

GEOSTATISTICAL VARIABLES INFLUENCING *LIVESTOCK GUARDIAN DOGS (LGDs)* MOVEMENT IN MOUNTAIN SETTINGS. A PREDICTIVE MAPPING CASE STUDY FROM NORTHERN ROMANIA

*Silviu Vasile BUMBAK*¹ 

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ABSTRACT

In Romania, a Carpathian nation by definition, pastoralism represents a cultural reference and, as such, its proxies are seen as ancestral users of mountain spaces. The cultural reference extends to the livestock guardian dogs (LGDs) present at the sheepfolds across the landscape. The dogs are seen as an integral part of pastoralism, providing security in an environment populated with large carnivores. However, through mountain tourism, a new category of landscape users is increasingly making its presence known, as many outdoor recreational activities in the mountains overlap with the pastoral calendar. This situation creates a potential for conflict between two distinct categories of landscape users. The research hypothesis states that the flock and the dog's presence are not randomly distributed but follow a spatial pattern characterized by key geostatistical variables, with varying degrees of significance and predictive power. To demonstrate this in a GIS environment (QGIS), 9 geostatistical variables (topographic, environmental and control variables) were selected as representative for a 113 km² area used by two LGDs from two sheepfolds in the lowlands of Igriș Mountains, Maramureș Land, northern Carpathians. All geovariables were reclassified as categorical data using a 1-5 rules-based risk scale. The reclassified geovariables were used to build a weighted theoretical model mapping the areas where the probability of their presence is high. Using telemetry data collected during a 60-day monitoring campaign of the two LGDs for validation (over 1200 daytime observation points), the analysis shows that over 78% of the daytime LGD activity was concentrated in areas with medium to high (over 3.5) probability risk. These results indicate that topographic variables can influence LGD presence and serve as predictors of occurrence. The environmental variables can highlight areas of high occurrence, while the high density of observations near the control variables shows how they act as anchors, concentrating the dogs' movement in their vicinity. Case studies of this kind have the potential to contribute to the design process of smart solutions for trail management instruments based on predictive mapping, integration of results into dedicated trail apps, spatial planning and design trails, information, and signaling infrastructure.

Keywords: *Livestock guardian dogs (LGD); Telemetry data; Mountain tourism; Geostatistical variables; Potential for conflict; Predictive mapping; Trail management.*

1. INTRODUCTION

In the last decades, mountain landscapes have become increasingly multifunctional, as grazing areas overlap with those frequented by mountain tourism practitioners, leading to spatial superposition and interactions between the shepherds and their dogs and the practitioners of mountain tourism (Landry & Drouilly, 2020; Gehring et al., 2010). This type of interaction can generate mixed effects: convergent effects such as the touristification of the sheepfolds that capitalize on the presence of the tourists, selling produce and services. These effects are best seen on highly developed, marketized trails such as the newly developed Via Transilvanica, a long-distance, cross-country trekking and biking trail (Tășuleasa Social, 2026). At the other end, divergent effects are occurring across the majority of Romanian mountain areas, at least in part due to often problematic encounters in the field between tourists and livestock guardian dogs that protect flocks (Bailey et al., 2025). This type of land-use conflict encourages avoidance and fear-based perceptions that can develop in the minds of tourists into true "landscapes of fear" (Gaynor et al., 2019; van Bommel et al., 2023; Tuan, 2013).

¹ *Babeș-Bolyai University of Cluj-Napoca, Faculty of Geography, Department of Human Geography and Tourism (Sighetu Marmației Extension), Romania, silviu.bumbak@ubbcluj.ro*

Many incidents have occurred over the years (Ivaşcu & Biro, 2020), mainly because mountain trails overlap the pastoral trails and their summer grazing calendar. This is one of the reasons why this paper focuses on this second category, as the presence of the LGD's, even though essential for the pastoral activities (Spencer et al., 2020; van Bommel & Johnson, 2024), represents a serious risk factor and a psychological barrier for the tourists, posing challenges for mountain activities management, safety, and overall experience.

From academic and practical spatial management perspectives, efforts should be directed toward identifying synergies that addresses this issue in a predictive and proactive manner and focus on smart coexistence and smart spatial co-management frameworks. One such synergy can come from the area of animal movement analysis in heterogeneous geographical spaces. These analyses can substantiate future predictive modeling efforts that offer a new perspective on spatial trail management in mountain areas that accommodate both user categories.

The main objective of the study is to predict LGD occurrence by conceptualizing a GIS-based modeling approach that combines selected key geostatistical variables of the land used in the grazing system at two sheepfolds in the Igriş Mountains, north of Romania. The study's purpose is to explain and understand the influence of these geovariables on LGD distribution. The results are presented as a predictive map highlighting areas of LGD occurrence probability. It was hypothesized that their movement is not random and can be determined by studying the spatial characteristics of the terrain used to navigate between grazing domains. Considering the LGD as a proxy for the sheep, it can be assumed that they move alongside them, following a spatial movement pattern influenced by those variables. As such, the flock's and the dog's presence are not randomly distributed but follow a spatial pattern characterized by key physical and environmental predictors with different degrees of significance.

One important element regarding the spatial dynamics of the LGDs, a proxy for the sheep, is that these animals do not exhibit full natural behavior. Their spatial dynamics are influenced by the shepherd's decisions. We assume that these decisions are based on choices, knowledge, possibly restrictions, and that the geovariables we choose are representative of the decision-making processes in traditional pastoral landscapes. For exploratory validation of the model, the selected geovariables were combined with telemetry data from a field monitoring campaign of two LGDs at the two sheepfolds involved in the study.

Even though this is a case study, it presents a conceptual and methodological approach to better understand the spatial probability of LGD occurrence. It highlights the LGD as an important element of the pastoral system, while also acknowledging them as a source of friction in their interactions with people. This is important because the area of LGD-human interactions represents an understudied field, especially regarding the Carpathian Mountains. This is the case mainly because the academic interests have focused more on human-wildlife (especially large carnivores such as bears) conflicts. The reactive outcomes of such encounters, even though rare compared with incidents involving LGDs, have often been reported in a sensationalist manner in the press.

Findings of this type can also contribute to a shift in perspective by moving towards proactive conflict-management solutions that favor coexistence. Regarding the spatiality of LGD occurrence, the findings also demonstrate the real spatial footprint of traditional pastoral practices in heterogeneous landscapes, highlighting preferred areas of activity and providing a better understanding of the geographical context that favors them.

From an outdoor recreation planning perspective, they can contribute to predictive mapping of the vulnerability of tourist trails to LGD occurrence. This area of recreation planning usually relies on input on general mountain safety criteria, such as static potential risks, avalanche risk assessments, various geomorphological risks (e.g., rockfall), trail difficulty and technicality, etc. In a paper-to-practice scenario, predictive mapping of LGD occurrence can represent a tangible tool in the decision-making process and design of smart solutions of trail management and safety in mountain areas, such as trail routing and rerouting options, maps highlighting trail vulnerability to this kind of danger, integration of results into dedicated trail apps, and spatial planning of information and signaling infrastructure.

1.1. Description of study area and sheepfolds involved in the field monitoring campaign

The findings from a previous study focused on a primary analysis of movement of two LGDs (Bumbak et al., 2024) were also used to delineate the area of interest for this exploratory study. We used the maximum extent of their whereabouts (home range) from the telemetry data interval and expanded it by about 2–3 kilometers in each cardinal direction to define an area of approximately 113 km², considered suitable for the study’s purposes. This section of land is situated in the northern Carpathians, north of Romania, in the western part of the region known as Maramureş Land, with strong cultural, identitarian, and pastoral traits.

