INSTITUTO POLITÉCNICO DE BRAGANÇA
ipb Escola Superior Agrária

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Seasonal Grazing Patterns of Sheep Herds: A GPS-Based Study in Northern Portugal

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Dissertation presented to the School of Agriculture of Bragança in partial fulfillment of the requirements for the degree of Master of Science in Forest Resources Management

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Bragança
July 2025

This research was funded by Portuguese national funds through the Foundation for Science and Technology (FCT) under the project PASTOPRAXIS Local adaptative responses of pastoralism to climate change in the Natural Park of Montesinho (Portugal)-(MTS/CAC/0028/2020).

fct Fundação para a Ciência e a Tecnologia

PASTOpraxis

To my mother,
whose care wraps around me like warmth on the coldest days—
a quiet strength that never wavers, even from afar.

To my father,
whose words lift me higher than fear ever could—
fueling my steps with every speech, every belief, every "you can".

To my sister from another mister,
soon to share this journey with me on Portuguese soil—
your presence is a celebration I carry in advance.

And to the one who called me day after day, without fail—
who checked in, cared, and stayed present through it all.
You may never know the depth of what that meant,
but in my eyes, you are the echo between the lines,
a quiet rhythm that reminded me I was never alone.
But in the end, the sunset is beautiful, isn't it?

This work is for you.
In every page, a trace of your love.

Aknowledgments

First and foremost, Alhamdulillah. I am deeply grateful to Allah for granting me the strength, courage, and perseverance to complete this Final Year Project.

I would like to express my heartfelt gratitude to my supervisors, Professor José Castro and Professor Marina Castro, for their patience, availability, generous mentorship, and valuable insights throughout this thesis. I also extend my warm thanks to Mohamed Fellahi, whose assistance and advice made a real difference during the development of my work.

I am grateful to my co-supervisor, Professor Salaheddine Essaghi, for his support and commitment to my academic progress. I would also like to thank my professors at the Hassan II Institute of Agronomy and Veterinary Medicine, especially Professor Mohamed Yessef and Professor Soufiane El Ayadi, for their insightful advice and continuous encouragement.

To my professors at the Polytechnic Institute of Bragança, thank you for your kindness and support during this academic year. Your advice and openness have made a lasting impact on both my learning and personal development. I am especially thankful to Professors Paulo Cortez, Amílcar Teixeira, and João Azevedo for their dedication and guidance.

I am deeply thankful to the Hassan II Institute of Agronomy and Veterinary Medicine for making this double-degree mobility possible in collaboration with the Polytechnic Institute of Bragança. This experience has been transformative, both academically and personally.

To my parents—thank you for being my unwavering source of strength. Your unconditional love, sacrifices, and endless support—both emotional and financial—have been the foundation of everything I've achieved. You are, and will always be, without a doubt, my greatest motivation. I'm proud to honor your efforts through this degree. And to my little brothers: I miss you more than words can express.

To the amazing friends who made this year brighter and stood by me with love and laughter—both my international companions and my dear Moroccan friends—thank you for being an unforgettable part of this chapter in my life. A special mention to Fafa, Kenza, Rim, Douaa, Mehdi and Ayman: no matter the distance, your presence is always felt.

Last but not least, I want to thank me. I want to thank me for believing in me. I want to thank me for doing all this hard work. I want to thank me for having no days off. I want to thank me for never quitting. I want to thank me for always being a giver and trying to give more than I receive. I want to thank me for trying to do more right than wrong. I want to thank me for just being me at all times.

Abstract

Pastoral systems in Mediterranean mountain regions are increasingly challenged by climatic shifts, landscape transformations, and the need for sustainable resource use. Yet, how these pressures shape daily and seasonal grazing decisions in traditional systems remains insufficiently understood. This thesis investigates the spatio-temporal dynamics of sheep grazing in Montesinho Natural Park, northern Portugal, using 15 months of high-frequency GNSS collar data from a Churra Galega Bragançana Branca ewe.

GPS trajectories were processed through Geographic Information Systems (GIS) to derive variables such as grazing duration, movement length, and land cover use. were complemented by terrain variables—including elevation, relative slope position (RSP), and topographic wetness index (TWI)—and by temporal markers tied to solstices and equinoxes. Principal Component Analysis revealed three dominant behavioral patterns: seasonal intensity of grazing, spatial shifts between plateau croplands and valley mosaics, and transitions between spring pastures and autumn shrublands.

Results show that grazing behavior is not only shaped by daylight duration and temperature but also reflects strategic adaptation to terrain and vegetation structure. Summer grazing is characterized by extended, bimodal activity patterns and high land-use diversity, while winter behavior is more constrained in both time and space. These findings underscore the value of fine-scale movement data for understanding traditional grazing systems and supporting adaptive, landscape-sensitive management practices in protected areas.

Keywords: Sheep grazing behavior, Churra Galega Bragançana Branca, Montesinho Natural Park, GPS collar, Seasonality, Land use dynamics, Climatic variations, Pastoral systems.

Resumo

Os sistemas pastorais nas regiões montanhosas do Mediterrâneo enfrentam desafios crescentes devido às mudanças climáticas, transformações da paisagem e à necessidade de uso sustentável dos recursos. Esta tese explora a dinâmica espaço-temporal do pastoreio de ovinos no Parque Natural de Montesinho, no norte de Portugal, através da análise de mais de 15 meses de dados de alta frequência obtidos por colares GNSS aplicados a uma ovelha da raça Churra Galega Bragançana Branca. O objetivo foi avaliar como variáveis ambientais e ciclos sazonais influenciam o comportamento de pastoreio, o comprimento dos trajetos e as preferências de uso do solo.

As trajetórias GPS foram processadas com recurso a Sistemas de Informação Geográfica (SIG) para extrair variáveis como o comprimento e a duração do pastoreio, bem como o uso do solo. Estas foram complementadas com variáveis topográficas—incluindo altitude, posição relativa na encosta (RSP) e índice de umidade topográfica (TWI)—e com marcadores temporais associados aos solstícios e equinócios. A análise estatística, incluindo a Análise de Componentes Principais (PCA), revelou três dimensões comportamentais principais: intensidade sazonal do pastoreio, transições espaciais entre campos de cultivo no planalto e mosaicos nos vales, e mudanças entre pastagens primaveris e matos outonais.

Os resultados mostram que o comportamento de pastoreio é moldado não apenas pela duração da luz do dia e pela temperatura, mas também reflete uma adaptação estratégica à estrutura do terreno e da vegetação. O pastoreio no verão caracteriza-se por padrões de atividade bimodais prolongados e elevada diversidade de uso do solo, enquanto no inverno o comportamento é mais restrito no tempo e no espaço. Estes resultados destacam o valor dos dados de movimento em escala fina para compreender os sistemas tradicionais de pastoreio e apoiar práticas de gestão adaptativas e sensíveis à paisagem em áreas protegidas.

Palavras-chave: Comportamento de pastoreio ovino, Churra Galega Bragançana Branca, Parque Natural de Montesinho, colar GPS, RStudio, sazonalidade, dinâmica de uso do solo, variações climáticas, sistemas pastorais.

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	DRT	Grazing Duration
	LGT	Grazing Length
Daily cycle	**START**	Deviation from 06:00 AM (grazing departure time)
	END	Deviation from 18:00 PM (grazing return time)
Annual cycle	**SS**	Proximity (in days) to Summer Solstice (June 21)
	WS	Proximity (in days) to the Winter Solstice (December 21)
	VE	Proximity (in days) to Spring Equinox (March 20)
	AE	Proximity (in days) to the Autumnal Equinox (September 22)
Physical system	**ALT**	Elevation (m a.s.l.)
	RSP	Relative Slope Position
	TWI	Topographic Wetness Index
Land Use / Land Cover (LULC)	**CROPS**	Temporary rain-fed or irrigated crops
	AGRICULTURE	Agriculture with natural and semi-natural spaces
	PASTURES	Improved pastures
	SHRUBLANDS	Shrublands
	OAKS	Forests of other oaks
	BROADLEAFS	Other broadleaf forests
	H_SHANNON	Shannon Diversity Index

1. Introduction

Pastoralism in Northern Portugal represents a significant component of the region's cultural and economic landscape, shaped by both historical practices and ongoing socio-ecological dynamics. The area's rugged mountains, characterized by limited resources, have fostered extensive grazing as a primary livelihood strategy, particularly in regions where forestry and sparse pasture dominate land use patterns (Fonseca et al., 2023). Changing weather patterns and altered landscapes are undermining traditional grazing systems and putting herding livelihoods at risk. Pastoral groups are therefore modifying their management strategies and grazing routines to protect both their income and cultural heritage (FAO, 2019).

As part of the PASTOpraxis project, this study explores how climate change affects rangeland-based grazing systems. Focusing on the relationship between flocks and their environments, the research seeks to identify practical approaches that reduce climate-related risks and help preserve the traditional grazing of sheep and goats within Montesinho Natural Park (Castro et al., 2022).

Between March 2022 and July 2023, Global Navigation Satellite System (GNSS) collars continuously recorded the positions of a Churra Galega Bragançana Branca flock in the Montesinho Natural Park (PNM), generating more than a year of high-resolution movement data spanning all seasonal cycles.

The recorded data were processed in Geographic Information Systems (GIS) to generate indicators of grazing duration, distance traveled, and the use of different land cover types, and then analyzed with RStudio. Elevation, slope position, and moisture gradients (represented by the Topographic Wetness Index) were integrated to assess how terrain characteristics shape flock behavior.

Although recent research has shown the value of GPS and GNSS collars for precisely monitoring livestock movement, understanding how sheep adjust their grazing patterns to seasonal and landscape variability in Montesinho remains limited. This knowledge gap restricts the capacity to develop informed management strategies that can enhance pastoral resilience and safeguard the cultural heritage associated with traditional grazing.

The present study aims to contribute to addressing this gap by characterizing the daily and seasonal grazing behavior of sheep herds within Montesinho Natural Park. The general objective is to analyze how grazing paths, timing, and space use are structured by environmental conditions and temporal drivers. The specific objectives are:

- To quantify the variability in grazing duration and movement length across daily and seasonal cycles.
- To evaluate the influence of temporal markers—specifically, the proximity to solstices and equinoxes—on grazing behavior and timing.
- To investigate the correlation between landscape use and the need for shelter, water, and food.
- To examine how grazing locations relate to landscape attributes, including elevation, slope position, topographic wetness, and land cover types.
- To assess patterns of land use preference, such as the use of orchards, shrublands, and temporary crops throughout the year.

This document is organized into five chapters:

- The first chapter introduces the research context, highlights its significance, and outlines the main objectives.
- The second chapter provides a review of existing studies on sheep grazing behavior and the monitoring techniques used to evaluate its impacts.
- The methods chapter explains the procedures adopted, including the deployment of GNSS collars and the data analysis workflow.
- The fourth chapter presents and discusses the results, combining descriptive statistics and inferential analyses to uncover key patterns and insights.
- The final chapter summarizes the main findings and explores their implications for sustainable grazing practices and climate change adaptation.

2. Literature Review

2.1. Overview of Pastoralism and Extensive Grazing Systems

2.1.1. Definition and Types of Grazing Systems

Pastoralism and extensive grazing are dynamic concepts often discussed within the contexts of ecological sustainability and socio-economic frameworks. The literature provides various definitions that emphasize the adaptability of pastoral systems based on environmental, social, and economic factors.

2.1.1.1. Definitions of Pastoralism and Extensive Grazing

Pastoralism is typically defined as "the extensive production of domestic livestock, primarily dependent on the grazing of natural forages" (Gregorini et al., 2022). This definition highlights a reliance on natural resources, which can vary significantly depending on regional ecosystems. Some authors extend this definition to include practices where pastoralists actively modify their environments through various means, such as improving pastures or diversifying herd diets (Kaufmann, 2009). This adaptability reflects the necessity of pastoralists to survive amidst environmental challenges, such as droughts or changing market demands.

Extensive grazing, often intertwined with pastoralism, involves the large-scale movement of herds across vast areas to seek pasture and water, typically characterized by less direct human intervention compared to intensive farming systems (Gregorini et al., 2022). The extensive grazing approach promotes ecological balance and is fundamental to many traditional pastoral communities worldwide (Moritz, 2012).

2.1.1.2. Classification of Grazing Systems

Grazing systems can be classified in several ways, notably into transhumant versus sedentary and intensive versus extensive categories. Transhumance refers to the seasonal movement of livestock between fixed summer and winter pastures. Such systems allow pastoralists to exploit different ecological zones, providing a mechanism to access varied resources throughout the year (Rodgers, 2020). Conversely, sedentary systems may involve keeping herds in fixed locations, drawing on nearby foraging resources, which could lead to increased environmental stress if not managed sustainably.

The intensive versus extensive dichotomy also plays a crucial role in classification. Intensive pastoral systems employ more domestic feeds and modern zootechnical practices to maximize livestock productivity, often at the cost of increased resource input and potential environmental degradation (Moritz, 2012). In contrast, extensive systems maintain lower inputs and higher dependence on natural pastures, which can foster resilience in fluctuating environmental conditions, although they may also be vulnerable to overgrazing and resource scarcity (Hènane et al., 2012).

In the context of Montesinho Natural Park, the grazing system does not correspond strictly to either transhumant or fully sedentary categories. Instead, it follows a localized mobile system, where herds shift their position daily and seasonally across a mosaic of land uses and altitudes, but always within a restricted radius around the home corral. This form of short-range mobility is adapted to the park's topographic complexity and fragmented land ownership. Flocks typically leave the corral in the morning, graze across temporary croplands, pastures, shrublands, and forest edges depending on the season, and return by evening. The movement patterns are dynamic and responsive to forage cycles, temperature, and terrain structure, exemplifying a semi-sedentary and landscape-responsive model of pastoralism that is typical of the Montesinho region.

Upon further examination, it is crucial to recognize the fluidity of pastoral practices, as many practitioners employ hybrid strategies that incorporate both intensive and extensive methods, especially in response to pressures such as urbanization or climate change (Moritz, 2012; Kenee et al., 2020). These practices highlight the need for comprehensive frameworks that accommodate the adaptability of pastoral systems in diverse socio-ecological contexts.

2.1.2. Importance and Benefits of Extensive Grazing

Extensive grazing advocates for animal welfare by allowing livestock to exhibit natural behaviors. Research indicates that these systems provide opportunities for species-specific behaviors such as grazing and social interaction, which are crucial for their mental and physical well-being (Rivero & Lee, 2022). Studies show that grazing is associated with lower incidences of health issues such as lameness compared to intensive systems, where animals may be confined and experience stress due to overcrowding (Wilkinson et al., 2021). Furthermore, milk from cattle grazing on pasture has shown higher levels of beneficial nutrients, positively impacting human health (Burow et al., 2013).

The relationship between extensive grazing and pasture health is complex. Well-managed extensive grazing can enhance soil health, maintain biodiversity, and support the regeneration of native plant species, which contributes to pasture productivity (Carreira et al., 2025). Effective strategies, such as rotational grazing, can mitigate overgrazing and promote ecological balance, thereby ensuring sustained forage availability and preventing land degradation (Ripamonti et al., 2023). Conversely, intensive systems may lead to soil compaction and fertility loss due to heavy machinery and concentrated feeding strategies, contributing to long-term degradation (Cao et al., 2023).

Economically, extensive grazing systems provide significant benefits to rural communities. They often enable smallholder farmers to access markets without heavy reliance on external inputs, preserving financial resources and biodiversity (Stampa et al., 2020). Additionally, products from extensive systems frequently meet the growing consumer demand for sustainably produced goods, which can command premium prices in the market (Grandin, 2018). Increased transparency and sustainability in food sourcing are consumer trends that extensive grazing systems can fulfill, enhancing the economic viability for rural producers (Sinclair et al., 2019).

Extensive grazing systems play a vital role in preserving cultural landscapes, as they are closely tied to traditional farming practices and local customs. The management of grazing animals is key to the conservation of historically and ecologically valuable landscapes (Ripamonti et al., 2023). Local community involvement in grazing sustains cultural identities and practices, adding social value to land management often overlooked in intensive systems (Grayson, 2003). For instance, native ponies grazing in the Dartmoor and Exmoor regions of the UK reflect both ecological and cultural heritage (McDonald et al., 2024).

2.1.3. Extensive Grazing in Northeastern Portugal: A Mediterranean Mountain

Historically, pastoralism in Northern Portugal is deeply rooted in traditional practices that integrate both local ecological knowledge and cultural identity. As highlighted by Rego et al. (2019), shepherding in this region embodies not just economic activity but also cultural expression tied to the broader agrarian landscape. This multifaceted approach has engendered a unique pastoral framework whereby socio-economic factors, cultural dynamics, and environmental stewardship converge (Rego et al., 2022). In contrast, pastoral systems in other Mediterranean countries, such as Greece, exhibit a long-standing reliance on herd mobility and the transhumant lifestyle, primarily driven by climatic and topographic variations that dictate grazing patterns (Hadjigeorgiou, 2011).

Where Northern Portugal diverges from other Mediterranean pastoral systems is primarily in its landscape and land use strategies. While excessive grazing has led to significant environmental changes, such as deforestation in parts of Italy, the Montesinho Natural Park implements grazing in a more controlled manner, prioritizing sustainability objectives (Bilali et al., 2021). This contrasts with findings from other regions where pastoralism can exacerbate land degradation.

Montesinho Natural Park (PNM) specifically exemplifies the interplay of pastoralism with protected area nature conservation, drawing a notable contrast with other Mediterranean grazing systems. The PNM, with its rugged terrain and diverse ecosystems, provides a habitat for both pastoral activities and biodiversity conservation. According to Matias et al. (2021), the PNM is characterized by its montane forests and associated ecosystems that support a variety of wildlife, which further complicates the pastoral landscape. This protective framework encourages a sustainable approach to pastoralism, emphasizing the coexistence of farming practices and conservation goals. Such a model contrasts with certain Mediterranean systems where pastoral activities are often marginalized due to agricultural expansion and intense land use, demanding a more integrated management strategy to recapture ecological integrity, although this aspect was not specifically addressed in any cited reference (Fernandes, 2019).

Overall, while Northern Portugal's pastoral systems adopt ecological principles shared by Mediterranean regions—such as landscape maintenance and biodiversity enhancement—they are distinct in their historical context and adaptive management strategies, especially within natural parks. Efforts in PNM exemplify a sustained commitment to integrating traditional pastoral practices with modern environmental management, embodying the dual objectives of socio-economic viability and ecological stewardship (Castro et al., 2024).

2.2. Grazing Behavior and Patterns in Sheep

2.2.1. Social and Ecological Drivers of Grazing Movement

Sheep are inherently social animals, and their grazing behavior is significantly influenced by social dynamics within the flock. Leadership roles within a flock often dictate movement patterns, with dominant individuals leading the way to foraging areas. Research indicates that sheep utilize social information to enhance foraging efficiency, particularly when unfamiliar forage sources are encountered. Naive individuals forage more efficiently in the presence of informed individuals, underscoring the significance of social learning in their grazing behavior (Vartparonian & Leu, 2023). Furthermore, social cohesion within the flock can mitigate stress, promoting collective movement towards regions with better forage availability (Bhateshwar et al., 2025).

Ecological variables, such as vegetation structure, seasonality, and soil moisture, also influence grazing behavior. The timing of grazing is often adapted to the phenological stages of vegetation growth, with sheep timing their movement to coincide with the peak availability of high-quality forage (Gedir et al., 2020). The accessibility and distribution of forage resources shape grazing routes, compelling sheep to traverse landscapes optimally to maximize energy intake while minimizing travel (Wang et al., 2010). Additionally, the nutritional quality of forage is critical;

sheep prefer regions that offer a diverse array of plant species, which enhances their dietary intake while allowing them to avoid overgrazing (Pérez-Ruchel et al., 2023). This reinforces the necessity for careful landscape stewardship to balance ecological and grazing needs (Karbo et al., 2009).

While much attention is given to the ecological and social interactions within the flock, the daily presence and decisions of the shepherd remain an often underexplored but central driver of route selection, grazing timing, and landscape use—particularly in mountainous systems like Montesinho, where terrain complexity and seasonal constraints demand human oversight.

One critical aspect of shepherding is the ability of the shepherd to adapt to the varying behaviors of sheep. The shepherd's influence is closely related to the concept of "behavioral-mode switching," where the human dynamically adjusts interactions based on context and the flock's behavior. (Nalepka et al., 2017) discuss how emergent multi-agent coordination can be facilitated by the shepherd in ways that allow sheep to exhibit rhythmic coordination, paralleling the natural collective behavior of flocking animals (Nalepka et al., 2017). This underscores the shepherd's role in not just directing sheep but also facilitating their natural behavioral expressions.

Moreover, communication between the shepherd and the flock can leverage sensory modalities. Yaxley et al. (2021) found that incorporating auditory cues during shepherding tasks can decrease stress responses in sheep and enhance predictability, which directly impacts movement patterns (Yaxley et al., 2021). This highlights the importance of sensory feedback in shepherd-led movement strategies, demonstrating that shepherds must be attuned not only to their sheep's physical location but also to their psychological states.

The organizational structure of shepherding often includes communal practices where households share shepherding responsibilities, enhancing adaptability and resilience of management practices in extensive grazing systems. While the provided reference Havas et al. (2013) discusses shared grazing responsibilities, it does not directly relate to communal shepherding dynamics specifically leading to sheep behavior adaptation, thus it has been excluded.

The behavior exhibited by sheep when under threat or disturbance, whether from shepherds or other stimuli, demonstrates their adaptive response mechanism, which is crucial for effective herd management. Studies confirm that disturbances can induce increased movement and alert reactions in sheep (Konold et al., 2008), suggesting that managing these stresses is essential for effective shepherding.

2.2.2. Seasonal and Temporal Dynamics in Grazing

Grazing patterns in sheep exhibit considerable variability across seasons and times of day. During the spring and summer months, when forage is most abundant, sheep tend to graze longer and more frequently compared to autumn and winter, when forage quality diminishes (Cosgrove et al., 2003). Diurnal patterns also emerge, with grazing typically peaking during the cooler hours of the day and decreasing during peak heat, particularly in arid environments (Atkin-Willoughby et al., 2022). This circadian rhythm enables sheep to minimize water loss and heat stress, showcasing their adaptive strategies to cope with environmental constraints (Edwards et al., 2005).

Temporal strategies adopted by sheep include selective grazing, where individuals may choose specific plant types depending on their availability and quality at different times of the day or year (Devine et al., 2019). In addition to actively selecting for quality forage, sheep may also employ behavioral adaptations such as wait times in shade to conserve energy during hotter periods. This kind of strategic grazing aligns closely with fluctuations in plant phenology, demonstrating an intricate relationship between sheep movement and environmental conditions (Webby & Sheath, 2000). By understanding these seasonal and temporal dynamics, pastoralists can better manage grazing practices to ensure sustainable livestock production (Atiba et al., 2021).

2.2.3. Influence of Vegetation Dynamics through the Annual Cycle

Vegetation dynamics play a pivotal role in determining grazing site selection throughout the year. As seasons change, so do the types and quantities of available forage, driven by climatic conditions, which influence plant phenology. For instance, in temperate regions, sheep tend to select areas with newly sprouted grasses during the spring months, reflecting a preference for young, nutritious forage (Walker et al., 2006). As summer progresses, the focus shifts toward different species that may be more resilient to heat, impacting both site selection and feeding behavior (Wood et al., 2012).

However, it is important to note that the spatial unit of grazing is not chosen by the animal alone. The shepherd plays a central role in selecting the broader landscape units or habitats that the flock will access, based on terrain, seasonal availability, and management goals. Within those zones, sheep then make finer-scale decisions on which plant species and parts to consume.

Forage quality and availability are further interlinked with soil health and moisture availability. Regions characterized by fertile, well-drained soils often yield higher-quality forage, attracting grazing pressure (Zhang et al., 2022). Sheep will selectively graze in areas where nutrient availability aligns with their dietary needs, thus impacting grazing intensity and subsequent vegetation dynamics (Widdup & Barrett, 2011). The relationship between grazing and vegetation health underscores the importance of rotational grazing practices that allow rest periods for vegetation regeneration, thereby maintaining ecosystem balance and ensuring continuous forage availability (Utrilla et al., 2005).

2.2.4. Influence of Terrain Features on Forage Accessibility

Topographic features significantly influence sheep grazing behavior by altering access to forage. The slope, elevation, and wetness of terrain can dictate which areas are more accessible for grazing (Salinas-Melgoza et al., 2018). For instance, steeper slopes may deter grazing due to the physical effort required, while more level ground typically provides easier access to nutritious plants (Wagler et al., 2024). Additionally, features such as wetlands offer rich forage but can also present challenges, as waterlogged areas may be avoided during certain times of the year (Gedir et al., 2020).

Terrain constraints modify both grazing routes and the intensity of feeding. In regions with pronounced elevation changes, sheep tend to utilize certain established trails that provide easier access to forage while avoiding more arduous direct routes (Rodríguez et al., 2024). Moreover, these topographical barriers can lead to the establishment of localized grazing patterns that exacerbate overgrazing in more accessible areas, requiring careful management to prevent long-term degradation (Ismiraj et al., 2024). The integration of terrain features into grazing management strategies can enhance the sustainability of sheep farming practices by ensuring optimal use of available resources (Egeru et al., 2015).

2.3. Technologies in Livestock Monitoring

2.3.1. Traditional and Direct Observation Methods

Traditional monitoring methods for livestock grazing behavior have long relied on direct observation. Shepherds and farmers have utilized techniques such as visual assessment of grazing patterns, movements, and health indicators among sheep (Indra et al., 2022). These direct methods allow for immediate data collection on animal behavior, facilitating timely management decisions. However, such techniques are not without limitations; they can be labor-intensive, time-consuming, and prone to human bias (Atkin-Willoughby et al., 2022). Moreover, variations in terrain and flock dynamics can complicate comprehensive assessments, making it difficult to achieve consistent and objective data collection over larger scales (Webby & Sheath, 2000).

The advent of technology has enabled more precise methods of monitoring livestock behavior, addressing many of the limitations associated with traditional observation methods. Incorporating tools such as aerial imagery and satellite tracking systems enhances the understanding of grazing patterns and the spatial dynamics of livestock herds, offering richer datasets for analysis (Ahmad et al., 2020). While these modern techniques augment knowledge significantly, they also present challenges such as data management complexity and the potential for high costs associated with technological adoption (Zhai et al., 2021).

2.3.2. GNSS/GPS Collar Monitoring

GPS (Global Positioning System) collars, equipped with GNSS (Global Navigation Satellite Systems) technology, have become essential tools for monitoring livestock movements and grazing behaviors (Castro et al., 2021). By providing real-time tracking data, researchers gain valuable insights into grazing patterns, habitat utilization, and interactions within livestock groups (Samuel-Nakamura et al., 2017; Edwards et al., 2005).

Figure 1: Monitoring goat herd movements using solar-powered GPS collars (Fan et al., 2022)

2.3.2.1. Accuracy and Reliability

Recent advancements have significantly improved the precision of GNSS collars, achieving positional accuracy between 90-94%, as confirmed by visual observation comparisons (Fogarty et al., 2015). Techniques such as buffer zones and rolling averages further minimize GNSS errors, enhancing data reliability (Kodam, Duthie, & Waterhouse, 2017).

2.3.2.2. Integration with Other Technologies

Integrating GNSS with accelerometers, weather sensors, and machine learning algorithms enhances livestock monitoring capabilities. Such multifaceted solutions facilitate timely management actions by detecting critical events like parturition, thus significantly contributing to animal welfare and productivity (Fogarty et al., 2021).

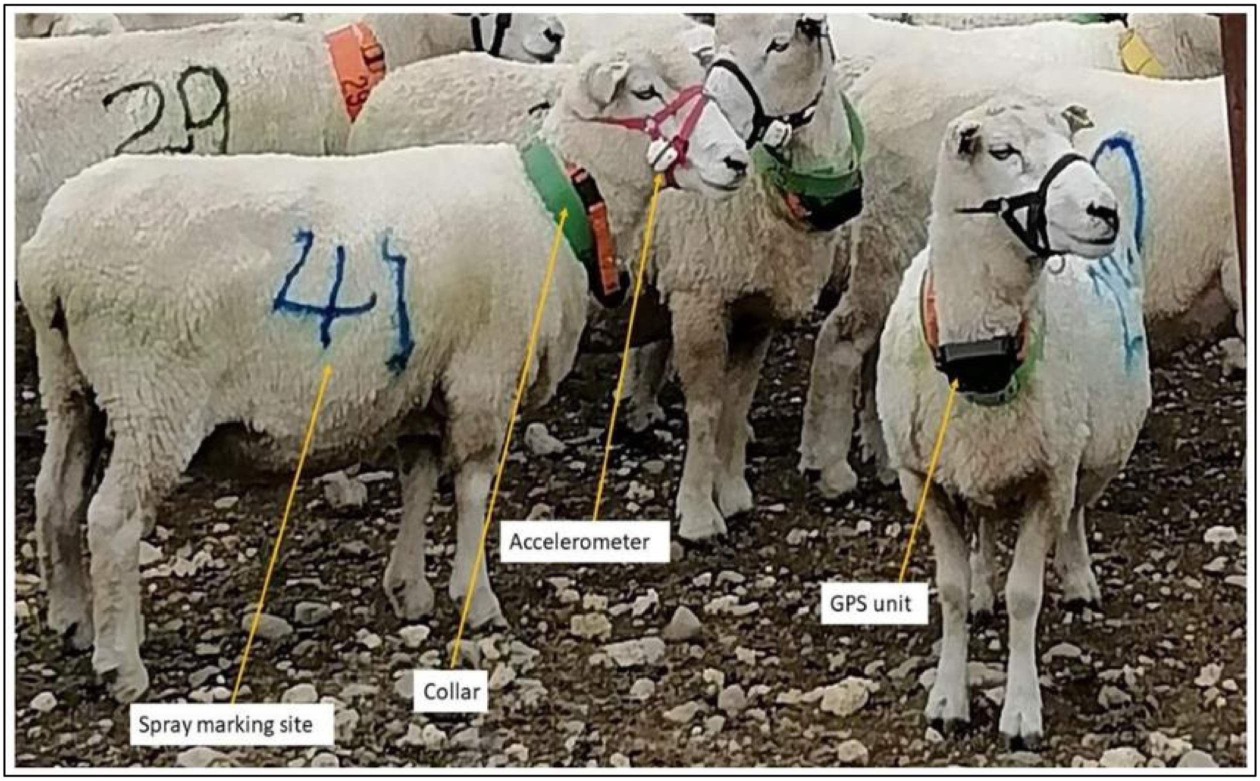


Figure 2: A photo of sheep with spray marks wearing accelerometers, GPS, and collars (Bunyaga et al., 2023)

GNSS collars effectively differentiate activities such as grazing, resting, and transit, enabling detailed studies of livestock movement patterns and preferred grazing locations. Castro et al. (2020) highlight that GNSS receivers are highly effective in monitoring sheep flock movements, enabling accurate estimation of grazing durations across various land use areas and providing comprehensive spatial data on animal movements. For example, in Serra de Montemuro, Portugal, GNSS collars accurately monitored sheep and goats flock distribution, significantly contributing to reproductive management improvements (Castro et al., 2023).

