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Geolocation tracking to monitor spatial distribution and habitat selection of cows, horses and sheep grazing in mountainous areas

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ABSTRACT

Precision Livestock Farming (PLF) technologies offer an opportunity to monitor livestock, enhancing farmers' decision-making for improved control, better animal performance, and reduced environmental impact through proper management of pasture areas. The objective of this study was to assess the potential of data provided by commercial geolocation collars, along with open data resources such as information on natural habitats, topography, and vegetation, to detect grazing preferences of mountain livestock. We monitored 240 animals from three different herds and species (140 cows, 50 horses, and 50 sheep) during the grazing season (6 months) using geolocation collars in the Alt Pirineu Natural Park (80,000 ha), located in Catalonia, Spain. Animal distributions were analysed spatially and temporally across different seasonal periods (Spring: May-Jun, Summer: Jul-Aug and Autumn: Sep-Oct). Geolocation data were used to assess livestock preferences and avoidances regarding different types of terrain, land cover, and vegetation, estimated using Jacob's selection index (JSI), a metric indicating whether animals use a particular area more or less than expected based on its availability. Additionally, we examined the influence of these environmental factors and the distance to water sources on animal distribution, and we identified high-density grazing hotspots. Results indicated that cows and horses positively selected areas with lower altitudes (JSI = 0.29 and 0.17, $p < 0.05$) and gentler slopes (JSI = 0.38 and 0.22, $p < 0.05$), whereas sheep preferred higher altitudes (JSI = 0.10, $p < 0.05$). Only cows showed a preference for areas with bare or dispersed vegetation. In general, all three species selected land covers such as open forests, meadows, wetlands, and water points, but changed depending on the season and species. The distance to water was greater for cows and sheep, particularly during the summer, whereas only horses showed a strong dependence on proximity to water sources. Finally, we identified and compared high-density grazing hotspots among the three species. These findings reveal not only interesting heterogeneity in distribution patterns among species sharing the same area, but also clear seasonal differences. In conclusion, data automatically collected from geolocation collars demonstrate strong potential for studying livestock grazing preferences, particularly in remote or hard-to-access mountainous areas. This information improves our understanding of livestock-environment interactions without requiring physical presence and can be effectively applied to support extensive grazing management.

Simple summary: Precision Livestock Farming (PLF) technologies, such as geolocation collars, help farmers monitor animals more effectively and manage pastures sustainably. In this study, we tracked 240 animals (cows, horses, and sheep) in a mountainous natural park in Catalonia, Spain, over six months. Using geolocation data combined with information about the landscape, we analysed where and when different species preferred to graze. We found that cows and horses tend to use lower, gentler areas, while sheep prefer higher ground. All species avoid dense forests, favouring open habitats like meadows and wetlands, with seasonal and vegetation-based variations in preference. Horses stay closer to water sources due to their fibrous diet, while cows and sheep showed less dependence on water proximity. Riparian zones and fens, though highly attractive to large grazers, are ecologically sensitive and require careful management, such as selective fencing. Sheep was the most diet selective, with horses being the least. These insights suggest that tailored grazing strategies, such as species rotation, habitat-based planning, and multi-species-grazing, can optimize pasture use while protecting fragile ecosystems. These insights highlight how geolocation tracking can improve livestock management in remote mountain areas, helping farmers make better decisions and improving conservation.

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1. Introduction

Extensive livestock production is based in seasonal pasture system, where animals are allowed to graze on pasture areas during certain parts of the year (best weather and forage conditions). This system is widely recognised as a provider of ecosystem services, including the provision of livestock production, the preservation of open habitats and biodiversity, and the protection of watersheds, among others (Kaufmann, et al., 2013; Seddaiu et al., 2018; Bragaglio et al., 2020). This system integrates both economic and ecological requirements while allowing livestock to graze freely. However, free-grazing practices lead to spatially heterogeneous grazing patterns (Liu et al., 2012), resulting in uneven forage utilization, with some areas experiencing overgrazing and others accumulating an excess of woody plants. This uneven distribution can lead to negative environmental impacts, such as soil erosion, vegetation degradation, and altered nutrient cycling (Blackburn and Henriksen (1983); Kauffman and Krueger, (1984)). The detection of possible overgrazing areas and management of livestock movement is therefore critical for ensuring the sustainability of these pasture-based systems (Bailey, 2004), especially in mountainous landscapes, where livestock distribution is even more irregular (Teague et al., 2004; Barnes et al., 2008; Bailey et al., 2015) and might reduce livestock performance (Bailey et al., 2001).

Several factors influence livestock distribution, including species, breed, reproductive status, orography, access to water, plant community composition, and climatic conditions, such as temperature dynamics and wind patterns (Ganskopp and Bohnert, 2006, 2009). Seasonal variation also plays a significant role, as daylight length and environmental temperature affect foraging behaviour (Rutter, 2006; Hessle et al., 2008). For instance, in paddocks used during the growing season, characterized by higher forage availability and lower grazing pressure (i.e. more available biomass per animal unit), livestock tend to select habitats dominated by high-quality vegetal species (McNaughton, 1986; Fuhlendorf and Engle, 2001). Conversely, out of the growing season when forage is scarce (and the pressure over resources increases), livestock tend to decrease selectivity, foraging on all available plants and patches, regardless of their quality (Vallentine, 2001). Moreover, some cattle avoid steep slopes and areas far from water sources (Valentine, 1947; Mueggler, 1965) while concentrating in riparian zones (Bailey, 2004). Furthermore, in areas where different species of livestock and wildlife share grazing resources, movement patterns and forage intake by livestock are likely to affect and be affected by numerous ecosystem properties (Kemp and Michalk, 2007), including vegetation dynamics, wildlife behaviour, and disease transmission.

Bakker (1998) stated that “multi-species grazing” at low stocking rates in large-scale pasture systems can maintain or create highly diverse ecosystems, with minimal livestock care. In a similar manner, multi-species grazing can increase microbial diversity in the soil (Mhuireach et al., 2022) and soil carbon sequestration (Rowntree et al., 2020). This practice increases the structural and compositional variation of vegetation and helps prevent the encroachment of woody species, managing landscapes and reducing fire risk. Therefore, multi-species grazing may affect vegetation differently than single-species grazing, as livestock species vary in diet preferences, digestive physiology, terrain use, and their potential to influence vegetation development (Walker, 1994; Rook et al., 2004; Bakker et al., 2006). For example, ruminant digestive system allow cows and sheep to extract more digestible dry matter than horses from medium-quality grasses (defined by their fibre and protein content) influencing animal’s distribution. In fact, dietary specialization among species can be assessed by comparing the nitrogen content of the pasture with faecal nitrogen from the animals, serving as an indicator of protein intake (Dalmau Bueno, 2005). However, little research has been carried out on this topic, despite its widespread use in Spain (Culos et al., 2025) and the increasing support it is receiving across Europe (Bakogiorgos and Pantera, 2024; Carlier et al., 2009).

