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Use of New Technologies to Determine the Locomotion Energy Expenditure and Livestock Activity Patterns of Free-Grazing Sheep in Mountain Pastures

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Abstract: This study assessed the daily energy expenditure and activity of sheep in mountain pastures in the Pyrenees (Spain), using Global Positioning System (GPS) and accelerometer data. Sheep traveled an average of 9.6 km daily, and the average daily energy expenditure due to locomotion was 3.20 MJ.day^{-1}. Activity exhibited a bimodal grazing pattern, peaking in early morning and late afternoon, with reduced movement at midday and night. Despite an average loss of 0.65 points of the body condition score (BCS), most sheep remained within the optimal range. This study demonstrates the substantial energy demands of sheep grazing in the rugged terrain of mountain pastures and the effectiveness of GPS and accelerometer technology in capturing detailed activity patterns, providing insights for optimizing grazing strategies and livestock management.

Keywords: behavioral patterns; ovine; GPS; accelerometers; body condition score; grasslands; grazing management

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1. Introduction

Mountain pastures in the Pyrenees are found across montane, subalpine, and alpine zones, reaching the highest elevations of the range. These areas are expansive, situated above the treeline, and often shaped by human activities over centuries. Traditionally, they support transhumant or transterminant sheep grazing along with other livestock species and are generally communally owned [1]. In addition to offering high-quality forage for grazing, these landscapes provide a range of ecosystem services and functions that benefit society, contributing to both agriculture and environmental sustainability [2,3]. Mountain agroecosystems were historically stable due to their isolation, but significant changes have taken place since the mid-20th century, accelerating in recent decades. These include the decline of agro-pastoral activities, changes in land use, and fewer farms with larger flocks [4,5]. Sheep farming, once the most traditional and predominant livestock activity in the Pyrenees, has been progressively replaced by cattle [6]. Reduced livestock numbers and a shortage of shepherds have shifted management practices from guided herding to free-roaming livestock, causing an uneven grazing distribution [7]. Sheep are crucial for maintaining highland summer pastures through their grazing habits, which influence plant diversity and vegetation structure. Their selective grazing, much more pronounced than that of cattle, and their activities, such as trampling, defoliation, seed dispersal, and nutrient redistribution via feces and urine, help shape the cover, structure, and composition of the plant communities in these areas [8].

The adoption of new technologies in grazing management has revolutionized livestock farming, offering more precise and efficient tools to monitor and optimize pasture use [9]. Animal behavior is a key factor in understanding pastoral system management. Devices, such as Global Positioning System (GPS) trackers, accelerometers, and drones, enable real-time tracking of animal movement, activity levels, and environmental conditions. These technologies not only potentially improve livestock health and productivity by enabling data-driven decisions but also contribute to sustainable grazing practices by preventing overgrazing and undergrazing and enhancing pasture regeneration [10–14]. Several studies have examined the use of triaxial accelerometers to assess the daily activities of sheep on pasture, including resting, grazing, and movement behaviors [15–20]. These activity patterns are influenced by several factors [21], including the topography, vegetation distribution, resting areas, and water sources. Additional factors affecting sheep movement include physical barriers, environmental familiarity, and habitat fragmentation or limitation induced by human activity [22]. Mendizabal [23] suggested that sheep, in the absence of directed grazing by the shepherd, select certain vegetation units over others, concluding that the animal moves selectively to find food to meet its energy requirements. In mountain pastures, the flock travels relatively long distances, and the energy expenditure of locomotion significantly contributes to their energy requirement [24–27]. It is important to know this expenditure as it can limit the energy available for maintenance and production. The feeding of livestock in mountain pastures must ensure that sheep maintain good productive conditions, meaning there must be a correct energy balance between intake and energy expenditure. Various authors have proposed methods for estimating energy consumption due to locomotion in sheep, based on formulas that consider the distance traveled by livestock and the slope [23,28,29]. The advent of new technologies, specifically the use of GPS for locating herds, facilitates knowledge of the herd's position and allows tracking of the routes and distances traveled by the livestock, enabling the application of the formulas proposed by these authors.

Mountain pasture grazing must also be economically viable while maintaining adequate animal nutritional status; therefore, it is essential to determine whether this energy demand impacts the sheep's body reserves, potentially affecting their productivity. In field conditions, two methods commonly used to assess the nutritional status of sheep are body weight and body condition score (BCS). While body weight can predict growth in young animals, it is less reliable for mature sheep due to variability in size, digestive content, and pregnancy, among other factors, while BCS, is more accurate for evaluating a sheep's nutritional status [30]. The method of lumbar palpation standardized by Russel et al. [31] is widely used to assess BCS in sheep. While there are several studies on body condition of ruminants in extensive production systems [32–35], changes due to summer grazing at mountain pastures in sheep flocks are very scarce to our knowledge.

The objective of this study was to monitor the activity of free-grazing sheep in summer mountain pastures using accelerometers and GPS devices. Specifically, the study aimed to determine daily activity patterns, estimate the energy expenditure associated with locomotion and assess the variation in body condition score. This knowledge can help to establish effective management guidelines for flocks that optimize sustainable grazing strategies that preserve the ecological integrity of mountain pastures and support the balance between livestock productivity and environmental conservation.