Table 1 : Comparative Table of GNSS Applications in Livestock Management

Species	Technology	Context	Aim	Citation
Livestock (general)	Satellite-based GPS + IoT systems	Indonesia livestock waste management	Enhance sustainability via real-time waste monitoring	(Hudono et al., 2024)
	GPS technology	Predation risk assessment in Western Iran	Understand grazing behavior influenced by predator presence	(Mohammadi et al., 2019)
Goats	GPS collars with accelerometers	Forest rangelands, Southern Mediterranean	Optimize grazing patterns and productivity	(Chebli et al., 2022)
	GPS collar technology	Dairy goats grazing	Enhance understanding of foraging behaviors and energy balance	(Chebli et al., 2022)
Cattle	GPS shock collars (virtual fences)	UK cattle herd trials	Evaluate welfare implications and practical use of GPS collars for managing movement, preventing injuries, and enabling targeted monitoring	(McCormick & Stokes, 2023)
	GPS + motion sensors	Extensive rangelands	Real-time alerts for detecting abnormal behaviors	(Mancuso et al., 2023)
	GPS collar technology	Arizona rangelands	Analyze stocking density impacts on cattle association and land use	(Tobin et al., 2021)
Sheep	GPS collar technology	North-eastern Portugal's small ruminant systems	Adjust GPS tracking protocol for better land management	(Castro et al., 2022)
	GPS tracking collars	Predator management and enhancement	Improve flock safety and breeding management	(Bailey et al., 2021)

2.3.2.4. Economic Considerations

The costs of monitoring included both the purchase of equipment and the subscription to web platform services, emphasizing the importance of balancing financial investment with the desired level of precision (Castro et al., 2022). While GNSS technology requires significant upfront expenditures, recent technological advances have made these tools more affordable and widely accessible, promoting their adoption in extensive livestock research and management (Trotter et al., 2010).

2.3.2.5. Challenges

GNSS collars face practical limitations, including potential loss or damage, which can lead to data collection gaps (Molle et al., 2021). Social dynamics within livestock groups also complicate data interpretation, as leadership roles may significantly influence movement patterns (Zhai et al., 2021). Nevertheless, combining GNSS with other monitoring tools helps address these challenges, improving overall livestock management practices (Utrilla et al., 2005).

Continuous technological improvements promise to further enhance GNSS capabilities, supporting sustainable livestock grazing practices. Future developments will likely broaden the practical applications of GNSS, aiding researchers and livestock managers in adapting to evolving environmental conditions and ensuring effective resource management (Trotter et al., 2010).

2.3.3. GIS and Remote Sensing Applications in Grazing Pattern Analysis

Geographic Information Systems (GIS) and remote sensing have become invaluable tools for analyzing grazing patterns and their ecological impacts. These technologies facilitate the integration of spatial data and environmental variables, allowing for comprehensive assessments of grazing behavior in relation to habitat features (Indra et al., 2022). GIS enables researchers to visualize and manipulate data related to sheep movement, forage availability, and landscape characteristics, providing insights that can improve pasture management practices (Amar et al., 2010).

The application of remote sensing allows for large-scale monitoring of vegetation changes and habitat conditions over time, enhancing the understanding of ecological drivers behind grazing behavior. For example, studies utilizing satellite imagery can track changes in forage biomass availability relative to rainfall patterns (Devine et al., 2019). Furthermore, combining remote sensing data with GIS-based analyses permits more nuanced spatial analyses, which can inform land use planning and sustainable agriculture practices (Commun et al., 2009).

2.4. Environmental Sustainability and Climate Change Impacts

2.4.1. Grazing Impacts on Rangeland Ecosystems

The impact of grazing on rangeland ecosystems can be both positive and negative, depending on management practices and grazing pressure. On one hand, properly managed grazing can promote plant diversity, improve soil fertility, and enhance overall ecosystem resilience (Maheswaran et al., 2022). Negatively, overgrazing can lead to soil degradation, reduced plant diversity, and increased erosion rates, significantly impairing ecosystem health (Oñatibia et al., 2023). Undergrazing occurs when there are too few animals in relation to the area's capacity, resulting in an excessive accumulation of plant biomass, which can hinder pasture regeneration and increase the risk of forest fires. Both extremes can negatively impact the ecological balance and sustainability of pastoral systems. Herbivory influences vegetation structure and composition, which in turn affects wildlife habitat and biodiversity (Bhateshwar et al., 2025).

Grazing pressure has profound implications for soil properties. Studies indicate that intense grazing can diminish soil organic matter and alter microbial communities, negatively affecting soil quality and its ability to support plant growth (Rankins et al., 2024). Conversely, moderate grazing regimes can stimulate grassland dynamics, fostering conditions that promote nutrient cycling and soil health (Utrilla et al., 2005). Thus, grazing management must balance animal needs with ecological health to sustain both livestock productivity and environmental quality (Edwards et al., 2005).

2.4.2. Ecosystem Services Provided by Extensive Grazing

Well-managed grazing systems provide crucial ecosystem services, including biodiversity maintenance, carbon sequestration, and nutrient recycling (Walker et al., 2006). These services contribute significantly to landscape sustainability and resilience, particularly in areas prone to environmental stressors such as climate variability (Zhang et al., 2022). For instance, grazing promotes the growth of diverse plant communities, enhancing habitat quality for various wildlife species while also supporting livestock production (Mamedkuliev, 2020).

Extensive grazing fosters rangeland health by maintaining nutrient cycling through effective manure deposition, which enhances soil fertility (Indra et al., 2022). Such integration can stimulate plant growth, ensuring a continuous forage supply for livestock while preserving ecological integrity (Villepique et al., 2015). Additionally, the socio-economic benefits of sustainable grazing practices can help support rural communities and contribute to livelihoods through agricultural production and ecosystem service enhancement (Amar et al., 2010).

2.4.3. Pastoralist Adaptation Strategies to Climate Change

Pastoralists have historically adapted to climatic variability through various strategies that enhance herd resilience. Measures include shifting grazing locations, managing herd composition, and employing herd mobility to access better resources (Ghimire et al., 2017). Moreover, the adoption of innovative practices such as water conservation techniques and forage preservation has illustrated adaptability in response to changing climatic conditions, ensuring herd productivity (Fan et al., 2021).

Effectiveness can vary based on local conditions and individual circumstances. For instance, the use of drought-resistant forage species and alternative grazing plans can mitigate the impacts of climate stress on pastoral systems, improving long-term sustainability (Garin et al., 2000). As climate change continues to pose challenges, continuous adaptation and learning will be critical to maintaining productivity and ecosystem health within pastoral systems (Beale et al., 2023).

2.4.4. Policy and Governance for Sustainable Grazing Systems

The integration of grazing livelihoods with rangeland conservation represents a complex challenge, particularly in Mediterranean ecosystems characterized by unique ecological and socio-economic dynamics. Effective policy frameworks, incentive schemes, and common-property arrangements can significantly impact grazing management practices and conservation outcomes.

One effective policy framework involves the implementation of Payment for Ecosystem Services (PES) schemes. These schemes provide financial incentives to local livestock herders to adopt sustainable grazing practices that align with conservation goals, such as wildfire prevention through targeted grazing (Varela et al., 2018). For instance, the RAPCA (Red de Áreas Pastorales para la Prevención de Incendios, or Network of Pastoral Areas for Fire Prevention) initiative exemplifies such a scheme, offering incentives for shepherds to manage grazing in a manner that reduces flammable biomass, thereby promoting both rangeland health and community livelihoods (Varela et al., 2018). This dual focus on conservation and socioeconomic viability is crucial, as overgrazing and land degradation can result in biodiversity loss and ecological imbalance, particularly in Mediterranean landscapes (Papanastasis et al., 2015).

In addition to PES (Payment for Ecosystem Services), common-property arrangements in the management of rangelands can facilitate sustainable grazing practices. Many Mediterranean grazing systems function as common-pool resources, where local communities collectively manage access to pastures. However, these systems require careful governance to prevent over-exploitation (Bennett et al., 2010). The challenges associated with property rights pertain to the potential fragmentation and privatization of communal lands, which can undermine the effectiveness of traditional pastoralist practices (Schmidt & Pearson, 2016) . Strengthening community-based management structures can enhance resilience and adaptability among pastoralists, particularly when institutional supports are aligned with the socio-economic realities of pastoral livelihoods (Zinsstag et al., 2016).

The design of incentive structures is another critical factor influencing pastoral practices. For example, institutional support can include mechanisms that reward sustainable grazing practices, thereby directly impacting the livelihoods of pastoralists in regions where the grazing pressure is significant (Dong et al., 2007). In Mediterranean contexts, such support has proven essential for maintaining grazing traditions, ensuring that they contribute to preserving ecological integrity while sustaining local economies (Zinsstag et al., 2016). Conversely, insufficient institutional support can lead to unsustainable practices and the degradation of rangeland resources, which hampers the livelihoods of pastoral communities (Schmidt & Pearson, 2016; Zinsstag et al., 2016).

In Portugal, the Common Agricultural Policy (CAP) of the European Union has significantly influenced the livelihoods of pastoralists. There are critiques that the CAP may constrain pastoralist flexibility due to rigid guidelines that favor intensive agriculture over traditional practices (Nori, 2024) . This scenario illustrates broader challenges in Mediterranean regions, where traditional methods often conflict with modern agricultural policies. Reforms to the CAP could potentially better support multifunctional landscapes that integrate grazing and conservation (Carreira et al., 2025).

Additionally, diverse financial incentives aimed at conserving ecosystem services enhance the economic viability of rangelands. Public land uses, which support communal grazing and incorporate various ecosystem services, yield higher overall economic values compared to privatized land uses that primarily focus on immediate agricultural returns (Favretto et al., 2016). Sustainable management practices must adopt a holistic view of ecosystem services, ensuring that policies acknowledge their multifaceted benefits while incentivizing conservation.

2.5. Synthesis of Knowledge Gaps and Relevance to the Present Study

Despite rapid advances in livestock-tracking technology, the literature still offers only a fragmentary picture of how small-ruminant flocks in complex mountain of Northern Portugal landscapes adjust their daily and seasonal movements to intersecting ecological, topographic and climatic constraints. By coupling more than a full year of 5-minute-high-resolution GNSS collar records from a Churra Galega Bragançana flock with fine-scale GIS-derived elevation, RSP, TWI and COS-land-cover layers, and temporal markers tied to solstices and equinoxes, the present study delivers an integrated, data-rich portrait of sheep space-use dynamics in Montesinho Natural Park in the context of climate change. The resulting departure-time rules, pressure maps and preference indices give park staff and herders actionable tools for fire-break grazing and orchard integration, filling the science–practice gap and boosting pastoral resilience.

3. Material and Methods

3.1. Description of the Montesinho Natural Park

3.1.1. Location and Classification

Montesinho Natural Park (PNM), located in the administrative region of Alto Trás-os-Montes in northeastern Portugal and spanning across parts of the municipalities of Bragança and Vinhais, encompasses an area of approximately 74 224.9 hectares (≈ 742 km²). Designated as a "Natural Park" in 30 August 1979, under Portuguese Decree-Law 355/79, PMN is classified as a protected area under the International Union for Conservation of Nature (IUCN) category V, which emphasizes the management of protected landscapes and seascapes while allowing for sustainable human interaction with nature (Pereira et al., 2007).

3.1.2. Climate

The climate within Montesinho Natural Park is typically temperate, influenced by its elevation and geographical position. It experiences cold winters and warm summers, with average temperatures ranging from around 8°C in winter to 20-25°C in summer (Matos Silva et al., 2022). The average annual rainfall varies from 1262 (Montesinho mountain range) to 806 mm (Lombada plateau) with significant precipitations occurring during the autumn and winter months, which supports the park's extensive forest and vegetation cover (Castro et al., 2009; 2021).

3.1.3. Topograpy

This protected area is noted for its diverse ecosystems and cultural heritage, situated predominantly within mountainous terrain characterized by elevations ranging from the lowest point in the River Mente (436 m), its western border, to the top of Montesinho, at 1,487 m (Castro et al., 2009). The topography of the park is defined by its rolling hills, steep gradients, and various types of landscapes, which contribute to its unique biodiversity and ecological value (Fonseca, 2012; Matos Silva et al., 2022).

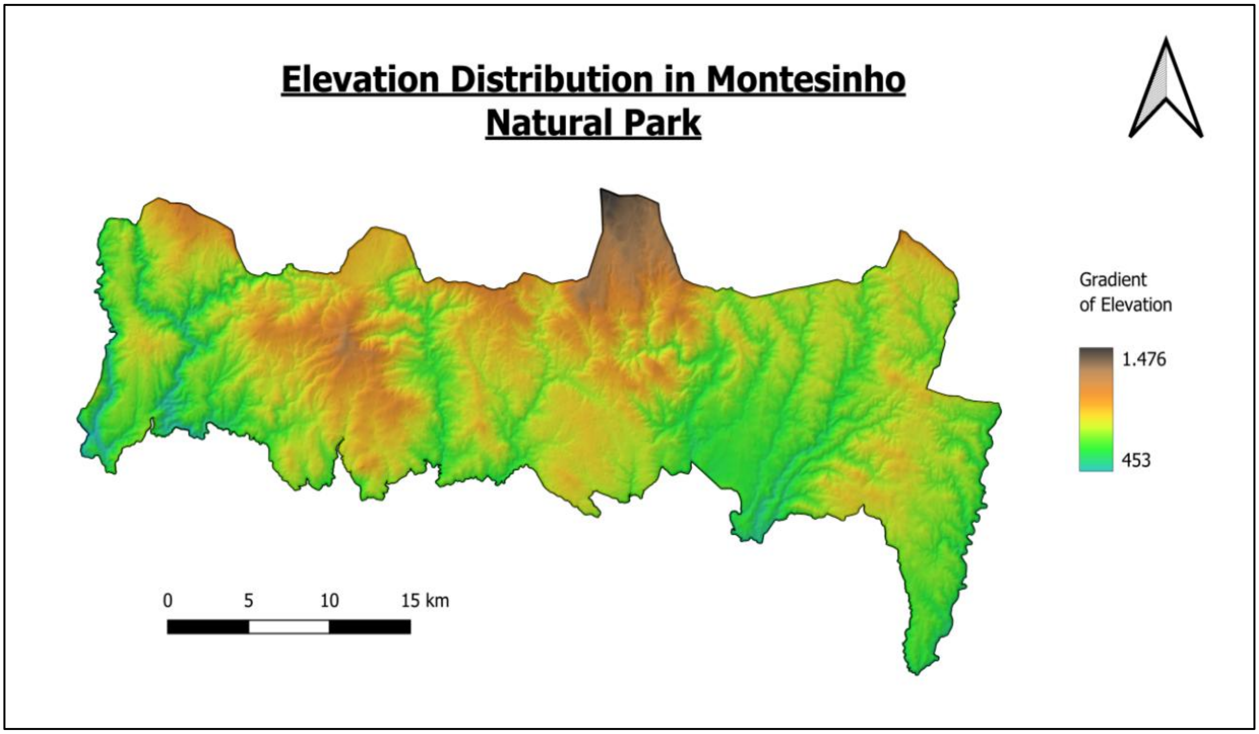


Figure 3: Elevation Distribution in Montesinho Natural Park Using Digital Elevation Model (DEM) Data

3.1.4. Hydrology

Hydrologically, the park is characterized by several rivers and streams, notably the Rio Sabor, Rio Maçãs, and Rio Tuela, all integral components of the larger Douro River basin. These waterways play a critical role in shaping the regional ecosystems and provide essential water resources for agricultural and pastoral activities.

3.1.5. Geology and Geomorphology

Geologically, the park is part of the northern Iberian Meseta, showcasing varied rock types and geological formations that are reflective of its complex geological history (Fonseca, 2012). The park's landscapes include a mix of natural wooded areas and traditional agricultural landscapes, supporting a rich array of flora and fauna. The geomorphology is marked by its predominant median elevation and the presence of significant geological features, such as river valleys and steep slopes, which collectively shape the habitat diversity within the park (Castro et al., 2009; Fonseca, 2012).

3.1.6. Landscape Units

The landscape of Montesinho Natural Park can be divided into five distinct units: Woodlands and rangelands, Rangelands with pineyards, Vinhais, Open landscapes, and Granite mountain (Castro et al., 2010).

Table 2: Extent of Montesinho Landscape Units and Their Share of the Park

Landscape Unit	Area (103 ha)	% PNM
Woodlands and rangelands	32.20	43%
Rangelands with pineyards	17.96	24%
Vinhais	14.95	20%
Open landscape	6.06	8%
Granite mountains	3.13	4%

Woodland and Rangelands – This is the park's most extensive zone, dominated by broad oak stands intermingled with brushy pastures. Despite the steep, uneven ground, it supports long-established flocks of sheep and goats and retains high ecological value (ICNF, 2019). This is the type of landscape where our study area is located.

Figure 4: Woodland–Rangeland Mosaic, Montesinho Natural Park

Rangelands with Pineyards – Here, Mediterranean scrub merges with scattered pinewoods and pockets of farmland, creating a patchy grazing matrix (ICNF, 2019).

Figure 5: Rangelands with pineyard, Montesinho Natural Park

Vinhais – Around Vinhais, small rural settlements manage a tapestry of fields, chestnut groves, and livestock plots that sustain both biodiversity and local livelihoods (ICNF, 2019).

Figure 6: Vinhais, Montesinho Natural Park

Open Landscapes – Southeast of the park, broad, gently sloping farmland is laid out in simple, rectilinear parcels, giving this sector a markedly open character (ICNF, 2019).

Figure 7: Open Landscape, Montesinho Natural Park

Granite Mountain – The highest, most rugged section rises on granitic bedrock, featuring sparse shrub cover, upland pastures and rocky escarpments that impart a remote, dramatic feel (ICNF, 2019).

Figure 8: Granite Mountain, Montesinho Natural Park

3.1.7. Land Use and Vegetation Types

Land use within Montesinho Natural Park predominantly consists of extensive agroforestry systems, chestnut orchards, oak and pine forests, shrublands, and agricultural areas characterized by traditional farming methods. The vegetation types range from Quercus woodlands to montane grasslands, which serve as habitats for various species, including many that are endemic or of conservation concern (Carvalho, 2016).

Oak woodlands, particularly those composed of species such as Quercus pyrenaica, dominate significant portions of the landscape. Shrublands composed of heath and broom species are widespread in higher altitude zones, while chestnut orchards and agricultural areas mainly occupy valleys and lower slopes, contributing substantially to local economic and cultural practices.

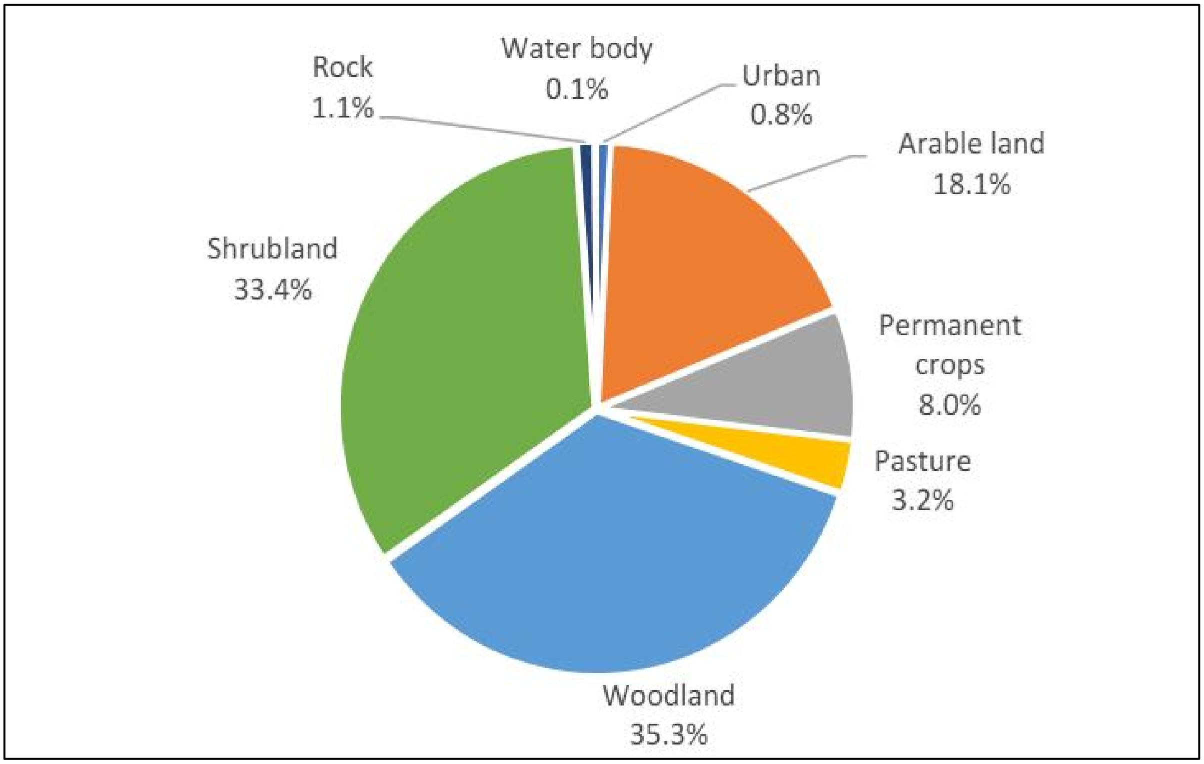


Figure 9: Land use (ha) in 2018. Source: Matos Silva et al., 2022 own elaboration using data from (Castro et al., 2021).

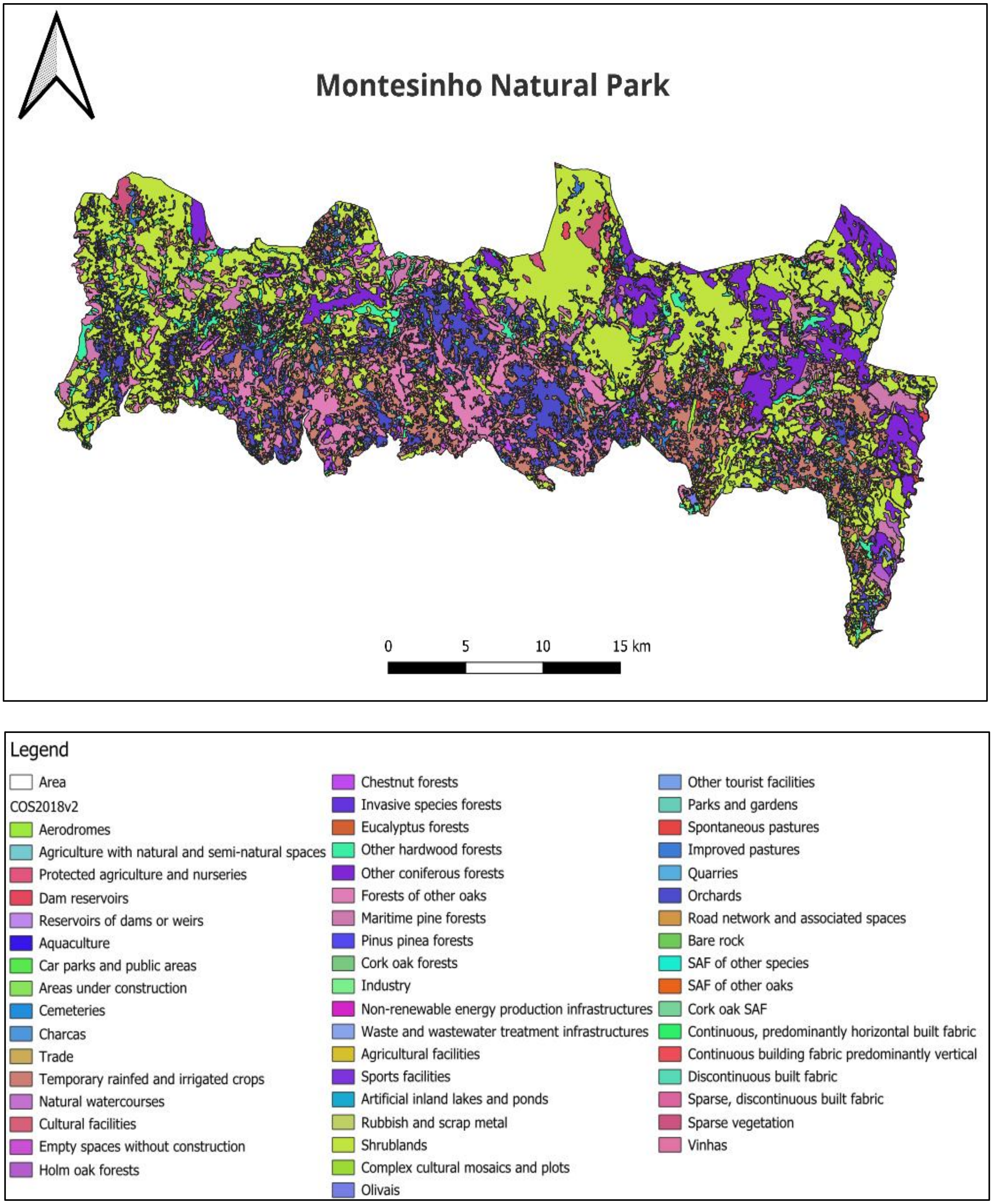


Figure 10: Land Use and Vegetation Types in Montesinho Natural Park According to the 2018 Land Use and Occupation (COS2018v2)

3.1.8. Fauna

A prominent feature of the fauna in Montesinho includes its mammal population, which comprises both common and rare species. Notably, the park serves as an essential habitat for the Iberian wolf (*Canis lupus signatus*) and the wildcat (*Felis silvestris*), both of which are classified as threatened within the region (Matias et al., 2021). The European badger (*Meles meles*) and various species of small mammals like the European hedgehog (*Erinaceus europaeus*) also find refuge within these ecosystems (Matias et al., 2021).

Birdlife is particularly abundant in Montesinho, with over 200 species recorded, making it a crucial area for avifauna conservation. Noteworthy species include the golden eagle (*Aquila chrysaetos*) and several migratory birds that stop in the park during seasonal migrations (Matias et al., 2021). The rich insect diversity in the park plays a critical role in supporting these populations, as they serve as a food source for many bird species (Matias et al., 2021).

In terms of amphibians and reptiles, Montesinho preserves a variety of native species, including the common frog (*Rana temporaria*) and the European pond turtle (*Emys orbicularis*), which are found in the park's freshwater habitats (Matias et al., 2021).

3.1.9. Sociocultural Heritage

The PNM supports about 9,000 residents living in 92 traditional villages, preserving a solid cultural heritage that is deeply intertwined with its natural landscape, reflecting a "transmontana" identity that underscores the historical relationship between the inhabitants and their environment (Matos Silva et al., 2022). This cultural heritage includes traditional agricultural practices, home gardens managed according to local customs, and community-oriented activities that foster cooperation and sustainability (Carvalho, 2016). For instance, the park is recognized for its Protected Designation of Origin (PDO) honey, cultivated from the endemic flora, indicating both the ecological health of MNP and the cultural practices surrounding traditional apiculture (Grosso et al., 2025).

Furthermore, the conservation initiatives within the park serve not only ecological purposes but also aim to maintain and revitalize these cultural connections, which are essential for the community's resilience and identity in the face of modernization (Castro et al., 2009).

3.2. Experimental Sites and Herds

3.2.1. Description of the Study Area

3.2.1.1. Location of the Study Area and the Corrals

The grazing zones of the sheep herd are located in the province of Trás-os-Montes e Alto Douro, specifically within the sub-regions of Coroa-Montesinho (commonly referred to as Montesinho Natural Park) and Nogueira-Bragança. The monitored sheep flock predominantly grazed within the Montesinho Natural Park, which forms part of the Natura 2000 Site of Community Importance (SIC). However, GPS data revealed that on certain days, the animals temporarily moved beyond the park's boundaries.

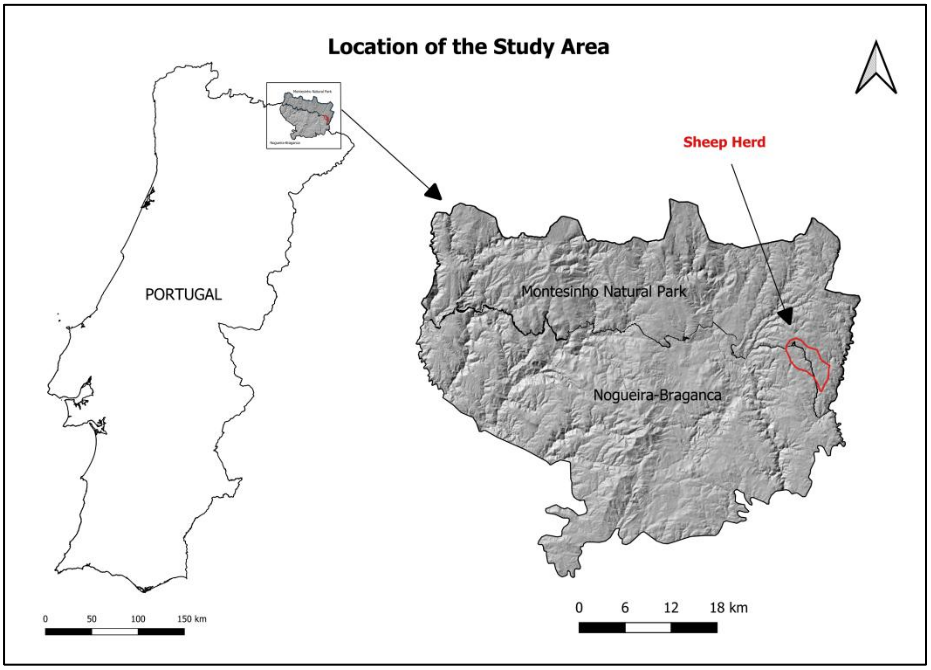


Figure 11: Location of the Study Area in Portugal and in the Homogeneous Sub-Regions (PROF TMAD)

The Table 3 below details the location and elevation of the corrals of the sheep herd.

Table 3: Location and Altitude of the Corrals

Corral	CRS	X (Easting)	Y (Northing)	Elevation (m)
1	ETRS89 / Portugal TM06 (EPSG : 3763)	125602,028	239334,887	859
2		130084,131	235906,033	736

Note: Although these corrals serve as the primary night shelters, GPS tracks show that the flock occasionally remains out overnight, especially during favorable summer weather.

Figure 12: Aerial Views of the Two Corrals Used in the Study

3.2.2. Herd Charachteristics and Selection

3.2.2.1. Breed Overview: Churra Galega Bragançana Branca

3.2.2.1.1. Origins, Naming, and Geographic Distribution

As a member of the broader Churra coarse-wool group, the Churra Galega Bragançana Branca is a traditional Portuguese sheep breed whose very name tells its story: "*Galega*" evokes the historic Galician cultural sphere, "*Bragançana*" anchors the breed in the highlands of Bragança in northeastern Portugal, specifically in the Trás-os-Montes region, and "*Branca*" refers to its distinctive white fleece. Its origins trace back to rural pastoral practices, where generations of selective breeding fostered the resilience and adaptability needed to thrive in the region's challenging landscapes (Teixeira et al., 2004).

Figure 13: Geographical Distribution of Churra Galega Bragancana Branca in Portugal (DGAV, 2018)

3.2.2.1.2. Morphological and Functional Characteristics

The Churra Galega Bragança Branca sheep is easily identified by the black or brown markings around its muzzle, eyes, and ears. Occasionally, the same markings can be found on its feet. Morphologically, the breed is characterized by its medium size, with ewes typically weighing between 50-60 kg and rams 70-80 kg. They possess a predominantly thin white fleece, which is semi-long and coarse, making it suitable for both meat and wool production (Rodrigues et al., 2019). Functionally, its robust body is known for its adaptability to less intensive farming conditions, thriving in extensive grazing systems that are prevalent in its native habitat (Ramírez-Retamal & Morales, 2014). This breed exhibits characteristics typical of hill sheep, such as a higher proportion of internal body fat compared to more specialized meat breeds, contributing to its dressing percentage and meat quality. Specific studies indicate that these sheep possess significant muscle and fat ratios, which are advantageous in meat production (Teixeira et al., 2004; Lazăr et al., 2016).