The monitoring of animal location provides key insights into grazing patterns (Agouridis et al., 2004; Betteridge et al., 2010; Swain et al., 2011), field occupancy, pasture utilization (Turner et al., 2000; Porto et al., 2015), and social affiliations within a herd (Veissier et al., 1998). However, collecting high-resolution movement data remains a challenge due to the vastness and heterogeneity of mountainous landscapes, as well as the logistical difficulties associated with direct observation (Turner et al., 2000). Additionally, a substantial portion of foraging activity occurs at night (Hulbert et al., 1998), further complicating traditional monitoring approaches. To address these challenges, Global Navigation Satellite System (GNSS) tracking technology offers an effective solution for continuous and large-scale monitoring of grazing livestock (Bailey et al., 2004; Schlecht et al., 2004). Unlike direct observation, GNSS data can be seamlessly integrated with spatial parameters stored in Geographic Information Systems (GIS), enabling detailed analysis of livestock movement and habitat preferences. The affordability and availability of commercial geolocation collars have further improved the feasibility of such studies (Millward et al., 2020; Hassan-Vásquez et al., 2022). In addition to GNSS, low-power wide-area network (LPWAN) technologies, such as SigFox and LoRa, are increasingly being explored for their potential applications in Precision Livestock Farming (PLF; Berckmans, 2017). These systems facilitate real-time data transmission, enhancing the ability to monitor livestock movement and implement timely management interventions. Nevertheless, several technical challenges remain, particularly regarding battery life, network coverage, and data transmission capabilities (Bailey et al., 1996; Bailey, 2004).

Livestock distribution across grazing areas is often analysed using GPS tracking data, applying methods like kernel density estimation (KDE) and spatial autocorrelation analysis (Elliott et al., 2000; Fortin and Dale, 2005). These tools are useful for identifying zones of concentrated grazing activity, which may correspond to overgrazed areas, and support the development of site-specific management practices to avoid land degradation. For example, relocating resources such as shade, water, or mineral supplements can encourage animals to graze more evenly throughout the pasture (Bailey, 2004). Other studies use geolocation data to study animal activity, grazing behaviour, home range, etc. In most cases, the distribution of livestock on pasture has been recorded by geolocations fixes in landscape units and analysed by calculating preference indices (Putfarken et al., 2008; Ganskopp and Bohnert, 2009; Meisser et al., 2014) or home ranges (Probo et al., 2013). Many of these studies on grazing animal behaviour and spatial site-use has been carried out in simplified systems, typically involving homogeneous, species-poor grasslands. In contrast, relatively few studies have addressed more complex pasture environments, characterised by diverse plant communities or involving multi-species grazing systems.

For this reason, the objective of this study was to analyse the distribution of cows, horses, and sheep fitted with geolocation collars in mountainous areas by: 1) evaluating spatial and vegetation community preferences using the Jacob Selection Index (JSI) and their influence on habitat preference, 2) assessing their spatial distribution and detecting grazing hotspots using KDE and 3) analysing diet selectivity by comparing pasture and faecal nitrogen (FN) between livestock species sharing the same grazing area. By improving our understanding of livestock distribution, this research aims to provide valuable insights for sustainable pasture management and conservation planning in extensive grazing systems.

2. Material and methods

The work described was conducted in accordance with current legislation (2010/63/EU Directive and 2019/1010 Regulation), the basic Code of Research Ethics proposed in March 2011 by the European Science Foundation (ESF), the European Federation of National Academies of Sciences and Humanities, also known as ALLEA (All European Academies) and with the approval of the Institute of Agrifood Research and Technology (IRTA) Ethical Committee, reference 2021/27.

2.1. Study area

The study was conducted in the Alt Pirineu Natural Park (PNAP), in the Northeast of Spain, located mainly in the region of Pallars Sobirà, Catalonia (42.39º N, 1.19º E) with an extension of 79,317 ha (ha). The PNAP, a mountainous region adjacent to the Pyrenees, lies between an altitude of 650 and 3143 m (m; Parcs naturals de Catalunya, 2020). It comprises the axial Pyrenees orographic area forming a mountain barrier stretching from Vall d'Aran (West) to Andorra (East) for some 30 kilometres (km). The PNAP is divided into three valleys — Valls d'Àneu, Vall del Cardós, and Vall Ferrera — each with its own unique characteristics and separated by a natural mountain range barrier. The climate of the area is strongly conditioned by the orography, which can be classified as a Mediterranean-Western Pyrenean type. The annual precipitation ranges from 700 millimetres (mm) at the bottom of the valleys to more than 1000 mm at the headwaters. Snow is present for approximately six months a year in the higher areas (from November to May). The average annual temperature fluctuates from 3.1 ºC to 20.3 ºC. The winters are very cold, and temperatures can fall below 0 ºC, and the summers can be cool or warm, although temperatures may well reach 30 ºC (METEOCAT, 2024). The PNAP presents well-preserved ecosystems of ecological value, made up of an agroforestry mosaic of mountain forests, scrub areas with pasture, and rocky areas. Most of the territory is covered by Eurosiberian or Boreoalpine vegetation. Below 2200 m, there are the mountain pine (*Pinus uncinata*) forests; the dominant shrubs are *Juniperus communis*, *Vaccinium myrtillus*, *Rhododendron ferrugineum*. The grassland is classified as a xerophilic, open montane grassland 'Xerobromion' (Carreras et al., 1983), dominated by grasses (*Festuca ovina* and *Festuca gautieri*) that co-occur with small forbs (such as *Hieracium pilosella*, *Achillea millefolium* and *Potentilla neumanniana*). The succession from grassland to shrubland is mostly driven by the dwarf shrubs: *Arctostaphylos uva-ursi*, *Juniperus communis* and *Juniperus sabina*. From around 2200 m, the area is covered by *Pinus uncinata* and *Abies alba* forests, while at higher elevations the landscape is dominated by natural meadows and rocky vegetation (Parcs naturals de Catalunya. GENCAT, 2020). The PNAP also had groundwater-fed wetlands rich in minerals, supporting high biodiversity and specialised plant species named fens. They play a key ecological role in water regulation and serve as priority habitats for conservation and at the same time, they are at risk due to livestock grazing on these areas. Moreover, the soils are subject to summer droughts, which cause the superficial soil layer to dry out considerably.

2.2. Livestock monitoring

We monitored the spatial position of 140 cows, 50 horses, and 50 sheep. These animals represented subsets of larger populations, including 15 herds of cattle totalling 732 animals, six herds of horses totalling 100 animals, and three aggregated flocks of sheep totalling 2600 animals. The three livestock species were from 14 different farmers, providing a representative sample of the whole natural park. Breeds were Bruna dels Pirineus for cows (*Bos taurus*), Pirinenc Català for horses (*Equus caballus*) and Ripollesa and Aranesa for sheep (*Ovis aries*), all local breeds registered in the Stud Book of Livestock Breeds: where data of animals belonging to a specific officially recognised breed are recorded. The animals were monitored during the grazing season (May to October) for four years (2020, 2021, 2022 and 2023). Animals were distributed across the three main valleys — Valls d'Àneu (11,389 ha), Vall del Cardós (22,247 ha), and Vall Ferrera (7665 ha) — covering a total of 41,302 ha to pasture. To record animal positions, we used commercial geolocation collars provided by Digitanimal Ltd. (Madrid, Spain). Each collar included a geolocation unit, a lithium battery pack lasting approximately one year, an IP67 enclosure resistant to water and dust, and a low-power wide-area (LPWA) communications module based on SigFox, which enabled the transmission of geolocation fixes from collars to the server in near real-time. Geolocation collars were configured to gather a geolocation fix of each animal every 30 min, if SigFox coverage was available, to preserve battery life. A 30-minute interval was selected as it offers an optimal balance between data reliability and battery conservation. With this configuration, a battery life of up to one year for the geolocation collars is ensured. Similar settings have been used in previous studies to investigate grazing preferences (Gipson et al., 2012; Hassan-Vásquez et al., 2022). The accuracy of the collars was approximately 100 m (Meisner et al., 2024).