2. Materials and Methods

2.1. Study Area

This research took place in the mountain grasslands of Collarada in the Central Pyrenees (Huesca, Spain) (Figure 1). The terrain is karstic with rugged and pronounced features, including the Collarada Peak, which reaches its highest point at 2886 m, and a minimum elevation of 1100 m. The annual average temperature and total rainfall for the period 1991–2021 were 7.4 °C and 1539 mm, respectively [36]. The Collarada mountain grasslands are part of the Natura 2000 Network site ES2410023 'Collarada y Canal de Ip', which is protected under the Habitat Directive 92/43/EEC (European Community) [37]. The lower third of the area is dominated by a *Pinus sylvestris* forest, while the upper section is characterized by herbaceous plant communities associated with the phytosociological alliances *Saponarion caespitosae*, *Festucion scopariae*, *Bromion erecti*, *Primulion intrincatae*, *Nardion stricatae*, and *Festucion eskiae* [21,38]. This region represents a typical highland summer pasture ecosystem in the Pyrenees and was selected for its logistical feasibility.

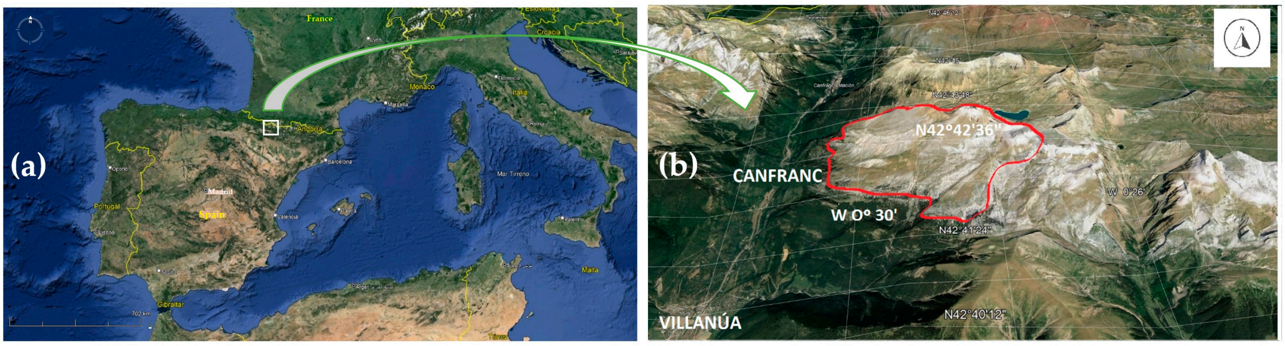

Figure 1. (**a**) Location map; (**b**) Collarada mountain (Villanua, Spain) and free-grazing study area (red line). Source: Google Earth.

The total area of the mountain grasslands of Collarada is 1857 ha. The study related to the free grazing period was conducted over an area of approximately 850 ha (Figure 1b).

2.2. Flock Monitoring

A flock owned by four farmers from nearby villages, within a 50 km radius, grazes these summer pastures. The sheep belong to the 'Rasa Aragonesa' breed, a local meat-producing breed known for its hardiness, strong flocking behavior, and excellent grazing capabilities, making them well-suited to the harsh mountain environment [39]. Based on the farmers' expertise and reproductive considerations, no lactating or pregnant ewes expecting to give birth during the grazing period were selected. Additionally, sheep in extremely poor body condition were excluded.

The study was conducted during the summer grazing seasons of 2019, 2020, and 2021. The ascent to the mountain pastures took place in early July. During the first two weeks, sheep grazed in the lower part of the grazing area under the supervision of a shepherd. From mid-July to mid-September, the flock roamed freely with minimal management, with shepherds visiting once a week to assess the condition of the flock. In case they found injured sheep, they led them to an enclosure near the shepherd's cabin to provide the appropriate treatment. Days when shepherds intervened in ways that altered the sheep's free movements were discarded. After this period, the flock was guided by a shepherd to other areas of the mountain pastures. The date of descent from the mountain pastures to the farmer's villages was determined by meteorological conditions and the availability of forage. In 2019, the descent occurred in two stages: the pregnant sheep descended on 25 September, while the rest followed on 22 October. In 2020, the descent took place on 26 September, and in 2021, on 5 October. The flock was composed of 1052 female sheep in 2019, 1087 in 2020, and 1302 in 2021. Four ewes were randomly selected among the most robust from the flock and fitted with collars equipped with tri-axial accelerometers and GPS trackers (Digitanimal SL, Madrid, Spain) [40] (Figure 2). Given the highly gregarious nature and cohesive grazing behavior of sheep, these four animals were assumed to represent the entire flock. Different sheep were selected each year, and the collars were worn continuously throughout the duration of the experiment.

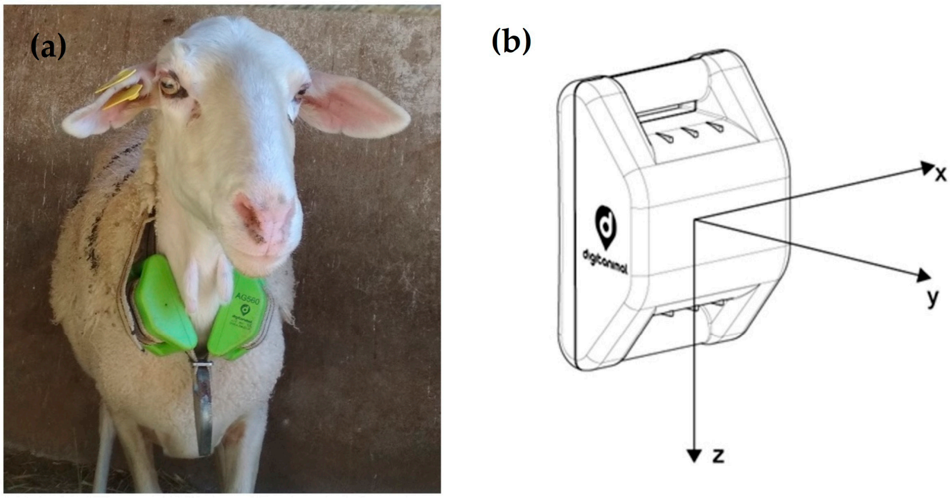

Figure 2. (**a**) Sheep equipped with accelerometer and Global Positioning System (GPS) tracker devices attached to collar. (**b**) Tri-axial accelerometer with its axes.