The region is a part of the external EU border territorial system with Ukraine (Ilieş & Grama, 2010). The local geography features a sedimentary piedmont with moderate fragmentation, bordering the Igniş volcanic mountains to the east. It decreases in altitude towards the eastern lowlands of the Mara River, one of the region's main systemic axes, where small to medium rural settlements are found. The altitudes of the area of interest range between 270 meters in the Mara River valley to approximately 1060 meters in the western highlands, with a median altitude of around 500 meters. The area represents the typical agricultural landscapes of the Carpathians, with a mosaic of natural vegetation (forests, natural grasslands, and shrubs) interspersed with patches of agricultural land and pastures.

Climatically, the area is representative of the Dfb Koppen classification, characterized by strong continental features (Kottek et al., 2006). It is also traversed east-west by local roads and trails that lead up to the highlands of the Ignis Mountains. These mountains have also become a popular hiking and biking destination for both local recreationists and tourists (see Fig. 1).

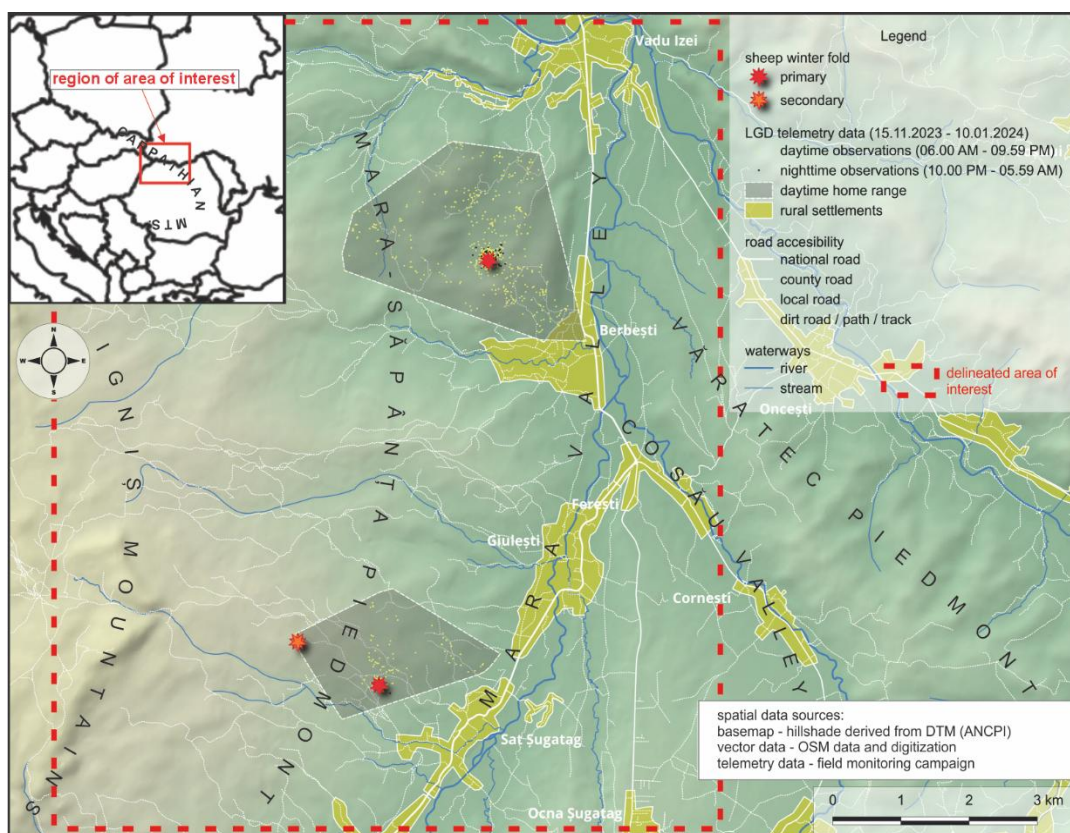


Fig.1. Delineation of area of study, location of sheepfolds and LGD field telemetry data.

2. LITERATURE REVIEW

The identification and parametrization of geostatistical and other predictors of animal movement in different environments, and proactive movement model build-up, represents a fertile research avenue in many academic fields (Laffan et al., 2012; Edelhoff et al., 2016; Rew et al., 2019; Khayli et al., 2021; Jacobson et al., 2024). Usually, this requires an interdisciplinary approach that combines statistics, modelling, and geographical analysis of terrain, land features, climate and weather features, other environmental and anthropic features, and animal ethology. This is frequently done in a GIS environment (Dănilă et al., 2024).

Papers covered subjects related especially to quantifiable spatial predictors (Avgar et al., 2013) of animal movement in mountain regions, such as topographic (Valderrama-Zafra et al., 2024) and land-use factors, habitat selection criteria and analysis (Avgar et al., 2016; Thurfjell et al., 2014), movement pattern identification (Preisler et al., 2013), tracking data representation and analysis (Seidel et al., 2018), and solutions applied in spatial management of interactions in areas frequented by people.

Another category included works related to the use of guardian dogs (Vercauteren et al., 2011; Rigg, 2001), their movement in mountain environments (Smith et al., 2026), flock and LGD spatial dynamics, and LGD's overall ethology during interactions with tourists in mountain settings (Bailly et al., 2026). It also accepted, as a proxy, a set of general features from previous research on animal movement, even when these were not directly related to other species. These features served as a methodological guideline, as they could be extrapolated to the present approach.

Environmental and topographical drivers were identified (Avgar et al., 2013) as influencing animal movement in a deterministic way by combining spatial variables (NDVI, land cover categories, distance to various landscape features, etc.) with temporal dynamic variables (precipitation, temperature, snow cover, length of day, etc.) in relation to the functional characteristics of the landscape in a cost-risk-benefit relationship. In another study, Avgar and his team examined resources as attractors that influence animal behavior and time spent in a given location using integrated step-selection analysis (Avgar et al., 2016).

Other papers mathematically demonstrate the utility of various habitat selection models, such as the step selection function, by considering real versus available spaces based on the animal's actual movement possibilities in a geographically heterogeneous environment (Fieberg et al., 2021). In other examples, authors highlight the importance of topographic factors such as natural or human-made obstacles—rivers, ravines, roads, fences, etc.—in restricting, conditioning, or guiding animal movement (Lempidakis et al., 2018), or propose a guideline for structural decomposition of the land (Panzacchi et al., 2016) based on primary topographical attributes (elevation, slope, terrain roughness index, etc.). All these spatial predictors influence the movement of animals from different species, which tend to adopt a least-cost, energy-saving movement pattern and to repeatedly use suitable movement corridors (Valderrama-Zafra et al., 2024).

Some researchers focused on the limitations of many predictive models, highlighting their predictive inadequacy outside the temporal and spatial sampling of the telemetry data or outside the parameter-defined environment (Winter et al., 2024). As a result, suggestions have been made to cross-reference telemetry data with, for example, spatial surveys or observations to improve the accuracy of predictive models (Lauret et al., 2025). Other authors highlight the importance of telemetry data abundance, sampling intensity, and the time frame over which the spatial data were collected for accurate predictions (Gerber et al., 2019).

Another aspect that caught our attention during the literature review was the importance of including correction variables (control variables), such as distance to specific landscape features, to avoid over- or underestimating landscape variables (Forester et al., 2009).

As the study's interest gravitated towards LGD ethology, which does not represent natural behavior but rather a controlled one aligned with the priorities of the sheepfold, we are aware that LGD movement is highly dependent on the shepherd's decisions. As such, any telemetry data from the dogs carries a certain degree of bias, as they represent instances of guided behavior.