In order to analyse choice of grazing sites by the animals, we identified and extracted grazing behaviour from the whole geolocations data set. We used R 4.4.3 (R Core Team, 2022) and the package "trajr" (McLean and Skowron Volponi, 2018) to recreate the daily animal trajectory and speed between each geolocation fixes. The "trajr" package uses sequential location data points (coordinates with timestamps) collected from the animal's movements to create steps characterised by length and direction. These steps correspond to vectors between consecutive locations, thereby creating a sampled trajectory. Afterwards, we were able to calculate indicators to study the activity and animal grazing behaviour. Following the methodology described in previous studies (Trotter et al., 2010; Cheleuitte-Nieves et al., 2020), the average velocity between two consecutive locations was used as an indicator of the type of behaviour. On average, these authors found that cattle spend 57.5 % of their time resting (including rumination), 40 % grazing and 2.5 % walking. Thus, they used percentiles 57.5 and 97.5 for the data distribution of the average velocity between consecutive fixes as thresholds to classify livestock locations, which corresponded to resting (low speed), grazing (medium speed) or walking (high speed). We used these percentiles for all three species separately, since each specie have different distribution of average velocities. Moreover, slope has a clear effect on animal velocity. Therefore, average velocity was multiplied by slope to improve the reliability of behaviour predictions in mountainous areas. According to this methodology, 1112,704 of the cows' records, 151,081 of the horses' records and 234,687 of the sheep records were classified as grazing (39.17 %). We considered the data from the collared individuals to be representative of their respective herds or flocks, as these animals were consistently observed within their groups during collar replacements and direct observation periods. Behavioural observations were conducted using focal and scan sampling methods three days per week for all species throughout the grazing period. Each observation session included 10-minute focal samples on 12 different individuals, along with six scan samples of the entire group. This information was recorded for different purposes and one of them was to evaluate the efficiency of collars to predict the behaviour. All focal data were recorded with precise timing and compared to the behaviours predicted by the collars. The main behaviours recorded during observations were matched to the collar-predicted behaviour within the interval (30 min) between two geolocation fixes. To assess the consistency between observed and predicted behaviours, we performed a Cohen's Kappa test, which showed an agreement exceeding 0.85, thus we considered the collar data to provide a reliable prediction of animal behaviour.

2.3. Open data resources

Several factors may affect livestock behaviour and distribution on pasture, like spatial variation or temporal variability throughout the study. For this reason, the following factors were studied using open data sources: altitude, terrain slope, orientation, Normalized Difference Vegetation Index (NDVI), distance to natural water resources, land cover and plant community. Altitude (meter) and NDVI were obtained as continuous raster data, and land cover and dominant vegetation type were obtained as polygons in shape format from the L'Institut Cartogràfic i Geològic de Catalunya (ICGC). Slope (%) was calculated for each 25 × 25 m rectangular cell inside the natural park by using the elevation raster. Orientation, expressed in degrees relative to azimuth, was also calculated for those pixels with a slope greater than 10 % (slopes below 10 % were considered flat terrain with no effect of orientation). NDVI was categorized as: "ground" (NDVI < 0.2), "dispersed vegetation" ($0.2 <$ NDVI < 0.4), "abundant vegetation" ($0.4 <$ NDVI < 0.6) and "high density vegetation" (NDVI > 0.6) following the criteria of technical specifications (Institut Cartogràfic i Geològic de Catalunya ICGC, 2024). We calculated the Euclidean distance from each geolocation fix to the water point polygon. Additionally, we determined the number of geolocation fixes per week and per area for each land cover polygon (dense forests, open forests, shrubs, meadows, wetlands, rocky areas, and water points) as well as for each plant community (pine forest, oak forest, silver fir forest, riparian forest, shrubs, meadows, and fens; Tables S1, S2, and S3). All these calculations were performed in R 4.4.3 (R Core Team, 2022), using the "sf" package (Pebesma, 2018) and the "raster" package (Hijmans, 2024).

2.4. Sampling procedure and chemical analysis of nitrogen

Pasture and faecal samples of all species were collected throughout the livestock grazing season for three years (2021, 2022 and 2023) at different locations and species in order to determine their nitrogen content. Five pasture samples of grass were randomly cut from the global pasture present in each location, where we found the animals, every month, achieving a total of 119 pasture samples. An average of 14 samples of fresh faeces from cows, horses and sheep were collected in each location where pasture samples were taken, resulting in 467 samples for cows, 257 samples for horses and 491 samples for sheep. Then, pasture and faecal samples were dried for 72 h after collection, at 60ºC in a forced air oven and were milled in a cyclotec mill (CT 293 Cyclotec FOSS), with a 1 mm sieve, based on standard methodology (Lyons and Stuth, 1991). Pasture and faecal samples were packed in ring-cups sample cells and were then scanned from 1100 to 2500 nm using a NIRSystems 5000 scanning monochromator (FOSS, Hillerød, Denmark). Reflectance was recorded at 2 nm intervals as log (1/R), where R represents the reflected energy. Nitrogen content was predicted by the "near-infrared reflectance spectroscopy" (NIRS; AOAC, 1990) and expressed on a dry matter basis.

2.5. Data processing and analysis

Prior to JSI calculation and KDE analysis, since the information provided by commercial geolocation collars may contain missing values due to lack of SigFox coverage, the raw data were pre-processed according to the following steps, inspired by Hassan-Vásquez et al. (2022): (1) from each day, collars that sent less than 10 fixes were removed; (2) daily trajectories were calculated; (3) trajectories with more than 10 km per day or more than 4 km between two geolocations fixes were rejected as not being natural distances; (4) trajectories were resampled to have geolocation fixes at standardized timestamps (every 30 min starting from midnight), having 48 fixes per animal per day; and (5) individual trajectories were smoothed using a Savitzky-Golay filter with a polynomial order of three and a filter length (window size) of five. Savitzky-Golay filter was used to smooth time series by replacing each value of the series with a new value obtained from a polynomial fit to a certain number of neighbouring points (including the point to be smoothed).

Livestock preferences in the study were estimated by counting whole geolocation fixes per area unit per week. Area units were grid rectangular cells (25 ×25 m) and structural vegetation polygons, depending on the objective of data analysis. The grid was created considering areas which at least one geolocation fix from a geolocation collar was recorded. This criterion was applied to ensure that the areas included in the analysis were demonstrably accessible to the animals, thereby providing a more accurate representation of their potential range and movement patterns. Weekly selection indices of the species were also calculated according to Jacobs (1974).

$$JSI = (r - p)/(r + p - 2^*r^*p)$$

where JSI was the value of the Jacobs selection index for a given area unit, r was the fraction of location fixes in that area unit, and p was the fraction of that area unit in the natural park. Selection indices varied from -1 (negative selection) to $+1$ (positive selection).

The result of the KDE analysis consists of a map (hexagonal grid cells) that represents the area of the territory most frequently used by animals in terms of density. The KDE creates isopleths of intensity of utilization by calculating the mean influence of data points at grid intersections (Steiniger and Hunter, 2013). Each isopleth contains a fixed percentage (e.g. 95 %) of the utilization density suggestive of the amount of time that the animal spends in the contour. We created a 100 m x 100 m hexagonal grid of cells overlayed on the geolocation fixes. This grid shape was selected based on the higher symmetry between cell neighbours, the Euclidean distance reduction (Birch et al., 2007) and the resolution for practical and ecological considerations. For example, the absolute measurement accuracy of the geolocation collars is approximately 100 m (Meisner et al., 2024). Then, a spatial join was performed to sum the number of geolocation fixes within each hexagonal cell to calculate the KDE using the "SpatialKDE" package (Caha, 2023). Based on the data distribution, three categories were defined: "low" (less than 25 % of KDE values), "medium" (between 25 % and 95 % of KDE values), and "high" (more than 95 % of KDE values).

The faecal-pasture nitrogen ratio (FN/PN) was calculated to assess dietary selectivity. A higher FN/PN ratio indicates that animals are ingesting more nitrogen than the average available in the pasture, suggesting increased foraging effort and a preference for plant species with higher nitrogen, and therefore protein content.