The accelerometers and GPS trackers used in the experiment were each housed in separate casings measuring 10.6 × 7.7 × 5.0 cm (Figure 2a). These casings were designed for use in extensive sheep farming and characterized by their robustness, waterproofing, and resistance to adverse weather conditions. To prevent movement around the animal's neck and ensure the correct positioning of the equipment, which facilitates data transmission and accurate location tracking, the collars were equipped with a counterweight at the bottom (Figure 2). The total weight of each collar with both devices was 1052 g, significantly below 1.32 kg, which corresponds to 2.2% of the body weight of a 60 kg ewe, the average estimated weight of the sheep in the studied flock. According to Hulbert et al. [41], this load does not influence animal behavior. As a result, ethical approval was not necessary for using this non-invasive equipment.

The GPS trackers allow real-time monitoring of the flock by wirelessly sending a message to Digitanimal servers via an IoT network (SigFox) [42], which had been previously checked to have good coverage in the study area. The devices were programmed to capture data at 11-min intervals, which was the minimum possible to ensure an adequate duration of the lithium battery that powers the devices, without the need to replace them throughout the entire summer period. Each tracking unit provides the following information: collar identifier, timestamp, animal's position in the geographic coordinate system (latitude and longitude), average and maximum acceleration on the XYZ axes, and the animal's surface temperature.

The GPS devices have an internal accelerometer, but since the 11-min interval was insufficient for the planned study, another triaxial accelerometer was placed on the same collar, which recorded the X, Y, and Z components of acceleration at 5-s intervals, as well as the time relative to the previous record (accumulated milliseconds). The data recorded by both the GPS devices and the accelerometers were provided annually at the end of each summer period in .csv format by the equipment supplier, Digitanimal SL. We used multiple devices to ensure data collection throughout the entire grazing season, accounting for the possibility of device failure. One of the GPS devices was inoperative during 2021.

2.3. Data Editing

2.3.1. Calculation of Distance, Slope, and Speed Between Two Consecutive Positions

The .csv file containing all data recorded by the GPS trackers were imported into the Microsoft Excel (version 16.0) program for calculations. Data from mid-July to mid-September for the 3 years 2019, 2020, and 2021 were selected for the study.

The geographic coordinates of each position were converted to the UTM WGS 84 system to obtain the X and Y coordinates in meters. The horizontal distance (*HD*), in meters, between two consecutive points (x_i/y_i; x_f/y_f) was calculated using the formula:

$$HD = \sqrt{\left(x_f - x_i\right)^2 + \left(y_f - y_i\right)^2}$$

The vertical distance (*VD*), in meters, was calculated as the difference in altitude between two consecutive positions $z_f - z_i$. Since the GPS devices do not provide altitude data for each record, the QGIS program (version 3.28 'Firenze') [43] was used for the calculation, obtaining the Z coordinate of each point from the intersection with the PNOA_MDT05 raster layer (digital terrain model) obtained from the Instituto Geográfico Nacional of Spain (IGN) download center [44], using the 'Point sampling tool'. The absolute distance (*D*), in meters, was calculated as:

$$D = \sqrt{(HD)2 + (VD)2}$$

To calculate the slope angle (*P*), the following formula was used, taking into account the vertical change in altitude (*VD*) and the horizontal distance (*HD*), and this value was subsequently converted to degrees using the DEGREES function in Excel:

$$\text{Slope (radians)} = \text{Arctangent}\left(\frac{VD}{HD}\right)$$

The time interval since the previous record, in minutes, was calculated using the timestamp. The speed (in m.min^{-1}) was calculated by dividing the absolute distance by the time interval between two consecutive positions.

2.3.2. Calculation of Daily Distance Traveled by the Flock, and Daily Energy Expenditure Due to Locomotion

The data obtained from all the GPS devices placed on the flock during the summers of 2019, 2020, and 2021 were used to estimate the energy expenditure of free-grazing sheep in Collarada summer mountain pastures. Among the formulas consulted in the literature for calculating energy consumption due to locomotion in sheep, the equation proposed by Brockway and Boyne [29] was chosen because it considers the most influential factors in locomotion, such as movement speed, slope, and distance traveled. The formula proposed by Clapperton [28] does not consider the speed of the livestock. These reasons were previously used by Prieto et al. [45] to justify its use in calculating the energy consumption of grazing goats and by Betrán et al. [46] for transhumant sheep movements. The latter also evaluated the more recent formula proposed by Mendizábal [23], but these authors suggested that it should be discarded as it yielded results far from the logical and expected. Therefore, in our study, the following equation by Brockway and Boyne [29] was applied to calculate the energy consumption due to locomotion between every two consecutive positions:

$$\text{Energy cost (J.kg live weight}^{-1}\text{. m)} = 2.35 + 0.389G + 0.0286G^2 - 0.036S + 0.00052S^2$$

where *G* is the slope (in degrees) and *S* is the speed (in m.min^{-1}). The result was multiplied by the average live weight (estimated at 60 kg) and by the distance between these two points (m) to obtain the energy consumed in Joules (J).

The daily distance traveled by the flock and the daily energy expenditure were calculated as the sum of all the data obtained for each day. The average value from the four devices was considered.