A recent applied study on the movement patterns of LGDs across several Carpathian massifs (Smith et al., 2026) found that telemetry data indicate LGDs tend to stay close to the sheep, reinforcing their guarding instinct. This finding underscores the idea that dogs are seen as proxies for sheep. However, in the same study, the authors found that the “LGDs were separated from the sheep at some point each day” and that their own roaming behavior (not parametrized in this paper) took them several kilometers away, increasing the risk of encounters with other landscape users such as recreationists or tourists. Highlighting these hazards, the authors suggest buffer zones of several hundred meters around popular trails, a sound recommendation that must be adapted to specific local conditions. We also looked at papers on the issue of the large numbers of LGDs found around sheepfolds and some of the effects they have on dog behavior. For example, the pack effect (not parametrized in this paper) around a single flock that instinctively protects it. In situations like this, the dogs can become an issue (Gehring et al., 2010), as they can easily enter into conflicts with people engaged in recreational activities in the same areas (Mosley et al., 2020). These situations also speak volumes about the micro-management solutions adopted by the shepherd and about dog training.

3. METHODOLOGY

A better understanding of the land characteristics is necessary to substantiate the previous findings and highlight the geographical characteristics of the areas where the LGDs spent more time. For this purpose, we conceptualized a methodological flow (see **Fig.2**) and identified the main spatial characteristics of the geographical context using a set of 9 geostatistical variables (see **Table 1** and **Fig. 2**) that reflect the concept of animal-guided behavior, as determined by the shepherd's decisions. The selected geovariables were grouped into three categories based on literature inputs considered suitable for the study's objectives. Firstly, a set of 4 topographical variables was considered - slope, aspect, TRI (Terrain Ruggedness Index), and TPI (Terrain Positioning Index) - followed by 2 environmental variables - NDVI (Normalized Difference Vegetation Index) and CLC (Corine Land Cover).

These were supplemented by 3 logistical variables, considered control variables—distance to sheepfolds (the most important control variable for the study), distance to streams, and distance to access routes—to avoid over- or underestimating the importance of the selected topographical and environmental variables. With the exception of CLC data obtained in vector format, all other data are categorical and represented in raster format.

Aside from the own vector data, open-source spatial data (roads/trails and streams) was also used to create a database in QGIS 3.44.8 (QGIS Development Team, 2026). For the continuous spatial data, since several topographic variables were considered as defining for the analysis, a high-resolution digital terrain model (DTM) was paramount. In this analysis, we assume that a dog's spatial predictability is influenced by the sheep's movement under the shepherd's guidance in search of patches with good food sources, while accounting for terrain accessibility. Therefore, deriving reliable topographical variables describing terrain's accessibility represented an important methodological step. We searched for several reliable open-source datasets and ultimately settled on DTM data tiles available from the Romanian National Agency for Cadastre and Land Registration (ANCPI, 2026). The resolution of the tiles covering the area of interest is 5 meters x 5 meters, offering good granularity of topographically derived information - slope, aspect, TRI, and TPI. For the study area, the TPI values range from -4.55 m to 4.06 m and, together with TRI values between 0 m and 19.2 m, indicate a fragmented landscape with clear topographical variations and induced differentiation of suitable grazing surfaces (TPI > 0.5 m and TRI between 0 m and 6 m).

These are important geostatistical variables influencing movement in a least-cost, energy-saving scenario, as sheep, like most gregarious animals, usually do not prefer steep or highly fragmented terrain, as it can impede or narrow movement to certain terrain corridors. They also favor, especially during periods outside the main grazing calendar, open, southern, sunny, low-inclined slopes (between 0° and 15°), avoiding narrow valleys used mainly as transit areas between feeding domains.

Table 1.

Selected geostatistical variables

geostatistical variable	data source	short description in the context of traditional shepherding
slope (°)	derived from DTM 5 m resolution (ANCPI)	indicates topographical features facilitates / limits access to feeding grounds influences accessibility and effort of movement influences site selection for sheepfold placement influences visibility
aspect	derived from DTM	indicates micro-climate characteristics Influences site selection for sheepfold placement Influences daily related movements influences vegetation structure
TRI (m)	derived from DTM	indicates natural suitable areas for movement usually, areas with high TRI values will be avoided facilitates / limits access to feeding grounds influences visibility
TPI (m)	derived from DTM	indicates natural suitable areas for movement and observations usually, areas with positive high TPI values will be favoured influences visibility
NDVI (-1.00 to 1.00)	derived from Landsat 8 tiles EROS Archive (USGS Earth Explorer)	valuable resource indicator indicates predominant vegetation indicates available areas for grazing (0.20 – 0.40) influences visibility
distance to sheepfolds (m)	field GPS location	spatial anchor and home range center indicates areas of high sheep and LGD activity influences the probability of occurrence (the probability decreases with distance from sheepfold)
distance to streams (m)	OSM data own digitization	valuable resource indicates priority areas near the grazing domains influences site selection for sheepfold placement implications on the daily movement (maximum distance)
distance to access routes (m)	OSM data own digitization	influences site selection for sheepfold placement indicates accessible corridors of movement, even in rough terrain increases speed of movement increases access to isolated areas indicates multi-use areas (vehicles, recreationists, tourists etc.)
CLC (classes)	European Environment Agency (EEA)	indicates the predominant land cover types and habitats indicates landscape features and fragmentation indicated favoured grazing areas – open meadows, grasslands. influences visibility

The NDVI data were obtained from Landsat 8 tiles downloaded using the USGS Earth Explorer web tool (EROS, 2020) for a suitable time interval relative to the field monitoring campaign - November 2024. Using the dedicated formula $(NIR-R)/(NIR+R)$, we obtained the necessary spatial raster data at a resolution of 30 meters by 30 meters, the best available. Optimal NDVI values (0.20-0.40) indicate a direct indicator of biomass location. As the field campaign took place outside the main summer grazing season, we considered that the NDVI data should be supported by a supplementary geostatistical variable defining the local habitats. For this purpose, we used the 2018 vector format Corine Land Cover data, downloaded from the Copernicus mission (European Environment Agency, 2020). The CLC data clearly differentiates the habitats, thus adding the necessary nuance. Other data were obtained in vector format (water streams/access ways) and represent OSM data (OpenStreetMap contributors, 2026), downloaded in QGIS and annotated through digitization where the data were incomplete. For digitization, georeferenced topographic map tiles 1 to 25.000 (MTD, 1980) were used, alongside open-source satellite imagery (Bing Virtual Earth, 2026; Esri Imagery, 2026). The vector data representing water streams and access routes were treated as non-hierarchical and used to derive two important control variables: distance to streams and distance to access routes. The distance to streams is an important control variable, as it indicates the distance to the nearest water sources, since the flock must remain in close proximity for watering. They also tend to move alongside existing roads and trails.