We used Generalised Linear Mixed Models (GLMMs) to analyse weekly JSI values, grazing frequency (expressed as the proportion of geolocation fixes within each grid cell per week) and distance to a natural water resource. Weekly JSI values were compared between species and seasons using a GLMM fitted with a Gaussian distribution. Topographic and vegetation variables (i.e., preference categories) were included as fixed effects, with week included as a random effect (temporal correlation). Water distance was compared between species and seasons and their interaction, and animal identification as a random effect (repetitive measure). Post hoc pairwise comparisons were conducted using Tukey's multiple comparison test across species, seasons, and preference categories. Grazing frequency, as a proportional response variable, was modelled using a GLMM fitted with a beta distribution, run separately for each species. Topographic variables and distance to water were included as fixed effects, while week and grid cell were modelled as random effects. A further GLMM was applied to compare pasture and faecal nitrogen contents, with species, valley, and season as fixed effects, and year included as a random effect (temporal correlation). Explanatory variables were scaled and centred before analysis and statistical significance was determined at $p < 0.05$. All analyses were conducted using R version 4.4.3 (R Core Team, 2022), with the packages "lme4" (Bates et al., 2015) and "glmmTMB" (McGillycuddy et al., 2025).

3. Results

A total of 3825,896 geolocation fixes were analysed, resulting in 2840,949 position records for the cows, 385,742 for the horses, and 599,205 for the sheep. As cows were the most numerous, they were also fitted with more geolocation collars and, consequently, yielded a greater number of position records.

3.1. Species preference using JSI

A total of 1568 JSI week values were used for detecting livestock

Table 1
Jacob's selectivity index (JSI) for cows, horses and sheep in relation of altitude, slope, orientation on and NDVI during the grazing season (6 months) of four consecutive years (2020–2023).

Preference	Category	Bovine JSI	Equine JSI	Ovine JSI	P-value
Altitude	< 1,800 m	0.379 ± 0.328^{a}	0.218 ± 0.463^{a}	-0.234 ± 0.617^{a}	Bov vs Equ: $p = 0.28$ Bov vs Ovi: $p < 0.05$ Equ vs Ovi: $p < 0.05$
	1,800-2,200 m	-0.335 ± 0.341^{b}	-0.146 ± 0.437^{b}	0.103 ± 0.590^{b}	Bov vs Equ: $p < 0.05$ Bov vs Ovi: $p < 0.05$ Equ vs Ovi: $p < 0.05$
	> 2,200 m	-0.405 ± 0.341^{b}	-0.289 ± 0.372^{b}	-0.441 ± 0.469^{c}	Bov vs Equ: $p = 0.63$ Bov vs Ovi: $p = 0.99$ Equ vs Ovi: $p = 0.36$
Slope	< 30 %	0.294 ± 0.246^{a}	0.167 ± 0.204^{a}	0.207 ± 0.339^{a}	Bov vs Equ: $p < 0.05$ Bov vs Ovi: $p = 0.28$ Equ vs Ovi: $p = 0.94$
	30-60 %	-0.201 ± 0.250^{b}	-0.092 ± 0.195^{b}	-0.022 ± 0.287^{b}	Bov vs Equ: $p < 0.05$ Bov vs Ovi: $p < 0.05$ Equ vs Ovi: $p = 0.43$
	> 60 %	-0.357 ± 0.200^{c}	-0.303 ± 0.205^{c}	-0.508 ± 0.237^{c}	Bov vs Equ: $p = 0.80$ Bov vs Ovi: $p < 0.05$ Equ vs Ovi: $p < 0.05$
Orientation	Flat	0.154 ± 0.323^{a}	-0.039 ± 0.330^{a}	-0.296 ± 0.360^{a}	Bov vs Equ: $p < 0.05$ Bov vs Ovi: $p < 0.05$ Equ vs Ovi: $p < 0.05$
	North	-0.195 ± 0.295^{b}	-0.232 ± 0.349^{b}	-0.430 ± 0.445^{b}	Bov vs Equ: $p = 0.99$ Bov vs Ovi: $p < 0.05$ Equ vs Ovi: $p < 0.05$
	East	-0.292 ± 0.321^{b}	-0.177 ± 0.275^{b}	-0.212 ± 0.442^{c}	Bov vs Equ: $p = 0.49$ Bov vs Ovi: $p = 0.92$ Equ vs Ovi: $p = 0.99$
	South	-0.001 ± 0.273^{c}	0.049 ± 0.238^{c}	-0.009 ± 0.366^{d}	Bov vs Equ: $p = 0.99$ Bov vs Ovi: $p = 0.99$ Equ vs Ovi: $p = 0.99$
	West	0.068 ± 0.210^{c}	-0.094 ± 0.293^{c}	-0.130 ± 0.446^{c}	Bov vs Equ: $p < 0.05$ Bov vs Ovi: $p < 0.05$ Equ vs Ovi: $p = 0.99$
NDVI	Ground	0.416 ± 0.296^{a}	-0.115 ± 0.329^{a}	-0.124 ± 0.435^{a}	Bov vs Equ: $p < 0.05$ Bov vs Ovi: $p < 0.05$ Equ vs Ovi: $p < 0.99$
	Dispersed vegetation	0.101 ± 0.166^{b}	-0.042 ± 0.200^{b}	0.093 ± 0.257^{b}	Bov vs Equ: $p < 0.05$ Bov vs Ovi: $p < 0.99$ Equ vs Ovi: $p < 0.05$
	Abundant vegetation	-0.181 ± 0.169^{c}	-0.046 ± 0.145^{b}	-0.061 ± 0.218^{c}	Bov vs Equ: $p < 0.05$ Bov vs Ovi: $p < 0.05$ Equ vs Ovi: $p < 0.99$
	High density vegetation	-0.071 ± 0.213^{d}	0.050 ± 0.230^{b}	-0.173 ± 0.276^{c}	Bov vs Equ: $p < 0.05$ Bov vs Ovi: $p = 0.06$ Equ vs Ovi: $p < 0.05$

Abbreviations: JSI = Jacob's selection index (calculated per week), NDVI = Normalized difference vegetation index. Different superscript letters within the same column indicate statistical significance ($p < 0.05$). P-values indicate statistical significance within the same row.

preferences. The distribution of the animals in the natural park was uneven and varied among species (Table 1). Cows and horses preferred lower altitudes compared to sheep. All livestock species had similar preferences on lower slope and rejected slopes facing North and East. Vegetation quantity as NDVI did not influence horses and sheep, whereas cows selected areas with more ground and dispersed vegetation.

The three livestock species showed a clear preference to be in open forests, meadows and wetlands and refused dense forests (Fig. 1, a). Horses, in contrast with sheep and cows, preferred water points and refused shrubs. Besides, they also had a higher preference for riparian forests of *Salix purpurea* and *S. eleagnos* and fens (Fig. 1, b). Meadows were clearly preferred by all the species but differed in terms of plant dominant communities (Table S4). For instance, cows preferred meadows of *Agrostis capillaris*, (JSI = 0.39) *Festuca nigrescens* (JSI = 0.47) and *Arrhenatherum elatius* (JSI = 0.61), while horses chose meadows of *Festuca eskia* (JSI = 0.44; especially in autumn, JSI = 0.63) and *Chenopodium bonus-henricus*. On the other hand, all livestock species did not prefer meadows of *Festuca gautieri*, *Nardus stricta* and *Ononis striata*. Interestingly, sheep was the only species that preferred shrubs, especially that of *Cytisus oromediterraneus*. For cows, horses and sheep, the major seasonal variability in JSI were on land covered by rocks (Fig. 2, a) and in meadows (Fig. 2, b). Moreover, summer was the season with the most variability. For example, only in summer, cows and horses preferred meadows of *Festuca airoides* while sheep preferred meadows of *Agrostis capillaris* (Table S4).