The GPS devices were programmed to send the position every 11 min, but there were some days when not all records were obtained due to coverage failures. Therefore, only records obtained in an interval longer than 9 min and shorter than 3 h, with respect to the previous record, were taken into account, accounting for 99.7% of the data provided by the GPS devices. Records obtained with less than 9 min were considered equipment malfunctions, and estimates of energy expenditure for intervals longer than 3 h were considered invalid because the duration made the estimates unreliable. The median time difference between the waypoints (position points within a route) within this interval was 14.3 min.

Data from 4 days in 2019, 5 days in 2020, and 4 days in 2021 were excluded due to shepherd's interventions on sheep movement. From the remaining days, a median of 96 records per day on average across the 3 years of the study was obtained, with the first quartile at 84 records and the third quartile at 106 records. To reduce the impact of days with fewer records, only data from days where the number of records exceeded the first quartile (more than 75% of records) were included: 40 days in 2019, 48 days in 2020, and 42 days in 2021.

The average daily distance and the daily energy expenditure of locomotion was calculated for each of the years of the study, 2019, 2020, and 2021, and for the different months of the summer season (July, August, September).

2.3.3. Determination of Daily Activity

The daily behavioral activities of sheep include grazing, standing, walking, lying, and ruminating [16,17]. For this study, two primary daily activities were considered: 'moving vs. resting' and 'grazing vs. non-grazing'. 'Movement' was identified in periods when the sheep were in motion (speed $\geq$ 2.6 m.min^{-1} [47]. Otherwise, they were considered to be in periods of inactivity or minimal movement, when the sheep were either resting or engaged in rumination. 'Grazing' was defined as the periods when sheep were actively consuming pasture.

Data provided by the GPS devices were used to determine the 'movement' activity. Only records collected by the GPS trackers within an interval exceeding 9 min but less than 15 min from the previous record were considered, which represented 85% of the total records. The average speed for each hourly interval was calculated, using the average of all data from the 3 summer seasons.

To determine the 'grazing' activity, data from the accelerometers were analyzed. In some cases, accelerometers were incorrectly positioned or tilted, with such issues documented during field observations, as these devices are very sensitive. Furthermore, all data were graphically represented, and those revealing inconsistencies were excluded from the analysis to ensure accuracy. In 2020, one of the accelerometers was not correctly attached, leading to inaccurate data that were discarded. Additionally, two devices malfunctioned in 2021. As a result, data from four devices were used in 2019, three in 2020, and two in 2021. Starting from the connection date and time of each accelerometer, which had been previously noted, the timestamp for each record was calculated by adding the accumulated milliseconds to the previous record. The accelerometer readings were converted to International System units (m.s^{-2}) by multiplying the recorded values by 9.8/256. The data were then grouped by minute using the median and further aggregated into 15-min intervals. Activity was classified as 'grazing' when the *Z*-axis acceleration, representing vertical head movement (Figure 2b), stayed within the range of [1, 4) for at least 5 min in each 15-min interval. This range was established based on field observations, correlating with the typical foraging motion of the sheep. This process was carried out by a qualified external collaborator from Digitanimal, who used the Python programming language [48]. The proportion of data classified as 'grazing' was calculated for every hourly interval throughout the day.

2.4. Body Condition Assessment

The body condition score (BCS) was assessed according to the method proposed by Russel et al. [31], which involves a subjective evaluation by palpation of the lumbar vertebrae area of the animals to assign a score reflecting their fatness, on a scale of 1 to 5 points, with higher scores corresponding to fatter animals and lower scores to leaner ones. Body condition was evaluated in 0.25-point intervals, as the condition was fairly similar across all sheep in the flock [49]. To ensure consistency, the evaluation was conducted on all occasions by the same person, a veterinarian with previous experience in body condition assessment (Figure 3).

Figure 3. Palpation of the lumbar vertebrae area of the sheep to assign body condition score (BCS) following Russel et al. [31].

All the sheep sent to Collarada mountain pastures by one of the four farmers were evaluated throughout the three years of the study (2019, 2020, and 2021). The sheep were identified by ear tags and ruminal boluses. The BCS for each sheep was assessed in the village where the farm was located, one day before and one day after the ascent to and descent from the mountain pastures. Sheep for which both records (before–after) were not available were excluded from the study. A total of 435 sheep were evaluated in 2019, 539 in 2020, and 531 in 2021, representing 41%, 50%, and 41% of the total flock grazing in Collarada during each respective year. Based on their nutritional status before moving to the mountain pastures, the sheep were classified as thin (BCS < 2.5), normal (BCS between 2.5 and 3.5), and fat (BCS greater than 3.5). The variation in BCS for those types was also evaluated.

The flock studied is associated to the cooperative 'Union de Productores de Rasa Aragones (UPRA)-Grupo Pastores' [50] that manages the genealogical book of the Rasa Aragonesa breed [39], who provided data regarding each animal's age and lambing history. The variation in body condition among different age categories was also studied, classifying the sheep as 'young ewes' (from 9 to 12 months), 'ewes' (between 1 and 6 years), and 'old ewes' (over 6 years-old). The variation in body condition was also evaluated based on the physiological state of the ewes. Ewes were classified into three categories: non-pregnant, early gestation (ewes that were pregnant while in the pastures but lambed more than one month after descending), and advanced gestation (ewes that gave birth within one month after descending from the mountain pastures).

2.5. Statistical Analyses

Data processing was conducted in Excel, and statistical analyses were performed using R software (version 4.1.2) [51]. First, a descriptive analysis was conducted to characterize the data distribution. The daily distance and the daily energy expenditure data follow a normal distribution (Shapiro–Wilk normality test, $p > 0.01$); therefore, the ANOVA test, followed by Tukey's post hoc contrasts, was applied to assess differences across years and months. A p-value of <0.05 was considered statistically significant.

