Odessa centre | Pastoralism Research, Policy and Practice

TYPE Original Research
PUBLISHED 05 February 2026
DOI 10.3389/past.2026.15757

Check for updates

Drought, grazing routes and resource use by small-ruminant pastoralists in Montesinho, northeastern Portugal

Ana Carolina Farias de Oliveira[1,2], José Castro[3], Isa Aleixo-Pais[1], Vitor Henrique Mistro Seripieri[1] and Marina Castro[1]*

[1]CIMO, LA SusTEC, Instituto Politécnico de Bragança, Bragança, Portugal, [2]Department of Crop Production and Engineering Projects, High Polytechnic School, University of Santiago de Compostela, Lugo, Spain, [3]Instituto Politécnico de Bragança, Bragança, Portugal

OPEN ACCESS

EDITED BY
Ioannis Hadjigeorgiou,
Agricultural University of Athens, Greece

*CORRESPONDENCE
Marina Castro,
marina.castro@ipb.pt

RECEIVED 17 October 2025
REVISED 28 December 2025
ACCEPTED 16 January 2026
PUBLISHED 05 February 2026

CITATION
Farias de Oliveira AC, Castro J, Aleixo-Pais I, Mistro Seripieri VH and Castro M (2026) Drought, grazing routes and resource use by small-ruminant pastoralists in Montesinho, northeastern Portugal. *Pastoralism* 16:15757. doi: 10.3389/past.2026.15757

Climate projections for the Mediterranean area indicate a rise in temperature and an increase in drought frequency, which directly impact water availability and consequently, ecosystems. In the protected area of Montesinho in northeast Portugal, sheep and goat pastoralism characterizes the landscape and plays an important socio-economic role. However, like in many regions of the globe, this historical activity is becoming increasingly unsustainable due to shifting climatic conditions. To understand the impact of climate change on water availability in the park and its consequences for small ruminant pastoralism, trends in rainfall and temperature were analyzed using historical climate data from 1951 to 2022, and semi-structured interviews with local shepherds provided insight into their perceptions on this matter. We used TWI and NDVI to map relative moisture and green forage patterns underlying shepherds' grazing-route decisions. Findings revealed a decrease in precipitation during winter and spring, with a significant increase during autumn months, and local knowledge revealed a focus on drying springs and shifts in seasonal patterns that led to pastoral adaptations like adjusting grazing routes and increasing reliance on alternative water sources. This study concluded that pastoralism in this region faces significant climatic challenges, highlighting the need to implement adaptive strategies to improve the livelihood of these communities and increase their resilience in a fast-changing environment. Large-scale aid and locally addressed actions, such as improving water infrastructures and promoting drought-tolerant vegetation growth, are key to the long-term sustainability of this ancient practice.

KEYWORDS

climate change adaptation, Mediterranean mountain rangelands, grazing management, livestock mobility, local knowledge, remote sensing

Introduction

Pastoralism is practiced in over 100 countries worldwide, supporting the livelihoods of approximately 200 million people and contributing 10% of global meat production (FAO, 2001; FAO, 2020). This production system emerges from a complex interplay of biophysical factors such as orography and climate, technological innovation, social dynamics, cultural traditions, and political structures involving regulation, protection, and support policies (Muhammad et al., 2019; Serrano-Zulueta et al., 2024). This activity delivers multiple economic, social, and environmental benefits. Economically and socially, pastoralism diversifies landowners' income and enhances food security, especially in remote or mountainous areas, becoming a vital means of subsistence (Karki et al., 2012; Garmendia et al., 2022). Environmentally, it contributes to improved soil health by increasing organic matter, enhancing nutrient cycling, and improving moisture retention (Teague and Kreuter, 2020; Lu et al., 2024). Pastoralism also mitigates climate change by increasing soil carbon sequestration (Wang et al., 2024) and reducing wildfire risk through the removal of combustible biomass by grazing (Rouet-Leduc et al., 2021; Davies et al., 2024). The economic importance of pastoralism varies worldwide, reflecting the diversity of the socioeconomic contexts in which it operates. In some countries, such as Mongolia, it is a central pillar of the national economy, contributing approximately 88% of the national GDP (Shagdar, 2002). In more diversified economies, its direct economic role may be smaller, but its social and environmental value remains substantial. In Europe, for example, grazing systems play a key role in maintaining rural landscapes, supporting biodiversity, and preserving cultural heritage. Its ecological role is illustrated by the vast areas occupied by permanent pastures, which cover around 34% of the European Union agricultural land, approximately 53 million hectares, highlighting the continued relevance of extensive pastoral systems (Leroy et al., 2018; Malek et al., 2024; United Nations Convention to Combat Desertification, 2024).

The social and environmental relevance of this activity is particularly evident in Mediterranean mountain regions, where pastoralism has long shaped both agroecosystems and rural lives (Gomez-Sal, 2001; Köhler-Rollefson, 2020; Manzano et al., 2021). These areas are often characterised by low-input systems, small family farms, and a strong biocultural heritage, and they host extensive grazing practices that are well adapted to local climatic and topographic constraints. One example is the Trás-os-Montes region in north-eastern Portugal, where the extensive pastoral system within the Montesinho Natural Park (PNM) has historically been a vital source of sustenance and a cornerstone of the local economy and social organization (Pinto et al., 2023). This system relies on daily mobile grazing, understood here as an extensive form of herding in which a shepherd (and dogs) accompanies the flock on foot and moves it through different forage patches during the day, rather than keeping animals in fixed paddocks. When stocking rates are kept at or below the local grazing capacity, this mobile use of the landscape results in short residence times on each patch and longer recovery periods for vegetation, helping to maintain pasture condition and reduce risks of overgrazing, vegetation loss, soil degradation, and erosion (Macheroum and Chenchouni, 2022). Similar pastoral systems have been documented in other mountainous regions of the Iberian Peninsula, including Galicia in north-western Spain (Serrano-Zulueta et al., 2024).

Pastoral systems are becoming increasingly vulnerable to the effects of climate change. Over the last decades, numerous studies have reported alarming climate trends that jeopardize pastoralism's predictability and stability (Luber and McGeehin, 2008; Stott, 2016; Clarke et al., 2022). According to the Intergovernmental Panel on Climate Change - IPCC (2021), the Mediterranean region could experience a temperature rise of 2 °C–3 °C under the RCP4.5 scenario, accompanied by more frequent hydrological, agricultural, and ecological droughts. Mountainous headwater regions, crucial for generating surface runoff and sustaining wetlands, are particularly vulnerable (Ozturk et al., 2015). Some projections estimate a 12%–15% decline in runoff due to decreasing precipitation (Yeste et al., 2021). Evidence from diverse regional studies illustrates these impacts in East Africa (Egeru, 2016), Morocco (Snaibi et al., 2021), and Nepal (Tiwari et al., 2020), where pastoralists face fodder shortages, water scarcity, livestock losses, and increased poverty. In Mediterranean mountain regions such as the PNM, climate change is already driving significant socio-economic and environmental impacts (Aleixo-Pais et al., 2025). According to Almeida et al. (2023), the region is particularly vulnerable to warming due to the strong dependence of local communities on climate-sensitive activities such as pastoralism. These broader climate impacts manifest locally as reduced forage availability, increased production costs, water scarcity, and greater income volatility for pastoral communities (Gentle and Maraseni, 2012). Extensive small ruminant systems are especially at risk due to limited water availability, which is worsened by rising temperatures (Henry et al., 2018; Joy et al., 2020). Although small ruminants are relatively resilient, they still experience negative effects under such conditions. These include body weight loss (Li et al., 2000; Alamer and Al-Hozab, 2004; Alamer, 2006), physiological and behavioural stress characterised by elevated cortisol levels, and reduced growth and reproductive performance as biological resources are redirected to survival functions (Koyuncu and Canbolat, 2009; Liker et al., 2010).

The growing climate risks highlight the urgent need for adaptation and resilience strategies in pastoral systems. As a representative socio-ecological landscape of Mediterranean mountain regions in Europe, the PNM offers a valuable case study for assessing the impacts of global change on pastoralism.

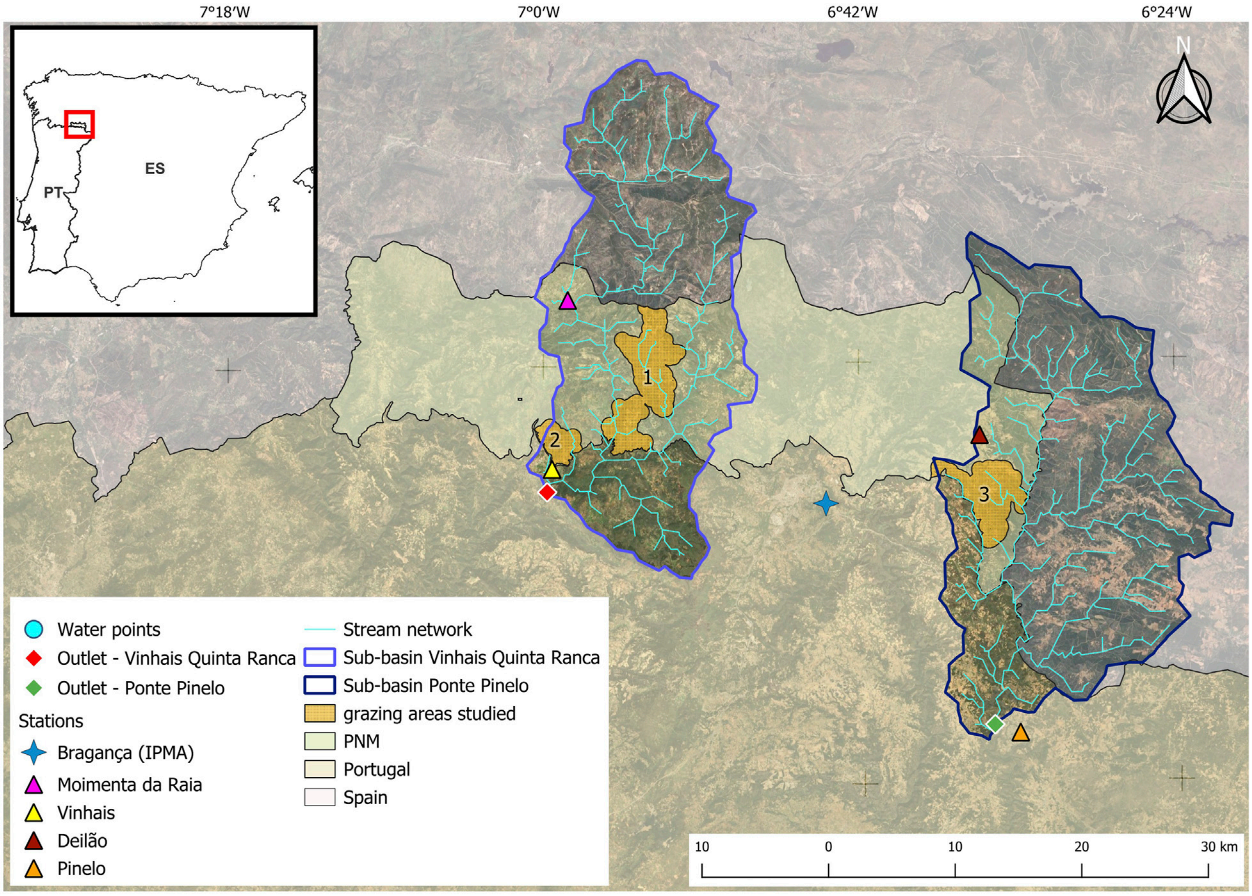

FIGURE 1
Map of the protected area of Parque Natural de Montesinho (PNM), depicting relevant geographical features and the subbasins and meteorological monitoring stations from where the data used in this study were collected. The inset image shows the Iberian Peninsula, comprising the countries of Spain (ES) and Portugal (PT).