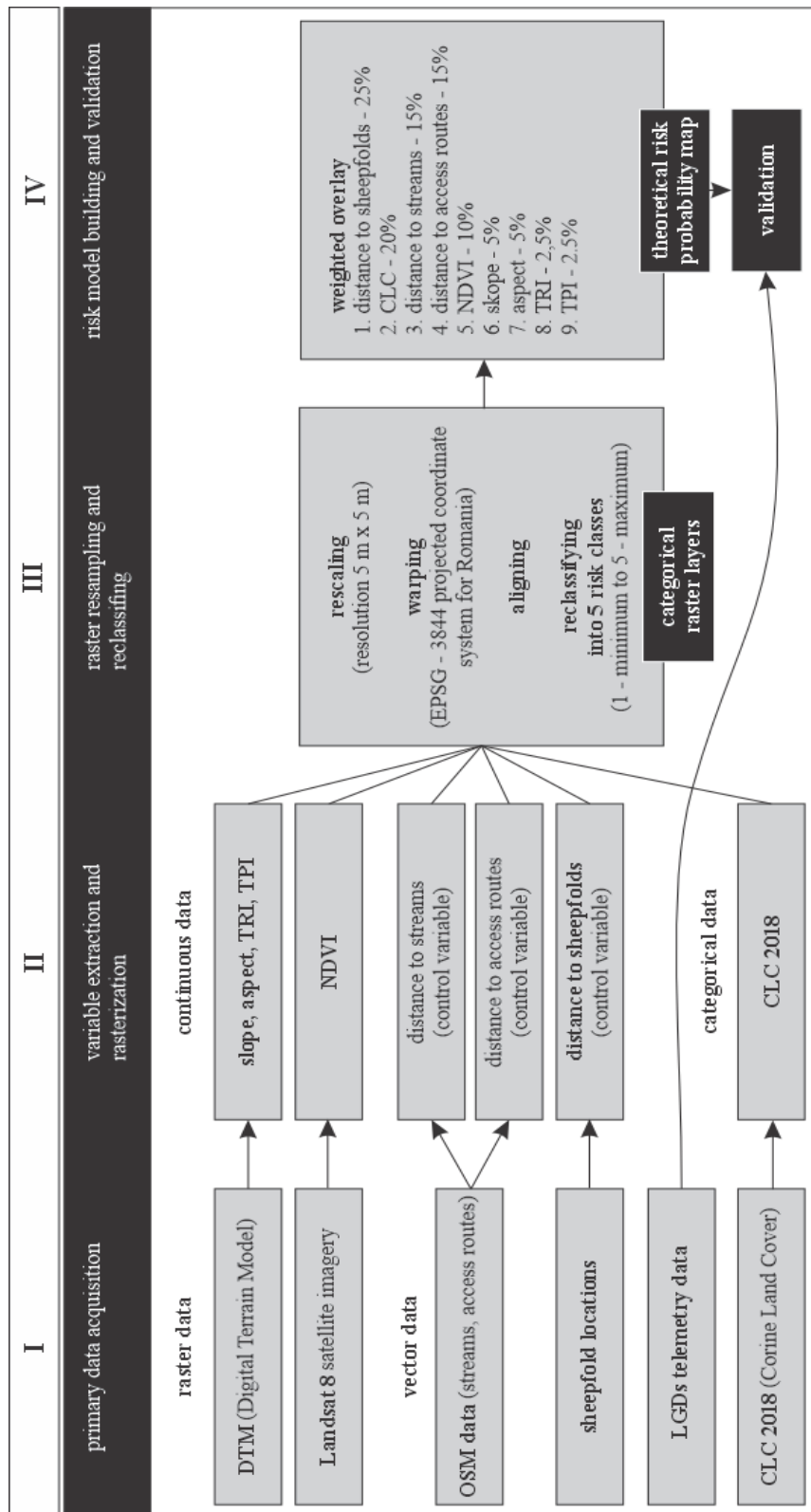


Fig.2. The main methodological stages of the case study.

Therefore, the distance to access routes was considered another important spatial predictor, with the shortest distances deemed critical, as these are the areas where encounters between dogs and people are most likely to occur. The most important control variable was derived from the own vector data representing the location of the sheepfolds - distance to sheepfolds. Based on the specificities of the pastoral system, the sheepfold was considered to act as a gravitational center, governing the entire sheepfold's activity and influencing the daily movements of the sheep and LGD's that tend to stay in or near the fold. For example, in the previous study (Bumbak et al., 2024), it was found that during the monitoring campaign, the LGDs patrolled areas of up to 6.6 km² (LGD 1) and 3.2 km², respectively, suggesting radial movement with gravitational tendencies.

To obtain the 3 key control predictors, the vector layers were rasterized using a proximity function based on Euclidean distance, where each cell represents the shortest distance to the features in question.

In order to better aggregate the data, next, the raster files were trimmed to the same extent and resampled at the best resolution available from the data - 5 meters x 5 meters. While doing so, all layers were reprojected to the Stereo 70 projection system (EPSG:3844), which is used in Romania. This system was preferred for this study due to its minimal spatial distortions and metric precision.

Considering the different units each of these raster files has, a risk scale was defined, ranging from 1 (low risk of encounter) to 5 (maximum risk of encounter) for each geostatistical variable, through a set of classification rules that were applied using the reclassification by table function in QGIS (see **Table 2**).

Table 2.

Raster data reclassification rules representing explicit thresholds related to the probability of LGD occurrences

geostatistical variable	risk categories				
	1 low risk	2 low to medium risk	3 medium risk	4 medium to high risk	5 high risk
slope (°)	> 45	30 – 45	15 – 30	5 – 15	0 – 5
aspect	N	NV / NE	W	E / SE	S / SW
TRI (m)	>15	10 – 15	6 – 10	2.5 – 6	0 – 2.5
TPI (m)	< -1.5	-1.5 – -0.5	-0.5 – 0.5	0.5 – 1.5	>1.5
NDVI (-1.00 to 1.00)	<0.20	0.75 – 1.00	0.55 – 0.75	0.40 – 0.55	0.20 – 0.40
distance to sheepfolds (m)	>2000	1000 – 2000	500 – 1000	200 – 500	0 – 200
distance to streams (m)	>1000	600 – 1000	300 – 600	100 – 300	0 – 100
distance to access routes (m)	>600	300 – 600	150 – 300	50 – 150	0 – 50
CLC (classes defined by the official nomenclature)	112 – discontinuous urban fabric	311 – broad-leaved forests 313 – mixed forests	242 – complex cultivation patterns 243 – land occupied by agriculture with areas of natural vegetation	324 transitional woodland-shrubs	231 - pastures 321 – natural grasslands
category descriptors	avoided areas	rare peripheral occurrence areas	transition areas with temporary occurrences	transition areas with frequent occurrences	core pastoral areas with permanent occurrences

In total, 9 raster layers (see **Fig. 3**) representing essential spatial characteristics as important predictors of the occurrence of the sheep and their proxies, the LGD's, were obtained (8 continuous raster layers and 1 categorical raster layer).