Energy expenditure was analyzed over the course of the study period, starting from mid-July (considered as day 1) and extending through mid-September. To observe trends in energy expenditure across this period, smooth curves were generated using the Loess method (locally estimated scatterplot smoothing) with a smoothing parameter set at 0.45. This approach allowed us to model the underlying pattern of energy expenditure as a function of time, smoothing out short-term fluctuations while capturing the general trend throughout the grazing period.

Additionally, the influence of meteorology on daily energy expenditure due to locomotion was analyzed. The total daily precipitation, average daily wind speed, and average daily temperature were obtained from the nearest weather station from the Spanish Meteorological Agency located 5 km away in Canfranc (Huesca, Spain) [52], at an altitude of 1170 m. The temperature on the surface of the sheep was obtained from the GPS device records. The correlation between daily energy expenditure and each meteorological variable, including sheep's surface temperature, were evaluated using Spearman's correlation test.

The BCS data from both the ascent and descent did not follow a normal distribution (Shapiro–Wilk normality test, $p < 0.01$), so non-parametric tests were used for statistical analysis. The Wilcoxon paired samples test was applied to determine if differences of values of BCS before moving to the mountain pastures and after the summer season were significant. Differences between years and the different categories (previous nutritional state, age, and physiological state) were assessed using the Kruskal–Wallis Test, followed by Tukey's post hoc contrasts.

3. Results

3.1. Average Daily Distance Traveled by the Flock and Average Daily Energy Expenditure

The average daily distance and standard deviation over the 3 years was 9.6 ± 1.5 km per day. The maximum distance covered by the sheep during the study period in a single day was 12.6 km on 20 August 2019 (Figure 4). On this day, a strong storm began at midnight, with 38 mm of accumulated rainfall overnight measured by the nearest weather station [36].

The average daily energy expenditure over the 3 years was 3.20 ± 0.57 MJ.day^{-1}. The maximum energy expenditure during the study period in a single day was 5.04 MJ on 30 August 2020. That was the day with the least average temperature measured on the surface of the sheep (18.4 °C), and the second least average temperature measured by the nearest weather station (10.4 °C).

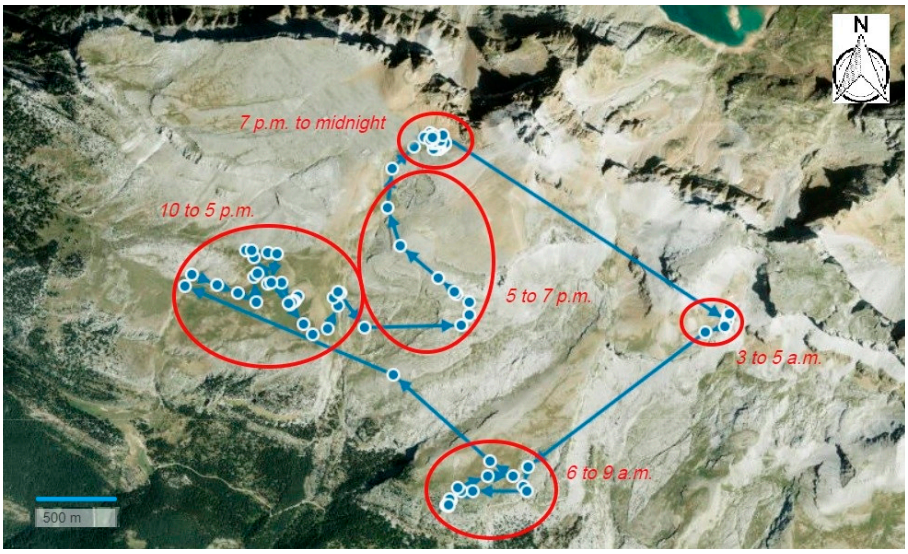

Figure 4. GPS waypoints of the flock at Collarada mountain pastures (Central Pyrenees, Spain) on 20 August 2019, with arrows indicating the direction of the tracks. Source: Tracks visualization obtained from TAME (Tagged Animal Movement Explorer) [53].

The results of average daily distance covered by the flock and average daily energy for locomotion for the three years of the study and for the three months of the summer season are shown in Table 1.

Table 1. Average daily distance, and average daily energy for locomotion of the flock at the Collarada mountain pastures (Central Pyrenees, Spain) for the three years of the study (2019, 2020, and 2021) and for the three months of the study period (July, August, and September). Different letters indicate statistically significant differences (ANOVA Test, $p < 0.05$).

	Number of Days	Daily Distance (km) (Mean ± sd)	Locomotion Energy Cost (MJ.day^{-1}) (Mean ± sd)
Year			
2019	40	9.9 ± 1.3	3.13 ± 0.44
2020	48	9.5 ± 1.4	3.20 ± 0.67
2021	42	9.3 ± 1.4	3.27 ± 0.57
Month			
July	34	9.1 ± 1.2 (a)	3.02 ± 0.59
August	61	9.7 ± 1.4 (b)	3.20 ± 0.59
September	35	9.7 ± 1.3 (a, b)	3.18 ± 0.49

No significant differences were found in the distance traveled and the daily energy expenditure over the 3 years of study (ANOVA test, $p > 0.05$). Statistical analysis indicated significant differences in the distance traveled during the different months of the summer season (ANOVA test, $p < 0.05$); these differences were found in the distance traveled in July and August. The differences in daily energy expenditure between the 3 months were not statistically significant (ANOVA test, $p > 0.05$).

The evolution of the daily energy expenditure along the whole study period, starting in mid-July (day 1) to mid-September (day 60), is shown in Figure 5. Energy expenditure increases during the first half of the period, then it descends slightly, and starts increasing again around days 45 to 50.