The objective of this study is to analyse the interaction between recent climatic dynamics, particularly changes in temperature and precipitation, and the spatial distribution of key resources for small-ruminant pastoralism in Montesinho Natural Park. The specific objectives are as follows: (a) to quantify long-term trends in temperature and precipitation, including changes in seasonal patterns; (b) to characterise how these climatic trends translate into the spatial distribution of vegetation greenness and moisture propensity, as proxies for forage and potential water availability; and (c) to examine how these environmental constraints influence grazing routes and daily management decisions, combining GPS-tracked herds with local pastoral knowledge collected through semi-structured interviews.

Materials and methods

Hydroclimatic data analysis was carried out to identify potential changes in rainfall and temperature patterns. Additionally, vegetation data (NDVI) and the topographic wetness index (TWI) were cross-referenced with GPS-tracked grazing routes to assess how these environmental changes influenced herd movements, particularly during hot and dry months. Moreover, semi-structured interviews were used to explore pastoralists' perceptions of these changes and the strategies they adopted in response.

Study area

This study was conducted in Parque Natural de Montesinho (PNM), in northeastern Portugal (Figure 1). The territory has a heterogeneous relief, with a plateau cut by deep valleys and some mountains consisting of flat to very steep slopes (Castro J et al., 2021). The average annual rainfall varies between 1262 (Montesinho mountain range) and 806 mm (Lombada plateau), and the annual temperature between 8.5 °C–12.9 °C (INMG, 1991). This is one of the largest and most biodiverse protected areas in Portugal, standing out for its remarkable natural values, which include a wide variety of habitats, fauna and flora, and landscapes of extraordinary beauty (Azevedo et al., 2016; Sil et al., 2019). Its physiographic characteristics, such as rugged terrain and specific climatic conditions, make it unsuitable for the implementation of intensive agricultural systems, yet favorable to extensive pastoral practices based on endemic sheep and goat breeds (Castro et al., 2009). The region has a low and ageing population residing in 98 villages within the park, and rural abandonment has been ongoing since the 1960s (Azevedo et al., 2011; INE, 2020).

Three grazing areas within the PNM were selected (Figure 1), covering approximately 10% of the park's total area (7,225 ha). These areas were identified within the framework of the PASTOpraxis project (MTS/CAC/0028/2020, 2021–2025) and are representative of the park's heterogeneous pastoral landscapes and distinct bioclimatic conditions. To gain a better understanding of grazing dynamics and management practices, six flocks of local sheep (Churra Galega Bragançana Branca e Preta) and goat (Cabra Preta de Montesinho) were tracked with GPS collars and systematically monitored throughout the study period. These sites encompass three distinct bioclimatic zones, highlighting the diversity of conditions within the region. Specifically, Areas 1 and 2 (Figure 1) fall within the upper humid and lower humid ombrotypes and correspond to the lower and upper supra-Mediterranean thermotypes. In contrast, zone 3 predominantly lies in the upper subhumid ombrotype, with a smaller section classified as upper humid and lower supra-Mediterranean thermotype (Monteiro-Henriques, 2010; Castro M et al., 2021).

To assess the hydrological processes of the study area, the river basin was adopted as the spatial analysis unit, a scale widely used across soil and water conservation studies, as well as in water resource management (Wang et al., 2016). Specifically, two hydrographic sub-basins were delineated: the Tuela river sub-basin upstream of the "Vinhais Quinta Ranca" hydrometric monitoring station (BHVQR) and the Maçãs river sub-basin upstream of the "Ponte Pinelo" hydrometric station (BHPP). Both sub-basins have a transboundary character, originating in Spain and flowing into Portuguese territory. Importantly, the delineation of these sub-basins was carried out to ensure that the areas monitored for grazing activities are fully encompassed within the spatial analysis framework (Figure 1).

Climate data and analysis

Assessment and calculation of climate normals

Climatological normals for precipitation and temperature were calculated to characterise the baseline climate conditions of the study area. Following the recommendations of the World Meteorological Organization (WMO, 2007), these normals were computed as average values over a standard reference period of 30 years. This approach provides a consistent climatic context for analysing hydrological processes and pastoral dynamics within the delineated sub-basins. Data was obtained from the online database of the Instituto Português do Mar e da Atmosfera (IPMA, 2023), specifically from the Bragança meteorological station (41°48′14″N, 6°44′34″W; 691 m altitude - Figure 1). This dataset was selected due to its robustness, completeness, and quality-controlled processing. A historical series of monthly precipitation and average temperature spanning 69 years (from 1951 to 2020) was used to calculate climatological normals over five distinct 30-year periods. These periods were 1951–1980 (T1), 1961–1990 (T2), 1971–2000 (T3), 1981–2010 (T4), and 1991–2020 (T5). Monthly average precipitation and temperature values were compiled for each period.

Rainfall trends

To provide a more spatially representative analysis of rainfall trends across the study area, rainfall data from four meteorological stations located within the sub-basins were analysed: Moimenta da Raia (02P/01C) and Vinhais (020/02UG) in the BHVQR sub-basin, and Deilão (02R/02G) and Pinelo (04R/02G) in the BHPP sub-basin (Figure 1). Data was obtained from the *Sistema Nacional de Informação de Recursos Hídricos* (SNIRH), which was selected because it includes a greater number of stations situated within the catchments that define the study area. Using multiple stations distributed throughout the catchments allows for a more robust and spatially detailed assessment of rainfall trends. Detailed information on the stations is provided in Table 1.

To detect possible increasing or decreasing trends in the monthly rainfall series, the non-parametric statistical test Mann-Kendall (Mann, 1945; Kendall, 1945) was used at a 5% significance level. This test assesses the presence or absence of monotonic trends in a dataset and is described by the S statistics, as presented in Equation 1.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sinal\left(x_j - x_i\right) \quad (1)$$

$$sinal\left(x_j - x_i\right) = \begin{cases} 1 \ se\, x_j - x_i > 0 \\ 0 \ se\, x_j - x_i = 0 \\ -1 \ se\, x_j - x_i < 0 \end{cases}$$

Additionally, the non-parametric Sen's slope estimator (Sen, 1968) was employed. This test assumes a linear trend to analyse the slope for each pair of sample points in the data series, indicating whether a trend exists and calculating its magnitude (Mondal et al., 2012; Bhat et al., 2021). The calculation for pairs follows Equation 2, where n is the number of pairs in the hydrological series of the variable used, X_j and X_k are the values of the variable at times j and k. The magnitude of the trend is calculated from the mean (β) of the Q_i values using Equations 3, 4.

TABLE 1 Summary of the main characteristics of the meteorological stations included in the sub-basin analysis on precipitation trends and magnitude.

Sub-basin	Stations	Location[a]		Monitored data period	Missing years
		Long. (N)	Lat. (W)		
BHVQR	Vinhais	41.827	−6.993	1932–2021	2001–2003, 2009–2014, 2016, 2017, 2019, 2020
	Moimenta da Raia	41.947	−6.976	1932–2006	2002
BHPP	Deilão	41.847	−6.586	1932–2020	2001–2009, 2012, 2013, 2015, 2016, 2018, 2019
	Pinelo	41.635	−6.552	1959–2022	2003–2006, 2012–2015, 2020

BHVQR - sub-basin upstream of the "Vinhais Quinta Ranca" hydrometric monitoring station; BHPP - sub-basin upstream of the "Ponte Pinelo" hydrometric station.
[a]Geographical coordinates in decimal degrees, referenced to WGS84.

$$Q_j = \frac{x_j - x_k}{j - k} \tag{2}$$

$$\beta = \frac{1}{2}\left(\frac{Q_n}{2} + \frac{Q_{n+2}}{2}\right) \text{ if n is even} \tag{3}$$

$$\beta = \left(\frac{Q_{n+1}}{2}\right) \text{ if n is odd} \tag{4}$$

Environmental drivers of grazing-route patterns in pastoral systems

To interpret the decision-making processes underlying the daily selection of grazing routes by shepherds and the influence of landscape features on these choices, we adopted a multifaceted and integrated approach. This involved integrating GPS tracking data from each herd and spatial analyses of environmental variables. We used indices of vegetation density and water accumulation potential to assess how these environmental factors influenced their route choices. By correlating the GPS-derived movement patterns with these environmental indices, we sought to understand the adaptive strategies pastoralists use in response to the spatial and temporal variability of forage and water availability.

To relate pastoral itineraries to topography, land cover, and water availability, we equipped one adult animal in each of six flocks with a GPS-GNSS collar recording a location every 5 min whenever the animals were outside the night pen. The monitored flocks ranged from ≈100 to 380 head and represented sheep-dominated systems in meadow–arable mosaics and chestnut orchards, as well as goat-dominated or mixed flocks using oak woodlands and shrublands (Table 2). A previous calibration study with the same type of collars in a 130-ewe flock grazing a finely subdivided 500-ha landscape showed that 5-min fixes were sufficient to reconstruct grazing and resting patterns and to map patch use at the scale of individual fields, while keeping battery life and data volumes manageable (Castro J et al., 2021). This is consistent with other work demonstrating that GPS logging intervals of 5–15 min allow reliable identification of grazing, resting, and travelling behaviour, particularly when combined with ancillary information or accelerometers (Ungar et al., 2005; McGranahan et al., 2018; Ermetin et al., 2022).

As a first step, grazing route data collected with a GPS collar in September 2022 were downloaded in.txt format, imported into QGIS 3.30.0, and processed to examine the spatial distribution of the herds during the hottest and driest hours of the day. A heat map was produced to identify areas with higher animal density (location points), reflecting a greater incidence of herd permanence/small movement in these areas. The month of September was selected as the point of analysis due to its representation of a critical juncture in the Mediterranean mountain climates, such as Montesinho, where soil water reserves are most depleted and herbaceous vegetation is under maximum stress, coinciding with the onset of the main autumn rains. In the Iberian Peninsula, numerous studies have demonstrated that late summer and early autumn frequently correspond to periods of heightened meteorological and agricultural drought, as the cumulative rainfall deficits from spring and summer are yet to be offset by autumn precipitation, thereby increasing the vulnerability of rainfed rangelands and extensive livestock systems (e.g., Barbancho, 2004). From a pastoral standpoint, this period marks the time when meadows and cereal stubbles have largely depleted their summer growth, shrub and tree foliage commences the process of senescence, and the reliability of natural watering points becomes most uncertain.

The next step involved producing spatialized maps of two key environmental indices: i) the Normalized Difference Vegetation Index (NDVI), and ii) the Topographic Wetness Index (TWI). The first one provides information on vegetation density and allowed us to assess the influence of forage availability and potential shading for the herds during particularly hot periods. The second identifies areas with greater or lesser potential for water accumulation (Kirkby, 1975; Beven and Kirkby, 1979), based on slope and upstream contributing area. This index enabled the identification of zones with higher soil moisture retention capacity and helped us understand spatial constraints related to water scarcity, especially during the summer.