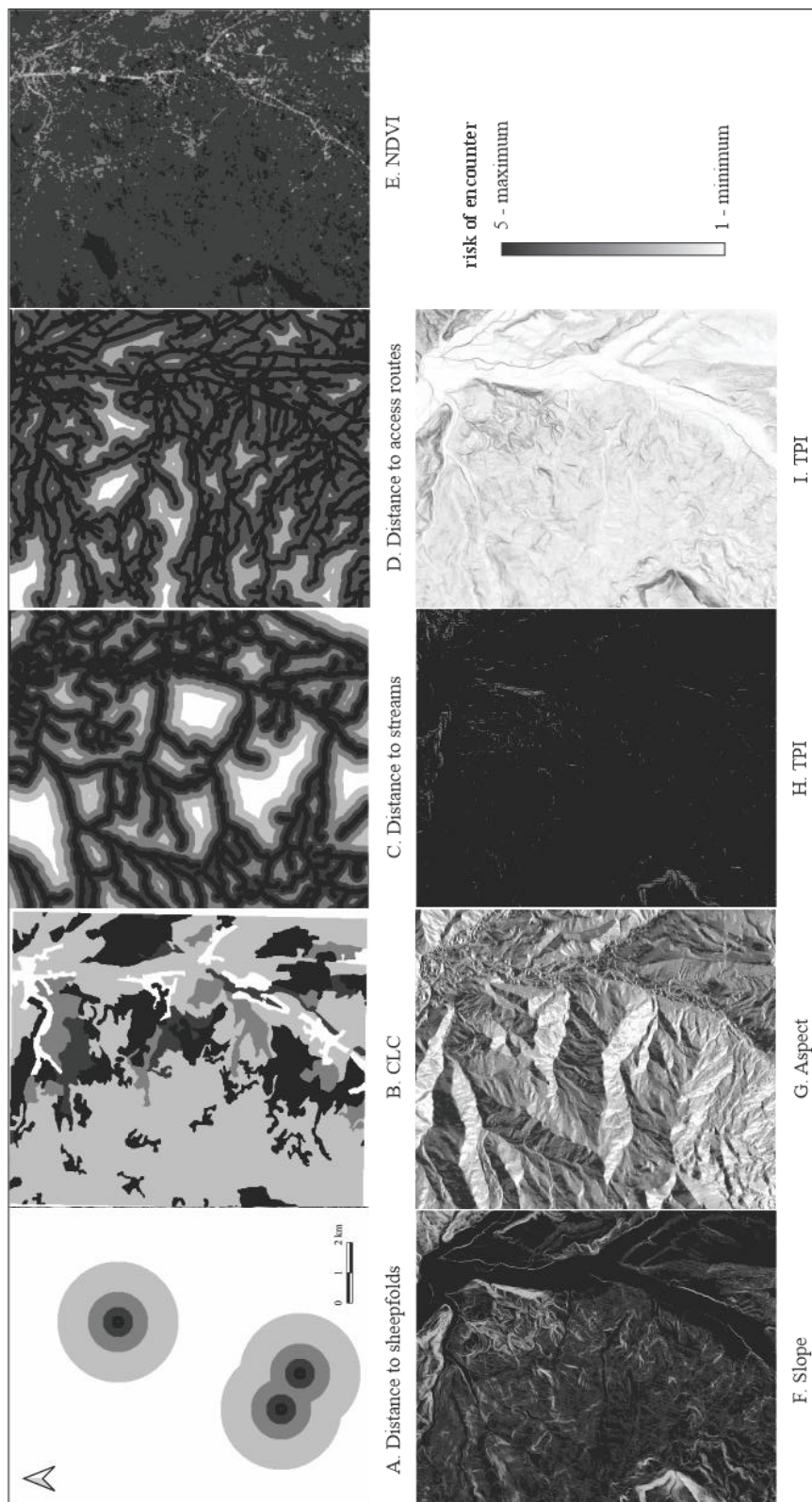


Fig. 3. Reclassified geostatistical variables representing essential spatial features for mapping the probability of encounter with sheep and LGD's .

The five risk of occurrence categories (see **Table 2**) define explicit thresholds for each geovariabile according to its own specificity, that conceptualize the spatial context of LGD occurrence probability.

For example, the 1st risk category (low risk) represents unsuitable areas with a very low theoretical probability of occurrence. This is mainly due to the topography's restrictiveness (very steep slopes, deep ravines), the northern exposure, the lack of vegetation, the presence of built areas (villages), and large distances from the three control variables.

The 2nd risk category (low to medium risk) refers to areas situated at the periphery of the usual grazing domains, where sheep or LGD occurrences can rarely be observed. This category is characterized by lower terrain, moderate to high terrain fragmentation, slope steepness and NW and NE exposure. These terrains are dominated by forestry vegetation (in the area in question, broad-leaved and mixed forests) and are situated far from the sheepfold compounds, water sources, or access routes.

In the 3rd risk category (medium risk) are areas with complex cultivation patterns, used as transition zones between grazing domains. These terrains are characterized by moderate steepness and terrain ruggedness and a predominantly western exposure, a feature exploited by the shepherds, especially in the afternoon. These terrains are situated at a moderate distance from the sheepherding infrastructure, access routes, and water sources, in a landscape dominated by mosaic agricultural lands interspersed with patches of natural vegetation.

The 4th category (medium to high risk) includes areas with gentle, low inclined upper slopes, predominantly with an eastern and south eastern exposure, favouring high chances of occurrence in the early hours of the day. These areas are situated close to the sheepfolds, water sources and access routes. The moderate NDVI values, combined with a mixed vegetation structure (forests and semi-natural areas with shrubs), make these areas highly prone to LGD occurrences, given the open transitional zones between forests and pastures.

The 5th risk category (high risk) indicates areas of very high LGD occurrence probability with favorable topographical, environmental and micro-climatic conditions for sheepfold infrastructure. These areas are found near permanent water and food sources (NDVI values of 0.20-0.40) and are characterized by terrain dominated by natural, spontaneous meadows and permanent grasslands used for grazing. Closeness to roads and trails facilitates the flock's movement during daily feeding routines.

For empirical validation purposes of the model, during November 15th of 2023 and 10th of January 2024, telemetry data were obtained from a field monitoring campaign of these livestock guardian dogs at two sheepfolds situated in proximity of one another, whose owners have agreed to participate in the study during two months in the winter period. The sheepfolds were managed at the time by two families, each possessing over 150 sheep and around 10 LGDs. At the time, we selected a young male (2 to 6 years of age) dog of Romanian traditional breeds from each sheepfold, based on several criteria discussed with the sheep owners.

This timeframe was selected following verbal negotiations and a process of trust-building. Approximately 60 days of high-intensity discrete telemetry data were gathered, with locations recorded every 30 minutes, using professional GPS trackers with GSM technology purchased from Digitalanimal, a company specializing in livestock monitoring based in Spain (Navarro et al., 2021). The first findings and the subsequent methodology were detailed in another paper published shortly after that (Bumbak, et al., 2024).

The telemetry data were used to compute home ranges and identify the most frequented areas by the animals during the night (10.00 PM - 05.59 AM) and the day (06.00 AM - 09.59 PM). In the previous study, the Kernel Density Estimation method was applied. It helped identify clusters of LGD presence near the winter folds, as well as other clusters in areas hundreds of meters away from the main compound, in certain locations (Bumbak et al., 2024). Questions remained about why these clusters were found in some areas but absent in others. Therefore, we considered that further insights could be gained by examining the defining features of the land that influence their spatial movement.

The next methodological step involved a weighted model built using a summing expression the raster calculator function in QGIS. It arithmetically combined each essential geostatistical variable multiplied with its assigned significance factor (%) as weights to obtain a theoretical occurrence probability map (see **Figs. 2** and **4**) that represents areas where the occurrence of sheep and, invariably, dogs can be high. We then superimposed the telemetry data and applied the zonal statistics algorithm in order to extract statistics and compare the data for validation.

4. RESULTS

The weighted, quantitative analysis of these geovariables using the raster calculator function in QGIS, combined with telemetry data on LGD movement, can highlight a spatial signature of high encounter rates, substantiating the development of predictive models for proactive management of mountain trails. To do so, a significance hierarchy was established for all 9 variables considered in the study. The weights corresponding to their significance (see **Fig. 3**) reflect personal and literature-based insights into sheep and LGD ethology at sheepfolds, as well as the traditional approach to shepherding in this part of the Carpathians.

In the proposed risk probability model, the control variables were ranked as most significant, totalizing 55%, while the environmental (30%) and topographical factors (15%) amounted for 45%. The distance to sheepfolds was considered the most important predictive variable with the highest significance (25%). The high percentage value reflects the importance of the geovariable acting as a true gravitational center and spatial anchor, reflecting the animals' immediate territorial reality.

The other two control variables distance to streams (15%) and distance to access routes (15%) were considered as defining variables representative of the dynamics of movement. Watering is as important as feeding, and it is assumed that the chances of encounter increase as the sheep and the dogs approach a water source. The distance to access routes is a multifunctional variable, as it defines the least-cost movement corridors for both categories of landscape users.

The environmental geovariables represented by the CLC (20%) and NDVI data (10%) – totalizing 30%, were considered defining variables representing habitat, land-use structure, and food resource. The difference in proportions is explained by the field monitoring campaign occurring during winter, when NDVI is less representative of the field conditions.

Of the proposed topographical geovariables for this model, the slope (5%) and aspect (5%) were considered conditional variables, while TRI (2.5%) and TPI (2.5%) were considered nuance variables influencing movement choices in a least-cost, energy-saving movement scenario.

Overall, the obtained risk probability map (see **Fig. 4**) emphasizes a strong interdependence between topography and the resource's location and availability.