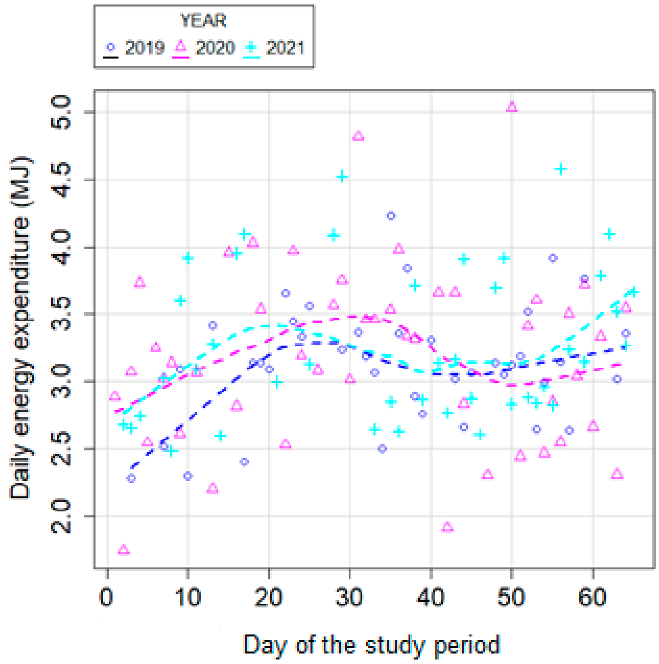

Figure 5. Scatter plot of the flock's locomotion energy expenditure at Collarada mountain pastures (Central Pyrenees, Spain) in relation with the advance of the study period, starting from mid-July (day 1) to mid-September, overlaid with a smooth curve (Loess, smoother parameter 0.45).

The relationship between average daily energy expenditure for locomotion and the temperature measured on the surface of the sheep and the meteorological variables (total daily precipitation, average daily wind speed, and average daily temperature) is illustrated in Figure 6. In all cases, a rho value close to 0 (rho < 0.1, Spearman's test) was obtained, indicating that daily energy expenditure was not linearly correlated with any of the meteorologic factors studied, and neither with the temperature on the surface of the sheep measured by the GPS devices.

3.2. Daily Activity of the Flock

The average speed and the results of the percentage of grazing activity for each hour interval of the day are shown in Figure 7.

Sheep started moving between 5 and 6 a.m., reaching the highest velocities around 7 a.m., with an average value of 13 m.min^{-1}. After this time, speed decreased, with a period of lower locomotion activity observed between 11 a.m. and 3 p.m. From 3 p.m., speed started increasing again, reaching a maximum at 6 p.m., when speed was, on average, 14 m.min^{-1}, and then started decreasing again. Between 10 p.m. and 6 a.m., speed was under 2.5 m.min^{-1}. Based on the threshold of 2.6 m.min^{-1}, 'moving activity', as an average, took place from 5 a.m. to 10 p.m. While nighttime grazing activity was minimal, sheep showed some grazing activity from 5 a.m. to 9 p.m., with two main grazing periods during which sheep spent over 60% of the time grazing: one in the morning, from 7 a.m. to 11 a.m., and another one in the afternoon, from 3 p.m. to 7 p.m. Grazing activity declined from 11 a.m. to 3 p.m. and was at its lowest between 10 p.m. and 5 a.m. During the daytime (7 a.m. to 9 p.m.), sheep spent 55% of the time grazing and 12% at nighttime. Overall, sheep spent 40% of the 24-h day on 'grazing' activity.