TABLE 2 Main characteristics of the six flocks monitored with GPS collars in Montesinho Natural Park.

Herd	Village/ grazing area (1–3)	Collared animal (species)	Dominant livestock and breeds	Approx. flock size (n animals)	Use in Sept 2022	Brief description of the grazing landscape
1	Palácios/3	Sheep	Churra Galega Bragançana Branca	380	Yes	Mixed mosaic of meadows, cereal fields, and shrubs
2	Zeive/1	Sheep	Churra Galega Bragançana Branca	260	Yes	Chestnut orchards, meadows, and cereal fields, plus shrub edges
3	Soeira/1	Sheep	Churra Galega Bragançana Preta	170	No Incomplete data	River-valley meadows and arable patches, with slopes
4	Vinhais/2	Sheep or goat	Mixed flock – goats (mostly Cabra Preta de Montesinho) and sheep (Churra Bragançana Preta)	200	Yes	Steep terrain with oak stands, shrubland, and cereal fields
5	Maçãs/1	Goat	Cabra Preta de Montesinho (with some crossbreeds)	130	Yes	Oak woodlands, chestnut orchards, shrubland, and meadows
6	São Julião de Palácios/3	Goat	Cabra Preta de Montesinho (with other local breeds)	100	No Incomplete data	Mosaic of small fields, oak woods, and shrubs on hill slopes

To derive a spatially explicit NDVI for the study area, later focusing specifically on the grazed sites, we downloaded Sentinel-2 Level 2A imagery captured on 21st September 2022, with only 0.06% cloud cover, using the Semi-Automatic Classification Plugin (SCP) in QGIS. To ensure the reliability of the analysis, a maximum cloud cover threshold of 5% was applied, after which the images were clipped to the defined region of interest. The NDVI was then calculated in QGIS using the raster calculator, following the standard Equation 5 and employing the spectral bands required for its computation: Band 8 (Near-Infrared, NIR) and Band 4 (Visible Red, RED). It is important to note that GPS data for the shepherd from Soeira village in September could not be recorded due to an equipment malfunction. By focusing on September 2022, an exceptionally dry year according to both meteorological records and shepherds' narratives, a conservative, "worst-case" picture of how water scarcity and forage decline shape daily grazing routes and force sheep and goat flocks to concentrate around the remaining moist and green patches identified by NDVI, TWI, and local knowledge is provided.

In parallel, to generate the Topographic Wetness Index (TWI) for the same area, the SAGA plugin in QGIS 3.30.0 was used. Specifically, the basic terrain analysis tool was applied to a Digital Elevation Model (DEM) with a spatial resolution of 30 m, derived from the Shuttle Radar Topography Mission (SRTM), resulting in a spatialized TWI map.

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)} \tag{5}$$

In the third stage, two composite maps were produced to analyze the spatial patterns of grazing activity in relation to environmental variables. The first map overlaid GPS-recorded herd routes, highlighting areas of higher point density, with the NDVI layer, enabling an assessment of grazing behavior in relation to vegetation density. The second map combined the same GPS data with the TWI layer to evaluate how grazing distribution corresponds to variations in topographic wetness.

In this study, the Normalised Difference Vegetation Index (NDVI) and the Topographic Wetness Index (TWI) are employed as complementary proxies of resource conditions, as opposed to being utilised as direct measures of water availability. The NDVI, derived from Sentinel-2 surface reflectance, offers an index of vegetation greenness and photosynthetic activity that is extensively employed as a remotely sensed surrogate for above-ground biomass and forage availability in rangelands. The TWI, computed from the digital terrain model, captures the tendency of particular terrain positions to accumulate or retain soil moisture based on upslope contributing area and local slope. While the TWI does not account for short-term rainfall variability, groundwater abstraction, or artificial watering structures, it assists in distinguishing valley bottoms and concave footslopes, where soil moisture persists for a greater duration, from ridges and convex slopes that dry out rapidly. Consequently, the NDVI is interpreted as an indicator of green forage and shade potential, and the TWI as an indicator of relative moisture propensity. The joint spatial patterns of both indices are then utilised to contextualise grazing routes and water-related management decisions at the end of the dry season.

Assessment of pastoralists' perceptions of climate change

To understand how local shepherds perceive and respond to climate change, we conducted semi-structured interviews with six shepherds of local breeds of small ruminants. The six interviewees were not selected at random; instead, they were identified in collaboration with local livestock associations and technicians as some of the most experienced and representative shepherds in the region. Collectively, they represent the main small-ruminant systems still operating in and around the Montesinho Natural Park, including predominantly sheep flocks and mixed or goat-dominated flocks, with herd sizes ranging from approximately 130 to almost 400 animals. Their grazing itineraries span different altitudinal belts, village territories, and hydrological contexts, from relatively water-rich valleys to more water-constrained upland areas. Interviews were conducted in Portuguese between May and September 2023 by accompanying each shepherd during grazing days. This walk-along design enabled the direct correlation of their narratives with observed routes, watering practices, and pasture conditions, thereby capturing the breadth of long-term experiential knowledge on changes in rainfall and water availability, and the diversity of adaptation practices currently employed to sustain extensive grazing under increasing climatic stress.

Our main aim was to gather their perceptions of recent climate change, particularly regarding rainfall patterns, and understand how these changes affect the availability and quality of water in the landscape. We also wanted to identify any adaptative strategies currently used to mitigate the impacts of drought and ensure the continuity of extensive grazing practices in this territory. To do so, we conducted semi-structured interviews based on a script comprising the main topics and questions to be asked (Bernard, 2017). This method followed a logically structured order of predefined ideas, ensuring reliable and comparable data. The choice of a qualitative approach was guided by the opportunity to explore in depth the richness of perception-based data and to fully capture the insights provided by a carefully selected group of interviewees. Interviews aimed at registering factual information regarding water availability and how shepherds perceive climate change in space and time. During the interviews, the pastors were informed in advance about the objectives of the study. It was explained that the data collection aimed at scientific purposes and that the interpretation of the information would contribute to a better understanding and enrichment of the objectives of the ongoing project. The interviews were conducted with the following questions:

a. When, during the year, does it usually rain in this territory? Have you noticed any changes in when it rains or how much it rains since you started shepherding?
b. Overall, would you say it has been raining more, less, or about the same as before*?
c. (If changes in rainfall were mentioned) - Have these changes in water resources led you to make changes in the usual grazing routes or times of beginning and end of the daily activity?
d. Does wind bring rain or cold/dry weather? If so, what are they called, and from which direction do they usually come?
e. (For shepherds whose animal sheds are provided with watering points) - Where does the water used to fill these structures come from (e.g., public network, river, well, rainwater)? And, when on the grazing routes, where do the animals usually drink water from (e.g., natural streams, springs, ponds, artificial troughs)?

*The term "before" was used in this study as a way to refer to a time in the past for each shepherd's lifetime.

During the field visits for those interviews, we also recorded the geographic location of several water points along the daily grazing routes, such as springs, streams, rivers, wells, ponds, and improvised structures built to store water. This step allowed for a more detailed characterization of the use and availability of water resources along the grazing routes, considering the shepherds' perceptions regarding changes in water availability over time.

Results

Shifts in precipitation and temperature patterns

Based on an analysis of regional climatological normals covering the period of 1951–2020, an increase of 1.0 °C in the mean annual temperature was identified along with changes in monthly precipitation patterns (Figure 2; Table 3). A consistent increase in the average temperature was observed over several months of the year. The most significant temperature increases were observed in spring and summer (March, 1.4 °C; June, 1.1 °C; July, 1.5 °C; August, 1.4 °C).

Regarding rainfall, a decrease was identified during the winter and spring months, with a reduction of around 39% in February between the T2 period (1961–1990) and the T4 period (1981–2020), and a sharp fall of around 20 mm for March in the previous T5 period (1991–2020). June also showed a 22% decrease compared to the last three climatological normals (T5, T4, and T3), which reinforces the overall downward trend in seasonal precipitation across time. This trend became more pronounced in each following climatic normal period (for example, the T4 downward rainfall trend was more pronounced than in T3). However, a recovery in rainfall was recorded in the most recent period analysed (T5), particularly with a significant increase in the autumn, where October experienced a 63% rise in rainfall compared to the T1 period. A similar trend to that seen in winter and spring was observed in the summer months. The most significant reduction in rainfall occurred in July, which also recorded the greatest increase in average temperature of all the months analysed (1.5 °C).

Contrasting monthly variations observed across time are also detected in the annual totals. Nevertheless, the decrease in rainfall observed for some seasons across the climatic normal periods does not reflect an overall effect. In fact, an increase in annual

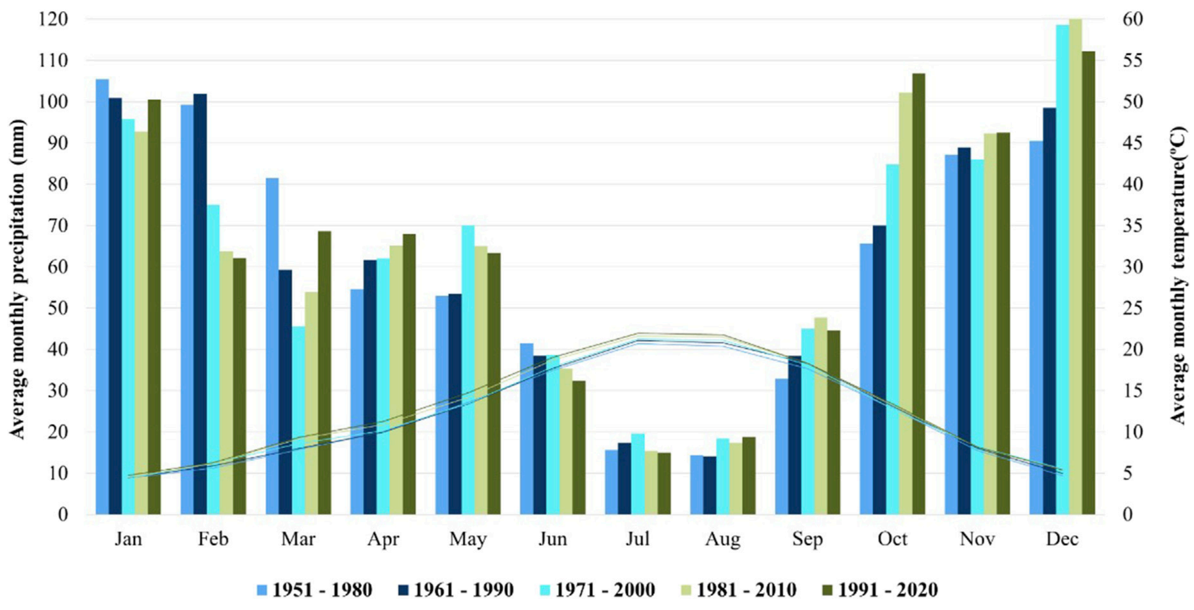

FIGURE 2
Climatological normals for average monthly rainfall and temperature. Data obtained from the IPMA meteorological station in Bragança, Portugal. The left-hand axis shows the monthly average rainfall in millimetres, represented by coloured bars for each month and period of the climate normal. The right-hand axis shows the average temperature in degrees Celsius, represented by coloured lines.