The factor with the largest effect on animals' distribution between species was slope. This factor was determinant in cows and horses, since they preferred lower slope, while sheep spent more time in places with a higher slope gradient (Table 2). Regarding the water points distance, horses had shorter distances (940 ± 983 m) than cows (1159 ± 1022 m; $z = 0.017$, $df = 2113$, $p < 0.05$) and sheep (1082 ± 824 m; $z = 0.034$, $df = 2113$, $p < 0.05$). Unexpectedly, during the summer, these distances increased in horses (965 ± 1077 m; $z = -0.098$, $df = 2113$, $p < 0.05$) but decreased in cows (1134 ± 952 m; $z = -0.025$, $df = 2113$, $p < 0.05$) and sheep (902 ± 547 m; $z = -0.058$, $df = 2113$, $p < 0.05$; Table S5).

3.2. Hotspots characterization

Cows grazed in 4973 ha (6.21 %), horses in 4994 ha (6.24 %) and sheep in 6775 ha (8.46 %) of the natural park. The pasture zones were shared by 19.69 % between cows and horses, 15.78 % between cows and sheep and 10.17 % between horses and sheep. We localized the grazing zones with higher density (hotspots; Fig. 3), characterized (Table 3) and compared them between species. In general, all livestock species were concentrated at altitudes around 1900 m, with a low average slope of 34 % and south-facing places, except for sheep, which were found on steeper average slope of 52 %. These hotspots also had abundant vegetation (NDVI = 0.46), were on average 1200 m from a natural water resource and were characterized by meadows for cows and horses, and meadows and shrubs for sheep (Fig. 4).

Cows and horses' hotspots were acidophilous and mesophile meadows composed of *Bellardiochloa variegata* and meadows of *Festuca eskia* found in the high Pyrenean mountains. On the other hand, sheep hotspots were meadows with shrubs composed of *Cytisus oromediterraneus*, a siliceous species found in dry, often sunny areas of the montane and high mountain stages. Hotspots were shared by 6.78 % between cows and horses, 6.01 % between cows and sheep and 7.39 % between horses and sheep.

3.3. Diet selectivity

The pasture nitrogen (PN) from the three valleys was statistically different ($F = 1.49$, $df = 113$, $p = 0.03$). In valls d'Àneu PN was higher (2.18 % ± 0.07, n = 40) compared to Vall del Cardós (1.94 % ± 0.05, n = 64) and Vall Ferrera (1.88 % ± 0.14, n = 12). There was not a statistically significant effect on PN over the season ($F = 1.59$, $df = 113$, $p = 0.21$), however it was a slight decrease on PN from spring with an average percentage of 2.21 % compared to summer with 2.02 % ($t = 1.54$, $df = 113$, $p = 0.28$) and to autumn with 2.00 % ($t = 1.67$, $df = 113$, $p = 0.22$). Regarding faecal nitrogen (FN), there were differences depending on the species, horses had a lower concentration of FN compared to cows (1.64 % vs. 2.03 %, respectively, $t = 7.96$, $df = 562$, $p < 0.05$) and sheep (1.52 % vs 2.14 %, respectively, $t = -9.01$, $df = 368$, $p < 0.05$). Sheep had a higher fraction of FN/PN (diet selectivity; 1.25 ± 0.05, n = 19) compared to cows (0.98 ± 0.06, n = 23; $t = -3.65$, $df = 22.4$, $p < 0.05$) and horses (0.81 ± 0.06, n = 21; $t = -5.42$ $df = 12.1$, $p < 0.05$). Finally, there was not a seasonal effect on their diet selectivity ($F = 0.37$, $df = 54$, $p = 0.69$).

4. Discussion

In recent years, numerous authors have highlighted the need to deepen our understanding of livestock grazing behaviour and its environmental impact (Scotton and Crestani, 2019; Rutter, 2010; Nendissa et al., 2023), particularly in the context of optimising grazing management strategies (Horn and Isselstein, 2022). This study examines various approaches analysing and quantifying the grazing preferences, distribution and diet quality of cows, horses and sheep, using PLF technologies.

4.1. JSI preferences

Findings from this study indicate differences in habitat distribution preferences among species. Cows and horses preferred lower altitudes and gentler slopes compared to sheep in accordance with other studies (Bailey, 2004; Kaufmann et al., 2013). Moreover, cows favoured flat areas with bare ground and dispersed vegetation, which aligns with the findings of Hassan-Vásquez et al. (2022), who investigated terrain slope, insolation or distance to water based on the spatial distribution of cattle. In contrast, horses and sheep demonstrated no preference in vegetation cover as analysed as NDVI. Based on these results, cattle and horses should be placed in flatter or moderately sloped areas to align with their terrain preferences (Ganskopp and Vavra, 1987; Ganskopp et al., 2000), while smaller livestock such as sheep or goats could be directed to higher and steeper areas that are less accessible to larger grazers (Falú et al., 2014). This approach may help reduce direct competition for forage and promote a more balanced use of available grazing resources, especially in mountainous areas.

Generally, findings from other studies noted that cows and sheep concentrated around water sources (Owens et al., 1991; Pinchak et al., 1991; Hart et al., 1993). Nevertheless, and contrary to those studies, we have seen that cows and sheep did not exhibit a clear preference for proximity to water resources, even during the summer months when temperatures were higher. In fact, those distances increased. This may be because animals seek cooler temperatures at higher elevations, moving away from water (Creamer and Horback, 2025). Moreover, the natural park contains a wide-reaching system of natural waterways, ensuring animals had constant access to water. This discrepancy suggests that water availability in heterogeneous, mountainous environments may function differently than in flatter, arid rangelands, and thus deserves further investigation. Rather than relying on a limited number of specific water locations, these animals had access to an extensive network of water sources throughout the natural park. So, opposed to other studies (Rivero et al., 2021; Putfarken et al., 2008; Tomkins et al., 2009), the strategic location of water and shade, might be not very efficient in trying to modify animal distribution. If this is the case, the strategic placement of salt or mineral supplementation points, as reported by Ganskopp (2001), can be used as a management tool to retain cattle within specific areas and thereby influence their spatial distribution. On the other hand, horses had been influenced by water resources and had shorter mean distances to them, particularly in spring and summer. This could be explained because horses have a more fibrous diet, which has lower water content. During periods of water stress, such as in summer, they visit water sources more frequently and spend prolonged periods near them (up to 73 % of the day; Stevens, 1988; Hall et al., 2016). Contrary to cows and sheep, on horses, the control and strategic placement of watering points could be an effective management tool, particularly to prevent them from accessing more vulnerable areas such as riparian forests (Kaweck, 2016) or mountain lakes.

All three livestock species demonstrated a clear avoidance of dense forests, and instead preferred open forests, meadows, and wetlands. This preference was likely driven by the availability of more accessible vegetation and the ability to forage more efficiently in these open habitats (Tofastrud et al., 2019). Dense forests, with their low light penetration and denser understory, are likely less suitable owing to scarce forage and restricted accessibility for deeper exploration. Land cover selection had also a seasonal effect on all the species, for instance, sheep rejected shrubs during spring and preferred them during the autumn, when shrubs bear fruits. Interestingly, in terms of dominant vegetation, horses had a strong preference to riparian forest compared to cows and sheep probably because they were looking for a specific vegetation in these areas (Crane et al., 1997). These riparian zones provide both drinking water and nutrient-rich vegetation, which are important for horses' dietary needs. Fens, which are habitats with abundant biomass but of relatively low quality, were positively selected by cows and horses despite their small area (0.33 %), likely because they are more adapted for wetter areas and consuming low-quality forage (O'reagain and Schwartz, 1995). In contrast to sheep, which are more selective and may suffer hoof problems under excessively damp conditions (Winter, 2009). These results highlight the high interest that big livestock animals have in riparian forests and fens, really delicate habitats, which raise higher concern and should be more protected (Boyd et al., 2017; Kaweck et al., 2018). A useful management strategy could involve assigning cattle and horses to less sensitive areas, given their strong preference for riparian habitats and fens, which are particularly vulnerable to degradation. In contrast, sheep, showing less interest in these habitats, could be used to graze in or near such areas, thereby reducing pressure from heavier grazers and mitigating ecological impact. The installation of fences at a specific height that allow the passage of smaller animals, such as sheep, but restrict access for larger livestock like cows and horses, could also be a valuable strategy. Investigating the effects of such measures would be of great interest for natural park management and conservation planning.