It confirms that topographical variables predict movement, either restricting or facilitating it. The environmental variables included in this study serve as indicators of food availability for the sheep, highlighting areas of high occurrence. The high density of observation points near the control variables indicates that they act as anchors, limiting the dogs' movement in their vicinity.

In our preliminary analysis, the data were split into time intervals, with the focus mainly on the daytime interval (06.00 AM - 22.59 PM), as this time frame is typically associated with recreational outdoor activities.

For validation purposes, we used this data set to obtain relevant results. The validation process assumed the overlay of over 1200 (N=1239) daytime observations covering 60 days from both LGDs. Firstly, over 78% of the total number of daytime observations (939 observation points) were recorded in areas categorized as at least 3.5 on the probability risk scale. Thus, this skew towards high values provides statistical validation of the theoretical risk model's high fidelity. The 3.9 to 4.2 median, corroborated by a 0.35 to 0.37 standard deviation, indicates that the observed LGD locations are strongly associated with the medium (category 3) and high-occurrence areas (categories 4 to 5) identified in the occurrence probability model. Another important aspect substantiating the model is the minimum value of 2.6, indicating that the dogs avoided almost completely the areas identified in the model as low (category 1) and low to medium risk (category 2).

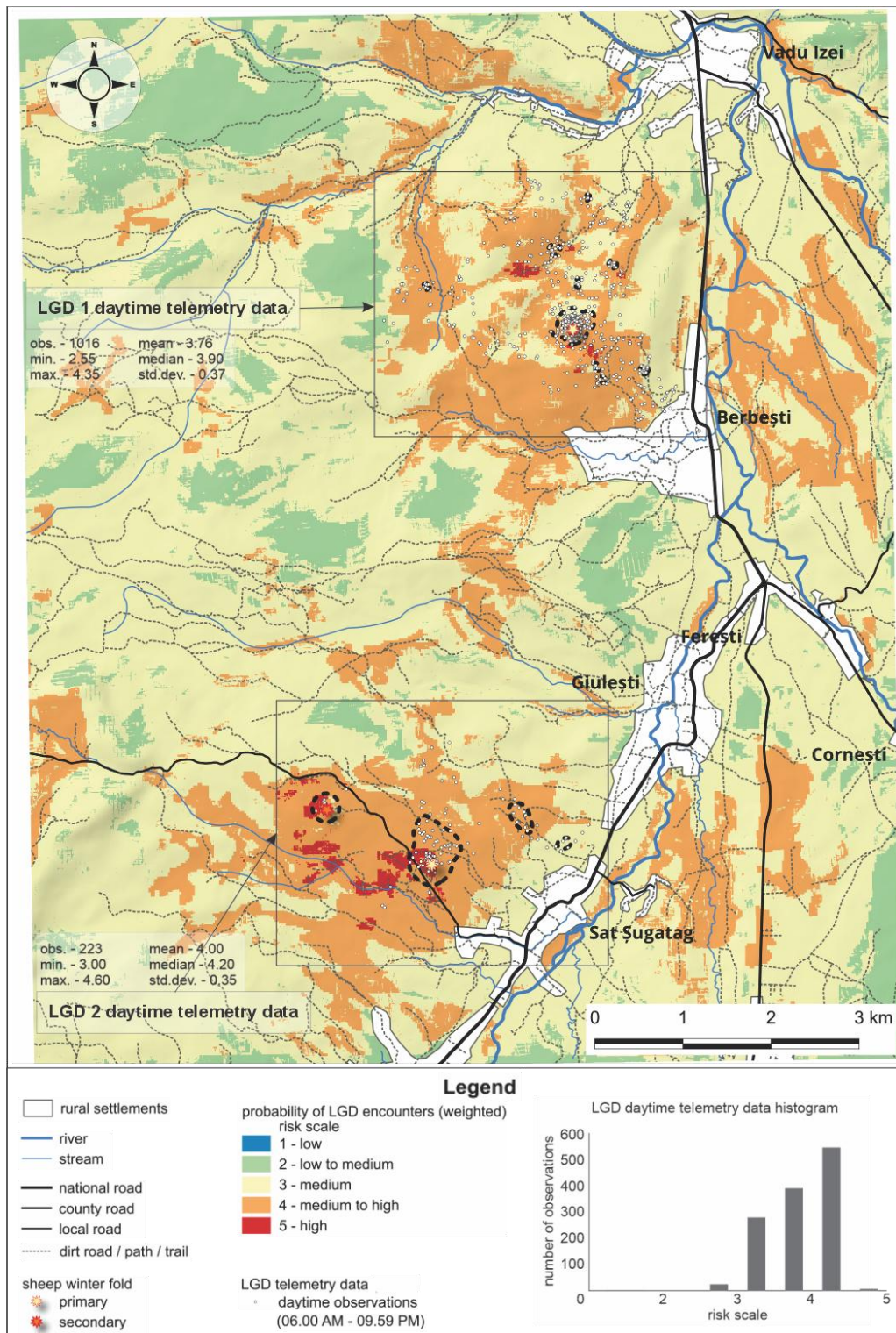


Fig. 4. Weighted theoretical occurrence probability map (9 weighted resampled geovariables) with overlay LGD daytime telemetry data used for validation purposes (spatial data sources: OSM data and field-collected telemetry data).

It also validated the criteria used to build rule-based risk categories (1 - minimum to 5 - maximum) by highlighting the avoidance of topographical areas with high slopes, dense wooded vegetation, or long distances relative to interest points/areas (sheepfold locations, water availability, and accessibility).

The study demonstrates that, even if the dog’s movement is acknowledged as induced by the shepherd’s decisions (which are not parametrized or otherwise accounted for in this study), it can still be considered highly predictable. This statement is also supported by the geostatistical variables selected and their overall significance in the model design, despite the telemetry data covering a winter interval, which is more representative of low-season outdoor activity.

To further support this, we tested our findings against a null model assuming LGD occurrences are randomly distributed and against our own model assuming they are not (see **Table 3**). For this purpose, the data analysis capabilities from M.Excel were used. A vector layer of randomly distributed points was generated to simulate the real daytime observations (N=1239). To parametrize and obtain an accurate estimate of the mean distance between the random points, the mean distance for the real observational points (171.5 m) was first calculated. This random points layer was sampled against the raster layer representing the theoretical occurrence probability map. Using the t.Test function, we ran a comparison to obtain a p-value < 0.001, as shown below.

Table 3.

Null hypothesis testing using the *t* Test: two-sample assuming unequal variances function (M.Excel).

parameters	LGD (1 and 2) real obs. points	random obs. points
mean	3.799416666	3.079691411
variance	0.145256123	0.149505836
observations	1239	1239
hypothesized Mean Difference	0	
df	2396	
t Stat	45.9123803	
P(T<=t) one-tail	0.000	
t Critical one-tail	1.645489838	
P(T<=t) two-tail	0.000	
t Critical two-tail	1.960954573	

The results confirm that the proposed model instead follows an intentional pattern of preferred spaces. The model is statistically significant, and LGD spatial occurrences do not exhibit wandering behavior.

4.1. Limitations

Although the results are encouraging, the study encountered several limitations. Given that the monitoring campaign took place in winter, outside the main pastoral season, questions can be raised about the validity of the winter spatial movement pattern relative to the summer pattern and its implications for the tourist dynamic in those areas, as summer is the prime outdoor season. This fact influenced the predictive power of another important variable - the NDVI, which was computed using autumn satellite imagery. Our findings validate low-season spatial movement characteristics.

Secondly, the field campaign produced 60 days of high-intensity spatial data, which is insufficient to substantiate a robust predictive risk probability model. The short timeframe, while valuable for an exploratory study such as this, limits the model’s ability to infer long-term LGD patterns by failing to capture essential details and shifts that occur over a full year or at least a full

pastoral season. Future field campaigns should focus on obtaining spatial data over a wider time interval.