TABLE 3 Mean annual precipitation values (mm) calculated for successive 30-year climatological normals between 1951 and 2020. Data provided by IPMA (https://www.ipma.pt/pt/index.html).

Climatic normal period	30-year period	Mean annual rainfall (mm)	Mean annual temperature °C
T1	1951–1980	741.3	11.9
T2	1961–1990	742.9	12.1
T3	1971–2000	759.4	12.3
T4	1981–2010	772.7	12.6
T5	1991–2020	778.9	12.9

precipitation is observed over the total period analysed. Derived from the same IPMA data, it was possible to calculate the mean annual rainfall as well as the mean for every 30 years (Table 3). An increase of 37.6 mm was observed across time, with mean annual rainfall rising from 741.3 mm in the T1 period to 778.9 mm in the T5 period.

In addition, precipitation trends were analysed on a sub-basin scale (meteorological stations of Vinhais, Moimenta da Raia, Deilão e Pinelo) using SNIRH data, as described in the methodology. Monthly trends were identified with non-parametric Mann–Kendall (Table 4) and corroborate with some patterns observed in climatological normals (Figure 2). Most months across the year did not show statistically significant changes in precipitation, but in March, April, and June (spring and summer), a decreasing trend was observed, whereas in October (autumn), the opposite trend was detected. Additionally, the magnitude of these trends, calculated using Sen's slope test, revealed the exact amount of rainfall that significantly changed across time, either with an increase or a decrease in precipitation (Table 4). For example, in October, which was the only month that had an increasing rainfall trend across all five climatic periods and three sub-basins, there was an increase in precipitation of 1.05 mm per year. Based on the data collected at Moimenta da Raia station, a similar trend was observed. In March, a decrease in the rainfall regime was detected (−1.05 mm).

While all stations listed in the SNIRH report are currently active, only the Pinelo station has data extending to 2022; the Moimenta da Raia records, on the other hand, end in 2006. While the series is relatively long, it contains numerous gaps. Pinelo shows the highest proportion of missing information, with approximately 53 years of records missing. Long and

TABLE 4 Changes in rainfall trends and its magnitude across the study period and at sub-basin level. Raw data obtained from meteorological stations (SNIRH).

Meteorological stations	Months	Trends - Mann Kendall	Sen's Slope (mm.year^{-1})
Vinhais	March	↓	−1.55
	April	↓	−0.65
	June	↓	−0.38
Moimenta da Raia	March	↓	−1.05
	October	↑	1.05
Deilão	March	↓	−0.81
	June	↓	−0.29

Downward arrows refer to a decreasing trend and upward arrows an increasing trend in rainfall calculated using Mann-Kendall non-parametric test. Sen's slope test measures the magnitude of the trend in a scale where negative values indicate a decrease in amount of rainfall per year (in mm), 0 no change and positive values an increase in rainfall.

continuous monitoring series with minimal gaps are essential for obtaining robust and representative results for a given region. Therefore, it is important to note that the amount of data missing for each sub-basin may influence the magnitude of the detected trends to some extent. Some methodological choices were made precisely because of these data limitations, to maximize the use of available records, such as not defining a common period across all series. Consequently, the use of complementary approaches is advisable. In this study, for example, rain gauge station data were supplemented with more complete climatological norms to provide a more robust assessment of climatological trends.

Spatio-temporal relationship between grazing routes and environmental drivers

The proposed methodology involved overlaying the GPS-recorded routes of each herd with TWI and NDVI index maps. This produced ten figures in total showing the grazing paths of each herd over a heatmap for water distribution (TWI) and another for potential forage and shade in the respective grazing areas (see Supplementary Figures 6–8). The maps presented in Figure 3 are an example of such maps and represent the grazing territory of one sheep herd (herd 2) within the sub-basin Vinhais Quinta Ranca for the month of September 2022. In this case, it is possible to observe that the positions of the herd at the warmest hours of the day coincide with areas where TWI values are higher, but not where NDVI is highest. This was most likely due to the generally low NDVI values observed for September 2022, which reflect the severe drought that affected the region during that summer. The Sentinel-2 image used for September 21st shows that most grazing areas had NDVI classes below 0.4, indicating sparse or moderate vegetation cover.

Despite the overall low vegetation density across the studied area, analysis of the recorded GPS data against NDVI values revealed a relative preference for areas with higher vegetation cover, particularly between 11:00 and 16:00, when solar radiation peaks (Figure 4). A higher concentration of GPS points was observed in NDVI intervals 0.1–0.3 and 0.3–0.4, and to a lesser extent in the 0.4–0.5 class and above.

Herd 5 stood out for concentrating approximately 52% of its grazing time in the 0.3–0.4 NDVI class, revealing greater use of areas with moderate vegetation density. Herd 2 had a more balanced distribution across classes but still showed a greater presence in relatively denser vegetation areas (34% in 0.4–0.5, 28% in 0.3–0.4, and 12.8% in >0.5). Herd 1, on the other hand, recorded the highest percentage of GPS points in the 0.1–0.3 class, which corresponds to the predominant class in the analysed area, accounting for approximately 78% of the records. To a lesser extent, herd 4 also concentrated a significant portion of its points (approximately 45%) in this same class for the same reasons of landscape characteristics. For all herds, the percentage of points recorded in the lowest NDVI classes (≤0.1) was low (less than 5%). In the higher classes (>0.5), values ranged from 1% to approximately 12%, depending on the herd.

These results reflect some of the environmental factors influencing the decision-making process of both the shepherd and the flock regarding the use of space in response to limitations in resources, pasture, and water. Overall, it is possible to observe a tendency in herds to remain in areas where moisture propensity and vegetation density are higher, during the hottest hours of the day.

Key insights into pastoralist perceptions and adaptations

The semi-structured interviews provided detailed and complementary information on how local pastoralists perceive changes in the weather, particularly in rainfall patterns and progressive temperature increase. Moreover, how these changes impact their agropastoral system. Their answers

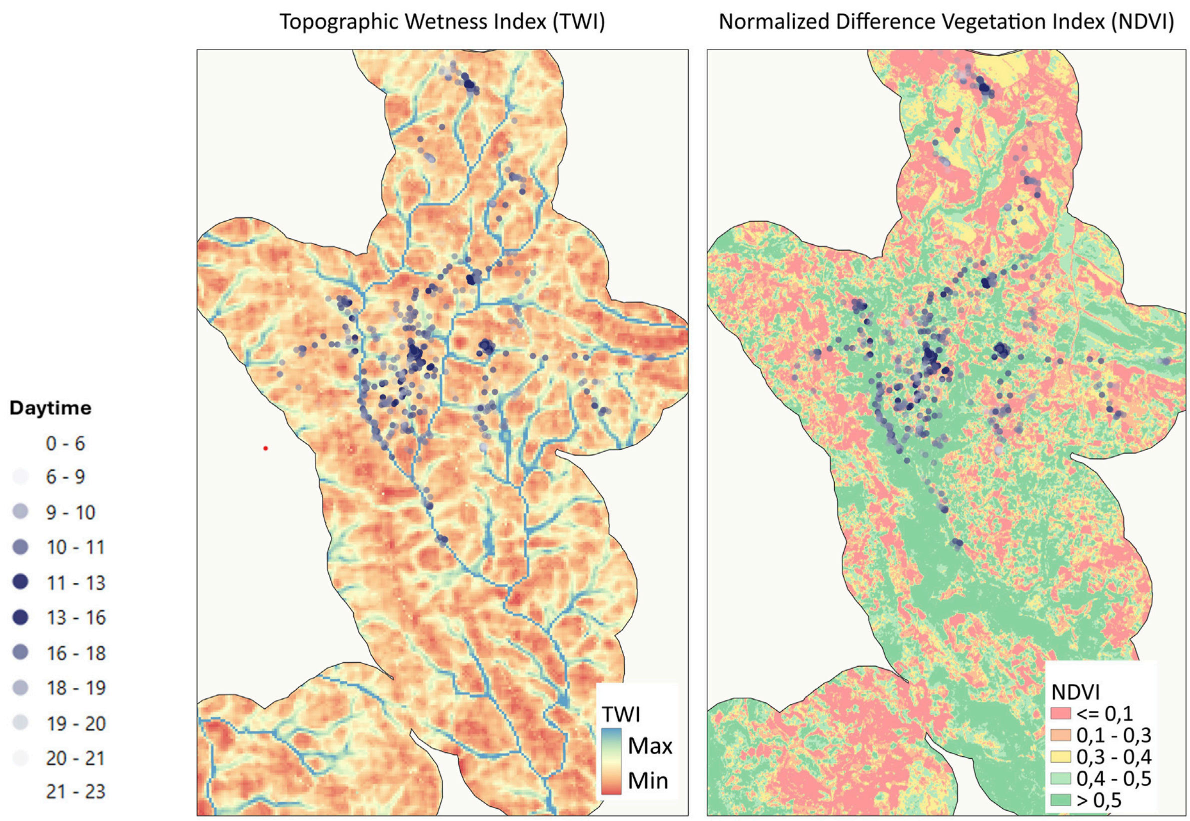

FIGURE 3
Overlay of grazing routes, and TWI and NDVI maps for herd 2 (sheep) over the month of September 2022. Higher TWI values indicate areas with greater potential for water accumulation. For NDVI, values closer to 1 represent higher vegetation activity. The locations of the herd are shown as blue points, with a colour gradient indicating the time of day; darker colours correspond to the hottest hours.

focused on four main points: perceived changes in precipitation and temperature patterns; observations of traditional climate indicators, such as wind direction; the consequences for water availability in their grazing territory; and the strategies they have adopted to deal with drought.

Pastoralists consistently reported that rainfall distribution has become more irregular in recent years and is therefore less effective in maintaining soil moisture and growing pasture. Historically, rainfall was distributed accordingly to seasons (more rain in spring, and snow and frosts in winter), favouring pasture growth and replenishing water sources. Recently, however, some rainfall events are taking place outside the expected seasons and becoming more extreme, with torrential rains occurring in traditionally dry months (i.e., June), followed by prolonged droughts. From the pastoralist's perspective, these climate changes have altered the region's hydrological dynamics. Streams and rivers now have historically low summer flows, and previously permanent springs have become seasonal. In many cases, smaller water lines and springs have dried up completely. According to one of the pastors, the flow of a local stream, which previously sustained two mills, has been minimal or non-existent since 2021. This has resulted in economic losses for all residents of the village. These changes have been attributed to reduced rainfall and increased private use of groundwater for irrigating crops.

