hashimoto, N., Matsuda, I., Koda, H., 2020. Animals exhibit consistent individual differences in their movement: a case study on location trajectories of Japanese macaques. Eco. Inform. 56, 101057 https://doi.org/10.1016/J.ECOINF.2020.101057.

Panzacchi, M., Van Moorter, B., Strand, O., Saerens, M., Kivimäki, I., St. Clair, C.C., Herfindal, I., Boitani, L., 2016. Predicting the continuum between corridors and barriers to animal movements using step selection functions and randomized shortest paths. J. Anim. Ecol. 85 (1) https://doi.org/10.1111/1365-2656.12386.

Pinter-Wollman, N., et al., 2013. The dynamics of animal social networks: analytical, conceptual, and theoretical advances. Behav. Ecol. 25 (2), 242–255. https://doi.org/10.1093/beheco/art047.

Riotte-Lambert, L., Matthiopoulos, J., 2020. Environmental predictability as a cause and consequence of animal movement. Trends Ecol. Evol. 35 (2) https://doi.org/10.1016/j.tree.2019.09.009, 163–17.

Sahani, N., Ghosh, T., 2021. GIS-based spatial prediction of recreational trail susceptibility in protected area of Sikkim Himalaya using logistic regression, decision tree and random forest model. Eco. Inform. 64, 101352 https://doi.org/10.1016/J.ECOINF.2021.101352.

Schlägel, U.E., Lewis, M.A., 2014. Detecting effects of spatial memory and dynamic information on animal movement decisions. Methods Ecol. Evol. 5 (11), 1236–1246. https://doi.org/10.1111/2041-210X.12284.

Seidel, Dana Paige, Dougherty, Eric, Carlson, Colin, Getz, Wayne M., 2018. Ecological metrics and methods for GPS movement data. Int. J. Geogr. Inf. Sci. 32 (11), 2272–2293. https://doi.org/10.1080/13658816.2018.1498097.

Shepard, E.L.C., Wilson, R.P., Rees, W.G., Grundy, E., Lambertucci, S.A., Vosper, S.B., 2013. Energy landscapes shape animal movement ecology, 182 (3), 298–312. https://doi.org/10.1086/671257.

Skidmore, A.K., et al., 2011. Geospatial tools address emerging issues in spatial ecology: a review and commentary on the special issue. Int. J. Geogr. Inf. Sci. 25 (3), 337–365. https://doi.org/10.1080/13658816.2011.554296.

Spencer, W.D., 2012. Home ranges and the value of spatial information. J. Mammal. 93 (4) https://doi.org/10.1644/12-MAMM-S-061.1.

Valderrama-Zafra, J.M., Fernández-Rodríguez, P., Oya, A., Carrasco, R., Rubio-Paramio, M.A., Garrido-Carretero, M.S., Azorit, C., 2022. Assessing 3D vs. 2D habitat metrics in a Mediterranean ecosystem for a wiser wildlife management. Eco. Inform. 101623 https://doi.org/10.1016/J.ECOINF.2022.101623.

Wangdi, T., Tobgay, S., Dorjee, K., Dorji, K., Wangyel, S., 2019. The distribution, status and conservation of the Himalayan musk deer Moschus chrysogaster in Sakteng wildlife sanctuary. Global Ecol. Conserv. 17, e00466 https://doi.org/10.1016/j.

Wiens, J.A., Moss, M.R., 2005. Issues and perspectives in landscape ecology. In: Cambridge Studies in Landscape Ecology. University Press, Cambridge, p. 390. https://doi.org/10.1017/CBO9780511614415.

Zaniewski, A.E., Lehmann, A., Overton, J.M., 2002. Predicting species spatial distributions using presence-only data: a case study of native New Zealand ferns. Ecol. Model. 157, 261–280. https://doi.org/10.1016/S0304-3800(02)00199-0.

Zonneveld, I.S., 1995. Land Ecology. SPB Academic Publishing, Amsterdam, p. 199.