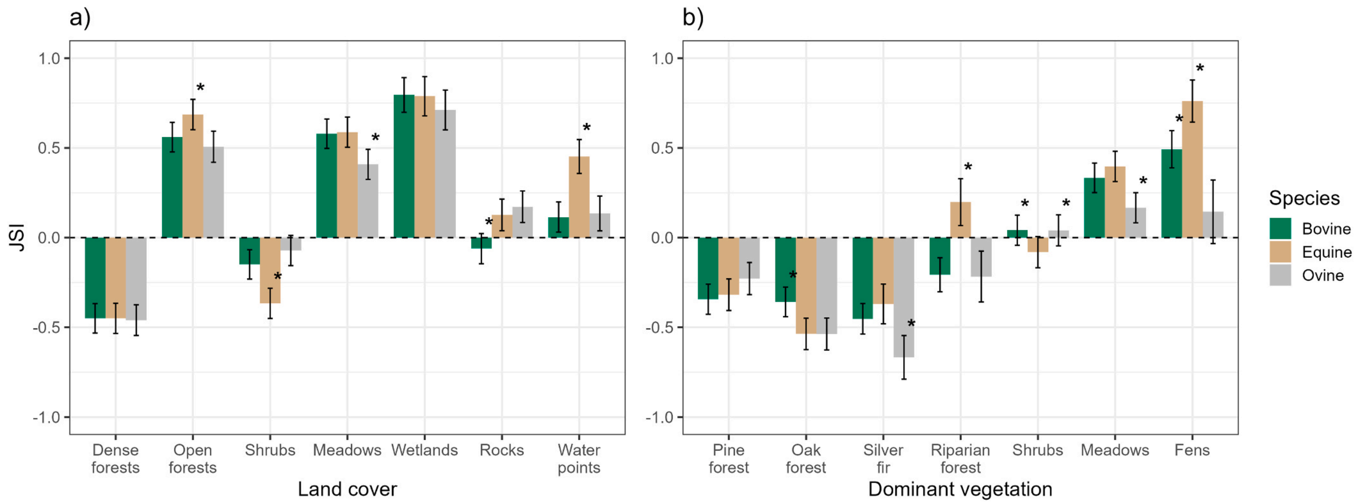

Fig. 1. Mean Jacob's selectivity index (JSI) and standard error for cows (dark green), horses (brown) and sheep (grey) in relation to land cover (a) and dominant vegetation (b) during the grazing season (six months) of four consecutive years (2020–2023). Asterisks (*) indicate statistically significant differences between species ($p < 0.05$).

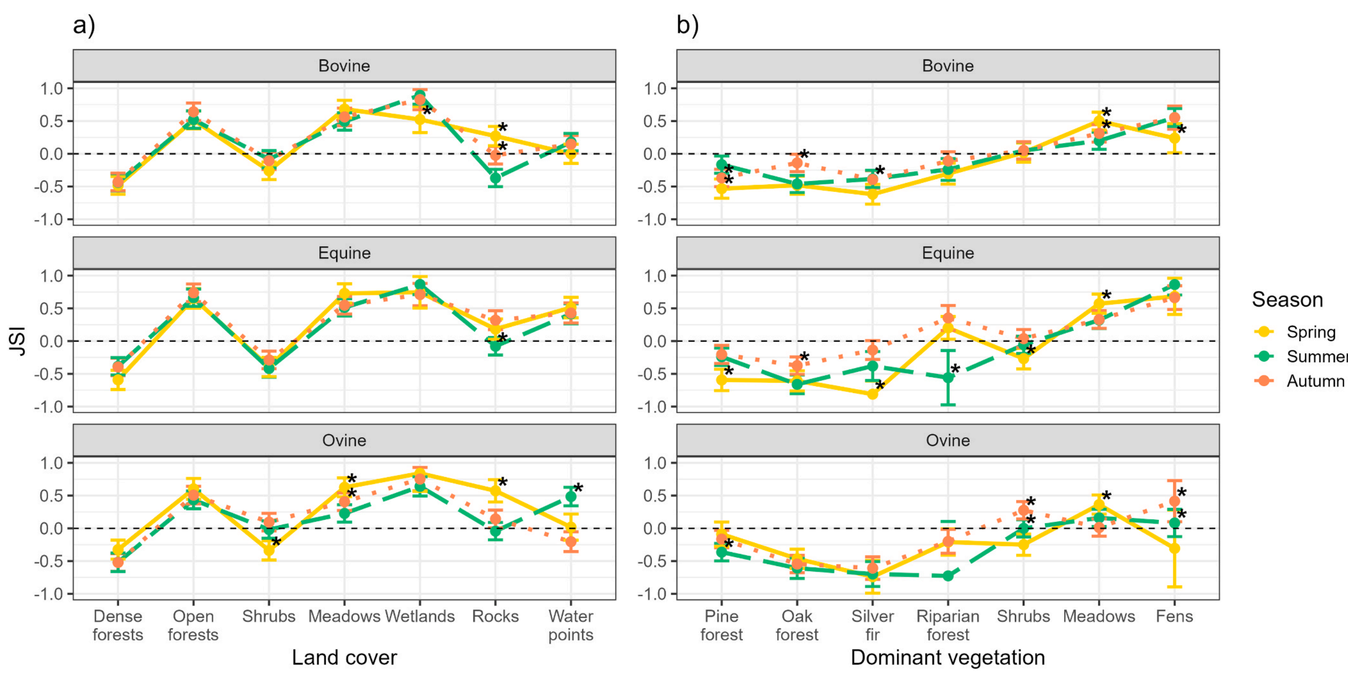

Fig. 2. Mean Jacob's selectivity index (JSI) and standard error for cows, horses and sheep in relation to land cover (a) and dominant vegetation (b) compared between spring (yellow line), summer (green dashed line) and autumn (orange dotted line) of four consecutive years (2020–2023). Asterisks (*) indicate statistically significant differences between species ($p < 0.05$).

The three species had a preference to graze in meadows, however these preferences changed depending on the predominant plant species. Cows stay more time in meadows of *Festuca nigrescens,* a palatable plant adapted to harsh environments and lower altitudes (1000 – 2000 m). Horses were more predominant in meadows of *Festuca eskia*, which is coarser and more fibrous, typically from higher altitudes (1800–2500 m; Goday and Martínez, 1963). Sheep selected meadows and shrubs of *Cytisus oromediterraneus*, a siliceous species typically found in dry, sunny areas. Although it is not very palatable and bitter (Pascual and Pascual, 2014), being a Fabaceae, it can fix nitrogen and improve soil fertility. As a result, indirectly benefiting more desirable forage plants (Meireles et al., 2013), thus grazing this plant is like a compensatory behaviour in low-pasture areas rather than a strict preference. This adaptation could be beneficial in environments where grass availability may be limited or where shrubs provide supplementary nutrients, particularly in drier areas. Moreover, seasonal changes in plant availability over the seasons existed, both in terms of species composition and quality, and they influenced livestock preferences. In spring, plants like *Arrhenatherum elatius* may become more palatable or accessible, while in autumn livestock selected more meadows of *Festuca eskia* likely due to the decrease of available pasture. An interesting management approach would be to implement rotational grazing systems informed by animal distribution, guided by seasonal vegetation dynamics and species-specific foraging behaviour. Nevertheless, this is just an approach of the most predominant vegetation species and warrants further investigation in plant census and identification to determine diet plant composition for each livestock species.