Thirdly, in the campaign, only two large guardian dogs from two sheepfolds were involved. Again, pertinent questions can be raised regarding the robustness of the output model. In the future, field campaigns should involve a larger number of LGDs from sheepfolds situated farther apart in Carpathian settings with nuanced physical, environmental, and logistical characteristics. Also, future approaches will focus on treating control variables as hierarchical spatial structures to avoid spatial simplification of key movement predictors.

5. CONCLUSIONS

The study tested the hypothesis that the spatial distribution of LGDs, proxies for sheep, is not random but is governed by landscape features with predictive power. Using an integrated spatial approach, the landscape of the area of interest was defined by 9 geostatistical variables, each with a certain degree of significance. All variables, once defined and cartographically represented, were reclassified as categorical data using a 1-5 rules-based occurrence risk scale. The reclassified layers were used to build a weighted theoretical probability risk map that highlights areas with a high occurrence of LGD. Using telemetry data for validation, the analysis shows that over 78% of daytime LGD activity was concentrated in areas with medium to high (over 3.5) risk probability. The model demonstrates high fidelity and can serve as a starting point for a methodological discussion in the predictive mapping of the vulnerability of trails used by recreationists. Even if the dog's movement is acknowledged as being induced by the shepherd's decisions, it can be considered as having a high degree of predictability, and, using key geostatistical variables, it can highlight a movement pattern with preferred and avoided spaces. These models and their associated cartographic outputs represent valuable spatial management tools that can support decision-making. The models can be used in the process of designing trails, spatial planning tools for mountain activities, information advisories, and complementary signaling infrastructure. They can also be used for trail management and safety in mountain areas (trail routing and rerouting options), for maps highlighting trail vulnerability to LGD occurrences, or integration of results into dedicated trail apps, at least in mountain areas with similar spatial, environmental, and logistical features to the area in question in this study.

REFERENCES

- Avgar, T., Mosser, A., Brown, G. S. & Fryxell, J. M. (2013) Environmental and individual drivers of animal movement patterns across a wide geographical gradient. *Journal of Animal Ecology*, 82(1), pp. 96-106. Available from: <https://doi.org/10.1111/j.1365-2656.2012.02035.x>.
- Avgar, T., Potts, J. R., Lewis, M. A. & Boyce, M. S. (2016) Integrated step selection analysis: bridging the gap between resource selection and animal movement. *Methods in Ecology and Evolution*, 7(5), pp. 619-630. Available from: <https://doi.org/10.1111/2041-210X.12528>.
- Bailly, N., Lecuyer, L., Ba, M. & Perrin-Malterre, C. (2026) Understanding encounters between recreationists and livestock guardian dogs as a basis for conflict management. *Journal of Outdoor Recreation and Tourism*, Volume 54. Available from: <https://doi.org/10.1016/j.jort.2026.101043>.
- Bailly, N., Perrin-Malterre, C. & Chanteloup, L. (2025) Tourists and livestock in mountain areas. A cycle of attraction, avoidance and mediation. *OpenEdition Journals*, Issue 28. Available from: <https://doi.org/10.4000/1600c>.
- Bumbak, S. V., Iliș, M., Hotea, M. & Hassan, T. H. (2024) Analysis of movement data from GPS-monitored livestock guardian dogs (LGDs) at two sheepfolds in the north-western Maramures Land, Romania using the Kernel Density Estimation method. Implications for outdoor tourism. *Geojournal of Tourism and Geosites*, 54(2spl), pp. 811-820. Available from: <https://doi.org/10.30892/gtg.542spl05-1256>.

- Dănilă, G., Cătănoiu, S., Roșca, S. & Coșofreț, C. (2024) GIS analysis of the spatial distribution of European bison (*Bison bonasus* L.) in Vânători Neamț Natural Park, Romania, between 2014 and 2019. *Geographia Technica*, 19(1), pp. 135-150. Available from: https://doi.org/10.21163/GT_2024.191.10.
- Edelhoff, H., Singer, J. & Balkenhol, N. (2016) Path segmentation for beginners: an overview of current methods for detecting changes in animal movement patterns. *Movement Ecology*, 4(21). Available from: <https://doi.org/10.1186/s40462-016-0086-5>.
- Earth Resources Observation and Science (EROS) Center. (2020) Landsat 8-9 Operational Land Imager / Thermal Infrared Sensor Level-2, Collection 2 [dataset]. U.S. Geological Survey. Available from: <https://doi.org/10.5066/P9OGBGM6> [Accessed: March 2026].
- Esri. (2026) World Imagery Basemap [digital map]. Retrieved using HCMGIS plugin in QGIS. Available from: https://server.arcgisonline.com/arcgis/rest/services/World_Imagery/MapServer/tile/{z}/{y}/{x} [Accessed: March 2026].
- European Environment Agency (EEA). (2020) CORINE Land Cover 2018 (vector), Europe, 6-yearly - version 2020_20u1. Available from: <https://doi.org/10.2909/71c95a07-e296-44fc-b22b-415f42acfd0> [Accessed: March 2026].
- Fieberg, J., Singer, J., Smith, B. & Avgar, T. (2021) A 'How to' guide for interpreting parameters in habitat-selection analyses. *Journal of Animal Ecology*, 90(5), pp. 1027-1043. Available from: <https://doi.org/10.1111/1365-2656.13441>.
- Forester, J. D., Kyung Im, H. & Rathouz, P. J. (2009) Accounting for animal movement in estimation of resource selection functions: sampling and data analysis. *Ecology*, 90(12), pp. 3554-3565. Available from: <https://doi.org/10.1890/08-0874.1>.
- Gaynor, K. M., Middleton, A. D., Power, M. E. & Brashares, J. S. (2019) Landscapes of Fear: Spatial patterns of risk perception and response. *Trends in Ecology&Evolution*, Issue 34, pp. 355-368. Available from: <https://doi.org/10.1016/j.tree.2019.01.004>.
- Gehring, T. M., VerCauteren, K. C. & Landry, J.M. (2010) Livestock Protection Dogs in the 21st Century: Is an Ancient Tool Relevant to Modern Conservation Challenges?. *Bioscience*, 60(4), pp. 299-308. Available from: https://digitalcommons.unl.edu/icwdm_usdanwrc/919.
- Gerber, B. D. et al. (2019) Extreme site fidelity as an optimal strategy in an unpredictable and homogeneous environment. *Functional Ecology*, 33(9), pp. 1695-1707. Available from: <https://doi.org/10.1111/1365-2435.13390>.
- Ilieș, A. & Grama, V. (2010) The external Western Balkan border of the European Union: premises for building functional transborder systems. *Annales, Ser Historia & Sociologia*, 20(2), pp. 457-468. Available from: <https://doi.org/10.3390/rs15245763>.
- Ivașcu, C. M. & Biro, A. (2020) Coexistence through the Ages: the Role of Native Livestock Guardian Dogs and Traditional Ecological Knowledge as Key Resources in Conflict Mitigation between Pastoralists and Large Carnivores in the Romanian Carpathians. *Journal of Ethnobiology*, 40(4), pp. 465-482. Available from: <https://doi.org/10.2993/0278-0771-40.4.465>.
- Jacobson, O. T., Barrett, B.J., Perry, S.E., Finerty, G.E., Tiedeman, K.M., Crofoot, M.C. (2024) A new approach to geostatistical synthesis of historical records reveals capuchin spatial responses to climate and demographic change. *Ecology Letters*, 27(5). Available from: <https://doi.org/10.1111/ele.14443>.
- Khayli, M., Lhor, Y., Bengoumi, M., Zro, K., El Harrak, M., Bakkouri, A., Akrim, M., Yaagoubi, R., El Berbri, I., Kichou, F., Berrada, J., Bouslikkhane, M. (2021) Using geostatistics to better understand the epidemiology of animal rabies in Morocco: what is the contribution of the predictive value?. *Helyion*, 7(1). Available from: <https://doi.org/10.1016/j.heliyon.2021.e06019>.
- Kottek, M., Grieser, J., Beck, C., Eudolf, B., Rubel, F. (2006) World Map of the Köppen-Geiger climate classification updated. *Meteorol. Z.*, Volume 15, pp. 259-263. Available from: <https://doi.org/10.1127/0941-2948/2006/0130>.
- 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. *International Journal of Geographical Information Science*, 26(11), pp. 2003-2007. Available from: <https://doi.org/10.1080/13658816.2012.721557>.
- Landry, J. M. & Drouilly, M. (2020) Interactions between livestock guarding dogs and wolves in the southern French Alps. *Journal of Vertebrate Biology*, Volume 69(3), pp. 20078.1-18. Available from: <https://doi.org/10.25225/jvb.20078>.