In response to water shortages in the territory, pastoralists adopted a variety of mitigation strategies. These include increasing the production of forage crops, such as Sudan grass, and storing larger quantities of hay to ensure a feed supply during the now longer drier periods; guaranteeing water availability at the barns/animal sheds and placing water containers in strategic points along the grazing routes; and using grazing routes that have easy access to water sources in the warmer periods to avoid animal heat stress. Shade availability has also become an important consideration when planning routes to protect herds from extreme heat and sometimes even from access to water. In addition, pastoralists continue to rely on traditional ecological knowledge, noting that rain-bearing winds typically come from the south, and that snow and frost have historically played a key role in guaranteeing underground water and

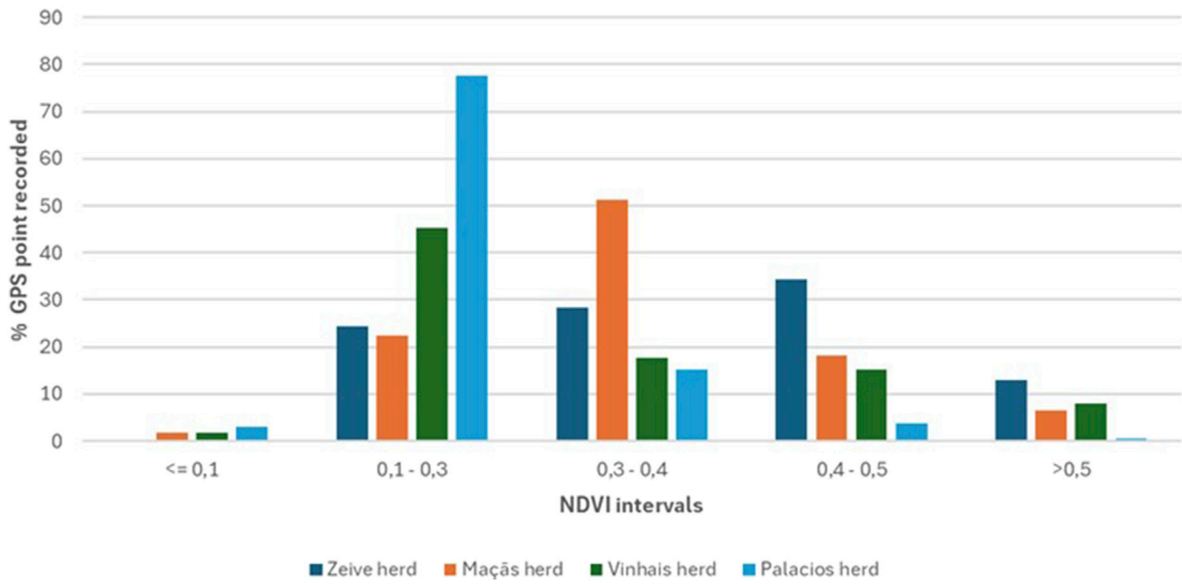

FIGURE 4
Percentage of GPS points recorded between 11:00 AM and 4:00 PM during September 2022, by NDVI class obtained from Sentinel-2 imagery dated 21st September 2022.

controlling soil diseases. Interviewees attribute the recent near absence of snowfall and frost in the winter to reduced spring and summer water flows, water spring bursts, and low-yield pastures. They also observe that not only are summers becoming drier, but also significantly hotter. Temperatures were sometimes described as 'unbearable' without shade, indicating an increase in extreme heat events compared with the past.

Water points on pastoral routes

Additionally, it was carried out the water points mapping through direct observation during a field trip with each pastor and supported by semi-structured interviews. We identified a total of fourteen water points used by the herds and obtained GPS coordinates for each (Figure 5). These include springs (1, 10, and 12), streams and rivulets (2, 3, and 5), wells (4 and 8), natural ponds (6, 7, 9, and 14), and a stone fountain that is currently dry (13). There are also artificial structures, such as cement ponds built by the village council (11).

During the field visits, and as confirmed by the shepherds, strong variability in water availability was observed. While some sites still have water and are used by the herds, others have reduced water quality due to vegetation overgrowth and high potential for eutrophication. Other sites were found to be completely dry. In several cases, the shepherds reported that these sources never dried in the past, although water flow would sometimes decrease. Currently, however, they are experiencing frequent droughts, particularly in summer. In summary, the results of this mapping indicate a reduction in the availability and quality of water, as well as increasing dependence on small springs and local infrastructure to ensure a supply for livestock.

Discussion

Evidence and trends of regional hydroclimatic changes

Climatological normal shifts observed in the last ~60 years show that the Montesinho mountains have been experiencing the adverse effects of climate change. The progressive increase in mean annual temperature detected in this study is consistent with the global increase in average air temperatures observed recently (IPCC, 2021). This pattern is particularly evident in the climatic hotspot regions with a Mediterranean climate (Giorgi and Lionello, 2008; Lionello and Scarascia, 2018; Costa et al., 2022), which is the case of the Montesinho region. The rainfall regime in this case study revealed a clear reduction during the winter and spring months, particularly in February and March. This pattern matches findings from Gonzales-Hidalgo et al. (2023) study, which identified similar precipitation pattern changes in Spain associated with different phases of the North Atlantic Oscillation (NAO). This atmospheric phenomenon is the main mode of variability of sea-level pressure over the North Atlantic Ocean and strongly influences precipitation, temperature, and wind patterns across Europe (Walker, 1924; Walker and Bliss, 1932). This climatic component plays a significant role in regional climate, and

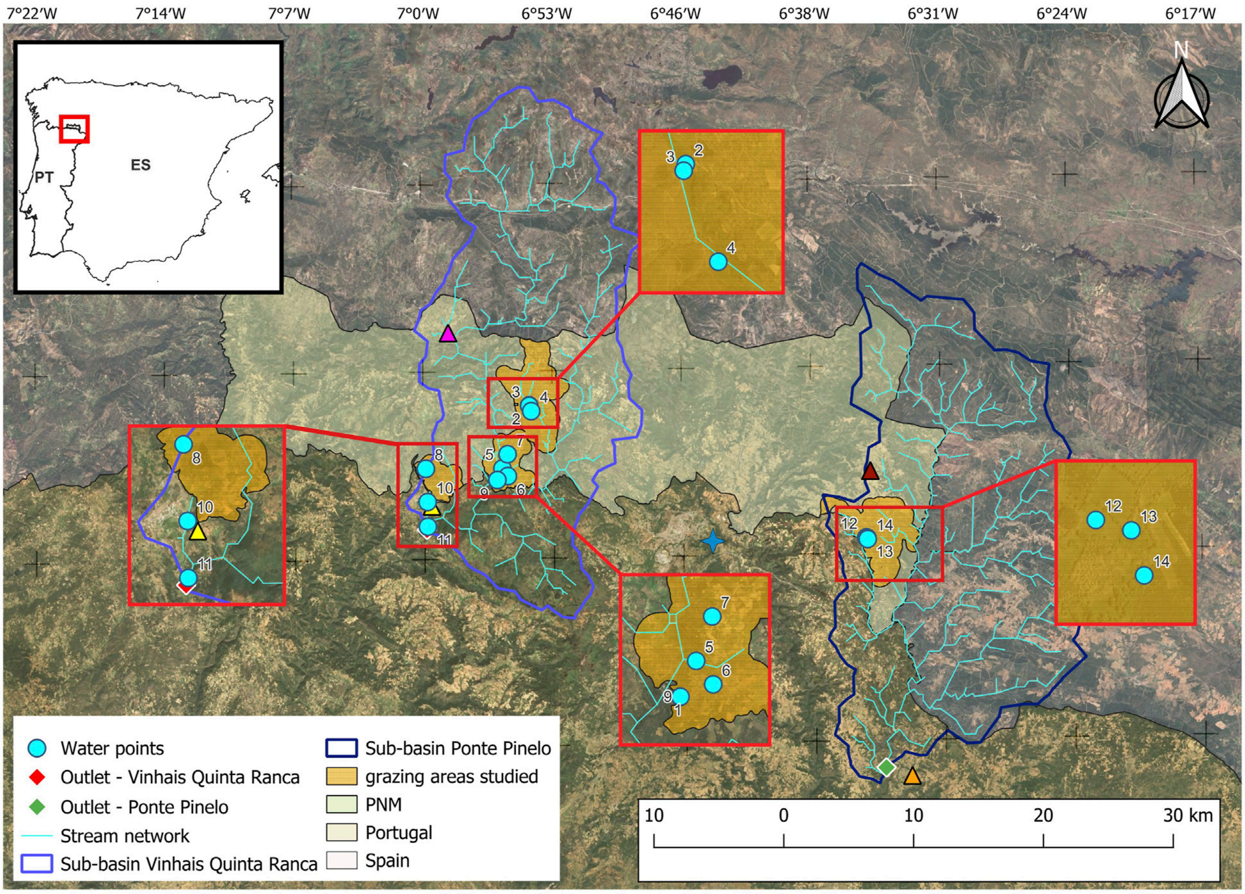

FIGURE 5
Location of key water sources in the two main sub-basins used by the shepherds' livestock. Geographic coordinates were recorded during field surveys conducted between May and September 2023.

projections suggest that, under high-emission scenarios, elevated NAO indices may become more frequent, potentially leading to increased precipitation in northern Europe and reductions in the south, as demonstrated in other studies (Ulbrich and Christoph, 1999; McKenna and Maycock, 2022). Research on regional climate, such as Coppola et al. (2005) and Rivosecchi et al. (2024), modelled the distribution of the NAO under different future climate scenarios, considering rising greenhouse gas emissions and increased average atmospheric temperatures. These studies show a trend towards more frequent positive NAO phases, which are associated with decreased precipitation and increased incidence of drought, particularly in southern Europe. Since the late 1960s, high NAO index values have been associated with reduced precipitation in Portugal (Hurrell, 1995; Hurrell and Van Loon, 1997; Espinosa and Portela, 2022), while increased precipitation tends to occur during periods of low NAO index. Though this relationship is more pronounced in southern Portugal (Zêzere et al., 2005), our results reveal a similar pattern for the northeast of Portugal. These regional-scale dynamics highlight the complexity of the interaction between the NAO and climate change. In some cases, the effects of NAO on hydroclimatic variables may be amplified or masked (Hergerl et al., 2023; Liné et al., 2024).

The analysis of rainfall trends and magnitude, as inferred from the data of each rain gauge station, confirmed the patterns identified in the climatological normals analysis. Though inferences of annual decreasing precipitation trends in some spring and summer months (March, April, and June) at Vinhais and Deilão meteorological stations appear small (between −0.29 mm and −1.55 mm per year), the cumulative effect across the hydrographic sub-basins might have a significant impact. A recent study conducted for Portugal (Espinosa and Portela, 2022) also revealed a significant decrease in precipitation over the last 51 years (1968–2019). The observed rainfall trends in this region, which is already facing severe drought, could drastically reduce water availability during the most critical months of the year, compromising animal health and pasture growth. On the other hand, the increasing trend in precipitation detected at Moimenta da Raia meteorological station for October

(+1.05 mm/year), corroborates the rise in autumn rainfall identified in the regional analysis of the present study and in other regions of the Mediterranean basin: Moroccan Atlas (Diani et al., 2019), Algeria (Bougara et al., 2020; Bouklikha et al., 2021), France (Folton et al., 2019), Spain (del Rio et al., 2011; Gonzalez-Hidalgo et al., 2011), and south Portugal (Paulo et al., 2012). This increase in autumn precipitation is particularly relevant for hydrological risk management, given that episodes of intense precipitation are also becoming more frequent in traditionally dry months. In Montesinho, this evidence was supported by the shepherds' knowledge, who reported episodes of extreme rainfall in June and August. Such events align with findings from other research. Coelho et al. (2020) confirmed an increase of approximately 20 days of very heavy rain per year, associated with climate change, particularly rising temperatures that intensify evapotranspiration processes.