Table 2
Results of the GLMM analysis on the influence of the independent variable on the grazing frequency of cows, horses, and sheep during the grazing seasons of four consecutive years (2020–2023).

Independent variable	Estimate	Std. Error	z-value	P-value
Bovine				
Altitude	−0.02	0.004	6.14	$p < 0.05$
Slope	−0.12	0.003	−37.95	$p < 0.05$
Orientation	−0.01	0.003	−1.35	0.17
NDVI	−0.01	0.003	0.27	0.79
Water distance	−0.04	0.004	−11.01	$p < 0.05$
Equine				
Altitude	−0.03	0.006	−4.28	$p < 0.05$
Slope	−0.11	0.007	−18.67	$p < 0.05$
Orientation	0.02	0.006	3.89	$p < 0.05$
NDVI	−0.01	0.006	−2.22	$p < 0.05$
Water distance	−0.07	0.007	−9.50	$p < 0.05$
Ovine				
Altitude	−0.03	0.047	−6.41	$p < 0.05$
Slope	−0.07	0.004	−15.65	$p < 0.05$
Orientation	−0.02	0.004	−4.31	$p < 0.05$
NDVI	−0.03	0.004	−6.90	$p < 0.05$
Water distance	0.01	0.005	3.11	$p < 0.05$

Abbreviations: NDVI = Normalized difference vegetation index. The independent variables were scaled to make it comparable between them before analysis.

4.2. Hotspots characterization

Thanks to geolocation fixes and KDE calculations, we were able to map the animals' distribution across the natural park. We detected hotspots of pasture intensity and characterized them. As a result, we found that cows and horses shared more pasture areas, while horses and sheep shared more hotspot areas. Horses appear to be more flexible as they share more pasture zones with cows and sheep. This might be due to similar preferences for altitude and land cover, but differences in digestive systems compared to ruminants (Menard et al., 2002; Osoro et al., 2015), resulting in reduced competition for food resources. Horses' spatial flexibility allows their use in buffer zones or less productive pastures, thus combining species can lead to more uniform vegetation use and reduce dominance of certain plants. Nonetheless, further and more specific behavioural observations would be needed to confirm whether this reflects flexibility or lower interspecific competition. Moreover, the hotspots of all three species had the highest KDE values in grids with meadows dominated by *Agrostis capillaris* for cows and *Festuca eskia*, for horses and sheep. These results are aligning with our findings on JSI preferences, but contrasting with other authors (Armstrong and Seddon, 2008; Fraser et al., 2009), who claimed major dietary differences between cows and sheep. This may be due to the experimental conditions, where grass was abundant, whereas other types of vegetation were present in lower quantities. Using remote sensing and geolocation data could be used to detect early signs of habitat degradation. Detecting these possible over-grazed hotspots can be highly useful for providing farmers with information to optimize livestock management while also helping natural park managers to protect and conserve zones at risk of degradation and over-grazing. Finally, by combining geolocation data with open-source environmental datasets, it is possible to map optimal and suboptimal grazing areas for each species, as well as to identify exclusion zones where grazing should be limited due to ecological sensitivity (Li et al., 2006; Feizizadeh et al., 2013; McGregor et al., 2014; Vieira et al., 2015).

4.3. Diet selectivity

Our results indicate significant differences in PN content among the three valleys, with Valls d'Àneu showing the highest values. This could be attributed to differences in soil fertility, vegetation composition, or grazing pressure (Afzal and Adams, 1992; Unkovich et al., 1998; Chen et al., 2014). There was less of a seasonal shift in PN than anticipated. We expected a decline, since protein (nitrogen) concentration in plants typically decreases as they mature due to dilution effects and the accumulation of structural carbohydrates (Maillard et al., 2015), however, it was very low and acted differently depending on the valley. In terms of FN, significant differences were found among species. As expected, horses had the lowest FN concentrations, while sheep had the highest, followed by cows. These differences likely reflect variations in digestive physiology and diet selection. Horses, as non-ruminants, have a less efficient nitrogen retention capacity compared to ruminants and prefer more fibrous plants (e.g *Festuca eskia*), which explains their lower FN values. Conversely, the higher FN levels in sheep and cows indicate a greater ability to extract nitrogen from forage. In accordance, the FN/PN ratio was significantly higher in sheep compared to cows and horses, suggesting more efficient nitrogen utilization in their diet and plant selection. This result aligns with previous studies indicating that sheep are more selective grazers (Dumont et al., 2007, Rutter, 2010), often targeting nitrogen-rich plant species, which could explain their higher FN/PN ratio. Although FN/PN ratios provide a useful proxy for dietary selectivity, future work incorporating botanical analysis would offer a more detailed understanding of species-specific diet composition. Finally, we did not detect any seasonal effect on diet selectivity, suggesting that the relative nitrogen intake efficiency of each species remains stable throughout the grazing season. This stability might be explained by their ability to adapt grazing behaviour to maintain a

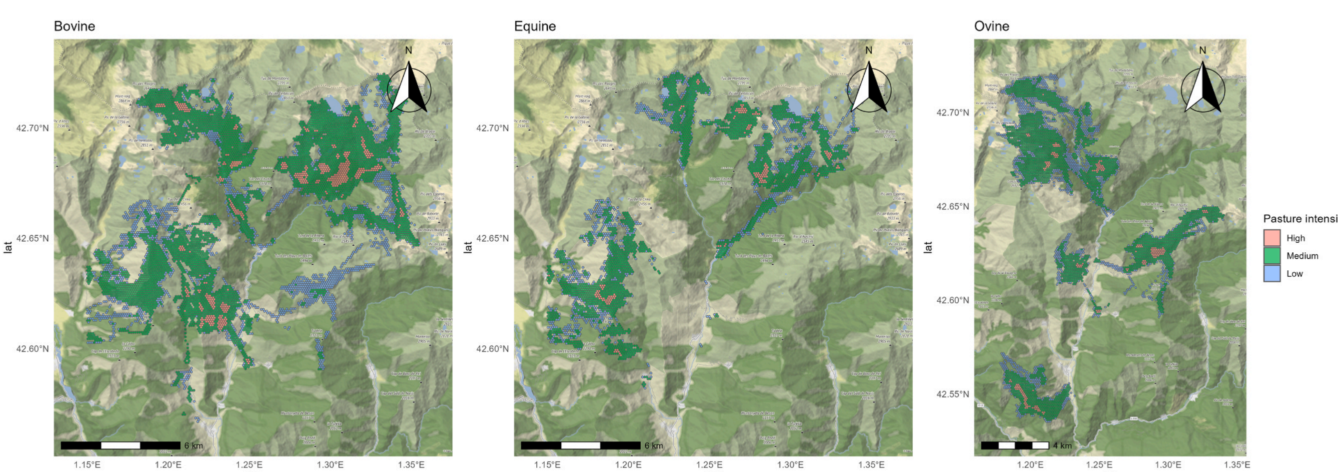

Fig. 3. Grazing distribution of cows, horses, and sheep represented using hexagonal cells and classified according to KDE values (low: KDE < 25 %, medium: 25 % < KDE < 95 %, high: KDE > 95 %), indicating grazing intensity in the Vall del Cardós valley (other valleys are shown in Figs. S1, S2, and S3).