Figure 14: Image of Manuel Joao's Churra Galega Brancana Branca Sheep Flock

3.2.2.1.3. Traditional and Current Uses

Traditionally, the Churra Galega Bragançana Branca was primarily valued for its meat and wool, which was historically crucial for textile production (Rodrigues et al., 2019).

The meat quality of Churra Galega Bragançana lambs has been noted to have favorable characteristics, such as tenderness and juiciness, influenced by their diet and rearing conditions (Camacho et al., 2013).

Table 4. Traditional and Current Uses of the Churra Galega Bragançana Branca Sheep

Traditional & Current Use	What it looks like in practice
Meat – "Cordeiro Bragançano" (Protected Designation of Origin (PDO))	Pasture-fed suckling lambs from Churra Galega Bragançana ewes are kept on hillside grazing circuits and slaughtered at 3-4 months. Whole chilled carcasses weigh (8–12 kg) and are prized in "*Terra Fria*" gastronomy for their tender, delicately marbled meat.
Wool – craft blankets and rugs	The breed's coarse churra wool is hand-spun every summer in Maçainhas (district of Guarda) and woven on manual looms into the traditional "*Cobertor de Papa*" blanket. A local cooperative keeps the process alive and markets small production runs to the domestic design sector, offering shepherds a modest secondary income stream.
Landscape services – silvo-pastoral grazing and fire-smart fuel reduction	• Flocks graze chestnut orchards (soutos) after harvest, eating fallen nuts and winter weeds; in *ferrã* orchards intercropped with cereals, they mop up the stubble in late winter/early spring. • During the dry season, they are walked onto surrounding shrublands, where browsing keeps biomass short and breaks up the fuel layer, a practice promoted EU-wide as a nature-based wildfire prevention tool.

3.2.2.1.4. Recovery Efforts

In 1970s-1980s, the Churra Galega Bragançana Branca population sharply declined as mechanization and rural exodus led to a drastic reduction in flock numbers, with some lines nearly disappearing.

Recovery efforts for the breed have gained momentum in recent years as part of broader initiatives to preserve native Portuguese livestock. Genetic conservation programs utilizing microsatellite markers have been implemented to ensure the breed's genetic diversity and viability (Crispim et al., 2014).

Table 5: Timeline of Recovery and Conservation Efforts for the Churra Galega Bragançana Branca

Year/Period	Recovery Efforts	Details
1994	Official national recognition	Inclusion of the breed in Portugal's National Program for the Conservation of Autochthonous Animal Genetic Resources, enabling access to targeted conservation funding.
Since 1995	Herd-book management by ACOB	ACOB (Associação de Criadores da Ovino Bragançano) began managing the official genealogical registry and performance records.
Early 2000s	Establishment of in-situ conservation herds	Core flocks were stabilized within the Bragança district, particularly in the Montesinho Natural Park, to preserve locally adapted genotypes.
2004 onward	Cryo-conservation of genetic material	The National Gene Bank (BPGV – Braga) began collecting and storing semen and embryos for long-term preservation.
Post-2010	EU agri-environmental subsidies (RAZA support)	Under the Common Agricultural Policy (CAP), breeders became eligible for "RAZA" payments (€30–40 per breeding ewe/year) for maintaining native breeds in traditional extensive systems.
2015	PDO status for "Cordeiro Bragançano"	Protected Designation of Origin label promotes quality lamb from the breed, adding value and incentivizing purebred rearing.
Ongoing (2010s–...)	Integration in sustainable farming and cultural initiatives	Breed promoted for wildfire prevention, orchard grazing, woolcraft revival, and rural tourism, linking conservation to economic sustainability.

In 2018, the "Livro Genealógico de Adultos" included: 11,816 ewes and 426 rams, from 103 breeders (DGAV, 2018).

3.2.2.2. Herd Management Practices

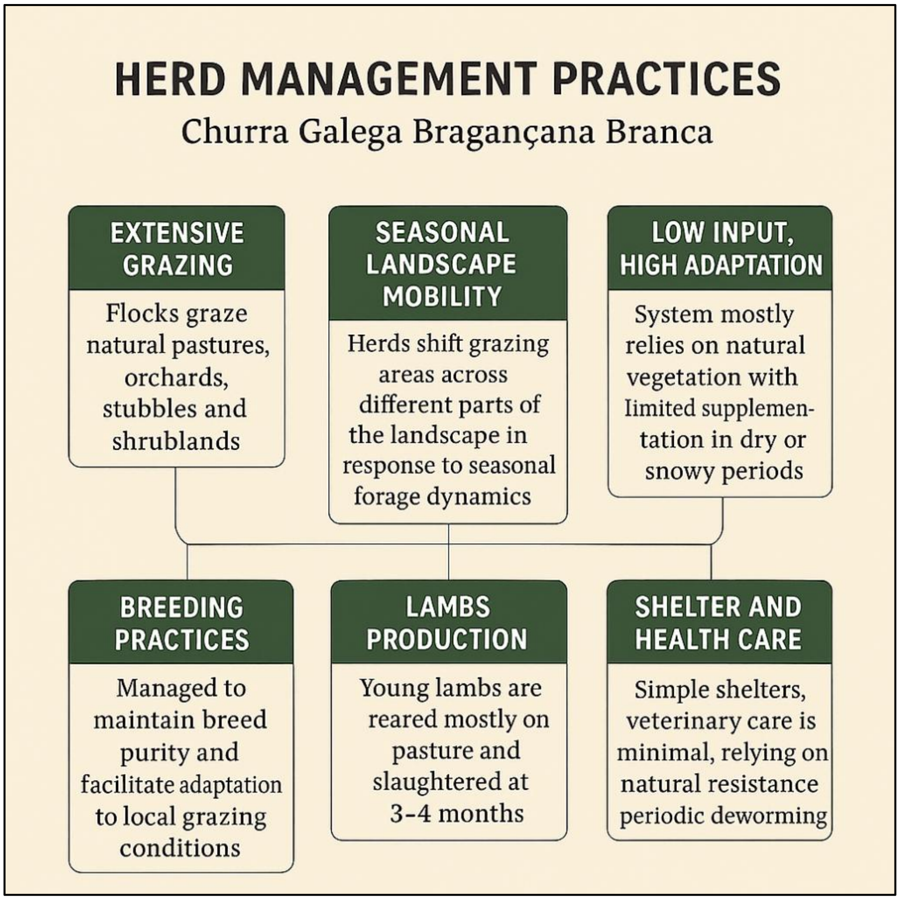


Figure 15: Herd Management Practices of the Churra Galega Bragançana Branca

3.3. Data Collection Methodology

3.3.1. GNSS Collar Technology Specifications GNSS and Deployment Protocol

A single individual from the flock was equipped with a GNSS collar to track its grazing movements, as shown in Figure 16. The sheep was chosen based on its good health and typical behavioral traits, ensuring it would reflect the general activity of the herd. (Castro et al., 2023).

The DOMODIS GNSS collar integrates GPS for positioning and GLOBALSTAR satellite communication to enable continuous remote data collection with minimal on-site handling. Designed with animal welfare in mind, the collar weighs 750 grams, remaining well below 1.5%

of the animal's body weight, and operates on a 3.7V, 7.8 Ah lithium-ion battery. Its compact size (115 × 65 × 40 mm) ensures minimal disruption to the animal's behavior. Battery malfunctions are typically reported by the shepherd every two months, at which point the battery is recharged; nonetheless, occasional failures can result in partial data loss. The device provides positioning accuracy ranging from 2 to 10 meters (Castro et al., 2022).

Figure 16: Image of the Selected Sheep with the GPS Collar

3.3.2. Temporal Scope and Frequency of Data Collection

The device is configured to record the animal's position every five minutes, except when the animal is resting, confined to the corral, or during technical interruptions. In ideal conditions, the collars operate autonomously for up to four months, depending on fix frequency and usage, reducing the frequency of handling.

Tracking data were retrieved from the DOMODIS web platform in .txt or .csv format, containing time-stamped GPS coordinates (date, time, latitude, and longitude). The dataset spans two collection periods: from March 21 to December 31, 2022, and from January 5 to July 6, 2023. For this study, a continuous 15-month interval was selected to compensate for initial collar malfunctions and to capture two spring seasons. This extended duration ensured more complete and reliable seasonal comparisons. The dataset also included the name of the animal's caretaker, allowing linkage with management context.

The methodology, including the use of a single collar per flock and 5-minute acquisition intervals, has been validated in previous work (Castro et al., 2022; 2023), demonstrating its reliability for capturing detailed grazing behavior in extensive systems.

3.3.3. Ancillary Environmental Data Sources (DEM, land cover)

To support the spatial analysis of grazing behavior, ancillary environmental data were incorporated, including a Digital Elevation Model (DEM) and a land cover classification map. The DEM was acquired with a 25-meter resolution and reprojected into the Portuguese national coordinate system (PT-TM06 / ETRS89, EPSG:3763) using the GDAL "gdalwarp" tool, ensuring spatial consistency with the GPS datasets. This elevation model provided essential topographic variables such as slope, aspect, and altitude, allowing us to evaluate how terrain influences grazing distribution and accessibility.

Land cover data were extracted from the Land Use and Land Cover Map of 2018 (COS2018 v2.0), developed by the General Directorate of Territory (Direção-Geral do Território, DGT). This high-resolution national dataset offered detailed information on the spatial distribution of land use types across Portugal and was instrumental in characterizing the environmental context of grazing activity. It enabled the identification of key habitat types used by the flock.

Both datasets were clipped to the boundaries of the study area and integrated into the GIS environment to investigate habitat selection patterns and landscape-level grazing dynamics.

3.4. Data Processing Workflow

3.4.1. Data Preparation, Cleaning, and Path Creation

To ensure the accuracy and relevance of the GPS data, a systematic cleaning process was performed using QGIS. First, all GPS points were projected into the national coordinate reference system (PT-TM06 / ETRS89). Immediately after projection, the original date-time entries—initially stored as text strings—were converted into proper datetime formats using the QGIS Field Calculator. These were then split into separate date and time fields using the *to_date* and *to_time* functions. This step was essential for ensuring temporal precision and consistency in subsequent analyses. Following this, daily trajectories were visualized by connecting points with directional lines and arrows to clarify movement patterns. This was achieved using the "*Points to Path*" tool, which converted chronologically ordered GPS points into line features, with a unique identifier for each day to separate individual trajectories. To indicate the direction of movement, arrows were added along the lines by adjusting the symbology settings: under the "*Marker Line*" option, arrows were selected and placed either on each vertex or at the midpoint of the line. This visualization allowed for a clearer understanding of the flock's spatial behavior throughout the year.

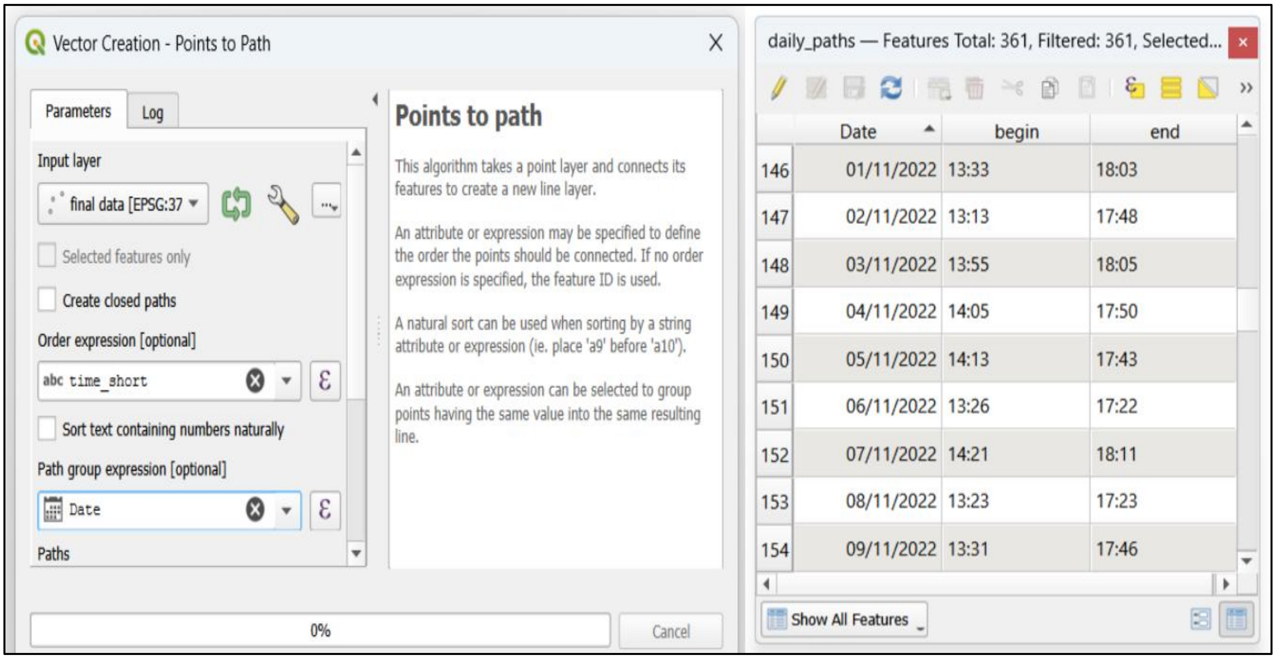
Nighttime points were excluded, and only one point at the start and one at the end of each grazing day—typically near the corrals—was retained to mark departure and return. Days with fewer than ten relevant trajectory points were excluded due to insufficient data density. Repeated or redundant location points were also removed. Additionally, battery-related interruptions, which occurred approximately every two months, resulted in missing data; these days were identified and discarded when data gaps compromised trajectory reliability. Finally, unlike the previous year's study, points recorded during midday resting periods in summer were preserved, recognizing that the flock often returns temporarily to shaded forest areas or corrals before resuming grazing in the afternoon.

Figure 17: Example of Data Cleaning and Path Visualization with Directional Arrows (20/03/2023)

To identify remaining inconsistencies, we visualized the data in RStudio by plotting record sequences on the x-axis against their corresponding timestamps on the y-axis. This approach made it easier to detect unusual time gaps or duplications that were not obvious during spatial cleaning, allowing for targeted corrections.

3.4.2. Creation of Grazing Paths (Points to Path)

Once the dataset had been cleaned and included only valid GPS points, daily movement paths were reconstructed again using the "Points to Path" tool in QGIS. By linking the sequential coordinates recorded throughout each day, this tool generated continuous trajectory lines that depicted the flock's grazing circuit—from departure near the corral to the farthest points accessed during the day and back. The resulting path layers not only mapped spatial movement but also preserved the temporal structure, making it possible to extract the exact start and end times of each grazing journey, as shown in Figure 18 below.



Vector Creation - Points to Path

Input layer: final data [EPSG:37

☐ Selected features only

☐ Create closed paths

Order expression [optional]: abc time_short

☐ Sort text containing numbers naturally

Path group expression [optional]: Date

Paths

Points to path

This algorithm takes a point layer and connects its features to create a new line layer.

An attribute or expression may be specified to define the order the points should be connected. If no order expression is specified, the feature ID is used.

A natural sort can be used when sorting by a string attribute or expression (ie. place 'a9' before 'a10').

An attribute or expression can be selected to group points having the same value into the same resulting line.

daily_paths — Features Total: 361, Filtered: 361, Selected...

	Date	begin	end
146	01/11/2022	13:33	18:03
147	02/11/2022	13:13	17:48
148	03/11/2022	13:55	18:05
149	04/11/2022	14:05	17:50
150	05/11/2022	14:13	17:43
151	06/11/2022	13:26	17:22
152	07/11/2022	14:21	18:11
153	08/11/2022	13:23	17:23
154	09/11/2022	13:31	17:46

Figure 18: Generation of Daily Grazing Paths in QGIS Using the "Points to Path" Tool

The left panel shows the configuration of the tool using “time_short” to order points and “Date” to group daily trajectories. The right panel displays a part of the resulting attribute table with automatically extracted start and end times for each grazing day.

3.4.3. Calculation of Grazing Variables

Figure 19 illustrates a schematic summary of the variable calculation process, offering a clear overview of the key variables used in the analysis.

These variables and their calculation methods were largely adapted from the methodologies developed in the master’s thesis of Fellahi (2024), who worked with the same sheep breed and context, and from the forthcoming article by Castro et al. (in prep.) focused on pastoral mobility in Montesinho Natural Park. This ensures continuity and methodological comparability within the PASTOpraxis project.

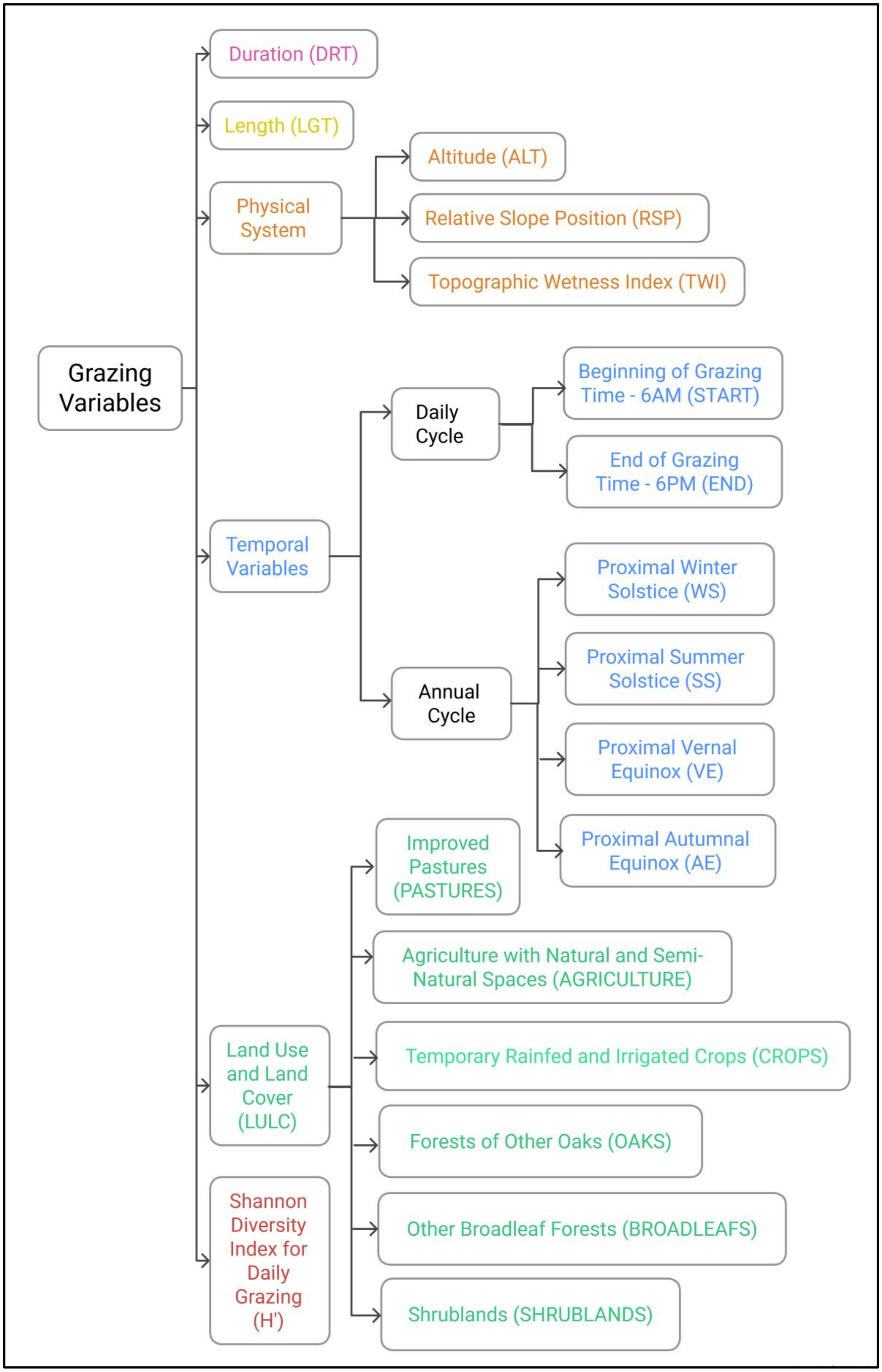


Figure 19: Schematic Overview of Grazing Variable Categories and Their Components

3.4.3.1. Lenght and Duration

After the daily trajectories were rebuilt as individual line features (Section 3.4.2), two basic movement variables were derived for every grazing day; these are summarized in Table 6 below.

Table 6: Computation of Core Movement Metrics : Duration (DRT) and Lenght (LGT)

Variable	Meaning	Tool	Expression	Units
Duration (DRT)	Net field-time (minutes) between the first and last valid GPS fixes of the day	Field Calculator	*round(("end" - "begin")/60)*	Minutes
Lenght (LGT)	Total horizontal distance walked between morning departure and evening return		*length($geometry)*	Metres

3.4.3.2. Temporal Variables

3.4.3.2.1. Daily Cycle

Drawing on the 2024 Fellahi’s thesis, which analyzed a GPS-tracked sheep flock in the very same Montesinho landscape, we limited the daily-cycle portfolio to just B-6AM (minutes from first fix to 06:00) and E-6PM (minutes from last fix to 18:00). Fellahi originally generated eight anchor-time metrics (Begin/End offsets to 06 h, 12 h, 18 h, and 24 h), but a stepwise screening showed that only the early morning and late evening offsets added unique information: in the correlation matrix, they acted as surrogates for all other start- and end-time lags, while the midday (12 h) and midnight (24 h) versions were strongly collinear and contributed little to the variance structure in PCA. Retaining B-6AM and E-6PM therefore captured the biologically meaningful extremes of the grazing day (heat-avoidance departures and light-limited returns) without inflating the model with redundant, low-influence variables.

Table 7. Calculation of daily-cycle temporal variables (B-6AM and E-6PM)

Variable	What it measures	Tool	Expression
B-6AM (START)	Minutes between the first valid GPS fix of the day and 06:00	QGIS Field Calculator	*minute(to_interval("Begin" - '06:00'))*
E-6PM (END)	Minutes between the last valid GPS fix of the day and 18:00		*minute(to_interval("End" - '18:00'))*

Negative values mean the event happened before the anchor (e.g., left earlier than 06:00); positive values mean it happened after the anchor.

3.4.3.2.2. Annual cycle

To position each grazing date within the seasonal light cycle, four distance-to-event variables were created; their definitions and ecological significance are presented in Table 8.

Table 8: Annual Cycle Variables: Nearest Solstice/Equinox Distances and their Grazing Relevance

Seasonal Marker	Fixed Date	Significance for Grazing Behaviour
Nearest Winter Solstice (WS)	21 December	Shortest days and longest nights; limited daylight constraints foraging while colder conditions raise energy demands.
Nearest Summer Solstice (SS)	21 June	Longest days and brief nights; extended light permits prolonged grazing but heightens exposure to midday heat.
Nearest Autumnal Equinox (AE)	22 September	Rapidly shortening days and cooling temperatures; the flock adjusts timing and range as daylight diminishes.
Nearest Vernal Equinox (VE)	20 March	Rapidly lengthening days and warming temperatures; spring growth and more daylight foster earlier, wider-ranging grazing.

For every record, we calculated the absolute day difference to the relevant solstice or equinox in three successive years—the current year, the preceding year, and the following year—and kept the smallest of the three values.

Using this three-year window eliminates the artificial jump that occurs at the turn of the year: a date such as January 2 is only 12 days after the December 21 solstice of the previous calendar year, not 353 days before the next one. Selecting the minimum absolute difference, therefore, yields a continuous, intuitive measure of photoperiod stage that runs smoothly across year-end.

3.4.3.3. Physical System

3.4.3.3 Physical-system variables (ALT, RSP, TWI)

3.4.3.3.1. Altitude (ALT)

The 25m DEM was first clipped to the study buffer (*Raster* > *Extraction* > *Clip Raster by Mask Layer*) and kept in PT-TM06. Mean elevation for each daily path was then written to a new field ALT (meters) with *Raster* > *Zonal Statistics*, setting the DEM as the input raster and “daily_path” as the vector layer; the statistic “mean” produced one representative altitude per grazing day.

3.4.3.3.2. Relative Slope Position (RSP)

A continuous RSP surface (range = -1 valley → +1 ridge) was generated from the DEM via *Processing* > *SAGA* > *Terrain Analysis* > *Relative Slope Position*.

SAGA-GIS “Relative Slope Position” offers two variants:

- ✓ Channel-Ridge mode → 0 to 1 (valley to ridge)   (default)
- ✓ Standardized mode → -1 to +1 (valley to ridge, mean = 0)

In our workflow, we kept SAGA’s Standardized output, so valley floors are negative and crests are positive (up to +1).

Using the same Zonal Statistics tool, the mean RSP value intersecting each path was appended to the attribute table in a new, unitless field RSP.

3.4.3.3.3. Topographic Wetness Index (TWI)

The Topographic Wetness Index (TWI) is a quantitative measure that characterizes the tendency of water accumulation in relation to local slope and upslope contributing area, thus reflecting topographic control on hydrological processes (Choubin et al., 2020). It is calculated as follows:

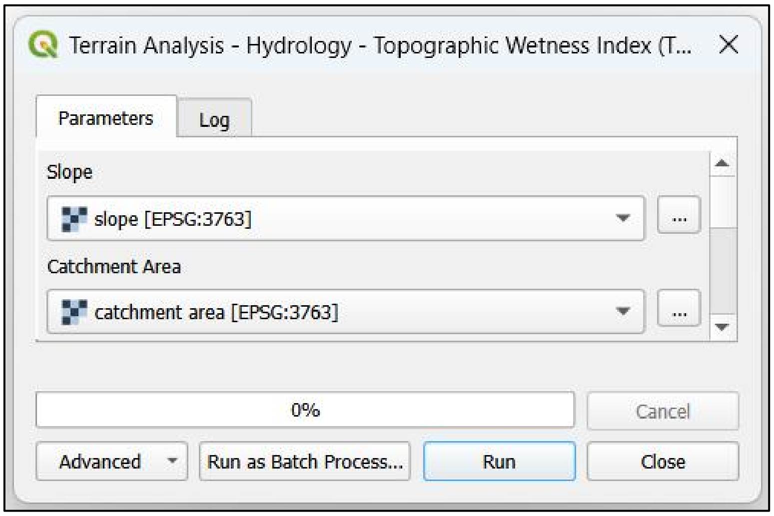
$$\boxed{\mathrm{TWI} = \ln\left(\frac{\text{specific catchment area}}{\tan(\text{slope})}\right)}$$

Figure 20: TWI Formula

Using the 25 m DEM clipped to the study buffer, we generated the two input rasters with SAGA tools:

- Local slope: *SAGA > Terrain Analysis > Slope*
- Specific catchment area (SCA): *SAGA > Hydrology > Catchment Area*

Both layers were then supplied to *SAGA > Hydrology > Topographic Wetness Index*, producing the composite raster TWI. Finally, the mean TWI for every day was extracted with *Zonal Statistics* and stored as TWI.



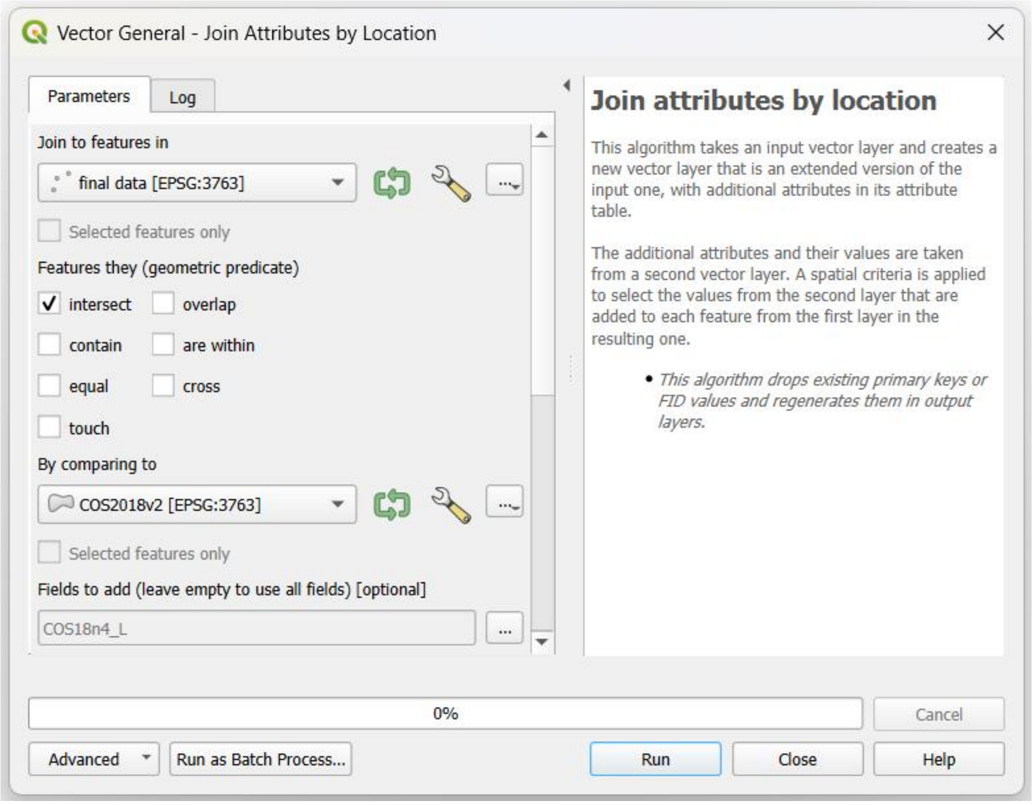
Slope: slope [EPSG:3763]

Catchment Area: catchment area [EPSG:3763]

Figure 21: QGIS Processing Dialogue for SAGA "Topographic Wetness Index": Slope Raster and Catchment Area Raster Selected as Inputs

3.4.3.4. Land Use & Land Cover (LULC)

To attach a land-cover identifier to every GPS fix, the cleaned point layer was spatially joined to the 2018 national land-cover map (COS2018 v2) using *Vector > General > Join attributes by location* (Figure 22). The points were set as the target layer and the polygon map as the reference layer; the **intersect** predicate was selected so each point inherited the attributes of the polygon it fell within. To keep the output concise, only the level-4 field COS18n4_L was requested because this category provides the finest thematically consistent description of land use that is still ecologically meaningful for grazing analysis. Finer levels would have fragmented the sample, while coarser (level-2) units would mask functional differences in grazing use.


Vector General - Join Attributes by Location

Join to features in
final data [EPSG:3763]
☐ Selected features only

Features they (geometric predicate)
☑ intersect ☐ overlap
☐ contain ☐ are within
☐ equal ☐ cross
☐ touch

By comparing to
COS2018v2 [EPSG:3763]
☐ Selected features only

Fields to add (leave empty to use all fields) [optional]
COS18n4_L

Join attributes by location

This algorithm takes an input vector layer and creates a new vector layer that is an extended version of the input one, with additional attributes in its attribute table.

The additional attributes and their values are taken from a second vector layer. A spatial criteria is applied to select the values from the second layer that are added to each feature from the first layer in the resulting one.

- *This algorithm drops existing primary keys or FID values and regenerates them in output layers.*

0%

Figure 22: Spatial Join Linking every GPS Fix to its Land Cover Class

The joined point layer was then exported as a CSV and imported into Excel. A PivotTable was generated with Date as the row field, COS18n4_L as the column field, and Count as the aggregation. The resulting matrix summarized, for each day, how many GPS observations fell within each land-cover class.