Impacts of rainfall pattern changes and pastoral adaptation strategies

The seasonal shift in rainfall from spring to autumn, as observed in the climatological analysis, has clear implications for extensive grazing in the PNM. Reduced winter and spring precipitation, when combined with earlier and more intense summer heat, results in a reduction of the period during which meadows and rainfed crops can accumulate biomass and recharge soil moisture. Previous studies in Mediterranean and African rangelands have demonstrated that, under such conditions, access to drinking water and to green forage becomes a primary constraint on the movement of herds and the duration of their stay in a given area (Goiran et al., 2012; Raizman et al., 2013; Garcia-Baquero et al., 2020; Nakano et al., 2020). The results of this study are consistent with this literature: during an exceptionally dry September, flocks concentrate their time in those parts of the landscape that still combine greener vegetation with better moisture conditions, while drier patches are mostly used as transit.

In this context, the Normalised Difference Vegetation Index (NDVI) and the Soil Moisture Index (SMI) are useful not as direct measures of "water resources", but as complementary proxies of forage and moisture conditions that facilitate interpretation of the Global Positioning System (GPS) tracks. A substantial body of research in arid and semi-arid regions demonstrates that NDVI exhibits a strong correlation with above-ground net primary production and standing biomass, and that seasonal changes in NDVI closely follow rainfall-driven fluctuations in rangeland productivity. In September 2022, when herbaceous growth had largely ceased, and numerous rainfed fields and meadows had already been cut or grazed, the remaining high-NDVI patches corresponded primarily to irrigated or spring-fed meadows, late-sown fodder crops, shaded wood pastures, and some shrub stands that retained green foliage. These are precisely the habitats that shepherds describe as "fresher" and that they actively target for late-summer grazing, thereby confirming that NDVI captures the spatial pattern of residual forage that is most relevant to flock movements at this time of year.

TWI introduces a topographic dimension to this depiction by identifying sections of the landscape where soil moisture is more likely to persist despite overall drought stress. Elevated TWI values frequently coincide with concave footslopes, drainage lines, and valley bottoms, where shallow groundwater and subsurface flow can sustain greener vegetation and more reliable water points. Conversely, low-TWI areas correspond to exposed slopes and ridges that rapidly dry out. When NDVI and TWI are combined, they provide a straightforward yet informative framework to comprehend why GPS locations cluster around particular meadows, springs, streamside pastures, and north-facing slopes in September 2022, and why other, drier parts of the mosaic are only briefly traversed. Rather than predicting animal behaviour mechanistically, the joint utilisation of NDVI and TWI assists in formalising shepherds' own descriptions of where "the green holds out" longest in the landscape, and highlights how access to these high-NDVI, high-TWI patches underpins the resilience of small-ruminant pastoralism during severe late-summer droughts.

These findings are consistent with previous research indicating that the decision-making process regarding where animals graze is strongly associated with resource availability, and that vegetation structure and composition influence route choices under challenging climatic conditions (Karki and Goodman, 2009; Castillo et al., 2020). In other Mediterranean pastoral systems, such as the Montado in southern Portugal and upland pastures in the Central Apennines, grazing routes tend to prioritise patches that optimise nutrient intake and offer better microclimatic conditions when forage is scarce (Serrano et al., 2021; Moscatelli et al., 2025). Species-specific preferences further modulate these choices: goats tend to exploit forested and shrub-dominated areas, while sheep more often use pastures and areas closer to villages (Hassidou, 2016; Van Valkenburgh et al., 2023). Rising temperatures add a layer of constraint, as demonstrated by Castro M. et al. (2021) for the PNM, with herds increasingly using shaded and ventilated sites during the hottest hours of the day (Vieira et al., 2019). Our results suggest that, in late summer, the most attractive patches are those that jointly provide green forage, shade, and easier access to drinking water.

The impact of changes in rainfall patterns on the broader forage base of these systems is a significant consideration, extending beyond the influence on daily routes. Shepherds have reported a decline in the quantity and variability of hay and grain yields used for winter feeding, coinciding with a decrease in rainy days during spring and greater inter-seasonal variability. This phenomenon is not unique; similar sensitivities of crop and pasture production to water scarcity have been documented in other regions.

For instance, Shortridge (2019) documented significant yield reductions under high-emission scenarios in North Carolina, while Fishman (2016) projected an 11% decline in rice productivity in India by mid-century. Additionally, Muñoz-Gómez et al. (2024) demonstrated that severe droughts in southern Spain can reduce pasture biomass by 40%–60%. In Montesinho, these trends result in higher production costs and a greater reliance on purchased feed, thereby weakening the economic viability of extensive systems.

Shepherds' narratives also emphasise growing uncertainty about groundwater and spring discharge, which they attribute to a combination of reduced rainfall, fewer snow events, land-use change, and increased local abstraction for irrigation. The lack of snow in particular has been identified as a factor that alters infiltration patterns and aquifer recharge in cold regions (Okkonen and Kløve, 2010), and similar concerns arise in this mountain context. For pastoralism, the critical point is not only the total volume of water stored underground, but whether springs, small streams, and traditional watering structures retain enough flow to sustain daily access along established routes during the dry season. Our data highlight the strategic role of these water points within grazing territories: when some of them dry up, herds are forced either to extend their walking distances, increasing labour and animal stress, or to concentrate for longer around the remaining functional points, intensifying grazing pressure on adjacent forage. Both pathways jeopardise the ecological and socio-economic sustainability of extensive sheep and goat systems under a warming and more hydrologically variable climate.

Conclusion

This study analysed temporal changes in precipitation and temperature patterns on a regional (PNM) and local (hydrographic sub-basin) scale and explored how pastoralists are adapting to these fast-evolving climate conditions.

Based on 69 years of hydro climatological data (1951–2020), an increase of 1 °C in the mean annual temperature was identified for the Montesinho region (northeast Portugal). There was also an increase in the average monthly temperature, reaching +1.5 °C in July. Monthly analysis using climatological normal as a reference revealed a shift in the precipitation pattern, with a significant decrease in rainfall for winter and spring months (e.g., 39% decrease in February) and a significant increase in autumn, particularly October (+63%). Although the traditionally wet months of winter and spring have become drier, the average annual rainfall has not decreased. This is likely associated with an increased frequency and intensity of extreme weather events across the year, particularly in October.

Statistical tests confirmed decreasing precipitation trends in spring and summer and increasing in autumn for the hydrographic sub-basins of PNM. Though of relatively small magnitude, these changes were also reflected in the local knowledge, with all shepherds highlighting the negative impacts of water shortage and declining quality on pasture productivity, while the decline in water quality was observed during our own fieldwork.

The integration of herd location analysis with local pastoral insight revealed that grazing routes coincide with areas of higher moisture accumulation and vegetation density, indicating that herd movement is guided by an adaptive strategy to cope with climatic severity. In short, this study reveals that herders in the PNM are aware of a fast-changing climate, marked by increasing temperature and unpredictable rainfall patterns, and are actively responding by developing practical adaptation strategies for a sustainable extensive pastoral system.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://snirh.apambiente.pt/index.php?idMain=2&idItem=1 https://www.ipma.pt/pt/index.html.

Ethics statement

We confirm that this study does not involve experimentation with animals and does not include human subjects; therefore, ethical approval and informed consent are not applicable.

Author contributions

AFO, JC, and MC developed the conception and design of the study. AFO, VMS, and IA-P conducted the fieldwork and data analyses. AFO, MC, IA-P, and JC wrote the initial manuscript draft. All authors contributed to the article and approved the submitted version.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This work was supported by the Foundation for Science and Technology (FCT), under the project MTS/CAC/0028/2020: PASTOpraxis, and by the

European Union's Horizon Europe research and innovation programme (AF4EU, grant agreement No. 101086563).

Acknowledgements

The authors thank all shepherds involved in the project as well as the two anonymous reviewers for their helpful and constructive comments and suggestions on the manuscript.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontierspartnerships.org/articles/10.3389/past.2026.15757/full#supplementary-material

References

Alamer, M. (2006). Physiological responses of Saudi Arabia indigenous goats to water deprivation. *Small Ruminant Res.* 63, 100–109. doi:10.1016/j.smallrumres.2005.02.017

Alamer, M., and Al-Hozab, A. (2004). Effect of water deprivation and season on feed intake, body weight and thermoregulation in Awassi and Nadji sheep breeds in Saudi Arabia. *J. Arid Environ.* 59, 71–84. doi:10.1016/j.jaridenv.2003.10.002

Aleixo-Pais, I., Castro, J., Frazão-Moreira, A., Castro, J. P., and Castro, M. (2025). Adaptação da pastorícia às alterações climáticas – Guia de boas práticas. *Bragança CIMO-IPB and CRIA*. doi:10.5281/zenodo.15303939

Almeida, A. M., Ribeiro, M. M., Ferreira, M. R., Roque, N., Quintela-Sabarís, C., and Fernandez, P. (2023). Big data help to define climate change challenges for the typical Mediterranean species *Cistus ladanifer* L. *Front. Ecol. Evol.* 11, 1136224. doi:10.3389/fevo.2023.1136224

Azevedo, J. C., Moreira, C., Castro, J. P., and Loureiro, C. (2011). "Agriculture abandonment, land-use change and fire hazard in mountain landscapes in northeastern Portugal," in *Landscape Ecology in Forest Management and Conservation* (Berlin, Heidelberg: Springer), 329–351.

Azevedo, J., Cadavez, V., Arrobas, M., and Pires, J. (2016). "Sustentabilidade da montanha portuguesa: realidades," in *Bragança: instituto Politécnico de Bragança*. Available online at: http://hdl.handle.net/10198/15034 (Accessed October 9, 2025).

Barbancho, A. C. (2004). Vulnerabilidade da região mediterrânica à hidrofobia dos solos. *Territorium* (11), 45–55.

Bernard, H. R. (2017). *Research Methods in Anthropology: Qualitative and Quantitative Approaches*. Lanham, MD: Rowman & Littlefield.

Beven, K. J., and Kirkby, M. J. (1979). A physically based, variable contributing area model of basin hydrology/Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant. *Hydrological Sci. J.* 24 (1), 43–69. doi:10.1080/02626667909491834

Bhat, M. M., Tali, P. A., and Nanda, A. A. (2021). Seasonal spatio-temporal variability in temperature over north Kashmir Himalayas using Sen slope and Mann-Kendall Test. *J. Climatol. Weather Forecast* 9, 288.

Bougara, H., Hamed, B. K., Borgemeister, C., Tischbein, B., and Kumar, N. (2020). Analyzing trend and variability of rainfall in the Tafna Basin (northwestern Algeria). *Atmosphere* 11, 347. doi:10.3390/atmos11040347

Bouklikha, A., Habi, M., Elouissi, A., and Hamoudi, S. (2021). Annual, seasonal and monthly rainfall trend analysis in the Tafna watershed, Algeria. *Appl. Water Sci.* 11, 77. doi:10.1007/s13201-021-01384-0

Castillo, M. S., Tiezzi, F., and Franzluebbers, A. J. (2020). Tree species effects on understory forage productivity and microclimate in a silvopasture of the southeastern usa. *Agric. Ecosyst. and Environ.* 295, 106917. doi:10.1016/j.agee.2020.106917

Castro, M., Castro, J. F., and Gómez-Sal, A. (2009). The effect of environmental conditions in the duration of daily grazing itineraries of small ruminants in Northeast Portugal. *Options Méditerranéennes* 91, 69–71.