- Lauret, V., Courbin, N. & Besnard, A. (2025) Integrating individual tracking data and spatial surveys to improve estimation of animal spatial distribution. *Ecosphere*, 16(5). Available from: <https://doi.org/10.1002/ecs2.70283>.
- 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. *Journal of Theoretical Biology*, 457(14), pp. 101-111. Available from: <https://doi.org/10.1016/j.jtbi.2018.08.024>.
- Microsoft. (2026) Bing Virtual Earth Basemap [digital map]. Retrieved using HCMGIS plugin in QGIS. Available from: <https://ecn.t3.tiles.virtualearth.net/tiles/a{q}.jpeg?g=1> [Accessed: March 2026].
- Military Topographic Directorate (1980) [Military Topographic Map of Romania]. Scale 1:25,000. Stereographic 1970 Projection. Sheets L-34-012-B-c; L-34-012-B-d; L-34-012-D-b; L-34-012-D-a. Bucharest: Military Topographic Directorate.
- Mosley, J. C., Roeder, B.L., Frost, R.A., Wells, S.L., McNew, L.B., Clark, P.E. (2020) Mitigating Human Conflicts with Livestock Guardian Dogs in Extensive Sheep Grazing Systems. *Rangeland Ecology & Management*, 73(5), pp. 724-732. Available from: <https://doi.org/10.1016/j.rama.2020.04.009>.
- Navarro, J., Martín de Diego, I., Carballo Pérez, P. & Ortega, F. (2021) Outlier detection in animal multivariate trajectories. *Computers and Electronics in Agriculture*, Volume 190. Available from: <https://doi.org/10.1016/j.compag.2021.106401>.
- National Agency for Cadastre and Land Registration (ANCP). (2026) Download MNT tiles application. [Dataset] Available from: <https://geoportal.ancpi.ro/portal/apps/webappviewer/index.html?id=50289a41aafc4e01aefd131c2105e374> [Accessed: March 2026].
- OpenStreetMap contributors. (2026) OpenStreetMap data extract for western Maramureş [Data file]. Extracted using QGIS. Available from: www.openstreetmap.org. [Accessed: April 2026].
- 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. *Journal of Animal Ecology*, 85(1), pp. 32-42. Available from: <https://doi.org/10.1111/1365-2656.12386>.
- Preisler, H. K., Ager, A. A. & Wisdom, M. J. (2013) Analyzing animal movement patterns using potential functions. *Ecosphere*, 4(3), pp. 1-13. Available from: <https://doi.org/10.1890/ES12-00286.1>.
- QGIS Development Team. (2026). QGIS Geographic Information System (version 3.44.8). QGIS Association. Available from: <https://www.qgis.org> [Accessed: March 2026].
- Rew, J., Park, S., Cho, Y., Jung, S., Hwang, W. (2019) Animal Movement Prediction Based on Predictive Recurrent Neural Network. *Sensors*, 19(20). Available from: <https://doi.org/10.3390/s19204411>.
- Rigg, R. (2001) *Livestock guarding dogs: their current use world wide*. Oxford: IUCN/SSC Canid Specialist Group Occasional Paper. Available from: <http://www.canids.org/occasionalpapers/>.
- Seidel, D. P., Dougherty, E., Carlson, C. & Getz, W. M. (2018) Ecological metrics and methods for GPS movement data. *International Journal of Geographical Information Science*, 32(1), pp. 2272-2293. Available from: <https://doi.org/10.1080/13658816.2018.1498097>.
- Smith, B. R., Yarnell, R.W., Whitehouse-Tedd, K., Marginean, M., Popa, R., Trewby, I., Faur, M., Uzal, A. (2026) So close yet so far: Movement patterns of livestock guarding dogs in a shared landscape in Romania. *Ecological Solutions and Evidence*, 7(2). Available from: <https://doi.org/10.5441/001/1.739>.
- Spencer, K., Sambrook, M., Bremner-Harrison, S., Cilliers, D., Yarnell, R.W., Brummer, R., Whitehouse-Tedd, K. (2020) Livestock guarding dogs enable human-carnivore coexistence: First evidence of equivalent carnivore occupancy on guarded and unguarded farms. *Biological Conservation*, Volume 241. Available from: <https://doi.org/10.1016/j.biocon.2019.108256>.
- Tășuleasa Social. (2026) *Via Transilvanica - Traveller Guide* [Online]. Available from: <https://www.viatransilvanica.com/en/vt-guide/> [Accessed: April 2026].
- Thurfjell, H., Ciuti, S. & Boyce, M. S. (2014) Applications of step-selection functions in ecology and conservation. *Movement Ecology*, 2(4). Available from: <https://doi.org/10.1186/2051-3933-2-4>.
- Tuan, Y.-F. (2013) *Landscapes of Fear* [Online]. University of Minnesota Press. Available from: <https://www.scribd.com/document/960679466/TUAN-Yi-Fu-Landscapes-of-Fear> [Accessed: April 2026].
- Valderrama-Zafra, J. M., Rubio-Paramio, M.A., Garcia-Molina, D.F., Mercado-Colmenero, J.M., Oya, A., Carrasco, R., Azorit, C. (2024) Impact of topographic factors on animal field pathings: Analysis and prediction of deer movement patterns. *Ecological Informatics*, Volume 80. Available from: <https://doi.org/10.1016/j.ecoinf.2024.102487>.

- van Bommel, L. & Johnson, C. N. (2024) Still a good dog! Long-term use and effectiveness of livestock guardian dogs to protect livestock from predators in Australia's extensive grazing systems. *Wildlife Research*, 51(1). Available from: <https://doi.org/10.1071/WR23008>.
- van Bommel, L., Magrath, M., Coulson, G. & Johnson, C. N. (2023) Livestock guardian dogs establish a landscape of fear for wild predators: Implications for the role of guardian dogs in reducing human–wildlife conflict and supporting biodiversity conservation. *Ecological Solutions Evidence*, 5(1). Available from: <https://doi.org/10.1002/2688-8319.12299>.
- Vercauteren, K. C., Gehring, T. M. & Landry, J. M. (2011) The dynamic role of livestock protection dogs in a changing world. *Journal of Veterinary Behavior: Clinical Applications and Research*, 6(1), p. 73. Available from: DOI:10.1016/j.jveb.2010.09.026.
- Winter, V. A., Smith, B.J., Berger, D.J., Hart, R., Huang, J., Manlove, K., Buderman, F.E., Avgar, T. (2024) Forecasting animal distribution through individual habitat selection: Insights for population inference and transferable predictions. *Ecography*, 2024(11), p. e07225. Available from: <https://doi.org/10.1111/ecog.07225>.