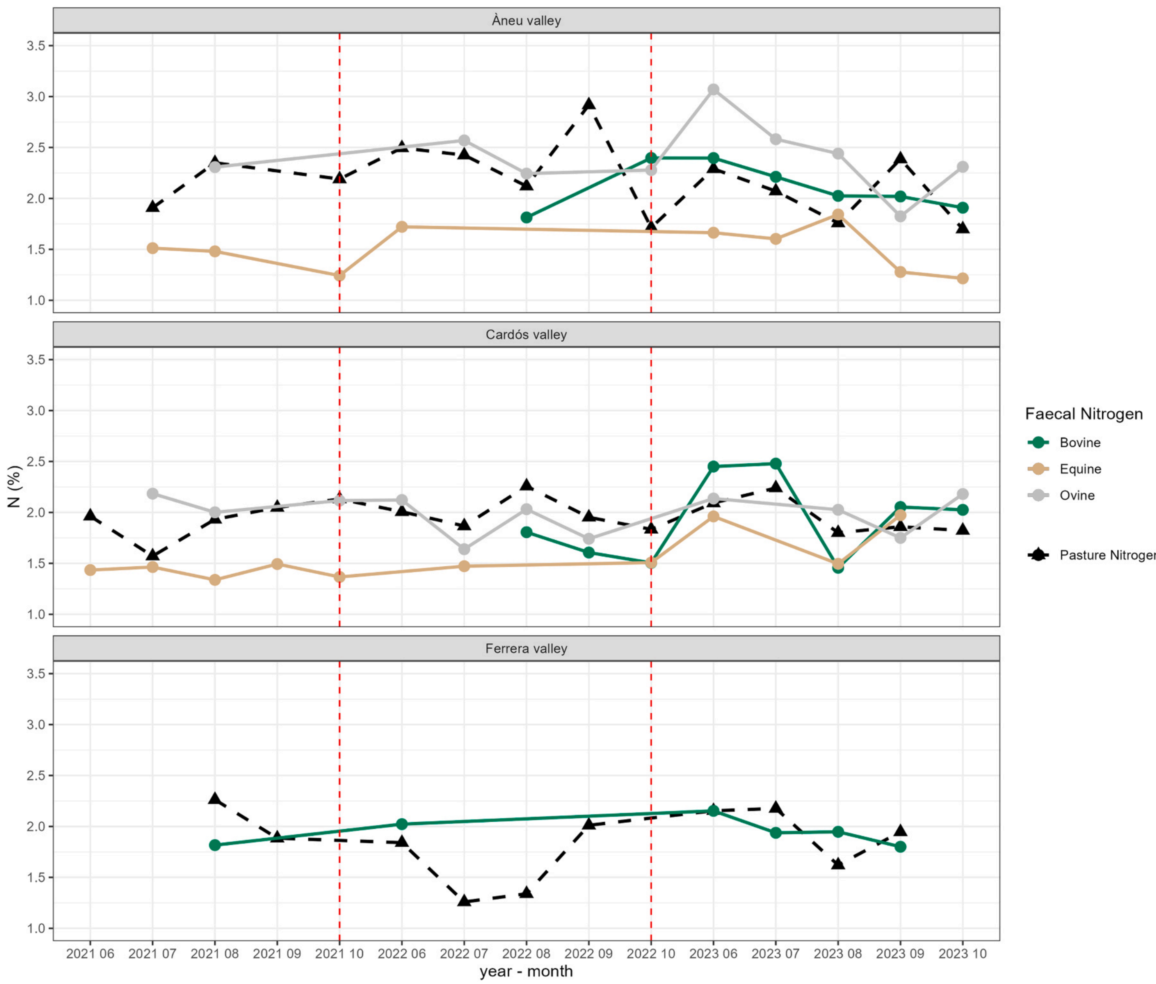

Fig. 4. Percentage of nitrogen content in pasture and faeces on a dry matter basis for the three different valleys (Àneu, Cardós and Ferrera in a dark dashed line) and cows (dark green line), horses (brown line) and sheep (grey line), from June to November, of three consecutive years (2021–2023).

Table 3
Mean values of the independent variables in high-density grazing areas (hotspots), by species.

	Bovine	Equine	Ovine
Altitude (m)	1800 ± 298	1952 ± 346	1936 ± 300
Slope (%)	38.4 ± 16.5	35.9 ± 14.5	51.8 ± 14.5
Orientation (°)	161 ± 57.5	196 + 64.1	210 ± 56.4
NDVI	0.492 ± 0.0874	0.442 ± 0.0797	0.435 ± 0.0718
Water distance (m)	1224 ± 1330	1248 ± 1077	1239 ± 829
Land cover	Meadows	Meadows	Meadows - shrubs
Dominant vegetation	Meadows	Meadows	Meadows - shrubs

Abbreviations: NDVI = Normalized difference vegetation index

relatively constant nitrogen intake, despite seasonal changes in forage availability and quality (Owen-Smith, 1994; Collins et al., 2017). Overall, these findings highlight how livestock species differ in nitrogen intake and utilization, which has implications for grazing management and ecosystem nutrient cycling. Indeed, farmers could adjust the composition and stocking density of livestock species to optimise nitrogen use across pastures. For instance, combining species with differing dietary selectivity and digestive efficiency, such as co-grazing sheep and horses, could help reduce overgrazing of high-quality forage and promote a more uniform utilisation of vegetation. Furthermore, recognising that some species maintain stable nitrogen intake despite seasonal changes enables more strategic planning, such as reducing the need for supplemental feeding or rotating those species through more marginal areas during periods of low forage quality.

5. Conclusions

This study demonstrates the potential of combining the information of commercial geolocation collars and open data sources to analyse livestock grazing preferences. Our findings suggest that terrain slope is a key determinant of site use, particularly for larger species such as cattle and horses, whereas vegetation type and cover had seasonal effect and varied depending on the livestock species. Assigning more agile species (e.g., sheep) to steeper terrain where others are less likely to graze could be a good measure to maximize use of the pasture area. Interestingly, the widespread availability of water in the study area appears to diminish its role as a limiting factor for livestock distribution, diverging from earlier studies in flatter environments. However, in horses, water distribution had a major effect on their distribution. Additionally, the strong selection of riparian habitats and fens by cattle and horses raises concerns over the conservation of these sensitive ecosystems, underlining the need for targeted management practices. The use of fencing may represent an effective strategy, allowing the passage of smaller animals while restrict access for larger livestock species. Hotspot analysis revealed overlapping use between species, with horses showing the greatest spatial flexibility. This has potential implications for multi-species grazing systems. Managing interspecies competition can lead to more uniform vegetation use and reduce dominance of certain plants. Meanwhile, differences in nitrogen intake and utilisation patterns suggest dietary specialisation among cows, horses and sheep. Altogether, these results highlight the value of geolocation-technology on approaches for both optimising grazing practices and biodiversity conservation. Further research is warranted to refine species-specific management strategies to modify land-use dynamics and plant selection, especially in the context of climate change, in order to adapt livestock production to these conditions. For instance, implementing multi-species grazing systems in selected areas, rotating livestock across different pasture zones to limit overgrazing, and identifying the most suitable areas for grazing, as well as the most vulnerable zones requiring protection, are key management adaptations.

CRediT authorship contribution statement

Emma Fàbrega: Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation. **Antoni Dalmau:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Roger Vidal-Cardos:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Chat GPT-4o to improve the article's readability and language. After using these tools, the authors reviewed and edited the content as needed and took full responsibility for the publication's content.

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Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.applanim.2025.106776.

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