Castro, J., Castro, M., and Gómez-Sal, A. (2021). Changes on the climatic edge: adaptation of and challenges to pastoralism in Montesinho (Northern Portugal). *Mt. Res. Dev.* 41 (4), R29–R37. doi:10.1659/MRD-JOURNAL-D-21-00010.1

Castro, M., Teixeira, A., and Fernández-Núñez, E. (2021). The nutritive value of different Mediterranean browse species used as animal feeds under oak silvopastoral systems in Northern Portugal. *Agrofor. Syst.* 95, 269–278. doi:10.1007/s10457-020-00588-1

Clarke, B., Otto, F., Stuart-Smith, R., and Harrington, L. (2022). Extreme weather impacts of climate change: an attribution perspective. Environ. Res. *Clim.* 1 (1), 012001. doi:10.1088/2752-5295/ac6e7d

Coelho, S., Rafael, S., Coutinho, M., Monteiro, A., Medina, J., Figueiredo, S., et al. (2020). Climate-change adaptation framework for multiple urban areas in northern Portugal. *Environ. Manag.* 66 (3), 395–406. doi:10.1007/s00267-020-01313-5

Coppola, E., Kucharski, F., Giorgi, F., and Molteni, F. (2005). Bimodality of the North Atlantic Oscillation in simulations with greenhouse gas forcing. *Geophys. Res. Lett.* 32 (23). doi:10.1029/2005GL024080

Costa, A., Graça, J., Barbosa, I., and Spiecker, H. (2022). Effect of climate on cork-ring width and density of *Quercus suber* L. in Southern Portugal. *Trees* 36, 1711–1720. doi:10.1007/s00468-022-02321-0

Davies, K. W., Boyd, C. S., Bates, J. D., Svejcar, L. N., and Porensky, L. M. (2024). Ecological benefits of strategically applied livestock grazing in sagebrush communities. *Ecosphere* 15 (5), e4859. doi:10.1002/ecs2.4859

Del Rio, S., Herrero, L., Fraile, R., and Penas, A. (2011). Spatial distribution of recent rainfall trends in Spain (1961–2006). *Int. J. Climatol.* 31, 656–667. doi:10.1002/joc.2111

Diani, K., Kacimi, I., Zemzami, M., Tabyaoui, H., and Haghighi, A. T. (2019). Evaluation of meteorological drought using the standardized precipitation index (SPI) in the high Ziz River basin, Morocco. *Limnol. Rev.* 19 (3), 125–135. doi:10.2478/limre-2019-0011

Egeru, A. (2016). Climate risk management information, sources and responses in a pastoral region in East Africa. *Clim. Risk Manag.* 11, 1–14. doi:10.1016/j.crm.2015.12.001

Ermetin, O. R. H. A. N., Karadağ, Y., Yıldız, A. D. İ. L., Karaca, Ö., Tüfekçi, H., Tufan, Y., et al. (2022). Use of a global positioning system (GPS) to manage extensive sheep farming and pasture land. *J. Hellenic Veterinary Med. Soc.* 73 (3), 4441–4448. doi:10.12681/jhvms.27354

Espinosa, L. A., and Portela, M. M. (2022). Grid-point rainfall trends, teleconnection patterns, and regionalised droughts in Portugal (1919–2019). *Water* 14 (12), 1863. doi:10.3390/w14121863

FAO (2001). *Pastoralism in the New Millennium. Animal Production and Health Paper No. 150*. Rome: Food and Agriculture Organization. Available online at: http://www.fao.org/3/y2647e/y2647e00.htm (Accessed October 9, 2025).

FAO (2020). *Innovative pastoralism – Achieving Productivity and Sustainability for Food Security*. Rome: Food and Agriculture Organization. Available online at: http://www.fao.org/3/cb1185en/CB1185EN.pdf (Accessed October 9, 2025).

Fishman, R. (2016). More uneven distributions overturn benefits of higher precipitation for crop yields. *Environ. Res. Lett.* 11 (2), 024004. doi:10.1088/1748-9326/11/2/024004

Folton, N., Martin, E., Arnaud, P., L'Hermite, P., and Tolsa, M. (2019). A 50-year analysis of hydrological trends and processes in a Mediterranean catchment. *Hydrology Earth Syst. Sci.* 23, 2699–2714. doi:10.5194/hess-23-2699-2019

Garcia-Baquero, G., Odriozola, I., and Aldezabal, A. (2020). Floristic composition mediates change in forage nutritive quality of Atlantic mountain grasslands after experimental grazing exclusion. *Agronomy* 11 (1), 25. doi:10.3390/agronomy11010025

Garmendia, E., Aldezabal, A., Galan, E., Andonegi, A., del Prado, A., Gamboa, G., et al. (2022). Mountain sheep grazing systems provide multiple ecological, socio-economic, and food quality benefits. *Agron. Sustain. Dev.* 42, 47. doi:10.1007/s13593-021-00751-7

Gentle, P., and Maraseni, T. N. (2012). Climate change, poverty and livelihoods: adaptation practices by rural mountain communities in Nepal. *Environ. Sci. and Policy* 21, 24–34. doi:10.1016/j.envsci.2012.03.007

Giorgi, F., and Lionello, P. (2008). Climate change projections for the Mediterranean region. *Glob. Planet. Change* 63 (2–3), 90–104. doi:10.1016/j.gloplacha.2007.09.005

Goirán, S. B., Aranibar, J. N., and Gomez, M. L. (2012). Heterogeneous spatial distribution of traditional livestock settlements and their effects on vegetation cover in arid groundwater-coupled ecosystems in the Monte Desert (Argentina). *J. Arid Environ.* 87, 188–197. doi:10.1016/j.jaridenv.2012.07.011

Gómez-Sal, A. (2001). "The ecological rationale and nature conservation value of extensive livestock systems in the Iberian Peninsula," in *Examples of European agri-Environmental Schemes and Livestock Systems and their Influence on Spanish Cultural Landscapes*. Editor R. G. H. Bunce (Wageningen: Alterra-rapport), 103–123.

González-Hidalgo, J. C., Brunetti, M., and de Luis, M. (2011). A new tool for monthly precipitation analysis in Spain: MOPREDAS database (monthly precipitation trends December 1945–November 2005). *Int. J. Climatol.* 31, 715–731. doi:10.1002/joc.2112

González-Hidalgo, J. C., Beguería, S., Peña-Angulo, D., and Trullenque-Blanco, V. (2023). MOPREDAS_century database and precipitation trends in mainland Spain, 1916–2020. *Int. J. Climatol.* 43 (8), 3828–3840. doi:10.1002/joc.8060

Hassidou, M. (2016). *Assessment of Grazing Selectivity in Relation to Land Cover: A Comparison Between Sheep and Goats*. Portugal: Master's Thesis. Instituto Politécnico de Bragança.

Hegerl, G., O'Reilly, C., Schurer, A., and Ballinger, A. (2023). The importance of accounting for the North Atlantic Oscillation when applying observational constraints to European climate projections. *Geophys. Res. Lett.* 50. doi:10.1029/2023GL103431

Henry, B. K., Eckard, R. J., and Beauchemin, K. A. (2018). Adaptation of ruminant livestock production systems to climate changes. *Animal* 12 (S2), S445–S456. doi:10.1017/S1751731118001301

Hurrell, J. W. (1995). Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science* 269 (5224), 676–679. doi:10.1126/science.269.5224.67

Hurrell, J. W., and Van Loon, H. (1997). Decadal variations in climate associated with the North Atlantic Oscillation. *Clim. Change* 36 (3), 301–326. doi:10.1023/A:1005314315270

INE (2020). *Anuário Estatístico da Região Norte 2020 [Statistical Yearbook of the Norte Region 2020]*. Lisbon: INE.

INMG (1991). O clima de Portugal. Vol. 4 – 4ª região: Normais climatológicas da região de Alentejo e Algarve, correspondentes a 1951–1980. *Fascículo XLIX*. Lisboa: Instituto Nacional de Meteorologia e Geofísica.

Instituto Português do Mar e da Atmosfera (IPMA) (2023). Normais climatológicas. Available online at: https://www.ipma.pt/pt/oclima/normais.clima/ (Accessed October 9, 2025).

IPCC (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press. doi:10.1017/9781009157896

Joy, A., Dunshea, F. R., Leury, B. J., Clarke, I. J., DiGiacomo, K., and Chauhan, S. S. (2020). Resilience of small ruminants to climate change and increased environmental temperature: a review. *Animals* 10 (5), 867. doi:10.3390/ani10050867

Karki, U., and Goodman, M. S. (2009). Cattle distribution and behavior in southern-pine silvopasture versus open-pasture. *Agrofor. Syst.* 78 (2), 159–168. doi:10.1007/s10457-009-9250-x

Karki, M., Sharma, S., Mahat, T. J., Tuladhar, A., and Aksha, S. (2012). Sustainable mountain development in the Hindu Kush–Himalaya: from Rio 1992 to Rio 2012 and beyond. *ICIMOD, Kathmandu*.

Kendall, M. G. (1945). *Rank Correlation Methods*. 4th ed. London: Charles Griffin.

Kirkby, M. (1975). *Hydrograph Modelling Strategies*. Leeds: University of Leeds, Dept. of Geography.

Köhler-Rollefson, I. (2020). "How can we make the livestock sector more resilient?," in *Rural 21 – The International Journal for Rural Development*, 4, 30–31. Available online at: https://www.rural21.com/fileadmin/downloads/2020/en-04/rural2020_04-S30-31.pdf (Accessed October 9, 2025).

Koyuncu, M., and Canbolat, O. (2009). University of Uludag, faculty of agriculture, department of animal science, Bursa, Turkey. *J. Animal Feed Sci.* 18, 620–627. doi:10.22358/jafs/66436/2009

Leroy, G., Hoffmann, I., From, T., Hiemstra, S. J., and Gandini, G. (2018). Perception of livestock ecosystem services in grazing areas. *Animal* 12 (12), 2627–2638. doi:10.1017/S1751731118001027

Li, B. T., Christopherson, R. J., and Cosgrove, S. J. (2000). Effect of water restriction and environmental temperatures on metabolic rate and physiological parameters in sheep. *Can. J. Animal Sci.* 80, 97–104. doi:10.4141/A99-057

Liker, S., Gunes, S., Murat, Y., Funda, K., and Ahmet, C. (2010). The effects of body weight, body condition score, age, lactation, serum triglyceride, cholesterol and paraoxonase levels on pregnancy rate of Saanen goats in the breeding season. *J. Animal Veterinary Adv.* 9, 1848–1851. doi:10.3923/javaa.2010.1848.1851

Liné, A., Parey, S., Cassou, C., and Msadek, R. (2024). Modulation of Northern Europe near-term anthropogenic warming and wettening assessed through internal variability storylines. *Npj Clim. Atmos. Sci.* 7, 40. doi:10.1038/s41612-024-00759-2

Lionello, P., and Scarascia, L. (2018). The relation between climate change in the Mediterranean region and global warming. *Reg. Environ. Change* 18, 1481–1493. doi:10.1007/s10113-018-1290-1

Lu, H., Chen, K., Chen, X., Zhou, S., Li, Y., Zhang, Z., et al. (2024). Multiple soil health assessment methods for evaluating effects of organic fertilization in farmland soil of agro-pastoral ecotone. *Agriculture* 14, 572. doi:10.3390/agriculture14040572