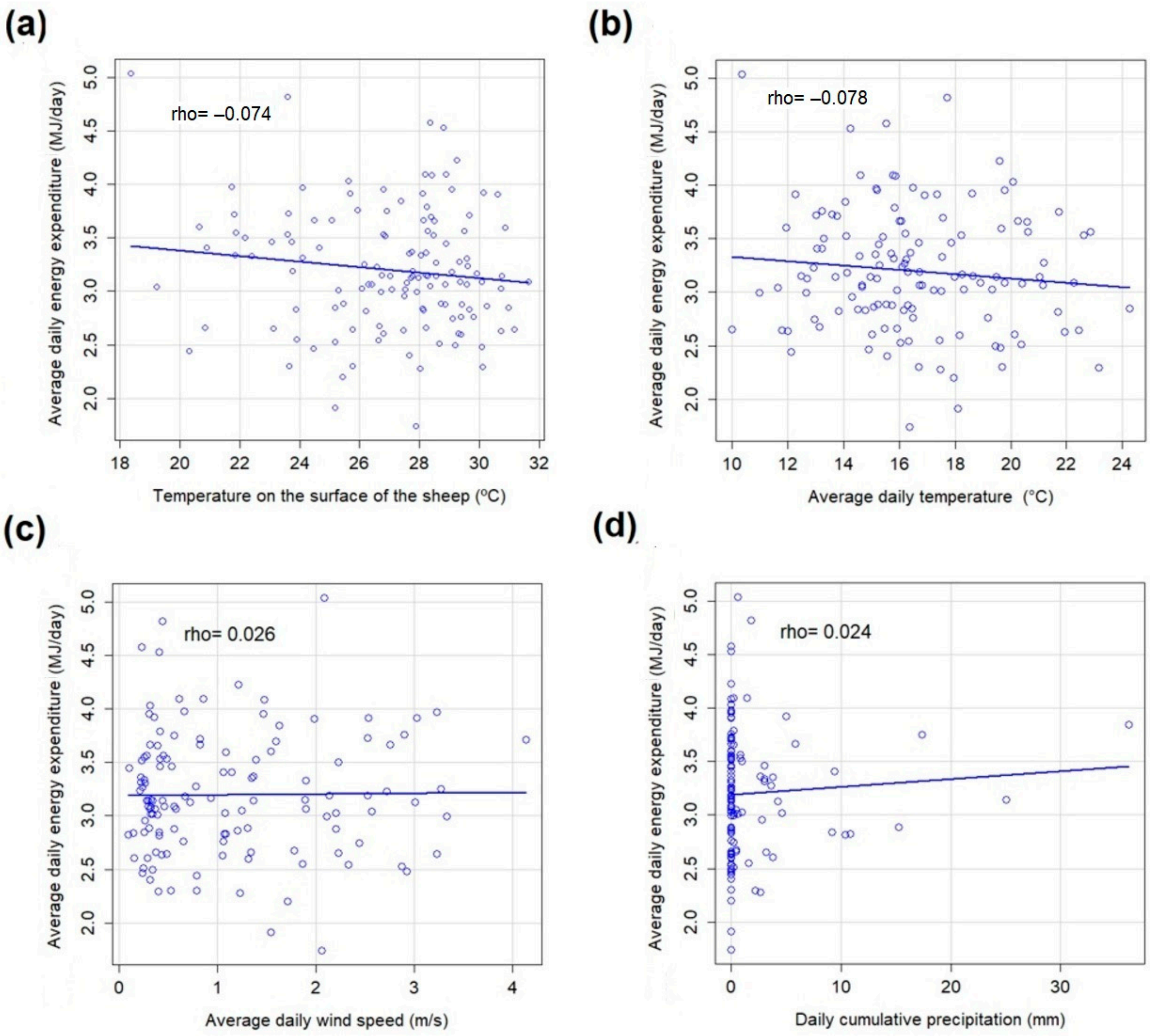

Figure 6. Scatter plot of the flock's locomotion energy expenditure at Collarada mountain pastures (Central Pyrenees, Spain) across the years 2019, 2020, and 2021 during summer seasons in relation to the temperature on the surface of the sheep (**a**) and meteorological variables [36]: average daily temperature (**b**), average daily wind speed (**c**), and daily cumulative precipitation (**d**).

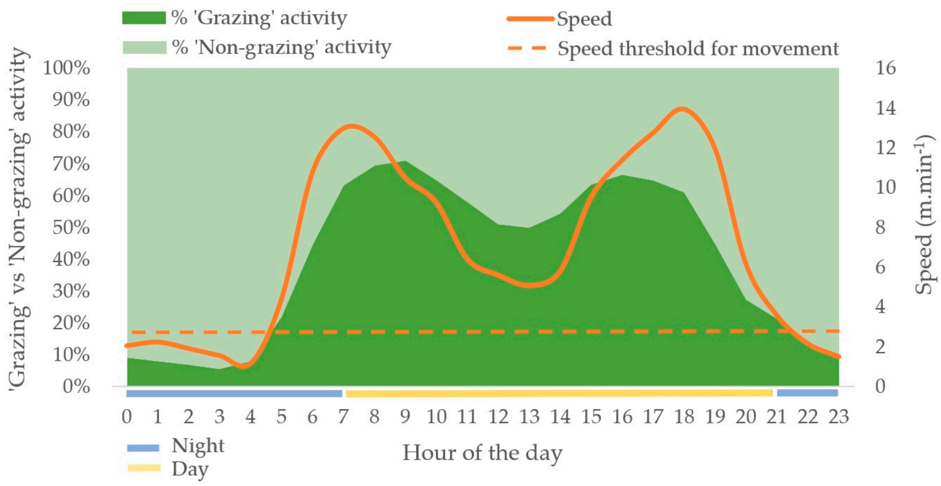

Figure 7. Hourly movement speed and hourly 'grazing vs. non-grazing' activity of the flock at Collarada mountain pastures (Central Pyrenees, Spain) across 2019, 2020, and 2021 during summer seasons. Error bars are not shown for clarity. Orange dotted line indicates 2.6 m.min^{-1} threshold for moving activity.

3.3. Body Condition of the Sheep

The overall BCS evaluated before moving to the mountain pastures had a three-year average value and standard deviation of 3.33 ± 0.63, compared to 2.68 ± 0.51 obtained the day after returning. This difference was significant (Wilcoxon paired samples test, $p < 0.01$). The result of BCS before and after the stay at the mountain pastures over the three years, and for the different categories considered in the study are shown in Table 2.

Table 2. Mean ± SD body condition score (BCS) of the flock grazing at Collarada mountain pastures (Central Pyrenees, Spain) before ascending and after descending at the end of the grazing period during the summer seasons of 2019, 2020, and 2021, along with the variation in BCS, expressed in both absolute values and percentages. Significant differences (Kruskal–Wallis test, $p < 0.05$) within the same column for each category (year, previous BCS, age, and physiological state) are indicated by different letters (a, b, c).