Using the PivotTable output, a frequency table was produced listing every COS18 n4 class together with its total number of GPS records and the corresponding percentage of the 18 900 fixes collected (Table 9). To focus subsequent analyses on meaningful habitat categories and reduce noise, all classes whose cumulative share was < 3 % were filtered out; only the six classes highlighted in grey were retained for the diversity and habitat-selection metrics that follow.

Table 9: Overall Frequency and Percentage of GPS fixes by COS18 n4 Land Cover Class (classes > 3 %highlighted for retention)

LULC CLASSES	COUNT	PERCENTAGE
Agriculture with natural and semi-natural spaces	2584	13,67%
Temporary rainfed and irrigated crops	11342	60,01%
Chestnut forests	76	0,40%
Other broadleaf forests	795	4,21%
Other coniferous forests	91	0,48%
Forests of other oaks	1041	5,51%
Maritime pine forests	123	0,65%
Shrublands	678	3,59%
Cultural mosaics and complex parcels	152	0,80%
Olive groves	5	0,03%
Spontaneous (natural) pastures	330	1,75%
Improved pastures	1370	7,25%
Orchards	200	1,06%
Continuous horizontal built-up fabric	62	0,33%
Discontinuous sparse built-up fabric	2	0,01%
Vineyards	49	0,26%
	18900	**100,00%**

3.4.3.5. Shannon Diversity Index

The class-by-day matrix obtained from the PivotTable was used to quantify the heterogeneity of land-cover use with the Shannon–Wiener diversity index, considering only the six classes retained after the 3 % threshold filter. This index was selected over Hill numbers because (i) it weighs rare land-cover classes sufficiently to detect occasional but ecologically significant forays into minor habitats, and (ii) its logarithmic form maintains comparability with previous regional grazing studies (Fellahi 2024; Oliveira 2023).

$$\boxed{H' = -\sum_{i=1}^{S} pi \ \ln pi}$$

Figure 23: Shannon-Wiener Diversity Index Formula

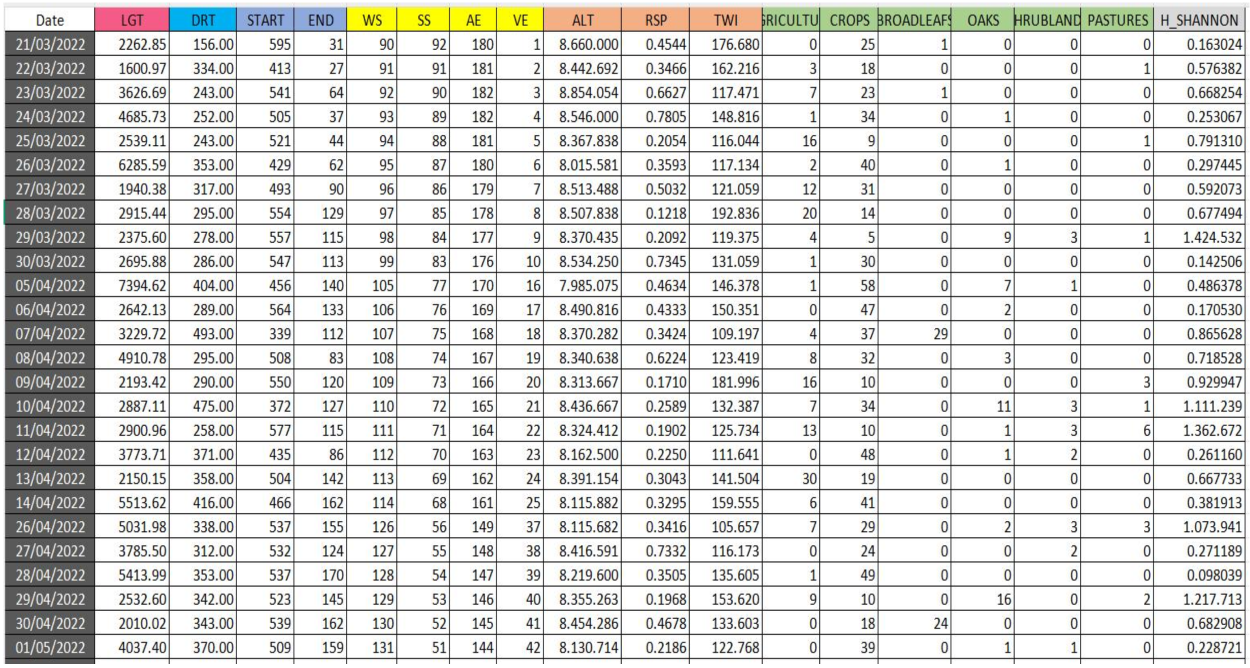
Where:

- S represents the total number of species.
- pi is the proportion of individuals or abundance of the i-th species relative to the total number of individuals across all species. pi = n/N
    - n is the individuals of a given type/species; and
    - N is the total number of individuals in a community.
- ln(pi) is the natural logarithm of pi.

Higher H′ values reflect greater diversity and evenness of land use, indicating that grazing was more evenly distributed across different landscape classes. In contrast, lower H′ values correspond to concentrated use in only one or two dominant land-cover types.

3.4.3.6. Final Data Preparation

A consolidated table was produced in which each row corresponds to a single grazing day and each column stores one of the derived variables; this day-by-variable matrix constitutes the input table for the forthcoming principal component analysis.



Date	LGT	DRT	START	END	WS	SS	AE	VE	ALT	RSP	TWI	RICULTU	CROPS	BROADLEAF	OAKS	HRUBLAND	PASTURES	H_SHANNON
21/03/2022	2262.85	156.00	595	31	90	92	180	1	8.660.000	0.4544	176.680	0	25	1	0	0	0	0.163024
22/03/2022	1600.97	334.00	413	27	91	91	181	2	8.442.692	0.3466	162.216	3	18	0	0	0	1	0.576382
23/03/2022	3626.69	243.00	541	64	92	90	182	3	8.854.054	0.6627	117.471	7	23	1	0	0	0	0.668254
24/03/2022	4685.73	252.00	505	37	93	89	182	4	8.546.000	0.7805	148.816	1	34	0	1	0	0	0.253067
25/03/2022	2539.11	243.00	521	44	94	88	181	5	8.367.838	0.2054	116.044	16	9	0	0	0	1	0.791310
26/03/2022	6285.59	353.00	429	62	95	87	180	6	8.015.581	0.3593	117.134	2	40	0	1	0	0	0.297445
27/03/2022	1940.38	317.00	493	90	96	86	179	7	8.513.488	0.5032	121.059	12	31	0	0	0	0	0.592073
28/03/2022	2915.44	295.00	554	129	97	85	178	8	8.507.838	0.1218	192.836	20	14	0	0	0	0	0.677494
29/03/2022	2375.60	278.00	557	115	98	84	177	9	8.370.435	0.2092	119.375	4	5	0	9	3	1	1.424.532
30/03/2022	2695.88	286.00	547	113	99	83	176	10	8.534.250	0.7345	131.059	1	30	0	0	0	0	0.142506
05/04/2022	7394.62	404.00	456	140	105	77	170	16	7.985.075	0.4634	146.378	1	58	0	7	1	0	0.486378
06/04/2022	2642.13	289.00	564	133	106	76	169	17	8.490.816	0.4333	150.351	0	47	0	2	0	0	0.170530
07/04/2022	3229.72	493.00	339	112	107	75	168	18	8.370.282	0.3424	109.197	4	37	29	0	0	0	0.865628
08/04/2022	4910.78	295.00	508	83	108	74	167	19	8.340.638	0.6224	123.419	8	32	0	3	0	0	0.718528
09/04/2022	2193.42	290.00	550	120	109	73	166	20	8.313.667	0.1710	181.996	16	10	0	0	0	3	0.929947
10/04/2022	2887.11	475.00	372	127	110	72	165	21	8.436.667	0.2589	132.387	7	34	0	11	3	1	1.111.239
11/04/2022	2900.96	258.00	577	115	111	71	164	22	8.324.412	0.1902	125.734	13	10	0	1	3	6	1.362.672
12/04/2022	3773.71	371.00	435	86	112	70	163	23	8.162.500	0.2250	111.641	0	48	0	1	2	0	0.261160
13/04/2022	2150.15	358.00	504	142	113	69	162	24	8.391.154	0.3043	141.504	30	19	0	0	0	0	0.667733
14/04/2022	5513.62	416.00	466	162	114	68	161	25	8.115.882	0.3295	159.555	6	41	0	0	0	0	0.381913
26/04/2022	5031.98	338.00	537	155	126	56	149	37	8.115.682	0.3416	105.657	7	29	0	2	3	3	1.073.941
27/04/2022	3785.50	312.00	532	124	127	55	148	38	8.416.591	0.7332	116.173	0	24	0	0	2	0	0.271189
28/04/2022	5413.99	353.00	537	170	128	54	147	39	8.219.600	0.3505	135.605	1	49	0	0	0	0	0.098039
29/04/2022	2532.60	342.00	523	145	129	53	146	40	8.355.263	0.1968	153.620	9	10	0	16	0	2	1.217.713
30/04/2022	2010.02	343.00	539	162	130	52	145	41	8.454.286	0.4678	133.603	0	18	24	0	0	0	0.682908
01/05/2022	4037.40	370.00	509	159	131	51	144	42	8.130.714	0.2186	122.768	0	39	0	1	1	0	0.228721

Figure 24: Overview of the Prepared Data for Computing the PCA

3.4.4. Statistical Analysis

Prior to the statistical analyses, the dataset comprising daily grazing variables was imported into RStudio. All variables were inspected for completeness and consistency. Initial exploratory analysis was performed using descriptive statistics and structure inspection, which confirmed that the dataset was correctly formatted and suitable for subsequent inferential statistical procedures. This step ensured that the analysis would be based on accurate and coherent data, supporting the reliability of the results.

3.4.4.1. Correlation Study

Before running the PCA, a quick, fully quantitative screen was carried out to verify that the retained variables were meaningfully related and to identify any pairs that were so strongly collinear that they would inflate the PCA without adding information. Table 10 displays the workflow used to build and screen the Pearson correlation matrix for the 18 grazing variables.

Table 10: Workflow Used to Build and Screen the Pearson Correlation Matrix for the Grazing Variables

Step	Action	Key R command / plug-in
1	Compute Pearson matrix (all variables already scaled)	`R M <- cor(my.data, method = "pearson")`
2	Obtain p-values (two-sided, α = 0.05)	`p <- Hmisc::rcorr(as.matrix(my.data))$P`
3	Visualise values, sign, and significance	`ggcorrplot::ggcorrplot(M, p.mat = p, type = "lower")`
4	Flag excessive collinearity – absolute	r

3.4.4.2. Suitability Tests

Before extracting principal components, the correlation matrix had to be checked for the two standard metric prerequisites of PCA: (i) significant common variance among variables and (ii) an overall sampling adequacy that is at least "mediocre" (Kaiser, 1974). Both diagnostics were run in R with functions from the "psych" package.

Table 11: Suitability Tests for PCA : Bartlett's Spherity Test & KMO Test

Test	Purpose	R Function	Decision rule
Bartlett's Test of Sphericity	Tests H0: the correlation matrix = identity matrix (no shared variance).	`cortest.bartlett(R, n)` where R is the Pearson Correlation matrix (pairwise complete cases) and n the number of grazing days.	A significant chi-square value (p-value < 0.05) suggests that the null hypothesis can be rejected, and there are significant correlations among the variables, making them suitable for factor analysis or PCA (Bartlett, 1950).
Kaiser-Meyer-Olkin (KMO)	Quantifies the proportion of common to unique variance (0–1).	`KMO(R)` → returns overall MSA and item-level MSAs.	Overall MSA ≥ 0.60 → adequate for PCA; < 0.50 would require remedial variable pruning or factor-analytic alternatives. Variables with item-MSA < 0.50 are flagged but retained if theoretically indispensable.

Table 12: Kaiser-Meyer-Olkin (KMO) Measure Interpretation Guide (Kaiser, 1974)

KMO Measure	Interpretation
$\mathrm{KMO} \geq 0.90$	Marvelous
$0.80 \leq \mathrm{KMO} < 0.90$	Meritorious
$0.70 \leq \mathrm{KMO} < 0.80$	Average
$0.60 \leq \mathrm{KMO} < 0.70$	Mediocre
$0.50 \leq \mathrm{KMO} < 0.60$	Terrible
$\mathrm{KMO} < 0.50$	Unacceptable

3.4.4.3. Principal Component Analysis

After verifying variable interrelationships (Section 3.4.4.1) and sampling adequacy (Section 3.4.4.2), a Principal Component Analysis (PCA) was performed in R to synthesize the multivariate structure of the grazing dataset. All analyses were run in an R Markdown workflow saved to the project root via “here::here()” to maintain relative paths.

Table 13: R Workflow (Packages, Key Functions) used to Perform the Principal Component Analysis

Step	Purpose	R package(s)	Main code / functions
Prepare data	z-scale the numeric grazing variables (one row = day)	base, dplyr	`X <- scale(df[vars])`
Compute PCA	Full-rank decomposition	FactoMineR	`pca <- PCA(X, ncp = ncol(X), graph = FALSE)`

Extract stats	Eigenvalues, loadings, cos^2, % contrib	factoextra	`get_eigenvalue(pca)`
			`pca$var$coord`
			`pca$var$contrib`

Visual checks	Scree + correlation circles + bar plots	factoextra,
		ggplot2,
		ggrepel
			`fviz_eig(pca)`
			`fviz_pca_var(pca, col.var="contrib", gradient.cols=c("#0091FF","#FFE04C","#FF2700"), repel=TRUE)`
			`fviz_contrib(pca, choice="var", axes=1:3)`

QC / save	Cross-check with prcomp; store object	stats, base	`prcomp(X)` `saveRDS(pca,"outputs/pca.rds")`

All graphical outputs were produced in RStudio to illustrate the multivariate results:

- **Scree Plot of Eigenvalues** — plots Eigenvalues against component number to highlight how much variance each axis explains.
- **Variable Contribution Bars** — quantify the share (%) that each variable lends to a given principal component.
- **Variables Correlation Circle(s)** — displays variables as arrows; length = strength, angle = correlation —makes clusters, oppositions, and trade-offs easy to spot on selected axes.
- **Individuals Score Plot** — scatters every grazing day in PC space, revealing gradients, groupings, and outliers among itineraries.
- **Season Colored Score Plot** — the same scores but points shaded by season, providing an immediate visual test of seasonal separation.
- **Biplot** — overlays variable vectors and individual scores, allowing direct linkage between specific days and the variables driving their positions.
- **Cos² Heat Maps** — display the squared cosine values; darker cells mark variables that are well represented (reliable) on each axis.

4. Results and Discussion

4.1. General Characterization of Grazing Itineraries

4.1.1. Elevation and Grazing Itineraries

Figure 25 overlays the flock's GPS tracks on a hillshade DEM, revealing that grazing occurs across the full elevational range of the study area (**613 – 937 m**). Paths are densest on the higher western ridges (dark tones), but they also extend downslope into the greener lower eastern sector, showing that the itinerary links both upland and lowland grazing zones within a single daily landscape.

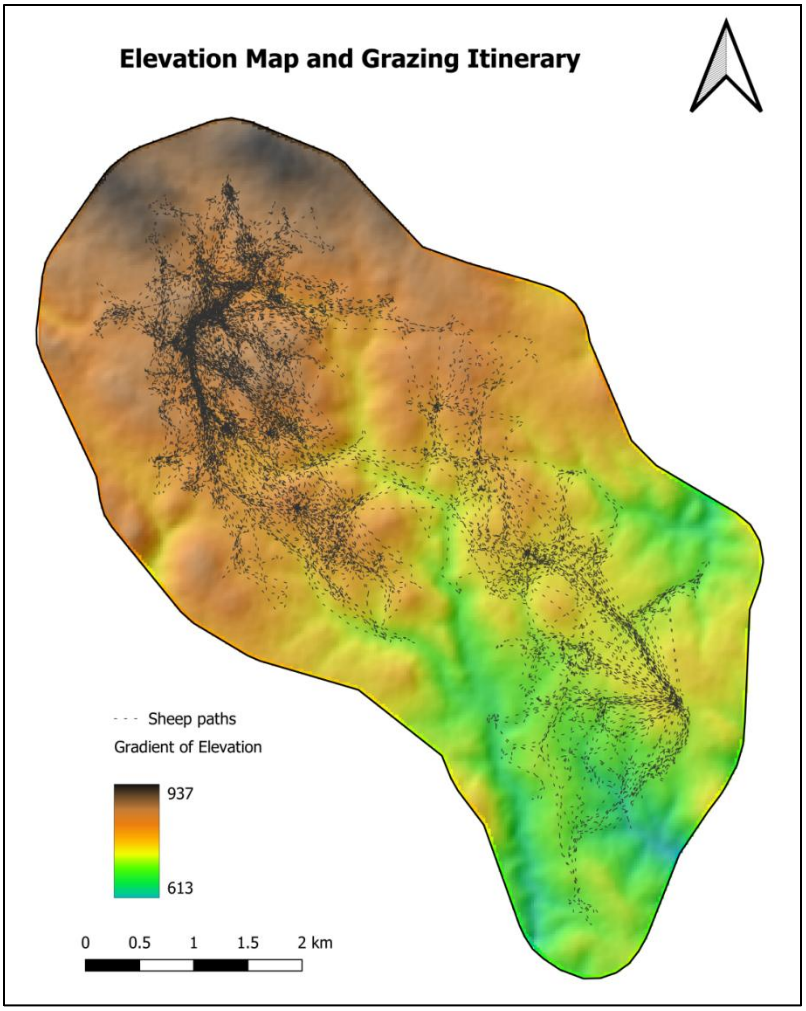


Figure 25: Elevation and Grazing Itinerary of the Study Area

4.1.2. Relative Slope Position and Grazing Itineraries

Relative Slope Position (RSP) is a dimensionless index that locates each cell along a hillslope from valley bottom to ridge crest: values near **–0.09** in Figure 26 represent the lowest toe-slope or valley positions (green), while values up to **+1.00** mark the highest ridges (red).

The paths show that the herd uses all slope positions but is densest on ridgetops and upper slopes, while the gentler lower-slope zones are traversed more sparsely, suggesting regular use of well-drained, elevated terrain—likely for visibility and breezier microclimates in warmer hours.

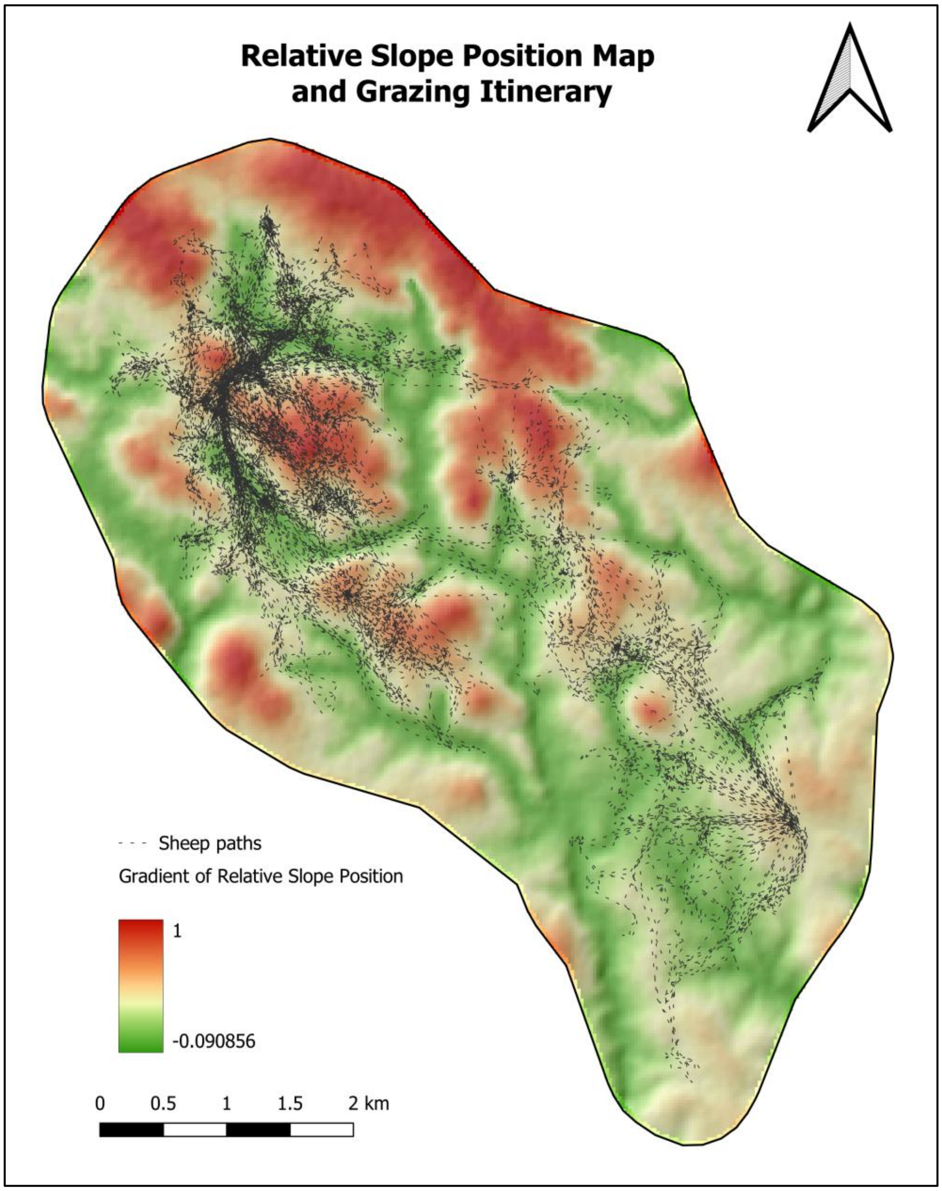


Figure 26: Relative Slope Position (RSP) and Grazing Itinerary of the Study Area

4.1.3. Topographic Wetness Index and Grazing Itinerary

In Figure 27 highlighting the Topographic Wetness Index, values span 3.9 (driest ridges) to 26.75 (wettest hollows): the pale zones at lower TWI mark well-drained high ground, while the deep blue patches highlight sheltered foot-slopes and valley bottoms that retain most water. Sheep tracks thread through the full gradient, showing they cross both dry and wetter micro-sites rather than favoring either extreme.

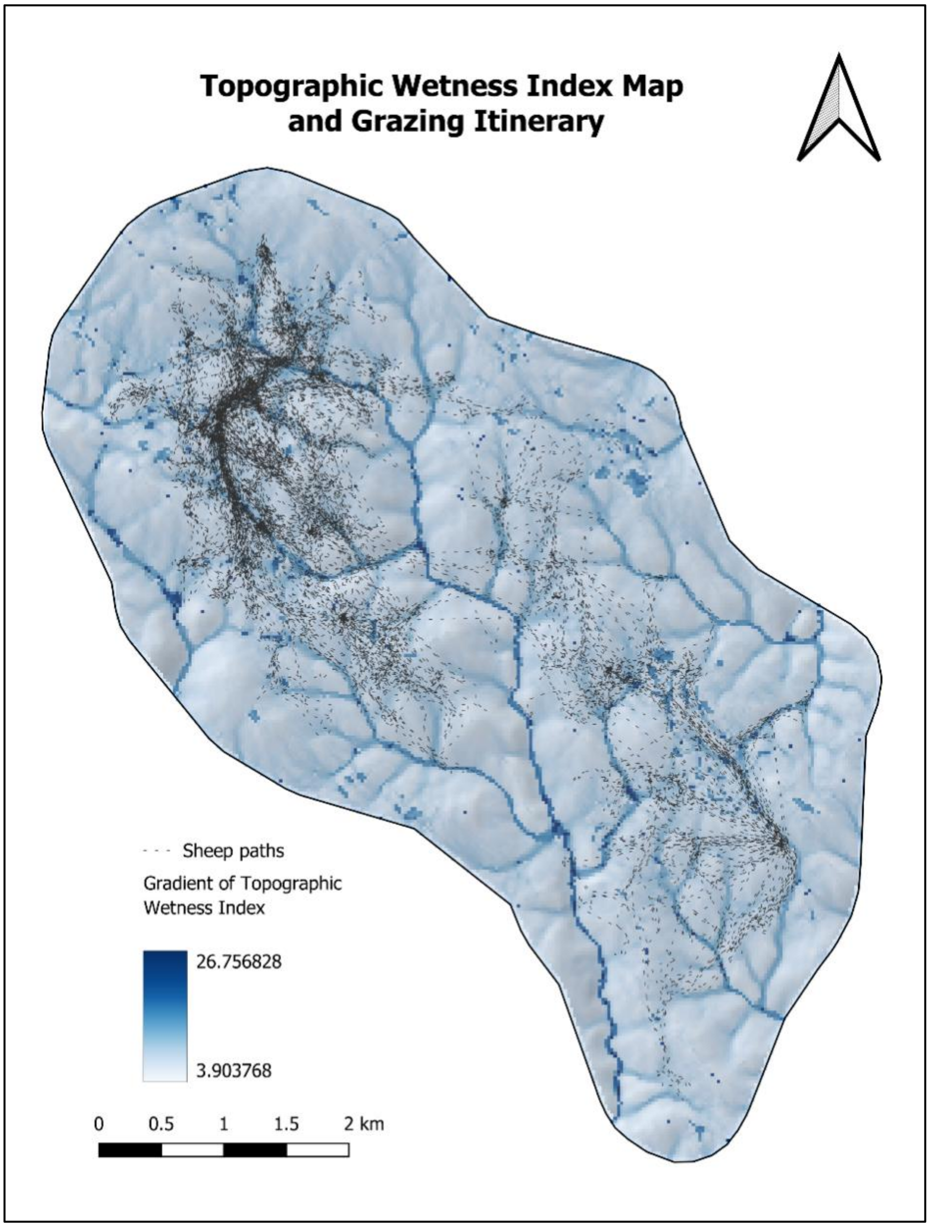


Figure 27: Topograhic Wetness Index (TWI) and Grazing Itinerary of the Study Area

4.1.4. Descriptive Statistics of the Calculated Variables

Table 14 presents the descriptive statistics that summarize both the **typical value** and the **spread** for each variable, showing how consistent sheep behavior and terrain conditions were during the study.

Table 14: Descriptive Statistics of Measured Variables

	Variables	Mean	Standard Deviation	Units
Paths	Duration (DRT)	537.368	282.753	Minutes
	Length (LGT)	4320.252	1915.232	Metres
Points	Elevation (ALT)	809.602	46.802	Metres
	Relative Slope Position (RSP)	0.308	0.157	Dimensionless
	Topographic Wetness Index (TWI)	14.328	1.975	Dimensionless

- ***Path-level Variables***

On average, the flock spends **about 9 hours outside the corral each day (537 ± 283 min)** and covers **4.3 km (SD 1.9 km)**. The large standard deviations—over 50 % of their respective means—reveal considerable day-to-day flexibility: on some days, the sheep range widely and stay out long, while on others they keep closer to base and return sooner, most likely adjusting to the season and weather.

- ***Point-level Terrain Variables***

GPS fixes occur at a fairly consistent altitude (**810 ± 47 m a.s.l.**) and mainly on **mid-slope positions (RSP ≈ 0.31 ± 0.16)**, while the **TWI mean of 14.3 (SD 2.0)** confirms the use of generally well-drained ground. Wet valley bottoms (low RSP, high TWI) are used only occasionally, suggesting the flock actively avoids persistently moist ground.

Overall, the variables depict a flock that **adjusts daily effort** (time and distance) to external conditions but **concentrates its activity on mid-altitude, moderately sloping, well-drained terrain**, where forage is accessible and footing is favorable.

Table 15 charts the data-cleaning process. Out of **27 330 raw records**, **18 899 (≈ 69 %)** were retained after cleaning, while **8 431** were discarded **(31 %)**. The final dataset covers **361 distinct grazing journeys**, with the highest single-day capture being **83 valid fixes on 11 May 2023**.

Table 15: Summary of GPS Dataset and Cleaning Outcomes for the Experimental Sheep Herd

Herd	Total Records	Records After Data Base Cleaning	Deleted Records	Grazing Journeys	Daily Maximum Records
Sheep	27330	18899	8431	361	83 (11/05/2023)

4.2. Data Visualisation

4.2.1. Distribution of GPS Points by Day and Time

The scatter plot below (Figure 28) illustrates the temporal distribution of recorded points for the sheep herd from March 2022 to March 2023.

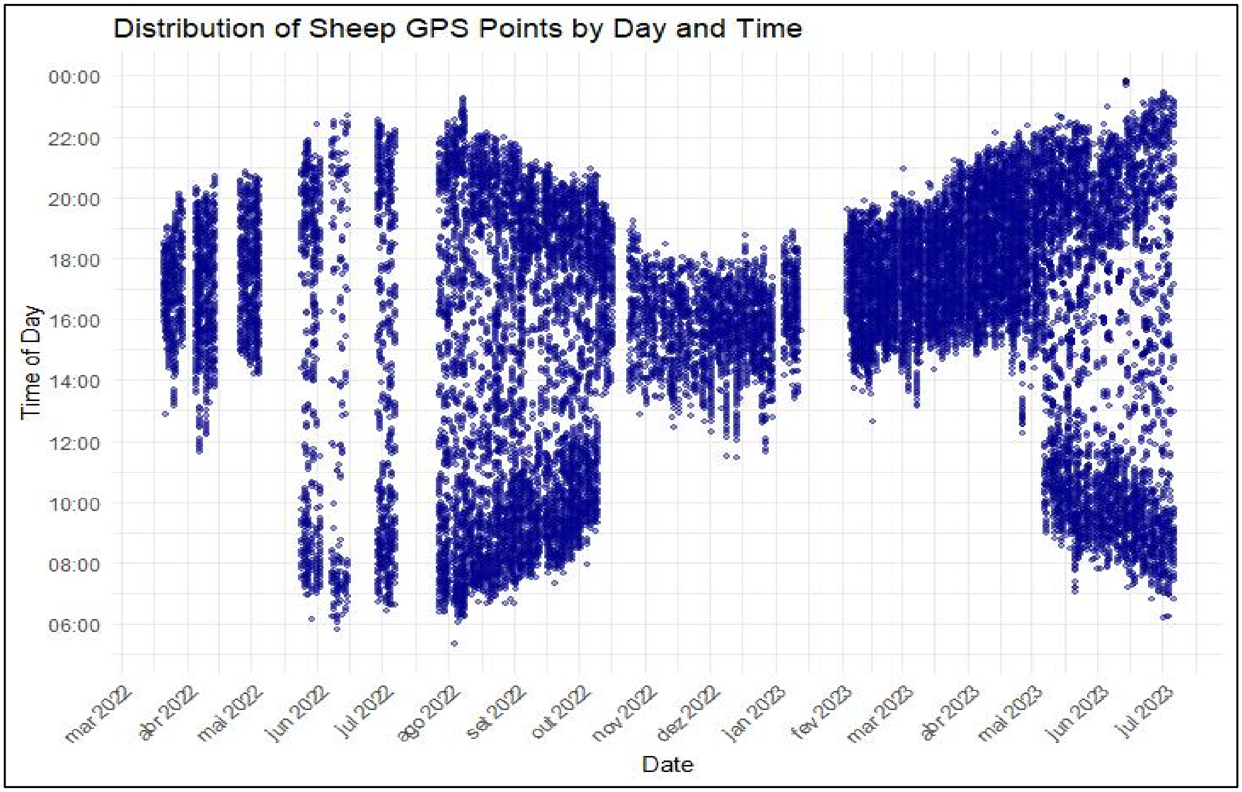


Figure 28: Distribution of Points by Day and Time

In early spring, fixes fell almost exclusively in mid-afternoon and early evening (≈ 14:00–20:00), indicating delayed turnout until pastures warmed. From late spring through the hot months of May–October 2022 the distribution became clearly bimodal: activity peaks occurred shortly after sunrise (≈ 07:00–10:00) and again from late afternoon until about 23:00, separated by a pronounced midday interval of inactivity that reflects thermoregulatory rest during the hottest hours.