Luber, G., and McGeehin, M. (2008). Climate change and extreme heat events. *Am. Journal Preventive Medicine* 35 (5), 429–435. doi:10.1016/j.amepre.2008.08.021

Macheroum, A., and Chenchouni, H. (2022). Short-term land degradation driven by livestock grazing does not affect soil properties in semiarid steppe rangelands. *Front. Environ. Sci.* 10, 846045. doi:10.3389/fenvs.2022.846045

Malek, Ž., Schulze, K., Bartl, H., Keja, W., Petersen, J. E., Tieskens, K., et al. (2024). Mapping livestock grazing in semi-natural areas in the European Union and United Kingdom. *Landsc. Ecol.* 39, 31. doi:10.1007/s10980-024-01810-6

Mann, H. B. (1945). Non-parametric tests against trend. *Econometrica* 13, 245–259. doi:10.2307/1907187

Manzano, P., Burgas, D., Cadahía, L., Eronen, J. T., Fernández-Llamazares, Á., Bencherif, S., et al. (2021). Toward a holistic understanding of pastoralism. *One Earth* 4 (5), 651–665. doi:10.1016/j.oneear.2021.04.012

McGranahan, D. A., Geaumont, B. A., and Spiess, J. W. (2018). Assessment of a livestock gps collar based on an open-source datalogger informs best practices for logging intensity. *Ecol. Evol.* 8 (11), 5649–5660. doi:10.1002/ece3.4094

McKenna, C., and Maycock, A. (2022). The role of the North Atlantic Oscillation for projections of winter mean precipitation in Europe. *Geophys. Res. Lett.* 49, e2022GL099083. doi:10.1029/2022GL099083

Mondal, A., Kundu, S., and Mukhopadhyay, A. (2012). Rainfall trend analysis by Mann-Kendall test: a case study of north-eastern part of Cuttack district, Orissa. *Int. J. Geol. Earth Environ. Sci.* 2 (1), 70–78.

Monteiro-Henriques, T. (2010). *Fitossociologia e Paisagem da Bacia Hidrográfica do rio Paiva*. Lisboa, Portugal: Instituto Superior de Agronomia. Ph.D. Thesis.

Moscatelli, S., Pesaresi, S., Wikelski, M., Tardella, F. M., Catorci, A., and Quattrini, G. (2025). Influence of pasture diversity and NDVI on sheep foraging behavior in central Italy. *Geographies* 5 (2), 26. doi:10.3390/geographies5020026

Muhammad, K., Mohammad, N., Abdullah, K., Mehmet, S., Ashfaq, A. K., and Wajid, R. (2019). Socio-political and ecological stresses on traditional pastoral systems: a review. *J. Geogr. Sci.* 29 (10), 1758–1770. doi:10.1007/s11442-019-1675-4

Muñoz-Gómez, M. J., Andreu, A., Carbonero, M. D., Blázquez-Carrasco, Á., and González-Dugo, M. P. (2024). Impact of water stress on Mediterranean oak savanna grasslands productivity: implications for on-farm grazing management. *Agric. Water Manag.* 303, 109025. doi:10.1016/j.agwat.2024.109025

Nakano, T., Bat-Oyun, T., and Shinoda, M. (2020). Responses of palatable plants to climate and grazing in semi-arid grasslands of Mongolia. *Glob. Ecol. Conservation* 24, e01231. doi:10.1016/j.gecco.2020.e01231

Okkonen, J., and Kløve, B. (2010). A conceptual and statistical approach for the analysis of climate impact on groundwater table fluctuation patterns in cold conditions. *J. Hydrology* 388 (1–2), 1–12. doi:10.1016/j.jhydrol.2010.02.015

Ozturk, T., Ceber, Z. P., Türkeş, M., and Kurnaz, M. L. (2015). Projections of climate change in the Mediterranean Basin by using downscaled global climate model outputs. *Int. J. Climatol.* 35 (14), 4276–4292. doi:10.1002/joc.4285

Paulo, A. A., Rosa, R. D., and Pereira, L. S. (2012). Climate trends and behaviour of drought indices based on precipitation and evapotranspiration in Portugal. *Nat. Hazards Earth Syst. Sci.* 12, 1481–1491. doi:10.5194/nhess-12-1481-2012

Pinto, R. A., Castro, M., Torres-Manso, F., and Rainha, M. (2023). A pastorícia no desenvolvimento dos territórios de montanha em Portugal: uma análise multidimensional aos desafios e oportunidades. *Rev. Port. Estud. Reg.* 63, 65–74. doi:10.59072/rper.vi63.79

Raizman, E. A., Barner Rasmussen, H., King, L. E., Ihwagi, F. W., and Douglas-Hamilton, I. (2013). Feasibility study on the spatial and temporal movement of Samburu's cattle and wildlife in Kenya using GPS radio-tracking, remote sensing and GIS. *Prev. Veterinary Med.* 111, 76–80. doi:10.1016/j.prevetmed.2013.04.007

Rivosecchi, A., Bollasina, M. A., and Colfescu, I. (2024). Future changes in the influence of the NAO on Mediterranean winter precipitation extremes in the EC-Earth3 large ensemble: the prominent role of internal variability. *Atmos. Res.* 304, 107391. doi:10.1016/j.atmosres.2024.107391

Rouet-Leduc, J., Pe'er, G., Moreira, F., Bonn, A., Helmer, W., Shahsavan Zadeh, S. A., et al. (2021). Effects of large herbivores on fire regimes and wildfire mitigation. *J. Appl. Ecol.* 58 (12), 2690–2702. doi:10.1111/1365-2664.13972

Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's tau. *J. Am. Stat. Assoc.* 63 (324), 1379–1389. doi:10.1080/01621459.1968.10480934

Serrano, J., Shahidian, S., Paixão, L., Marques da Silva, J., Morais, T., Teixeira, R., et al. (2021). Spatiotemporal patterns of pasture quality based on NDVI time-series in Mediterranean Montado ecosystem. *Remote Sens.* 13 (19), 3820. doi:10.3390/rs13193820

Serrano-Zulueta, R., Gómez-Sal, A., Pauné, F., Velado-Alonso, E., Garzón, J., del Prado, A., et al. (2024). A classification of pastoralism in Spain: understanding the past to address present challenges. *Nomadic Peoples* 28 (2), 242–274. doi:10.3197/np.2024.280206

Shagdar, E. (2002). The Mongolian livestock sector: vital for the economy and people, but vulnerable to natural phenomena. *Erina Rep.* 47, 4–26.

Shortridge, J. (2019). Observed trends in daily rainfall variability result in more severe climate change impacts to agriculture. *Clim. Change* 157, 429–444. doi:10.1007/s10584-019-02555-x

Sil, Â., Fernandes, P. M., Rodrigues, A. P., Alonso, J. M., Honrado, J. P., Perera, A., et al. (2019). Farmland abandonment decreases the fire regulation capacity and the fire protection ecosystem service in mountain landscapes. *Ecosyst. Serv.* 36, 100908. doi:10.1016/j.ecoser.2019.100908

Snaibi, W., Mezrhab, A., Sy, O., and Morton, J. F. (2021). Perception and adaptation of pastoralists to climate variability and change in Morocco's arid rangelands. *Heliyon* 7 (11), e08434. doi:10.1016/j.heliyon.2021.e08434

Stott, P. (2016). How climate change affects extreme weather events. *Science* 352 (6293), 1517–1518. doi:10.1126/science.aaf7271

Teague, R., and Kreuter, U. (2020). Managing grazing to restore soil health, ecosystem function, and ecosystem services. *Front. Sustain. Food Syst.* 4, 534187. doi:10.3389/fsufs.2020.534187

Tiwari, K. R., Sitaula, B. K., Bajracharya, R. M., Raut, N., Bhusal, P., and Sengel, M. (2020). Vulnerability of pastoralism: a case study from the High Mountains of Nepal. *Sustainability* 12 (7), 2737. doi:10.3390/su12072737

Ulbrich, U., and Christoph, M. (1999). A shift of the NAO and increasing storm track activity over Europe due to anthropogenic greenhouse gas forcing. *Clim. Dyn.* 15, 551–559. doi:10.1007/s003820050299

Ungar, E. D., Henkin, Z., Gutman, M., Dolev, A., Genizi, A., and Ganskopp, D. C. (2005). Inference of animal activity from gps collar data on free-ranging cattle. *Rangel. Ecol. and Manag.* 58 (3), 256–266. doi:10.2111/1551-5028(2005)58[256:ioaafg]2.0.co;2

United Nations Convention to Combat Desertification (2024). *Global Land Outlook: Thematic Report on Rangelands and Pastoralists*. Bonn, Germany: UNCCD.

Van Valkenburgh, P., Whitlock, B., and Wernke, S. (2023). Managing pastoral landscapes: remote survey of herding infrastructure in Huancavelica, Peru. *Antiquity* 98, 229–244. doi:10.15184/aqy.2023.174

Vieira, N. A., Silva, M. A. d. A. e., Caramori, P. H., Nitsche, P. R., Corrêa, K. A. B., and Alves, D. S. (2019). Temperature, thermal comfort, and animal ingestion behavior in a silvopastoral system. *Semina Ciências Agrárias* 40 (1), 403. doi:10.5433/1679-0359.2019v40n1p403

Walker, G. T. (1924). Correlations in seasonal variations of weather. VIII. A further study of world weather. *Memoirs Indian Meteorological Dep.* 24, 275–332. doi:10.1175/1520-0493(1925)53<252:CISVOW>2.0.CO;2

Walker, G. T., and Bliss, E. W. (1932). *World Weather V*, 4. Memoirs of the Royal Meteorological Society, London: Edward Stanford. 4 (36), 53–84.

Wang, G., Mang, S., Cai, H., Liu, S., Zhang, Z., Wang, L., et al. (2016). Integrated watershed management: evolution, development and emerging trends. *J. For. Res.* 27, 967–994. doi:10.1007/s11676-016-0293-3

Wang, Y., Wang, Z., Kang, Y., Zhang, Z., Bao, D., Sun, X., et al. (2024). Assessing the win–win situation of forage production and soil organic carbon through a short-term active restoration strategy in alpine grasslands. *Front. Plant Sci.* 14, 1290808. doi:10.3389/fpls.2023.1290808

WMO (2007). The role of climatological normals in a changing climate. Available online at: https://library.wmo.int/index.php?lvl=notice_display&id=16659#.Y_yqgnbMKCg (Accessed March 03, 2024).

Yeste, P., Rosa-Cánovas, J. J., Romero-Jiménez, E., Ojeda, M. G. V., Gámiz-Fortis, S. R., Castro-Díez, Y., et al. (2021). Projected hydrologic changes over the north of the Iberian Peninsula using a Euro-CORDEX multi-model ensemble. *Sci. Total Environ.* 777, 146126. doi:10.1016/j.scitotenv.2021.146126

Zêzere, J. L., Trigo, R. M., and Trigo, I. F. (2005). Shallow and deep landslides induced by rainfall in the Lisbon region (Portugal): assessment of relationships with the North Atlantic Oscillation. *Nat. Hazards Earth Syst. Sci.* 5 (3), 331–344. doi:10.5194/nhess-5-331-2005