As day length shortens and temperatures fall in November–December 2022, morning activity diminishes, and grazing is largely confined to 13:00–21:00. With the return of longer days in early summer 2023, fixes again shift toward late-day grazing, most occurring after 16:00. Periods with no data—late July–early August 2022 and mid-January 2023—result from temporary collar malfunctions and power loss rather than changes in flock management. Altogether, the changing breadth and timing of the point cloud underscore how ambient temperature and daylight jointly govern daily grazing behavior.

4.2.2. Total Records By Months

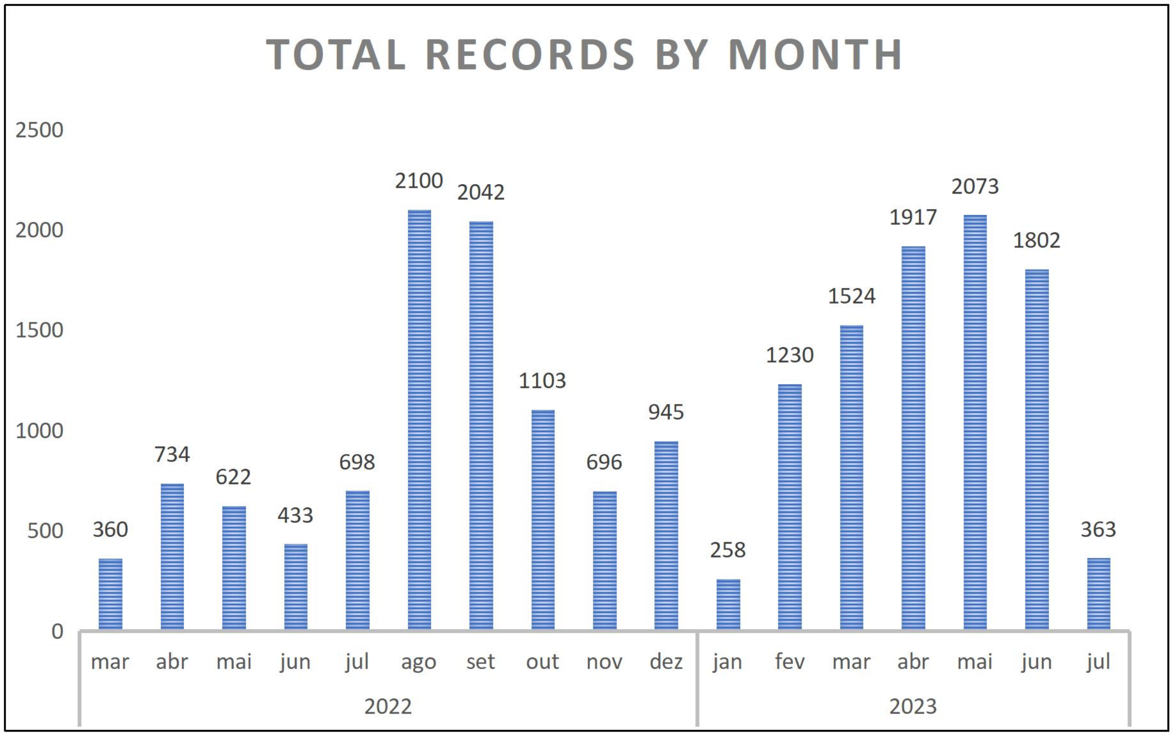


Figure 29: Total Records By Months

Monthly GPS output was far from uniform. During the initial deployment (March–July 2022) satellite lock and data-storage glitches limited output to fewer than 750 records per month. A high-output phase began in August 2022, when the sampling interval was shortened: August and September soared to 2 100 and 2 042 records, respectively, marking the year's peak. As autumn advanced, totals eased to 1 103 in October and slipped below 1 000 in November, reflecting a return to a longer duty cycle. December recovered slightly to 945 fixes, but January 2023 fell abruptly to 258 due to a battery failure.

Once the devices were serviced, data capture strengthened through spring 2023: February logged 1 230 records, March 1 524, and April–May reached 1 917 and 2 073 respectively. High activity persisted into early summer with 1 802 fixes in June, before July dropped to 363 because the month was only partially sampled. Overall, warmer months with fully functioning collars (August–September 2022 and April–June 2023) show the densest record streams, whereas lower counts correspond either to early low-frequency settings, deliberate duty-cycle extensions in late autumn, or short-lived equipment faults.

4.2.3. Land Use and Land Cover (LULC)

Figures 30 and 31 show that grazing activity is concentrated in just a handful of land cover types. By far the largest share of the itinerary (roughly 60 %) lies in temporary rain-fed and irrigated crops, indicating that most of the flock's recorded movement occurs across annual cropland. The next-largest slice—about 14 %—corresponds to agriculture with natural and semi-natural spaces, revealing that mixed farmland mosaics (fields interspersed with hedgerows, fallows, or small woody patches) form the second key component of the daily paths. All other classes exceed the **3 % threshold** only marginally: improved pastures (~7 %), forests of other oaks (~6 %), other broadleaf forests (~4 %), shrublands (~4 %). Together, these smaller wedges show that woodland edges and sown pastures are used, but much less frequently than crop fields. Every remaining class (chestnut, olive groves, orchards, built-up areas, etc.) falls below the 3 % cut-off and therefore contributes only a negligible length to the overall itinerary.

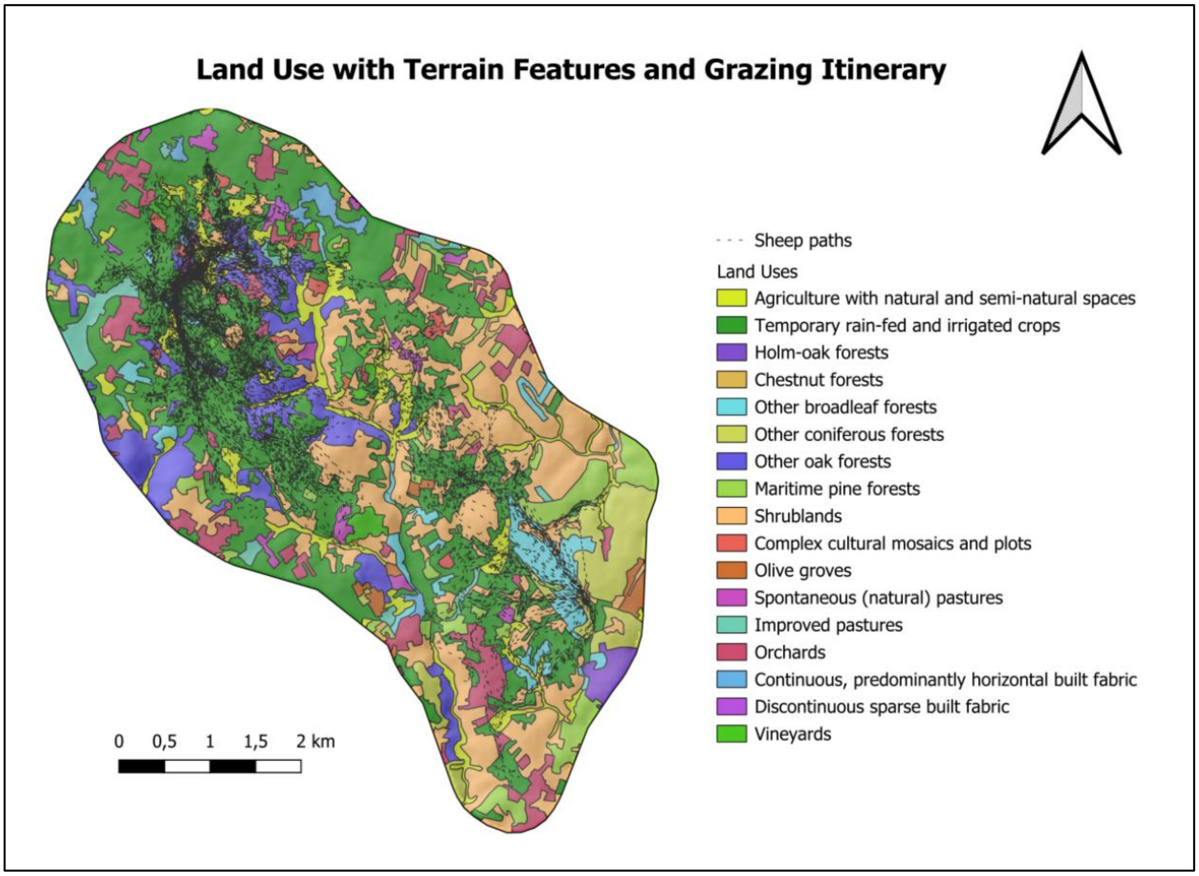


Figure 30: Land Use with Terrain Features and Sheep Movement Paths in the Study Area

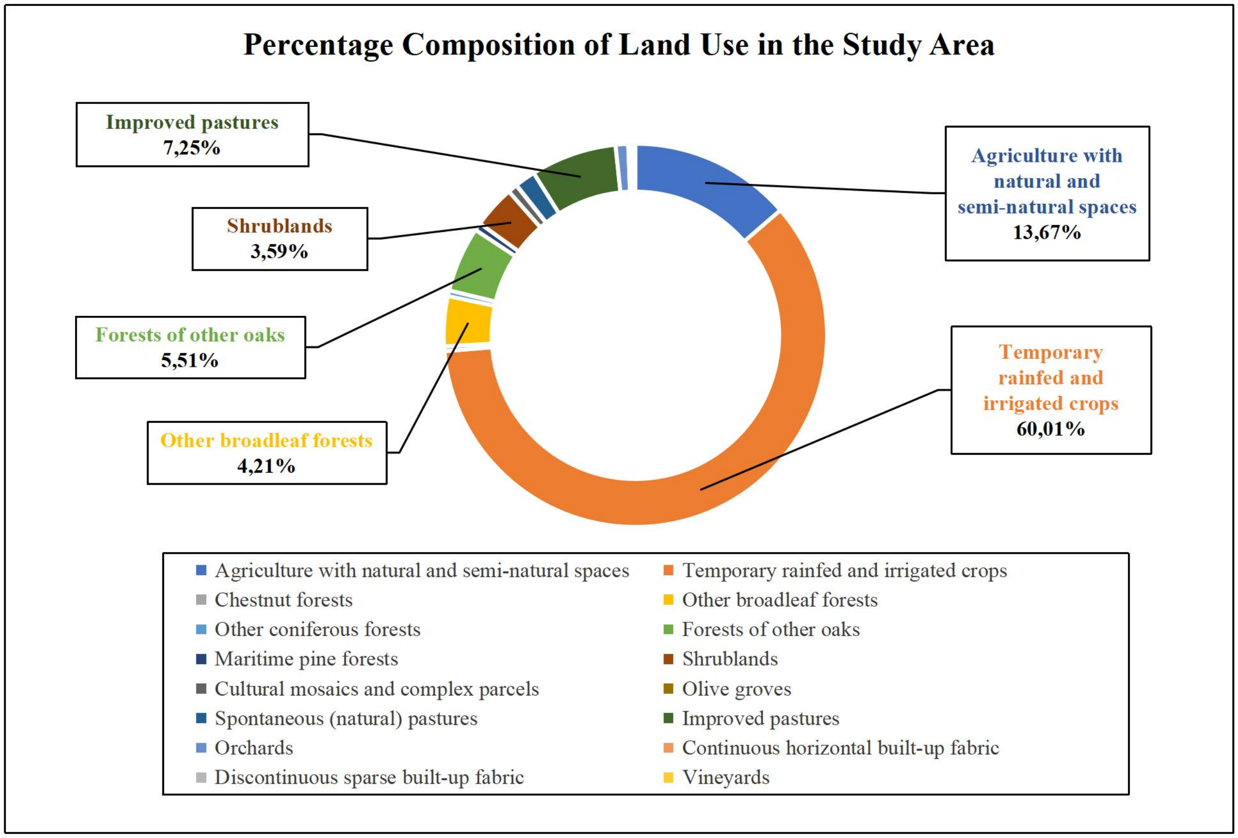


Figure 31: Pie Chart showing the Percentages of Land Uses in the Study Area

➢ Percentage Composition of Grazing Areas for the Herd by Season

Figure 32 highlights that, after filtering out land-use classes representing less than 3 %, the flock grazes predominantly in temporary rain-fed and irrigated crops—shown in orange—which account for about 70 % of GPS fixes in spring and summer and roughly 60 % in autumn and winter. Because **these crops fields lie on the upper plateau close to the corral**, the flock must **pass through them every morning and evening**; this daily transit inevitably inflates their share of the recorded points even when the day's effective grazing occurs elsewhere. Importantly, this crops class covers two rotational states of the same parcels: (i) actively growing cereals and (ii) post-harvest cereal stubble (chaume) left to rest or be re-sown the following season. The nutritional value of this land-use category therefore fluctuates through the year, from high-quality forage in spring to low-quality residue in late autumn and winter.

Still, clear seasonal patterns emerge. In autumn and winter, sheep make greater use of shrublands and agriculture with natural and semi-natural spaces, likely as fallback areas when preferred vegetation is less available. In spring and summer, there is increased use of improved pastures and forested patches, which offer early regrowth, forage diversity, and shade during hot days.

These trends suggest that while crop fields dominate the recorded positions, sheep adapt their habitat use seasonally in response to forage availability, temperature, and terrain structure.

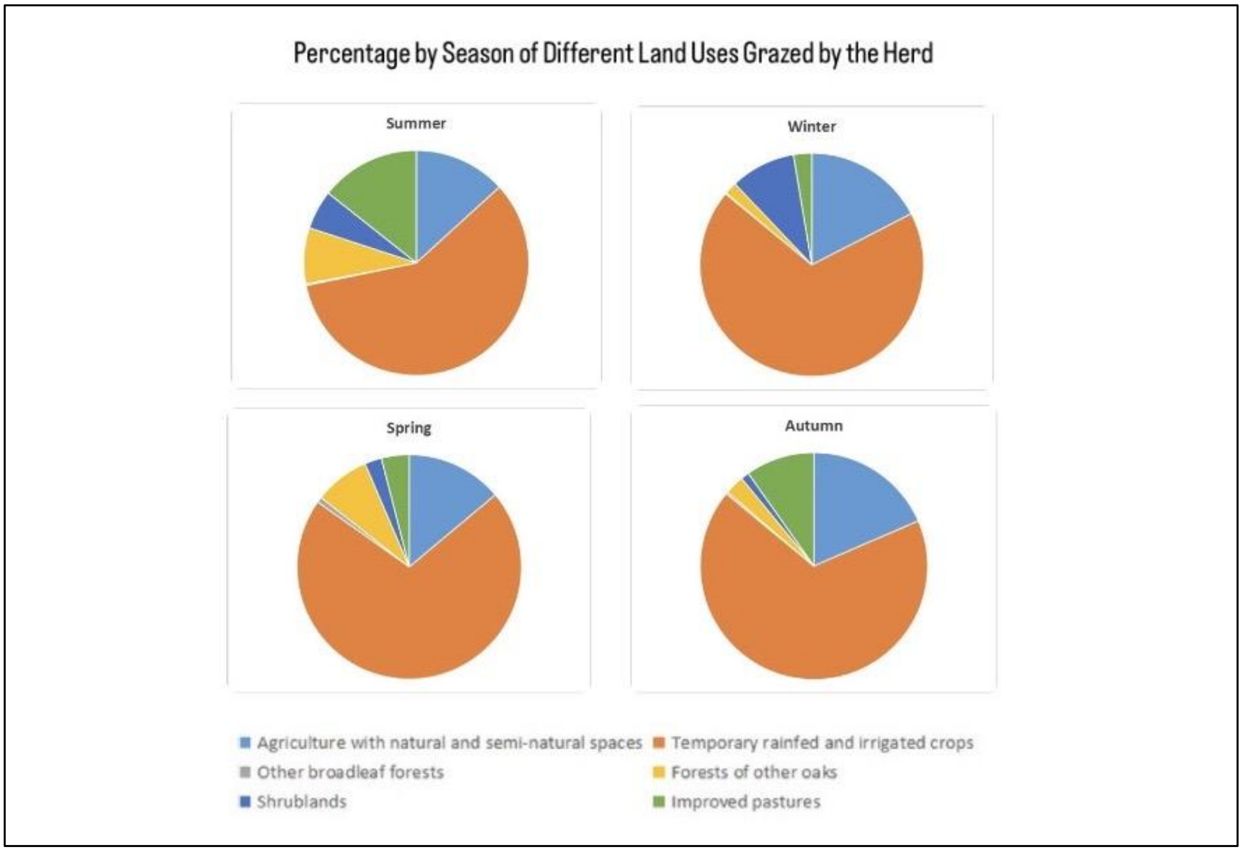


Figure 32: Percentage by Season of Different Land Uses Grazed by the Experimental Herd

4.2.4. Daily Grazing Duration with Seasonal and Annual Markers

Figure 33 plots the daily grazing duration (DRT) against time from March 2022 to July 2023, overlaid with colored bands for the four seasons and vertical lines marking solstices and equinoxes.

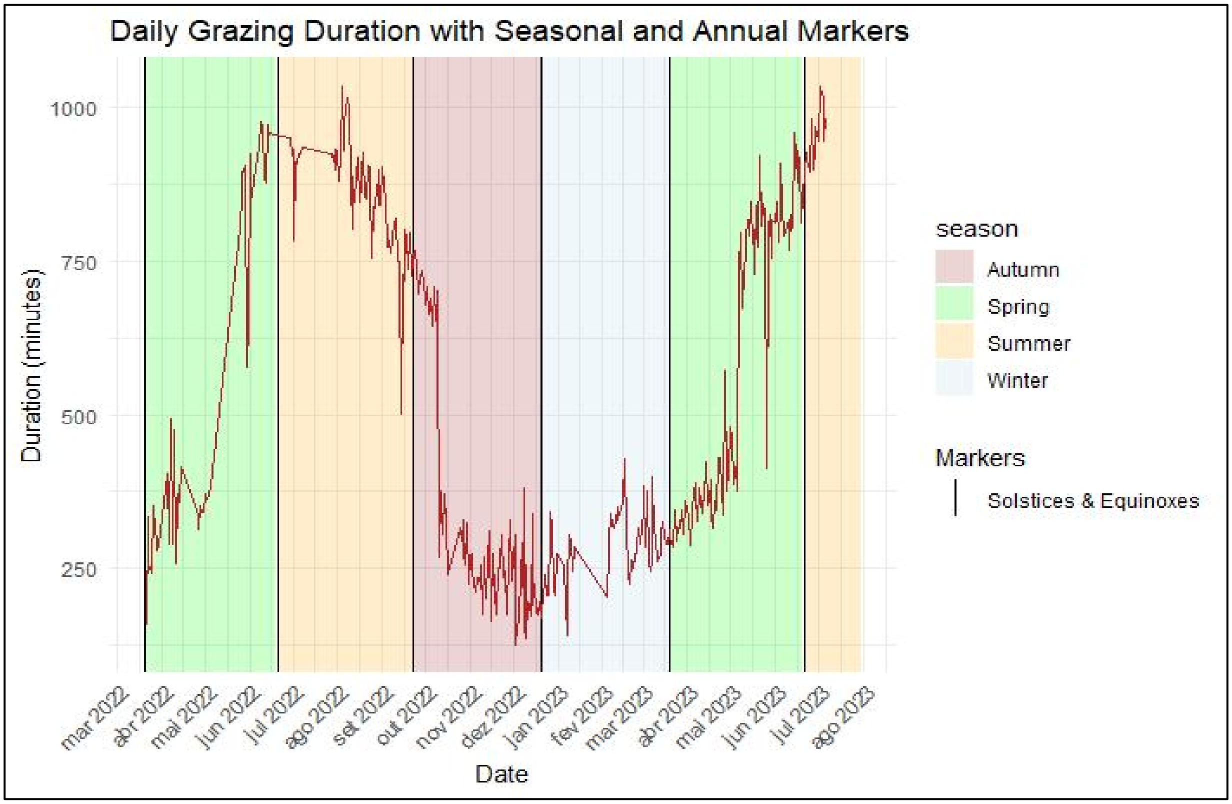


Figure 33: Daily Grazing Duration with Seasonal and Annual Markers

Grazing duration steadily climbs from roughly 200 min/day in early spring to peaks above 1 000 min/day in mid-June and early July—a large seasonal amplitude of over 800 min between winter minima and summer maxima—before declining through autumn to winter lows near 200–300 min/day. The solstice and equinox markers align closely with the inflection points in this trend, underscoring how shifts in day length and associated environmental conditions drive changes in foraging time.

Within those broad seasonal swings, shorter dips in July–August and occasional winter spikes betray the influence of transient weather events or pulses in forage quality. And despite longer overall durations in summer, the herd follows a two-phase grazing strategy—with active foraging in the cool morning and late afternoon separated by a scheduled midday rest—to capitalize on peak vegetation growth while avoiding midday heat. Together, these observations reveal how astronomical cycles, large seasonal amplitude, and within-season variability jointly shape the flock's grazing behavior.

4.3. Inferential Statistics

4.3.1. Correlation Analysis

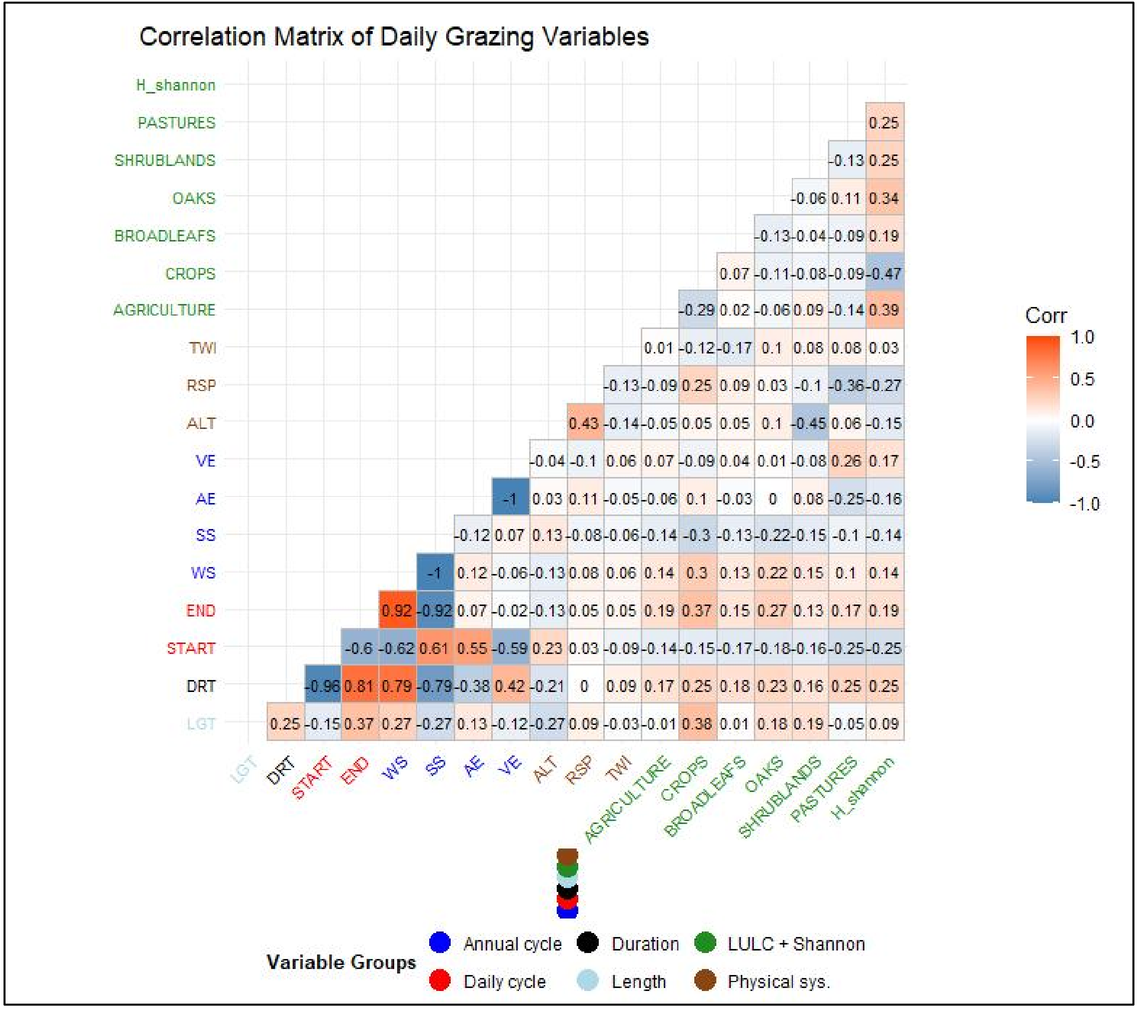


Figure 34: Pearson Correlation matrix of all the variables

Overall patterns

The Pearson correlation matrix (Figure 34) reveals several coherent clusters of associations across temporal, topographic, and land-use variables. Most strikingly, the grazing time shifts “START” (the difference between the start grazing time and 6AM) and “END” (the difference between the end grazing time and 6PM) correlate very strongly ($r = .92$, $p < .001$), indicating that days on which sheep begin grazing unusually early also tend to end grazing unusually late. These daily-cycle variables are themselves tightly linked to the annual-cycle markers: both START and END decline markedly as the “distance to winter solstice” (WS) increases (r = –0.62 and –0.79, respectively; $p < 0.001$), showing that midwinter days start later and finish earlier. Topographic features—elevation (ALT) and relative slope position (RSP)—exert only moderate positive influence on grazing routes ($r = 0.43$, $p < 0.01$), while Shannon diversity (H′) of land-use patches correlates positively with the proportion of temporary rainfed and irrigated crops ($r = 0.39$, $p < 0.01$). Together, these results underscore how grazing behavior integrates daily light-cycle constraints, seasonal photoperiod shifts, and landscape heterogeneity.

- **Rationale for dropping Duration (DRT)**

Although the grazing duration (DRT) is conceptually distinct, it is mathematically redundant given how we constructed START and END. Because START measures the offset from a fixed 6 AM anchor and END measures the offset from a fixed 6 PM anchor, the two alone fully determine DRT, which reflects an exact linear dependency:

$$\text{DRT}=(6\text{ PM}+\text{END})-(6\text{ AM}+\text{START})=720\text{ min }+\text{END}-\text{START}$$

Consequently, DRT correlates almost perfectly with START and END ($|r| \geq 0.96$), rendering the three variables collinear and causing the correlation matrix to become singular (Bartlett’s test of sphericity fails). Retaining all three would violate PCA’s assumption of linear independence and destabilize downstream multivariate analyses. By excluding DRT—while preserving the two fundamental daily-cycle measures—we eliminate redundancy without sacrificing any unique information.

- **Rationale for dropping Winter Solstice (WS) and Autumnal Equinox (AE)**

The four annual-cycle proximity measures to winter solstice (WS), summer solstice (SS), autumnal equinox (AE) and vernal equinox (VE) also form two perfectly inverse pairs: WS vs. SS and AE vs. VE both correlate at –1.00. This perfect negative collinearity arises because “days from winter solstice” and “days from summer solstice” are **mirror** images around midsummer, just as the two equinox distances mirror one another around the spring–autumn midpoint. Including both members of either pair again yields a singular correlation matrix and confounds PCA loading calculations. Consequently, WS and AE were removed, and SS and VE were retained. Practically, SS (proximity to summer solstice) and VE (proximity to vernal equinox) coincide with the periods of longest days, maximal and rapid day-length increase, respectively, which more directly influence pasture growth and sheep grazing behavior in this study context.

4.3.2. Suitabilty Tests Results

4.3.2.1. Bartlett's SphERity Test

To assess the factorability of the dataset, Bartlett's test of sphericity was conducted on the correlation matrix of the daily grazing variables. The test yielded a χ^2 of 2450.864 on 105 df with $p < 0.001$, decisively rejecting the null hypothesis that our correlation matrix is an identity matrix. In other words, many of our variables share non-zero correlations, so there is sufficient inter-correlation to justify proceeding with a dimension-reduction technique like PCA.

4.3.2.2. Kaiser–Meyer–Olkin Test

The overall Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy for these 15 variables was **0.69**, which falls into the "mediocre" range (0.60–0.69). This indicates that, while the dataset is just adequate for factor analysis, a handful of variables contribute less strongly to the common-factor structure.

Table 16: MSA Value for Each Variable

Variable	MSA
LGT	0.58
START	0.65
END	0.70
SOLSTICE	0.67
EQUINOX	0.64
ALT	0.74
RSP	0.57
TWI	0.54
AGRICULTURE	0.69
CROPS	0.59
BROADLEAFS	0.66
OAKS	0.77
SHRUBLANDS	0.68
PASTURES	0.63
H_shannon	0.60

4.3.3. PCA Results and Interpretation

4.3.3.1. Percentage of Variance Explained

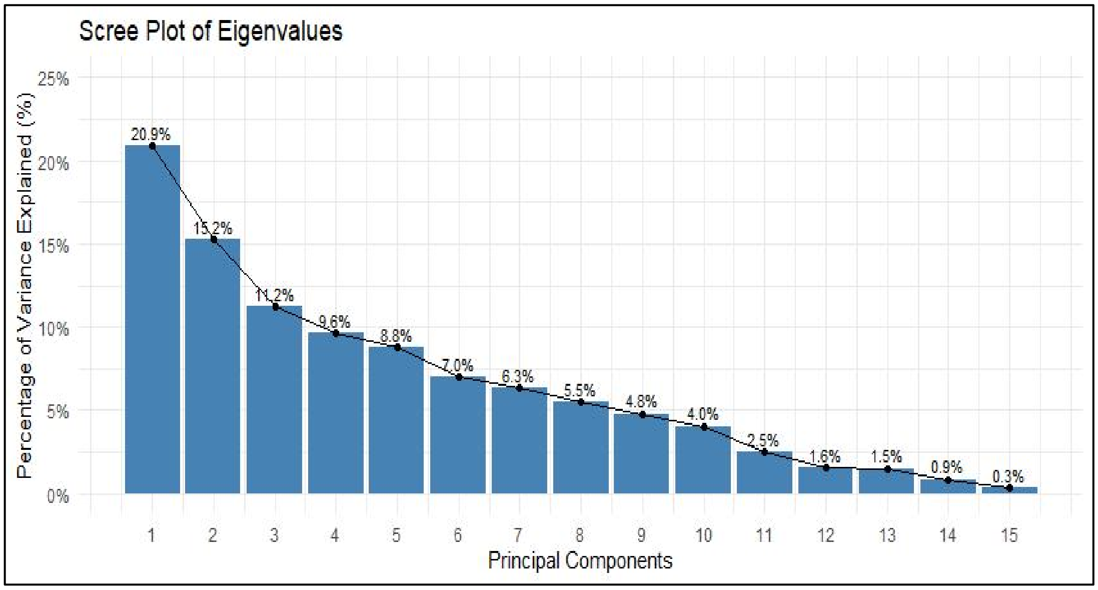


Figure 35: Scree Plot of Eigenvalues

Although components with eigenvalues > 1 continued through PC4 with a cumulative variance of 56.9 % (Table 17), we will retain only the first three axes because (a) the scree inflection occurred at PC3, indicating diminishing explanatory gain beyond that point, and (b) PCs 4–15 each explained < 10 % of variance and were dominated by singleton variables, offering little interpretative leverage. Collectively, the first three axes capture the orthogonal gradients most relevant to management and furnish a parsimonious yet informative ordination consistent with the Kaiser–Guttman criterion.

Table 17: Eigenvalues, Variance Percentage, Cumulative Variance Percentage for the First Dimensions

Component	Eigenvalue	% Variance Explained	Cumulative %
PC1	3.14	20.9	20.9
PC2	2.28	15.2	36.1
PC3	1.68	11.2	47.3
PC4	1.44	9.6	56.9
…	…	…	…

4.3.3.2. Contributions of the Variables to the Dimensions

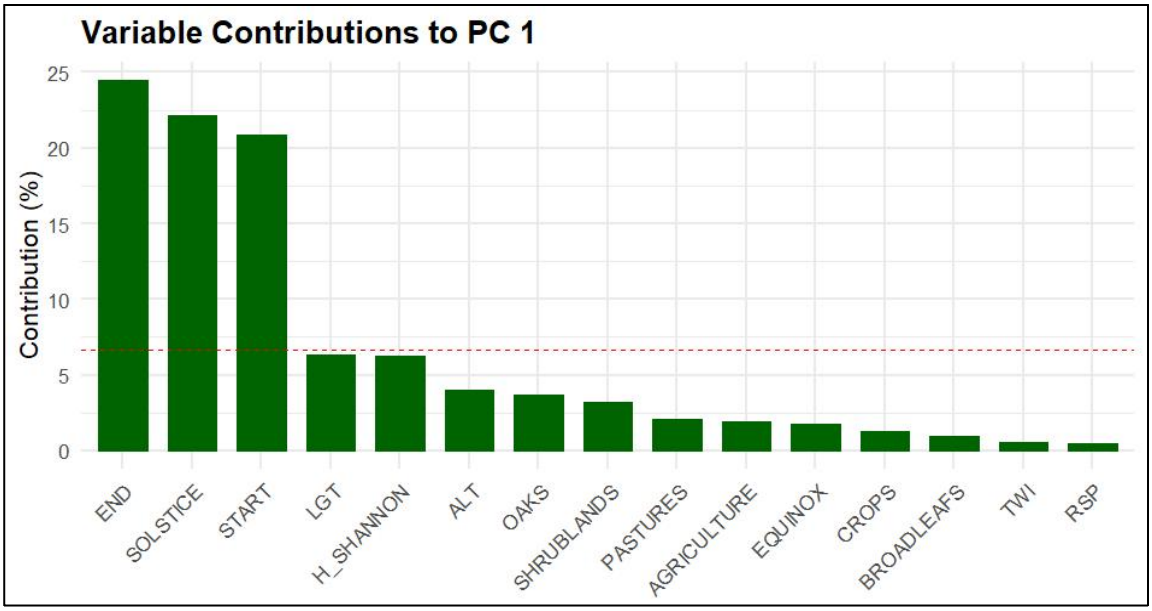


Figure 36: Contributions of Variables to PC1

PC1 explains 20.9% of the total variance. The variables that contribute most are END, SOLSTICE, and START, followed by grazing duration (LGT) and habitat diversity (H_SHANNON). This suggests that PC1 is shaped primarily by temporal grazing patterns and seasonal positioning.

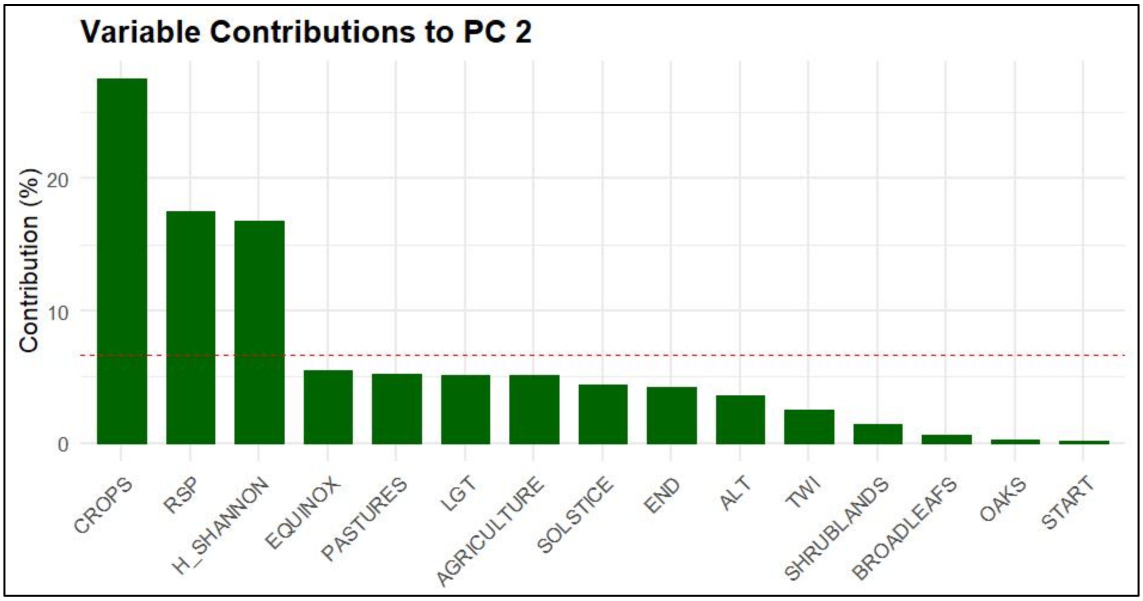


Figure 37: Contributions of Variables to PC2

PC2 accounts for 15.2% of the total variance. The largest contributors are temporary rainfed and irriguated crops (CROPS), relative slope position (RSP), and habitat diversity (H_SHANNON). This component is mainly influenced by land use and topographic variables, with some contribution from seasonal timing.

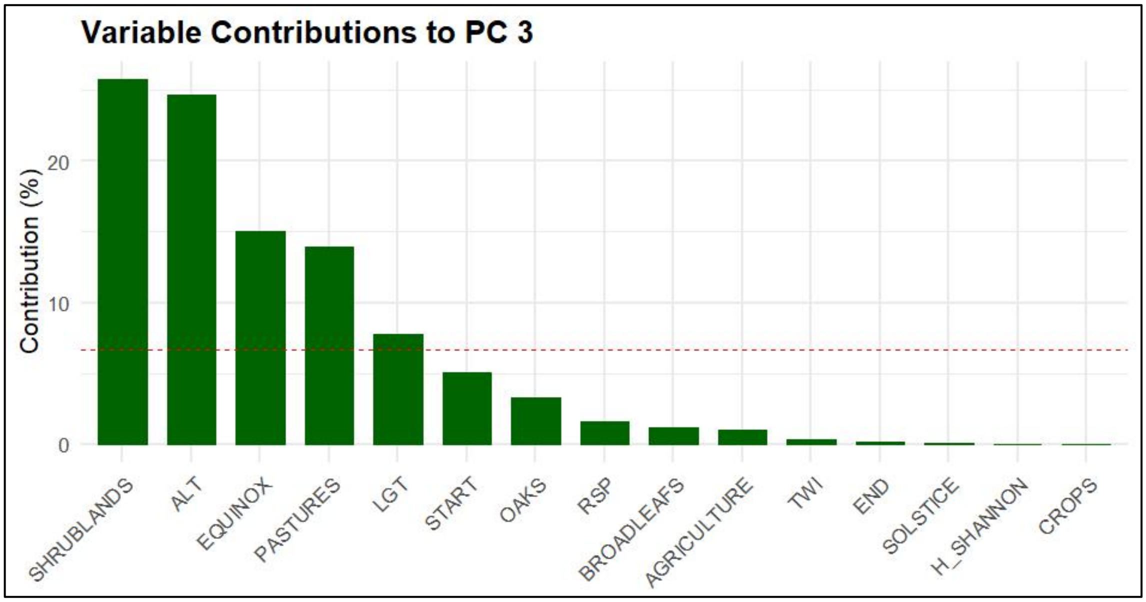


Figure 38: Contributions of Variables to PC3

PC3 explains 11.2% of the total variance. The most important variables are SHRUBLANDS, elevation (ALT), and EQUINOX (proximity to vernal equinox), followed by PASTURES and grazing duration (LGT). This component reflects shifts in land use and elevation across the seasonal cycle.

4.3.3.3. Correlations Between the Variables and the Principal Components

The loadings of each variable on the principal components represent both their strength of influence and the direction of their relationship with each axis. High positive or negative values define opposing ends of the ecological gradients captured by each component, helping to distinguish contrasting behavioral and environmental patterns. This polarity is essential for interpreting the meaning of each principal component in terms of ecological variation.

Table 18: The Loadings of Each Variable on the First Three Principal Components

	LGT	START	END	SOLSTICE	EQUINOX	ALT	RSP	TWI	AGRICULTURE	CROPS	BROADLEAFS	OAKS	SHRUBLANDS	PASTURES	H_shannon
PC1	0.252	–0.457	0.495	–0.471	0.134	–0.201	–0.068	0.072	0.139	0.113	0.097	0.191	0.179	0.143	0.251
PC2	0.227	0.036	0.205	–0.209	–0.235	0.189	0.418	–0.159	–0.226	0.525	0.079	–0.052	–0.121	–0.229	–0.409
PC3	0.279	0.226	–0.042	0.024	–0.388	–0.497	–0.127	0.059	0.100	0.002	–0.108	–0.181	0.508	–0.374	–0.010

Among the temporal variables, only SOLSTICE (proximity to the summer solstice) and EQUINOX (proximity to the spring equinox) were retained in the PCA. The two other seasonal markers—Winter Solstice (WS) and Autumnal Equinox (AE)—were removed. However, their biological meaning was not lost.

WS is the exact inverse of SOLSTICE, and AE is the mirror of EQUINOX. As a result, any positive loading on SOLSTICE corresponds to a negative association with WS, and the same logic applies for EQUINOX and AE.

For instance, a PC with a high positive loading on SOLSTICE represents grazing behavior close to midsummer, while low values on that same axis implicitly capture conditions close to midwinter (WS). Similarly, transitions associated with the spring equinox are reflected in EQUINOX loadings, while transitions around the autumn equinox (AE) are captured on the opposite side of the same dimension.

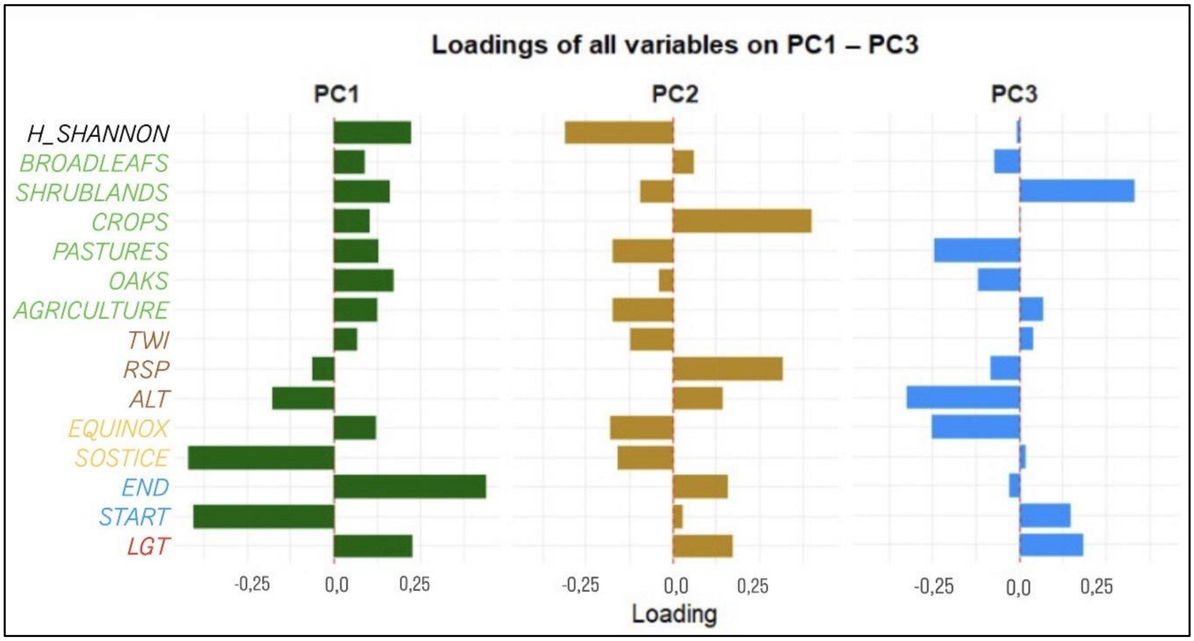


Figure 39: Bar Plot of Variable Loadings on PC1, PC2, and PC3

➢ PC 1 – Seasonal Intensity: How Long and When Sheep Graze

Table 19: Key Variable Loadings on PC1 and Their Ecological Interpretation

Variable	Contribution (%)	Loading	Interpretation
END	24.6%	+0.495	Sheep return much **later** in the evening during summer.
SOLSTICE	22.1%	–0.471	These long grazing days are close to the summer solstice (June 21).
START	21.0%	–0.457	Sheep leave earlier than 06:00 in summer.
LGT	7.3%	+0.252	Sheep graze over greater distances.
H_SHANNON	6.9%	+0.251	Sheep move through a larger variety of land-cover types.

PC1 clearly separates midsummer days from winter days and primarily reflects how long and flexibly sheep graze depending on the season.

Days with high PC 1 scores are typically in summer, when daylight is longest, and the flock starts grazing very early and returns long after 6:00 PM. On these days, sheep also explore a wider range of land use and cover greater distances, as shown by the positive loading on H_SHANNON and LGT (length).

However, it is important to note that long summer grazing days are not continuous. Because of high midday temperatures, sheep often take extended breaks around noon, seeking shade under trees or in forested areas. This resting behavior divides the day into morning and evening grazing sessions, with forest patches playing a critical role not only as a foraging resource but also as a thermal refuge.

In contrast, low PC 1 scores correspond to winter days when the flock stays active within a shorter, more constrained grazing time, with less movement and lower land use diversity due to cold temperatures and shorter daylight hours.

PC 1, therefore, represents a seasonal rhythm that balances daylight availability, temperature constraints, and behavioral flexibility, from short, direct winter grazing to longer, interrupted summer excursions that integrate both exploration and rest.

➢ PC 2 – Plateau Crops vs. Valley Mix (Spatial Gradient)

Table 20: Key Variable Loadings on PC2 and Their Ecological Interpretation

Variable	Contribution	Loading	Interpretation
CROPS	28.3%	+0.525	Sheep are in cereal fields, especially in winter.
RSP	18.2%	+0.418	They are on higher plateau or steeper slopes.
H_SHANNON	17.4%	–0.409	Habitat diversity is lower.
EQUINOX	6.4%	–0.235	Farther from the spring equinox.
PASTURES	6.2%	–0.229	Less time in pastures (more in cereal fields).

The high end of PC2 represents days when sheep graze on the low-diversity upper plateau of the study area, while the low end corresponds to days when they descend to graze in the more diverse valley floor and mid-slopes. To understand this pattern, it is useful to describe the local landscape, which includes three broad grazing zones:

a. The upper plateau, around 400–500 meters above sea level, is mostly dominated by temporary rain-fed and irrigated cereal fields (CROPS). This area has gentle slopes, homogeneous vegetation, and is located at the same elevation as the corral, making it easily accessible. Since sheep start and end their day there, they do not need to travel far to reach these fields. As a result, grazing days in this area tend to be shorter, which is reflected in the positive but moderate loading of grazing length (LGT) alongside CROPS. This zone is used more frequently in autumn and winter when the flock remains uphill to graze on post-harvest crop residues.

b. The mid-slopes are more heterogeneous, with patches of pastures, shrubs, oaks, and broadleaf forests. These are used in spring and summer when new vegetation appears.

c. The valley bottom, around 100–200 meters, is near a seasonal stream and includes shrublands, riparian areas, and mixed-use agriculture, which offers high habitat diversity.

This component also highlights the contrast between two landscape units:

✓ The **agricultural matrix**, located at a higher elevation, is open and uniform, primarily composed of cereal crops.

- ✓ The **forest matrix**, located in lower or mid-slope areas, offer a variety of habitats, including shelter, shade, and a mix of woody and herbaceous forage.

Thus, PC 2 reveals how the flock shifts between these two landscape types, depending on the season, forage availability, and topography.

➢ PC 3 – Habitat Transitions During Intermediate Seasons: Spring Pastures vs. Autumn Shrublands

Table 21: Key Variable Loadings on PC3 and Their Ecological Interpretation

Variable	Contribution	Loading	Interpretation
SHRUBLANDS	26.7%	+0.508	Sheep graze more in shrublands in autumn.
ALT	25.0%	–0.497	Shrublands are at lower elevations, farther downslope from the plateau.
EQUINOX	15.2%	–0.388	Sheep are farther from the spring equinox on shrubland days.
PASTURES	14.3%	–0.374	Sheep graze in improved pastures during spring.
LGT	7.2%	+0.279	Sheep travel longer distances to reach shrublands.

PC 3 reflects a more subtle habitat shift that occurs particularly in the intermediate transitional seasons: spring and autumn. The component contrasts the use of shrublands in autumn with the use of pastures and oak forests in spring.

High PC3 scores reflect grazing in low-lying shrublands, which are used primarily in autumn when other parts of the landscape offer limited forage. These zones are generally less diverse and less productive but still provide usable resources when needed. Since the corral is located on the upper plateau, accessing these distant shrublands requires the flock to travel longer distances each day, which explains the positive loading of grazing length (LGT) on this axis.

In contrast, low PC 3 scores are associated with the spring season, when sheep switch to improved pastures and nearby oak or broadleaf forests, where early fresh herbaceous plants appear. These areas are slightly higher in elevation and provide not only nutritional resources but also shelter and shade, which are particularly important as temperatures begin to rise.

This axis reflects the flock’s flexible response to seasonal transitions. Depending on forage availability, shade needs, and weather conditions, sheep target pastures and forests in spring while relying on shrublands as fallback areas in autumn. Their movement balances forage quality with the need for shelter and microclimate buffering.

4.3.3.4. Correlation Circles of the Combinations

- **Correlation Circle: Dimensions 1 and 2**

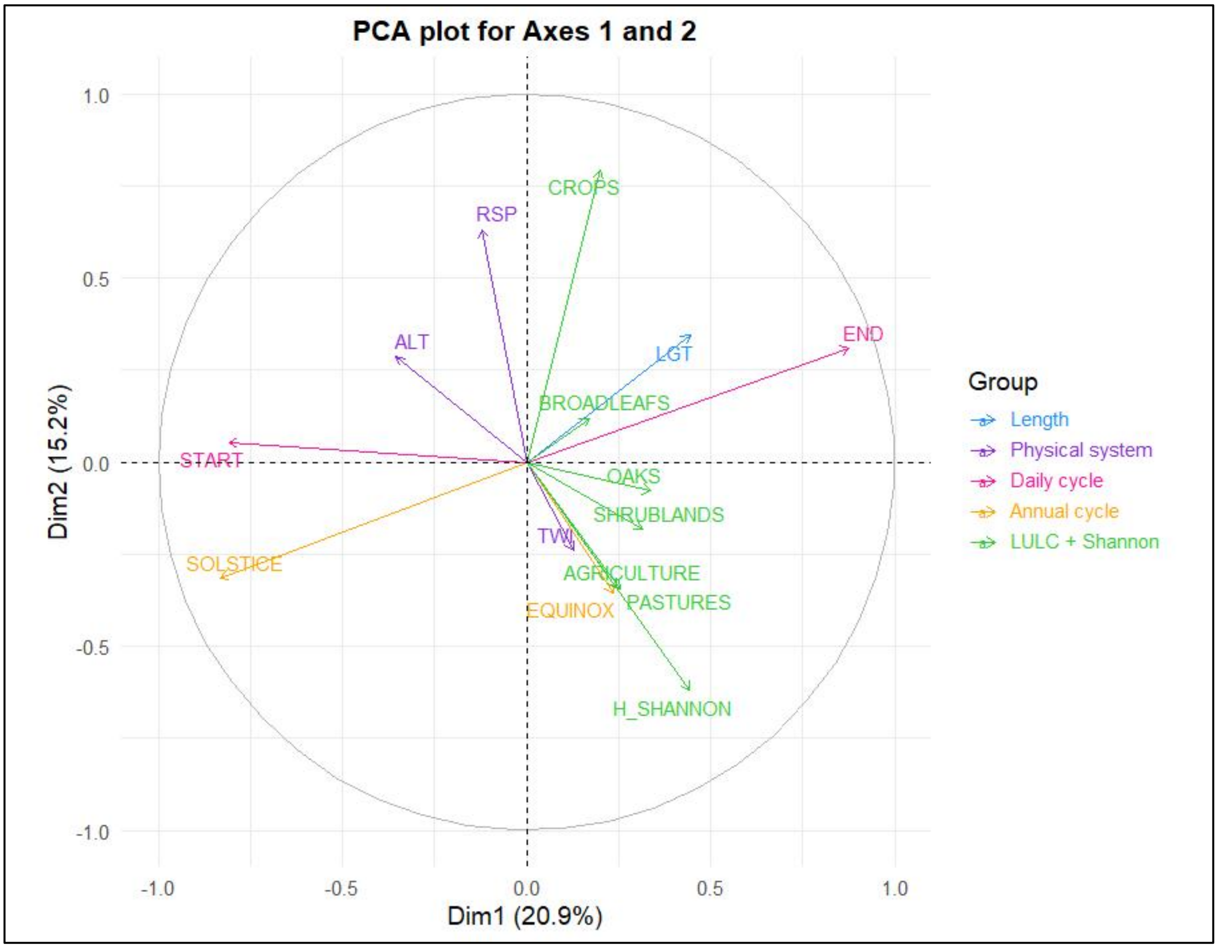


Figure 40: Correlation Circle for Principal Components 1 and 2

Figure 39 contrasts seasonal grazing timing (PC1) with a landscape and land-use gradient (PC2).

- PC1 (horizontal axis) clearly separates summer grazing patterns (high END, early START, long LGT, high H_SHANNON) on the right from winter patterns (high SOLSTICE, late START, low diversity) on the left. It reflects how long and how flexible the grazing is, with longer, more exploratory days in summer.
- PC2 (vertical axis) shows a spatial contrast. Positive scores are associated with high-elevation crop fields (CROPS, RSP), while negative scores align with diverse valley mosaics (H_SHANNON, AGRICULTURE). This supports the interpretation of PC2 as a ridge vs. valley land-use gradient, separating homogeneous plateau cropping from heterogeneous lower areas.

This plot highlights the flock's combined response to seasonal cycles and landscape position: in summer, sheep graze longer and more diversely; in autumn and winter, they stay closer to the plateau crops and move less.

- **Correlation Circle: Dimensions 1 and 3**

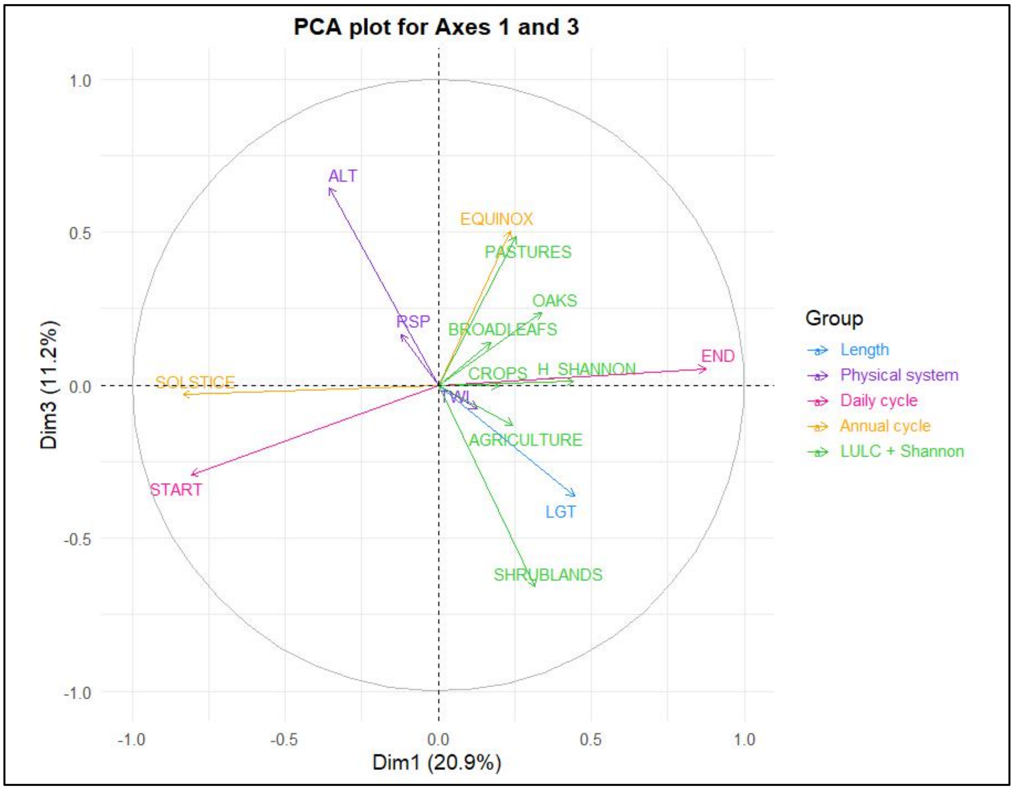


Figure 41: Correlation Circle for Principal Components 1 and 3

Figure 40 combines seasonal intensity (PC1) with the habitat transition gradient (PC3).

- PC1 repeats the summer vs. winter grazing pattern, as described above.
- PC3 (vertical axis) differentiates spring pastures and forests (low PC3: PASTURES, OAKS, EQUINOX) from autumn/winter shrublands (high PC3: SHRUBLANDS, with ALT and LGT in the opposite direction).

  - SHRUBLANDS are clearly separated downward from the rest, indicating that grazing in these areas is distinct, involving longer distances (LGT) and lower elevation (ALT).

  - The positive LGT direction here reinforces what your supervisor noted: going to shrublands requires traveling farther since they are located downhill, away from the corral.

This plot captures the temporal and spatial flexibility of spring/autumn grazing, where sheep adjust between nearby plateau fields, downhill shrub zones, and mid-slope pastures, depending on the season and forage.

- **Correlation Circle: Dimensions 2 and 3**

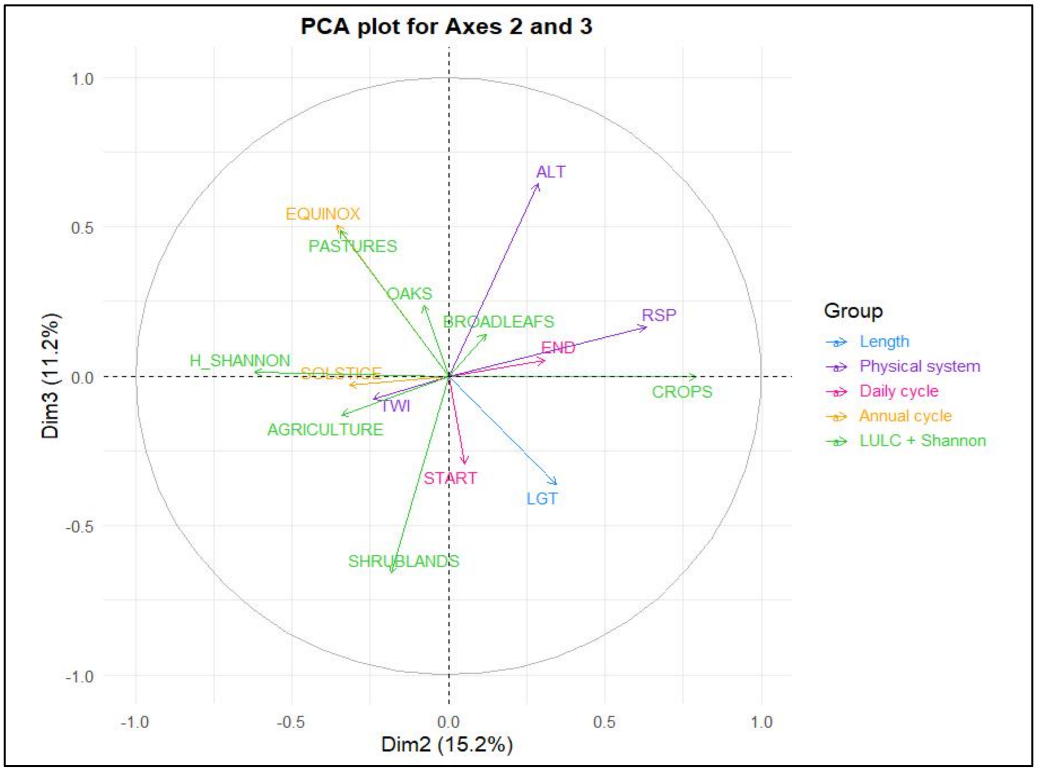


Figure 42: Correlation Circle for Principal Components 2 and 3

Figure 41 removes the seasonal timing axis (PC1) and focuses purely on landscape gradients and habitat transitions.

- PC2 still reflects the ridge-crop vs. valley-mosaic contrast: CROPS and RSP (top-right) versus H_SHANNON and AGRICULTURE (bottom-left).
- PC3 adds a second gradient: spring pastures/forests (EQUINOX, PASTURES, OAKS) on the top-left vs. shrublands and longer travel (SHRUBLANDS, LGT) on the bottom-right.

This plot is particularly useful for visualizing how different land-cover types group together. For example:

- Forests (OAKS, BROADLEAFS) and pastures cluster closely with EQUINOX—indicating their use in spring.
- CROPS are distant from shrublands and pastures, confirming they occupy a distinct zone on the plateau.
- SHRUBLANDS and LGT are closely aligned, reinforcing the idea of long-distance autumn/winter foraging into low areas.

4.3.3.5. Biplots of Individuals and Variables by Season

This section presents biplots combining individuals (daily observations) and variables, grouped by season, to explore how grazing behavior varies across the year in relation to environmental and spatial factors. By projecting both the variables and seasonal data points into the PCA space, these plots help visualize the overlap, separation, and seasonal clustering of grazing patterns, revealing how different conditions shape the flock's movements and habitat use.

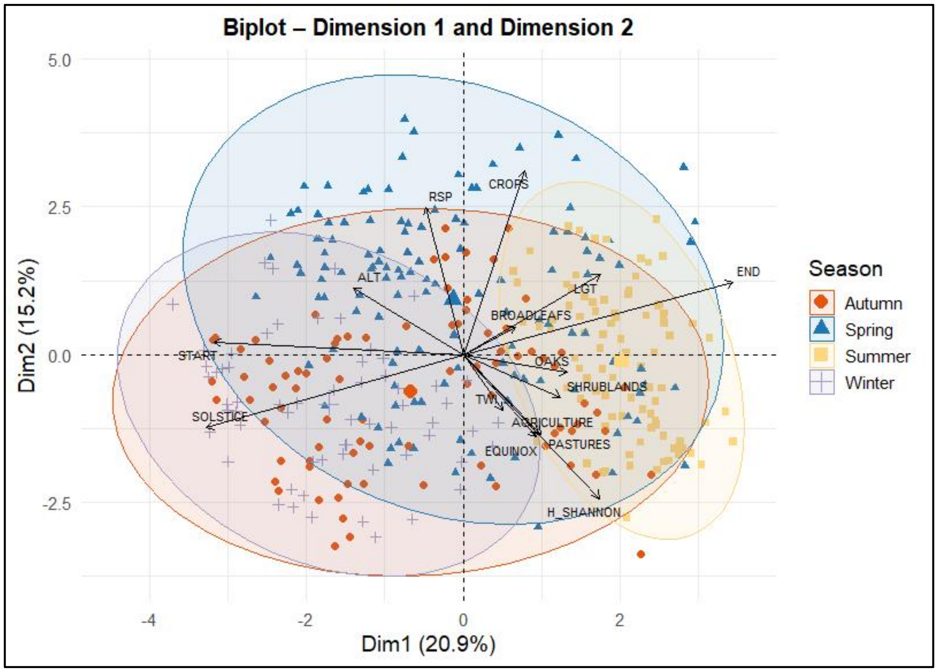


Figure 43: Visualization of Individuals and Variables by Season on axis 1 and 2

Figure 42 combines the effects of daily grazing rhythm and duration (PC1) with a spatial land-use and topographic gradient (PC2).

- ✓ Summer observations (yellow) are clustered on the right, in the direction of variables such as END, LGT, and H_SHANNON, indicating longer grazing days, later returns, and greater land-use diversity.
- ✓ Winter days (purple) are grouped on the left, aligned with START and SOLSTICE, corresponding to shorter, more constrained grazing patterns.
- ✓ Autumn data points (orange) are located higher along PC2, near CROPS and RSP, reflecting grazing on high-elevation cereal fields near the corral.
- ✓ Spring points (blue) are more dispersed, overlapping both the plateau crop zone and the lower, more heterogeneous valley areas, suggesting flexible habitat use during this transitional period.

This projection shows how the flock responds both to seasonal timing and to landscape structure, with clear differentiation between summer and winter routines, and a spatial shift between plateau and valley use.

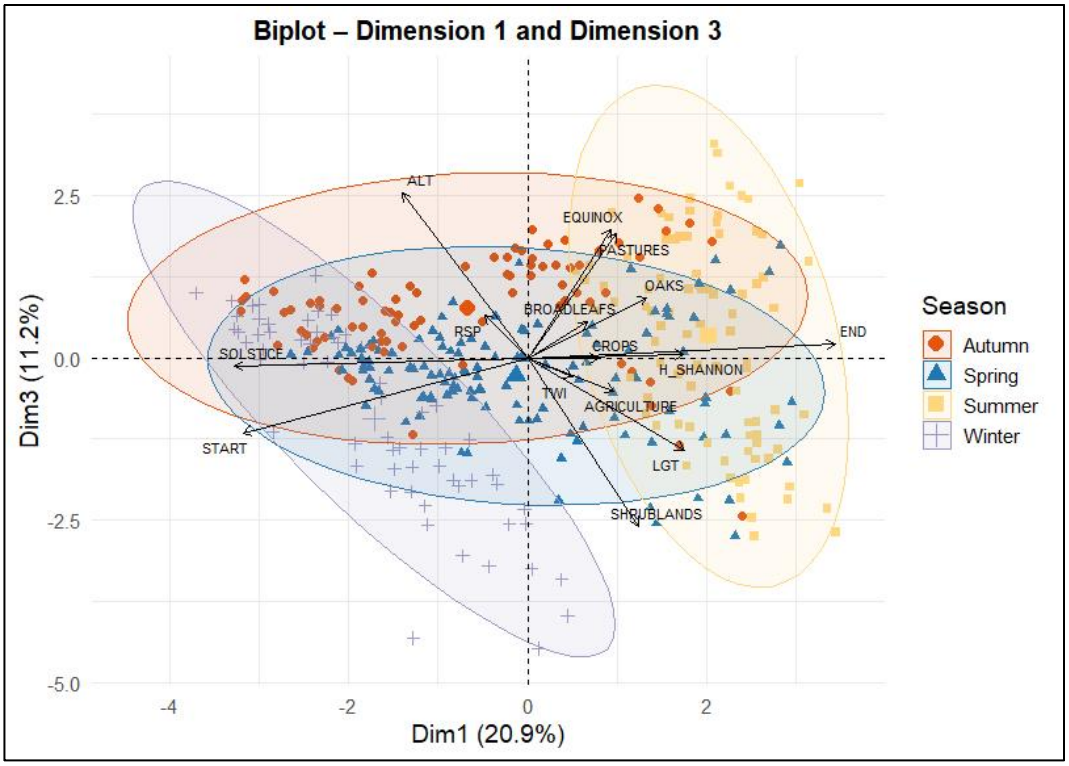


Figure 44: Visualization of Individuals and Variables by Season on axis 1 and 3

Figure 43 links seasonal grazing behavior (PC1) with a habitat transition axis (PC3) that reflects elevation and habitat structure.

- ✓ Along PC1, the seasonal separation remains evident, with summer on the right and winter on the left.
- ✓ PC3 differentiates spring grazing in pastures, oak forests, and mixed-use mosaics (EQUINOX, PASTURES, OAKS) from autumn/winter use of low-elevation shrublands (SHRUBLANDS, LGT).
- ✓ The positive loading of LGT supports the idea that reaching shrubland zones requires longer travel, as these areas are located downhill, farther from the corral.
- ✓ Spring observations cluster toward areas of early regrowth and shelter, while autumn points lie closer to plateau cropping areas.

This plot reinforces the idea of a spring-to-winter shift from structured, productive habitats to more distant fallback zones in the valley.

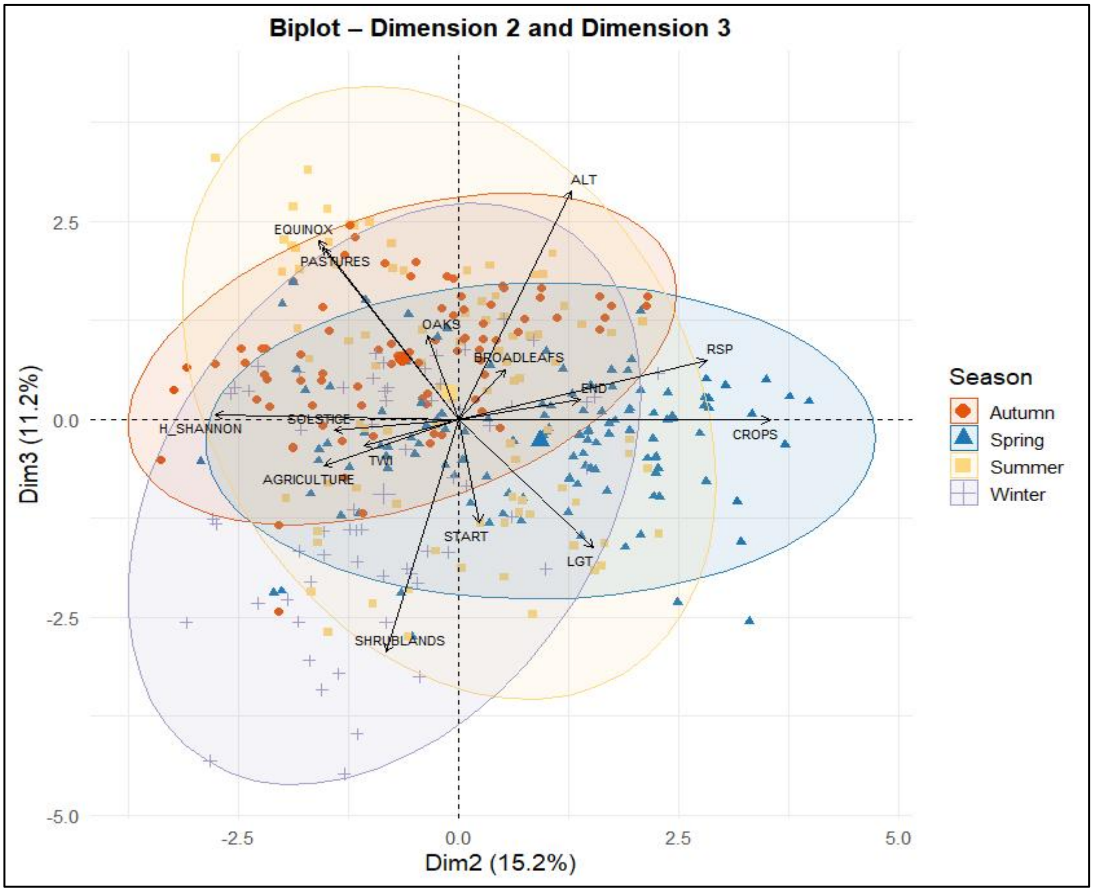


Figure 45: Visualization of Individuals and Variables by Season on axis 2 and 3

This biplot removes the explicit seasonal timing of PC1 and focuses on the interaction between landscape structure (PC2) and habitat transition (PC3).

✓ Spring points concentrate near PASTURES, EQUINOX, OAKS, and BROADLEAFS, indicating a preference for diverse, shaded, mid-elevation zones.

✓ Autumn and winter observations extend toward both plateau cropping areas (CROPS, RSP, ALT) and low-elevation shrublands, showing a dual strategy: using nearby high-ground fields when possible and descending to shrub zones when necessary.

✓ Summer points are mostly centered, leaning toward shade-providing habitats like forests and shrublands, in line with the need for shelter during hot days.

This projection emphasizes how habitat choice shifts both vertically and horizontally, driven by a combination of forage availability, elevation, and microclimate needs.

4.3.3.6. Biplots of Dimensions with Cosine Squared (cos2) Values

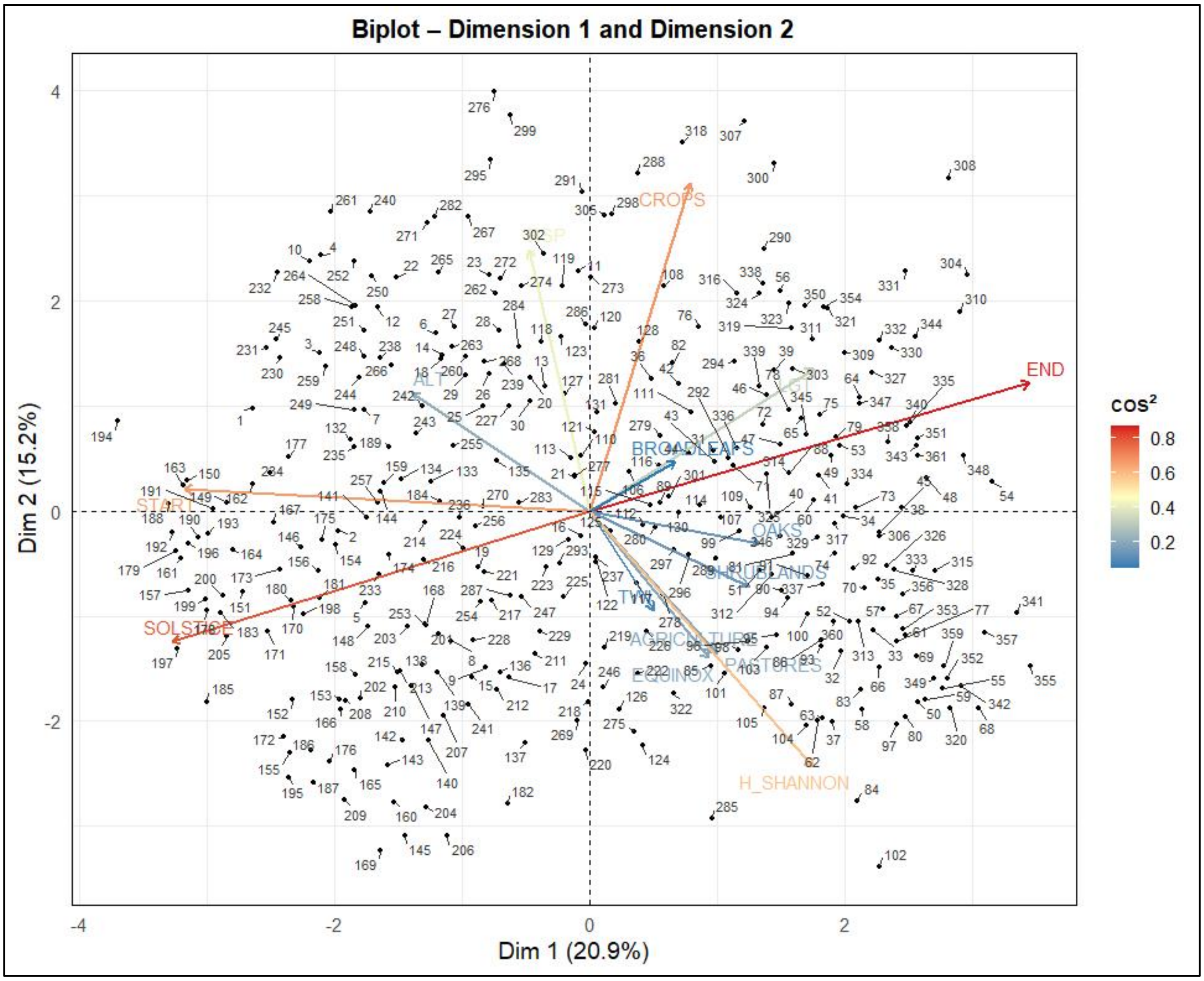


Figure 46: Biplot of Dimension 1 and Dimension 2 with Cosine Squared (cos2) Values

Figure 45 visualizes the distribution of individual observations along the first two principal components, with cos² values indicating how well each point is represented in this 2D space. Observations with higher cos² values (warmer colors) are more strongly explained by the combination of PC1 and PC2. Individuals aligned with variables like END, H_SHANNON, and LGT reflect longer and more diverse grazing days, typical of summer. In contrast, points aligned with SOLSTICE and START correspond to shorter, winter-type grazing patterns. The horizontal spread reflects the seasonal timing gradient, while the vertical spread shows the landscape use gradient between crops on the plateau and mixed-use valley areas.

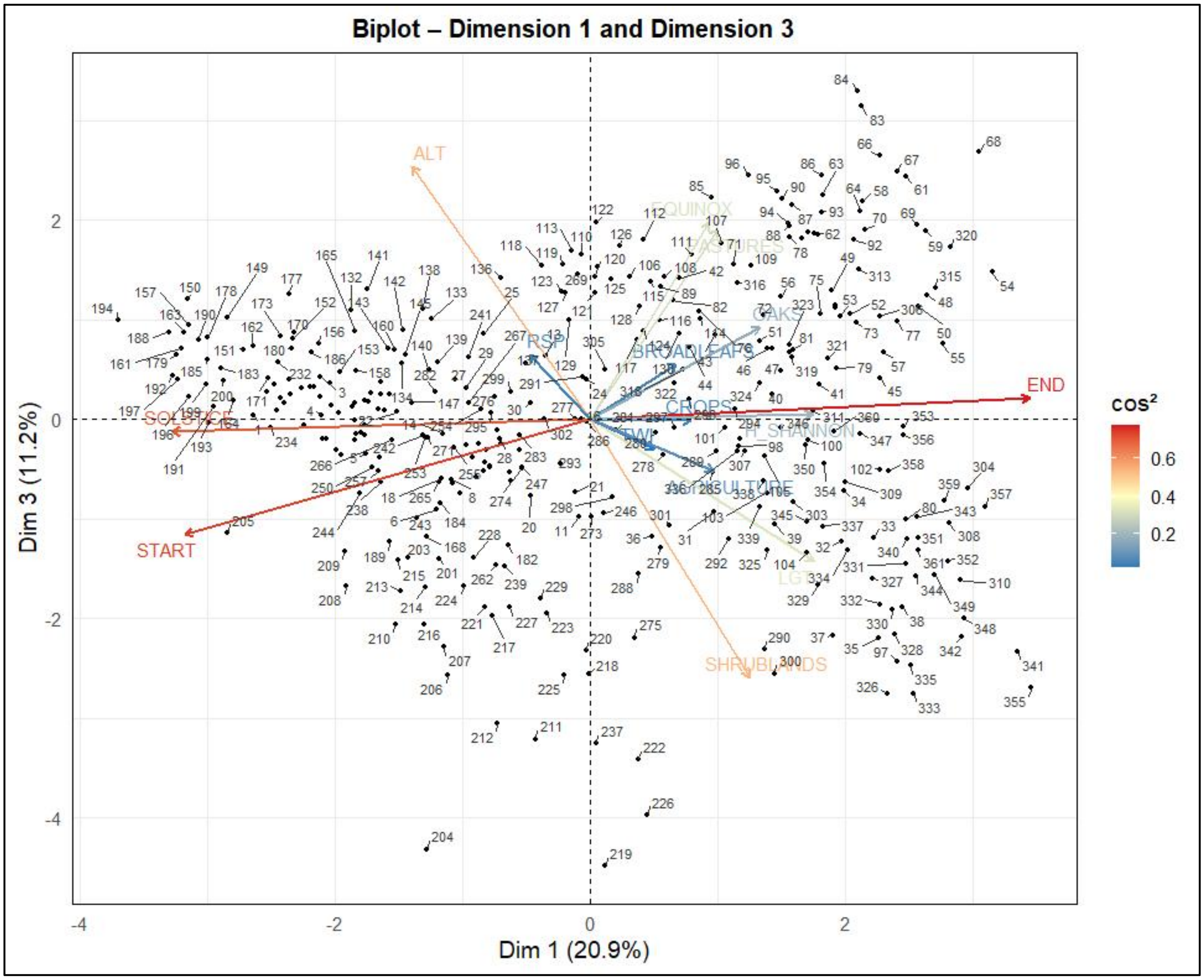


Figure 47: Biplot of Dimension 1 and Dimension 3 with Cosine Squared (cos2) Values

Figure 46 shows how individual observations are structured along the seasonal timing axis (PC1) and the habitat transition axis (PC3). Cos² shading reveals which days are best represented by this dimension pair. Observations near SHRUBLANDS and with high positive PC3 scores likely correspond to autumn and winter days involving longer travel to low-elevation shrub zones. Conversely, points closer to EQUINOX, PASTURES, and OAKS indicate spring days spent in more favorable and sheltered areas. The plot highlights how spring and autumn differ in elevation, forage quality, and distance from the corral.

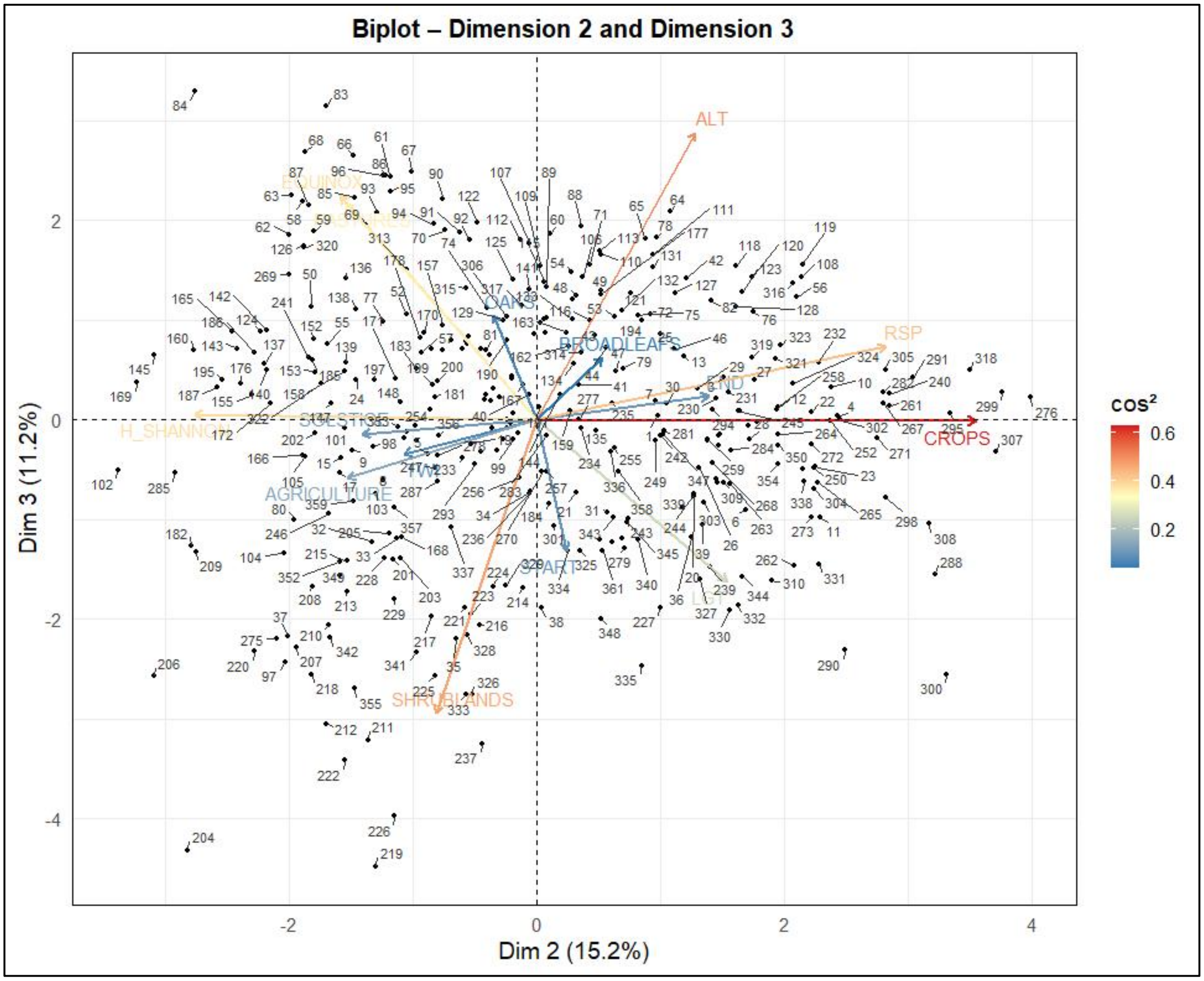


Figure 48: Biplot of Dimension 2 and Dimension 3 with Cosine Squared (cos2) Values

Figure 47 focuses on landscape structure (PC2) and seasonal habitat use (PC3), with cos² values indicating the strength of representation for each daily observation. Points aligned with CROPS, RSP, and ALT reflect plateau grazing in more homogeneous zones, commonly observed in colder months. In contrast, observations located toward SHRUBLANDS, AGRICULTURE, and H_SHANNON are associated with more heterogeneous valley areas, often used in transitional seasons. This plot clearly separates high vs. low elevation zones and illustrates how the flock adjusts its spatial strategy throughout the year based on environmental conditions and accessibility.

4.4. Discussion

4.4.1. Grazing Dynamics in Montesinho Natural Park: Seasonal Patterns, Land Use, and Climate Pressures

The grazing processus of sheep in Montesinho Natural Park is a complex response to environmental conditions, seasonal cues, and structural transformations in land use. Through the analysis of GNSS tracking data over 15 months, we observed distinct patterns that reflect not only traditional seasonal rhythms, but also ongoing shifts in climate and landscape. By integrating our results with three recent theses conducted in the same region—Oliveira (2023), Seripieri (2023), and Fellahi (2024)—we can better understand the mechanisms shaping flock mobility, and their implications for future pastoral management.

Author & Year	Focus	Shorthand used below
Ana Carolina Oliveira **(2023)**	Climate trends, hydrology, flock responses	Oliveira
Vítor H. M. Seripieri **(2023)**	Land-use change, 1995 → 2021	Seripieri
Mohammed Fellahi **(2024)**	GPS baseline of the same sheep breed in Vinhais	Fellahi

The first principal component (PC1) in our analysis captures the seasonal rhythm of grazing activity and appears closely tied to both photoperiod and temperature. Grazing itineraries in summer are long and bimodal, while winter outings are short and spatially restricted, with clear turning points aligning with solstices and equinoxes. Our results supported by Oliveira's (2023) findings, which document a significant warming trend in Montesinho: +0.7 °C in mean winter temperature and +1.5 °C in July maxima since 1951, reinforce her conclusion that climatic shifts are already affecting animal behavior. In 2023, for example, late grazing (END) was delayed by nearly one hour during the summer heatwave—a likely adaptation to rising afternoon temperatures.

In addition to photoperiod, water availability plays a key role in shaping grazing choices. Oliveira used the Topographic Wetness Index (TWI) to model potential moisture accumulation zones and found that shepherds increasingly depend on these areas during droughts. Our results similarly show that during the driest months (August–September), GPS fixes were over twice as likely to occur in the wettest quartile of the landscape, confirming that flocks seek shaded, moist refuges during heat stress. These findings, combined with Oliveira's interviews with local herders who emphasized the reduced reliability of water sources, underscore the growing need to incorporate microclimatic refuges into pasture planning and to preserve riparian corridors, shaded valley bottoms, and TWI-rich zones as emergency grazing buffers during extreme summers (Oliveira, 2023). Protecting these areas from degradation or afforestation with dense, non-grazable species (like conifer plantations) is, therefore, a vital recommendation. Measures such as rotational water troughs, tree-based shade zones, and flexible corral schedules should be explored to help herds cope with extreme heat without compromising grazing duration.

The second principal component (PC2) highlights a spatial axis ranging from plateau croplands to diverse valley mosaics. At the high end, sheep graze among cereal fields (CROPS) close to the corral, particularly in colder seasons when proximity and ease of access are paramount. At the low end, we observe transitions to lower elevations, where pastures, shrublands, and forest mosaics dominate. Seripieri's (2023) land use analysis confirms that these croplands are under threat: rain-fed crops in PNM declined by 53% between 1995 and 2021, while broom-dominated shrublands expanded by over 30%. This trend is reflected in our data, which shows an increasing reliance on shrublands in spring and autumn. These observations raise serious concerns: as croplands disappear (due to abandonment, aging farmer populations, or land cover change), flocks are increasingly dependent on marginal areas, which may be less productive, more fragmented, or more fire-prone.

This shift has both ecological and managerial implications. Shrubland expansion opens new, but fragile grazing zones, while the decline of cereal fields near corrals reduces the accessibility of high-quality forage during critical seasons. To address this, first, grazing calendars must be updated to incorporate the rotational use of shrublands, possibly integrating them into fuel load management strategies for wildfire prevention. Second, landscape-scale coordination is needed between pastoralists, park authorities, and landowners to manage transitions in land use. For instance, incentives could be provided for maintaining or restoring cereal stubble fields (chaume), which are heavily used by flocks in early autumn according to our GPS data. Revalorizing these abandoned fields through agri-environmental payments or local fodder contracts could simultaneously support pastoralism and rural livelihoods.

The third principal component (PC3) captures vertical and ecological shifts in grazing, particularly the move toward shrublands and broadleafs forests at lower elevations during resource-scarce periods. This was most pronounced in late winter and early spring, when sheep ventured downslope to broom-dominated zones—likely in response to post-harvest field limited nutrition. These results support Seripieri's (2023) recommendation to redesign circuits that account for a shifting landscape mosaic, while also highlighting the need to balance grazing pressure with conservation goals in expanding shrublands.

Comparing these patterns to Fellahi's (2024) GPS study reveals important differences. While both studies track the same breed (Churra Galega Bragançana Branca) over similar timeframes, the landscapes differ substantially. Fellahi's study zone in Vinhais includes more orchards and permanent agroforestry systems, while our site is dominated by woodland and rangeland. This difference is reflected in the structure of their grazing circuits. Fellahi reports more regular use of orchards and adjacent fields, with less emphasis on long-distance shrubland foraging. In contrast, our herd shows clear seasonal transitions between plateau cereal fields and remote valley shrublands, with longer travel days in autumn.

These differences underscore the need for context-specific management strategies within PNM. The same breed behaves differently depending on landscape configuration and land cover composition. Our results suggest that in wilder zones with fewer permanent agroforestry systems, seasonal transhumance or semi-nomadic routines may be more efficient than static grazing from a fixed corral. Conversely, in more humanized zones like Vinhais, as described by Fellahi, flocks may sustain more stable routines with less ecological cost. This comparison emphasizes the importance of tailoring grazing infrastructure (corrals, routes, water points) to the ecological reality of each zone within the park.

In summary, integrating our results with those of Oliveira (2023), Seripieri (2023), and Fellahi (2024) reveals several converging insights:

1. **Climate change is not a distant threat—it is already driving observable changes in grazing behavior**, with herders actively adjusting their routines. Rising temperatures are

shifting daily grazing schedules and prompting a growing reliance on cooler, moisture-retaining areas (Oliveira, 2023).

2. **Land use is is undergoing transformation.** Accelerated land-use change is reshaping the landscape, with permenanent crops disappearing and shrublands spreading. These changes are reshaping available grazing zones, requiring updated circuits and fire-adaptive strategies (Seripieri, 2023).
3. **Landscape heterogeneity leads to divergent grazing logics**, even with the same breed and climate, depending on terrain and land cover (Fellahi, 2024).

4.4.2. Comparative Analysis of Grazing Behavior in Mediterannean contexts : Northern Portugal vs. Northern Morocco

Moroccan GPS-collar studies on free-ranging Beni-Arouss dairy goats offer an almost mirror image of our work on transhumant ewes in Montesinho Natural Park, yet each context throws a different light on how Mediterranean livestock exploit space and vegetation. Methodologically, the two projects are indistinguishable: we equipped our ewe with DOMODIS collars (5 minutes interval), while the Moroccan study relied on Lotek 3300 SL loggers, that recorded fixes every five minutes also, filtered fixes with a 2-DOP < 6 threshold and purged stationary spikes with median-velocity gates, and cross-validated behaviour states against IceTag leg accelerometers (Chebli et al., 2022a). This parity ensures that any spatial or temporal divergences stem from landscape or management rather than sensor bias. Moroccan trajectories show tight, linear outbound paths and midday rests within 200 m radii at speeds below $0.4\,\mathrm{m\,s^{-1}}$ (Chebli et al., 2020), while our ewe ranges more widely but pauses in similar midday “siestas”, underscoring how human scheduling imprints a daily rhythm onto ostensibly free-ranging animals. Our reliance on a single GPS collar without accelerometry admittedly limits state resolution, yet the Moroccan dataset shows that a five-minute GNSS stream alone can still quantify journey length, climb and patch preference. Adding a lightweight leg sensor in future seasons would sharpen the partitioning of resting versus foraging without altering our GIS workflow.

In both regions a shepherd accompanies the flock from corral to range and back, yet the daily outing differs in scale: our ewe spends about nine hours in the field and travels 4.3 ± 1.9 km per day, punctuated by a pronounced midday rest when GNSS fixes cluster tightly beneath shade trees. Moroccan goats, by contrast, remain outside for nearly eleven hours at the height of summer and routinely exceed 6–7 km of horizontal displacement, trading a shorter rest for greater spatial exploration (Chebli et al., 2022b). Thus, when heat and forage scarcity coincide, goats respond by extending range whereas our ewe conserves distance and elongates resting bouts.

Landscape structure explains part of that behavioural split. Both herds experienced the same seasonal swing from spring abundance to summer scarcity, yet the landscape mosaics they occupy are almost inverse images. In the Western Rif, 30 % of the range is cork-oak (Quercus suber) forest, 45 % dense Cistus matorral, and only 25 % lowland barley strips tilled on gentle slopes (Chebli et al., 2020); Montesinho, by contrast, offers cereal stubble, oaks or shrublands, and residual woodland. Despite this reversal, both collars reveal a common rule of thumb: animals concentrate morning bites on nutrient-rich herbaceous patches and retreat to woody browse. Moroccan goats, true browsers, record 65–90 % woody intake, predominantly Cistus ladanifer, Myrtus communis and juvenile Quercus suber leaves (Chebli et al., 2020); our nominal grazer still lifts shrub-leaf bites in August as cereal stubble desiccates. Thus, species identity matters less than the shared need for a fallback resource once herb supply collapses.

Landscape feedbacks converge as well. Long-term surveys around Ain Rami and Derdara show that sustained goat browsing is shifting closed cork-oak stands toward open Cistus matorral, with a 25 % loss of tree cover between 1984 and 2014 (Chebli et al., 2018; 2020b). GIS overlays reveal the early stages of a comparable transition along crop–shrub ecotones frequented by the sheep. Because both patterns were detected via collar tracks married to remote sensing, movement corridors emerge as practical early-warning indicators of structural change, lending weight to the rotational resting already advocated by Moroccan land managers.

Seasonality governs the timing of these responses. Grazing time in the Rif falls from 57 % of the day in spring to 36–45 % in summer–autumn, with lost minutes reallocated to walking and lying (Chebli et al., 2022b). In Montesinho, principal-component analysis attributes a big part of variance in grazing behaviour to daylight length and daily start/end times, not to outright substitution of activities. Hence, where cropland remains accessible, animals modulate the timing of use within a fixed outing; where biomass collapses, they stretch spatial effort and accept a larger energy cost.

Topography adds a further energetic dimension. Moroccan collars register 140–420 m of daily climb per day on slopes up to 35 % (Chebli et al., 2022b), whereas our ewe's tracks centre on mid-slope positions (Relative Slope Position ≈ 0.31) at mean elevations around 810 m and cover fewer steep segments, implying lower cumulative climb. Those topographic differences help explain why goats incur July–October metabolisable-energy deficits of −0.8 to −1.3 MJ day^{-1}, while our ewe's estimated shortfall remains smaller (Chebli et al., 2022b; this study), solidifying our argument that strategic supplementation is essential regardless of whether the animal is a browser in shrub-oak forest or a grazer on Iberian cereal stubble.

Taken together, the two studies define a continuum of Mediterranean pastoral tactics shaped by land-use mosaic and terrain, and reinforce three conclusions: (i) Mediterranean small ruminants modulate spatio-temporal effort more readily than diet composition when confronted with seasonal scarcity; (ii) bite-rate compensation has physiological ceilings that translate into predictable energy deficits; and (iii) unmanaged deficits accelerate shrub encroachment, linking animal energetics directly to vegetation dynamics. Pooling collar streams from sheep and goats could thus yield real-time forecasts of energy balance and degradation risk, supporting adaptive supplementation and grazing plans that travel well across the Mediterranean basin.

5. Conclusion

This study addressed the critical challenge of understanding how traditional sheep grazing systems in Mediterranean mountain regions respond to seasonal environmental variability and ongoing landscape transformations. In particular, it focused on revealing the spatio-temporal dynamics of a Churra Galega Bragançana Branca herd in Montesinho Natural Park, where climate change and land-use shifts increasingly impact pastoral practices and ecosystem health. By analyzing 15 months of high-resolution GNSS collar data integrated with GIS and statistical methods, this research aimed to uncover the behavioral strategies that allow flocks to adapt to fluctuating resources, terrain constraints, and seasonal cycles.

The findings demonstrate that the herder's strategies are not static but highly responsive to seasonal and topographic conditions. During summer, grazing itineraries are longer, start earlier, end later, and encompass a more diverse range of land uses—often following a bimodal pattern to avoid midday heat. In contrast, winter grazing is shorter in duration and more spatially constrained, reflecting reduced daylight and limited forage availability. Spring and autumn represent transitional periods, with distinct habitat shifts—toward pastures in spring and shrublands in autumn—highlighting the flock's adaptive responses to ecological change.

The PCA results identified three main behavioral gradients: (1) the intensity and duration of grazing influenced by seasonality, (2) the spatial contrast between homogeneous highland croplands and heterogeneous valley mosaics, and (3) the use of specific habitats during seasonal transitions. Terrain variables such as elevation, relative slope position, and topographic wetness were shown to interact with land use in guiding flock movement.

By combining GNSS collar data with geospatial and statistical analysis, this research provides valuable insight into how traditional pastoral systems function within protected landscapes under varying environmental conditions. The results not only reinforce the ecological intelligence of herd behavior but also offer practical tools for adaptive management. Specifically, the findings can inform seasonal grazing planning, fire prevention strategies through targeted biomass reduction, and the integration of sheep grazing in agroforestry systems such as chestnut orchards.

In the context of climate change and rural landscape transformations, preserving and adapting traditional pastoral practices is both an ecological and cultural imperative. This study contributes to bridging the gap between empirical data and landscape-sensitive grazing management, reinforcing the role of extensive grazing in biodiversity conservation, ecosystem service provision, and rural resilience.

Finally, several recommendations emerge from our synthesis:

- ✓ **Protect microclimatic refuges** (TWI-rich valleys, shaded forest margins) as priority zones for summer grazing.
- ✓ **Revise grazing calendars** to incorporate land cover transitions, thermal stress thresholds, and drought probabilities.
- ✓ **Maintain or restore traditional cropland areas** near corrals through agri-environmental schemes or fodder contracts.
- ✓ **Encourage adaptive mobility models**—including rotational or semi-nomadic systems—especially in landscapes where static grazing routines are ecologically mismatched.
- ✓ **Extend research to diverse herds and ecological contexts** to test how generalizable these patterns are.

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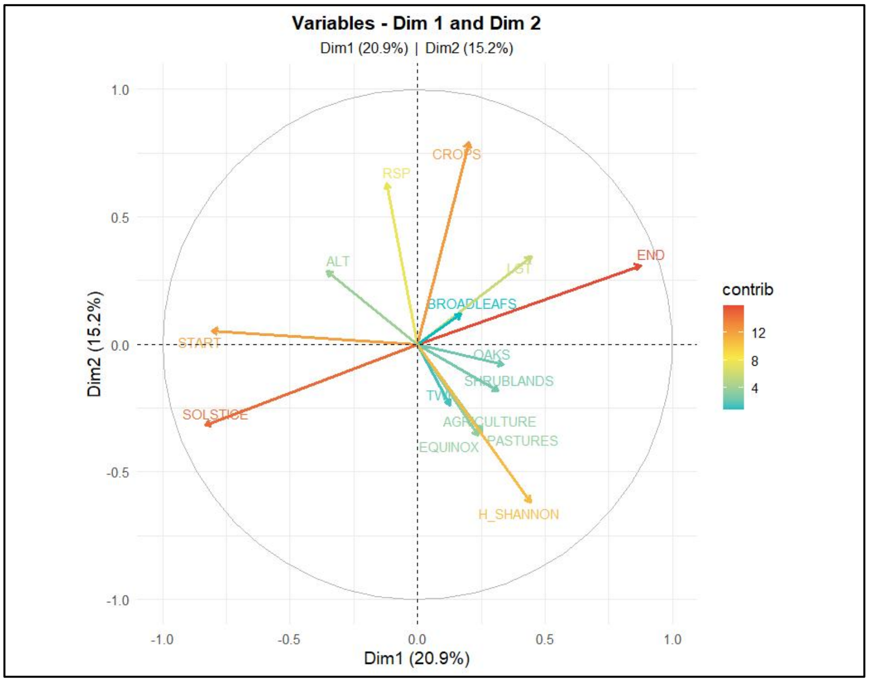
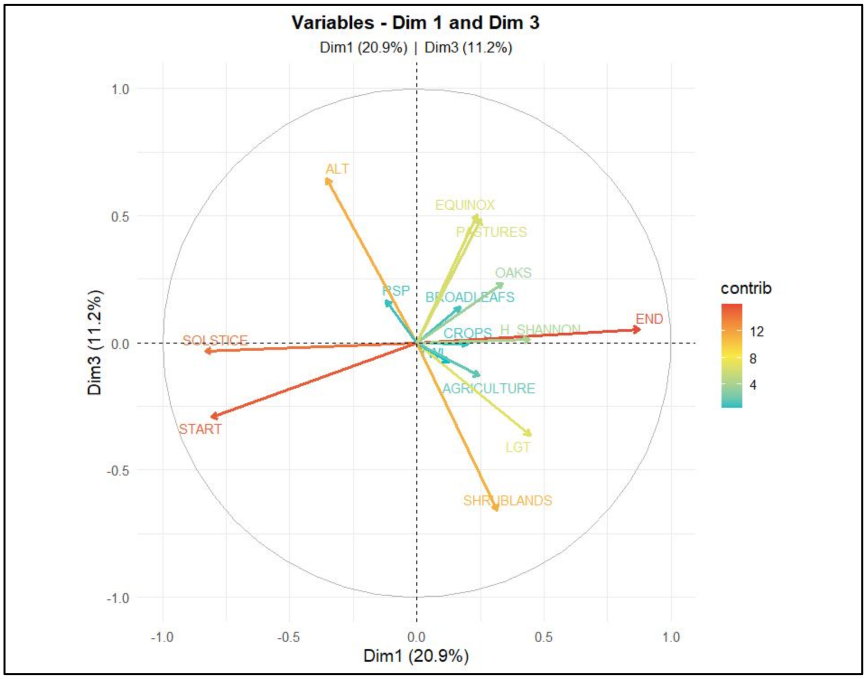
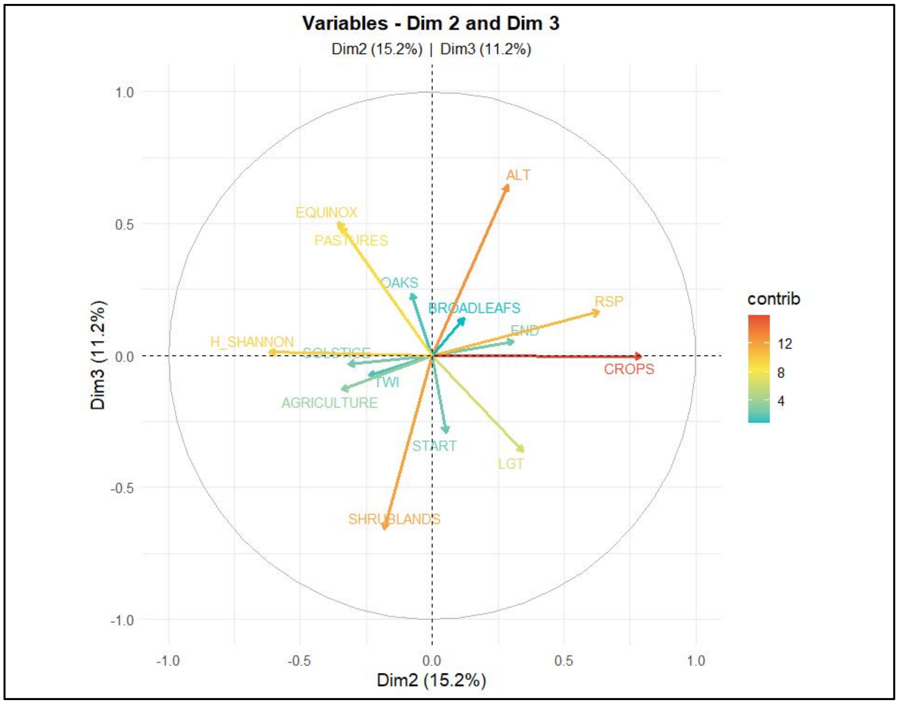
Appendices



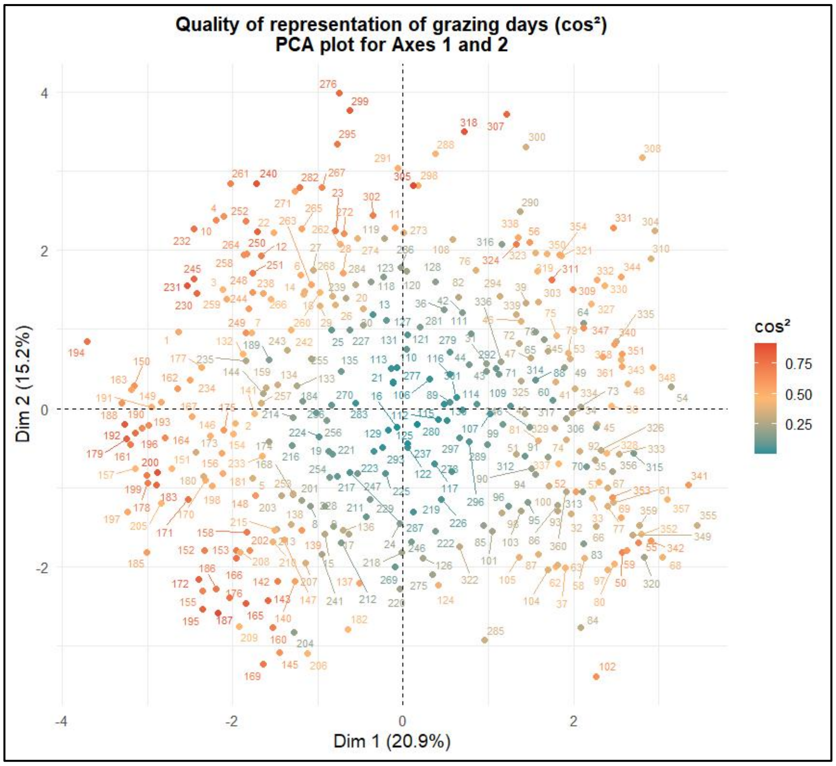
Appendix 1: Contributions of variables for the combined PCA plot of PC1 and PC2



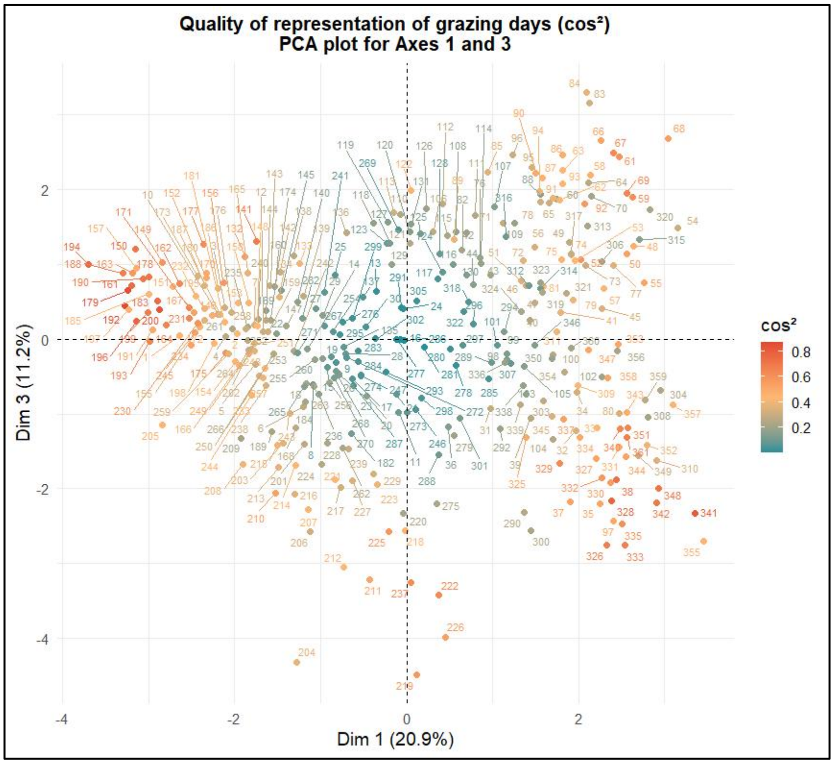
Appendix 2: Contributions of variables for the combined PCA plot of PC1 and PC3



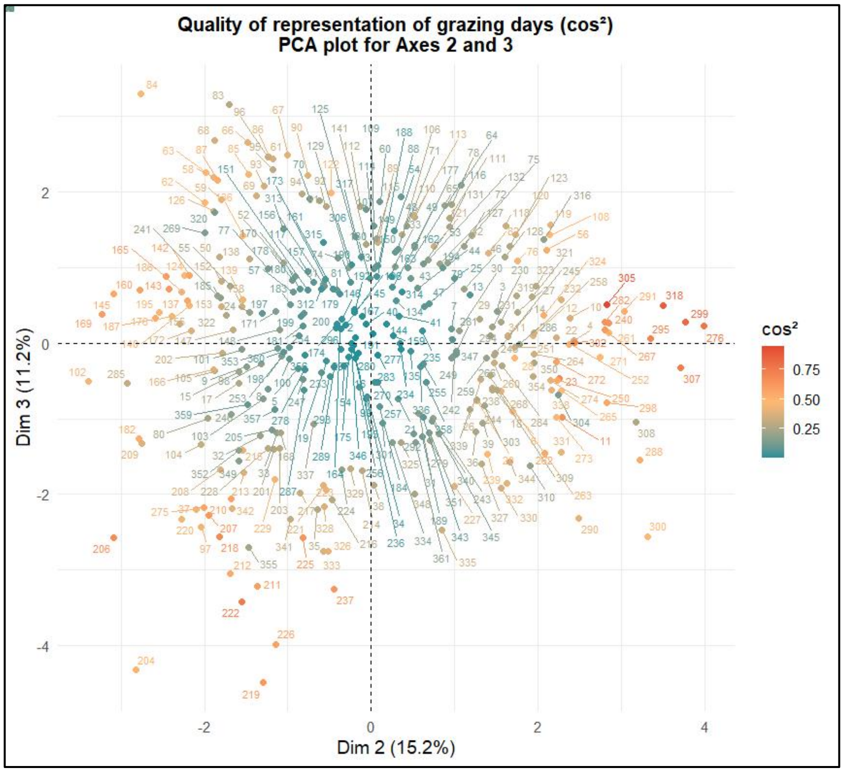
Appendix 3: Contributions of variables for the combined PCA plot of PC2 and PC3



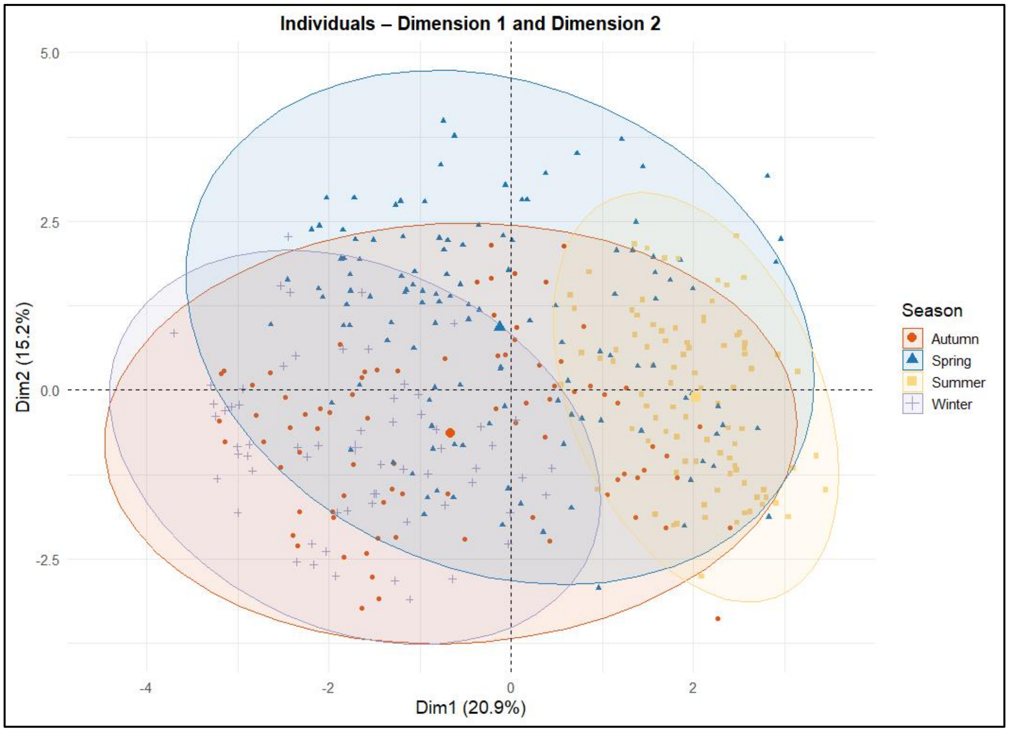
Appendix 4: Quality of Representation of Grazing Days on Dimensions 1 and 2



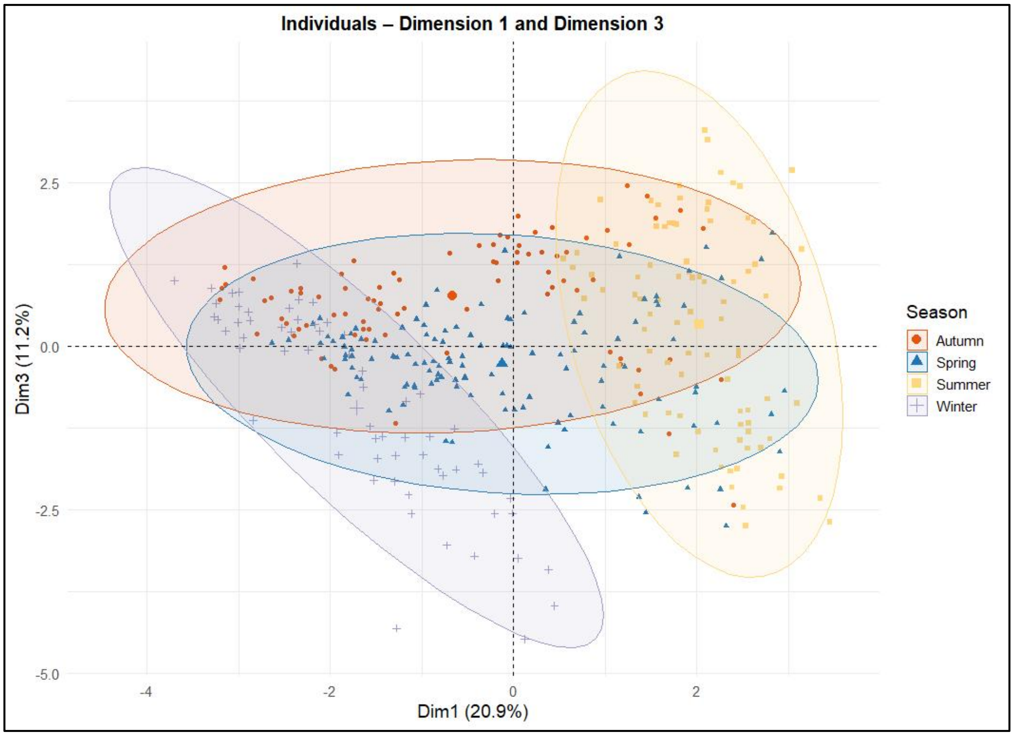
Appendix 5: Quality of Representation of Grazing Days on Dimensions 1 and 3



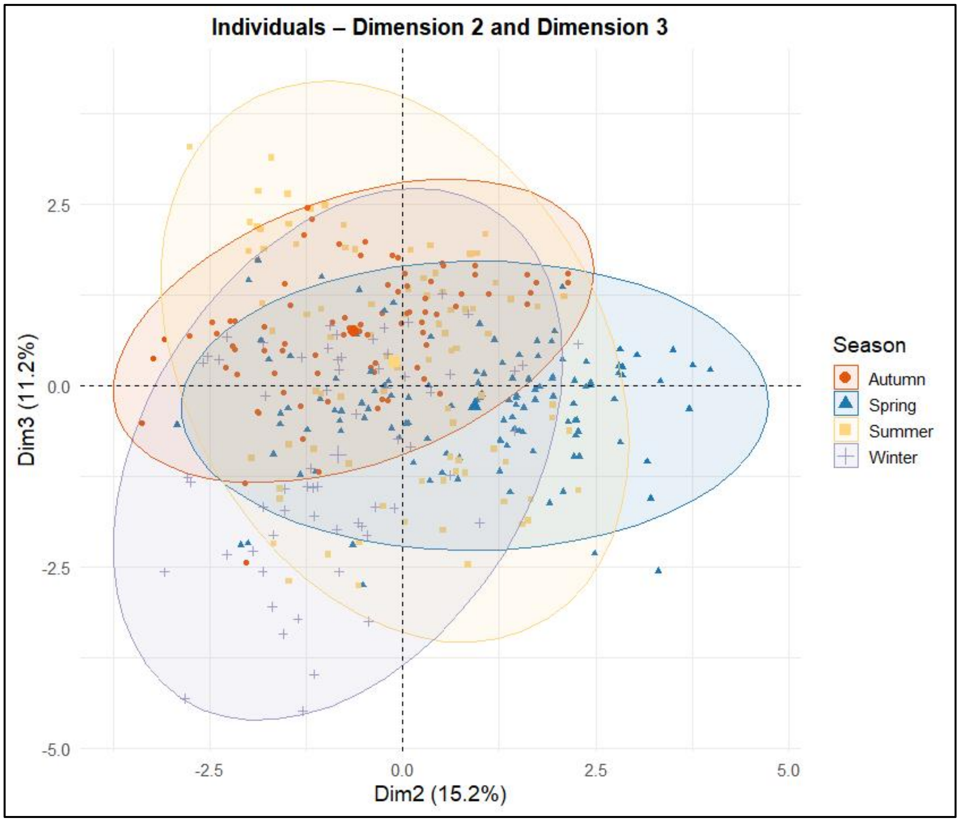
Appendix 6: Quality of Representation of Grazing Days on Dimensions 2 and 3



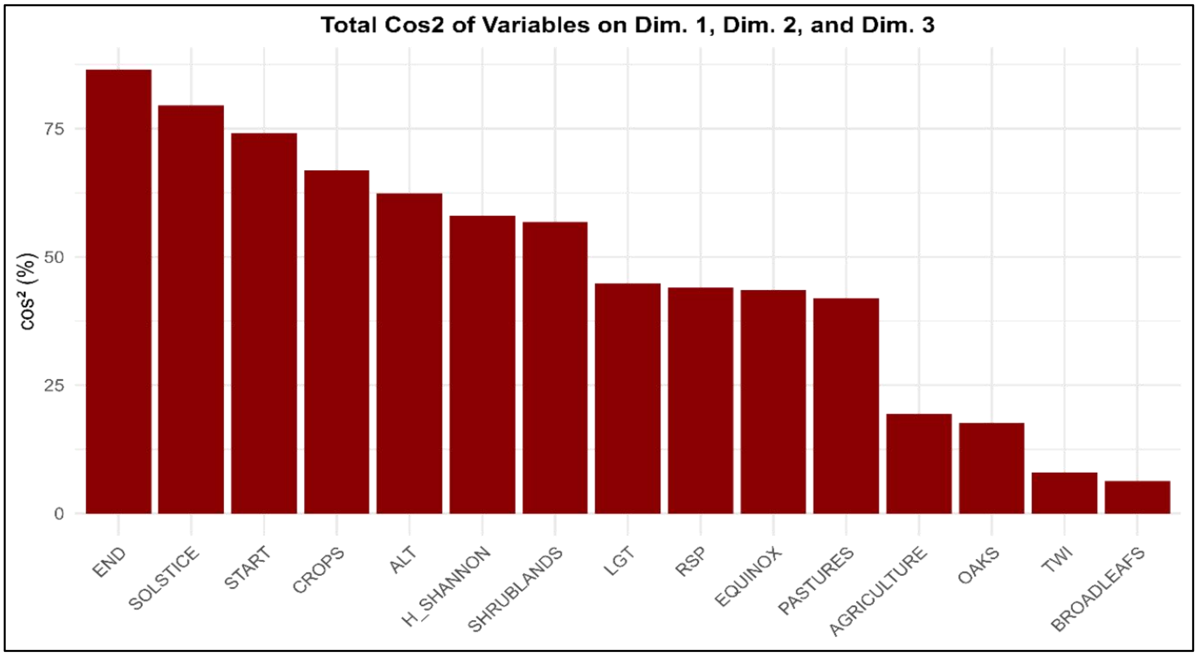
Appendix 7: Visualization of Individuals by Season on axis 1 and 2



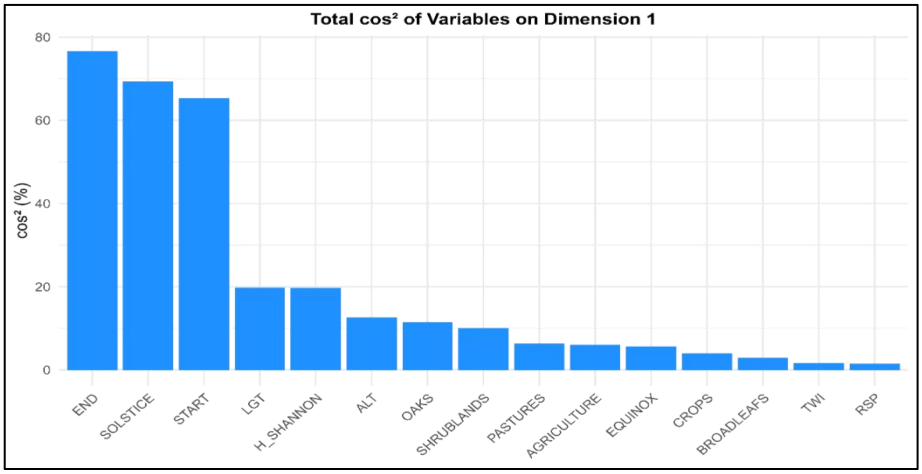
Appendix 8: Visualization of Individuals by Season on axis 1 and 3



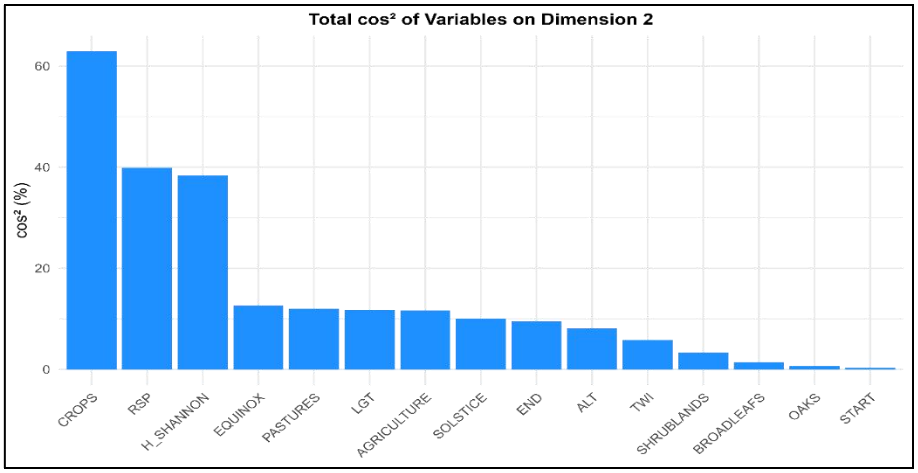
Appendix 9: Visualization of Individuals by Season on axis 2 and 3



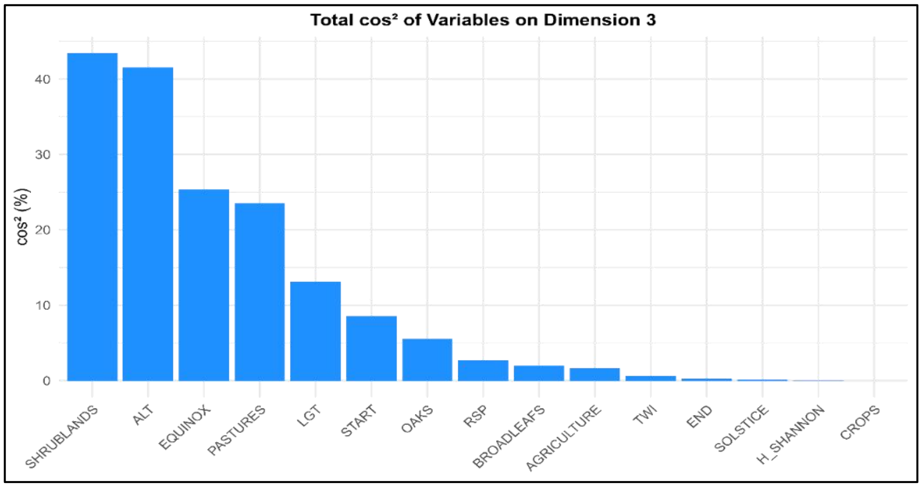
Appendix 10: Total Cos2 of Variables on Dimensions 1, 2, and 3



Appendix 11: Total Cos2 of Variables on Dimension 1



Appendix 12: Total Cos2 of Variables on Dimension 2



Appendix 13: Total Cos2 of Variables on Dimension 3