	Number of Sheep	BCS Before Ascending to the Mountain Pastures (Mean ± sd)	BCS After Descending from the Mountain Pastures (Mean ± sd)	BCS Variation During the Stay at the Mountain Pastures (Mean ± sd)	BCS Variation (%) During the Stay at the Mountain Pastures
Year					
2019	435	3.47 ± 0.47	2.73 ± 0.53	−0.74 ± 0.56 (a)	−21% (a)
2020	539	3.18 ± 0.70	2.58 ± 0.47	−0.59 ± 0.62 (b)	−16% (b)
2021	531	3.40 ± 0.64	2.73 ± 0.53	−0.64 ± 0.65 (a, b)	−17% (a, b)
Previous BCS					
Thin	91	1.89 ± 0.23	2.12 ± 0.45	0.40 ± 0.47 (a)	18%(a)
Normal	840	3.00 ± 0.32	2.57 ± 0.46	−0.44 ± 0.50 (b)	−15% (b)
Fat	574	3.99 ± 0.23	2.90 ± 0.50	−1.09 ± 0.50 (c)	−27% (c)
Age					
Young ewes	190	3.37 ± 0.48	2.55 ± 0.40	−0.83 ± 0.58 (a)	−24% (a)
Ewes	1204	3.32 ± 0.65	2.70 ± 0.51	−0.61 ± 0.61 (b)	−18% (b)
Old ewes	111	3.46 ± 0.63	2.67 ± 0.67	−0.80 ± 0.71 (a)	−23% (a)
Physiological state					
Non-pregnant	679	3.29 ± 0.61	2.68 ± 0.52	−0.61 ± 0.61 (a)	−18% (a)
Early gestation	483	3.29 ± 0.66	2.69 ± 0.47	−0.60 ± 0.62 (a)	−18% (a)
Advanced gestation	343	3.49 ± 0.59	2.65 ± 0.56	−0.82 ± 0.59 (b)	−24% (b)

Over the three years of the study, a decrease in BCS and in percentage of variation were observed. Differences between the three years were statistically significant (Kruskal–Wallis test, $p < 0.05$). In the year 2019, sheep lost more on average than in 2020; however, the BCS loss in 2021 was not significantly different from the previous years. Significant differences were found, both in BCS variation and percentage of variation with respect to the initial BCS, among the three weight categories (Kruskal–Wallis test, $p < 0.01$). 'Thin' sheep gained body condition, while sheep initially classified as 'fat', lost more body condition compared to the normal sheep. Significant differences were also found between age categories (Kruskal–Wallis, $p < 0.01$). Older and younger sheep lost the most body condition compared to ewes. Regarding physiological status, the differences were also significant (Kruskal–Wallis, $p < 0.01$). Sheep in advanced gestation lost more body condition compared to those in early gestation or non-pregnant sheep.

4. Discussion

Our findings reveal several key insights regarding the energy expenditure of locomotion, the daily activity patterns, and body condition variations of sheep in free grazing conditions at mountain pastures.

4.1. Distance Traveled by the Flock and Energy Expenditure of Locomotion

The average daily distance traveled by the flock was 9.4 km per day. This value is within the range 1.2–12.5 km/day of daily distance travelled found in other studies in different regions of the world [22]. The value of daily distance traveled by the flock at Collarada is higher than the distances reported in other studies in mountain ranges. Loridas et al. [54] estimated 4.5 km per day for flocks in Greek mountain pastures; however, this flock was penned at night, which may have affected the total daily distance traveled. Zanon et al. [27] reported 5.5 km per day for transhumant flocks in alpine pastures in Italy. Baum [24] found that sheep traveled an average of 6.9 km per day at a summer mountain range in Utah (US). The higher distances observed in our study may reflect the larger and more rugged terrain of the Collarada pastures. Baum [24] determined that sheep kept in larger pastures moved greater distances than sheep in smaller pastures, continuously moving for forage consumption.

Variation in daily distance traveled measures can be due to environmental factors, such as weather, or vegetation availability [22]. The maximum daily distance traveled by our flock was 12.6 km, recorded on a day when a strong storm occurred overnight. Consequently, the flock had to move to a safer, more remote area during the night, leading to an increase in the overall movement.

We observed an increase in distance traveled by the flock during the second half of the summer season. This is likely due to the need for sheep to travel further in search of fresh pastures and water, as natural water sources at higher elevations dry up, requiring the flock to move to lower areas with water troughs.

Sheep at pasture exhibit higher energy expenditure compared to confined conditions [45]. The average daily energy expenditure due to locomotion was found to be 3.20 MJ.day^{-1} over the 3 years of study. This value aligns with those reported in previous studies, where energy expenditure for locomotion at pasture ranges from 1.7 to 5.4 MJ.day^{-1} [45]. Zanon et al. [27] observed an average of 2.93 MJ.day^{-1} for sheep in mountain pastures in Italy during the summer months. Betrán et al. [46] estimated 4.2 MJ.day^{-1} during transhumance movements of flocks from the lowlands to the Pyrenees, highlighting increased energy expenditure during the movement of the flock towards the mountain pastures.

Notably, in our study, while the distance traveled did significantly vary, the energy expenditure associated with locomotion did not show significant differences across both years and months. This suggests that factors other than distance, such as terrain ruggedness, play a crucial role in determining the energy costs of locomotion, as has been observed in other similar species [55]. The Collarada mountain pastures are highly challenging for sheep due to the uneven landscape shaped by karstic formations. The smooth curves help us to visualize how energy demands evolved over the course of the summer. Energy expenditure rises during the first half of the period as the sheep progressively explore more terrain each day. It then slightly decreases, likely due to higher temperatures, before beginning to rise again around days 45 to 50, when sheep need to seek out fresher pastures [21].

The analysis of the potential relationship between energy expenditure and meteorological variables, such as total daily precipitation, average daily wind speed, and temperature, revealed no significant linear correlation. This indicates that the daily variations in energy expenditure were not influenced by these climatic factors. This result aligns with the findings of Armstrong and Robertson [56], who reported that ambient temperature and rainfall alone rarely impact the energy expenditure of free-ranging domestic sheep grazing in the U.K. hills, although they observed that wind greatly increased energetic costs in winter. While no linear relationship was observed, extreme values may significantly impact energy expenditure. The maximum energy expenditure over the three-year period occurred on the day with the lowest average temperature recorded on surface of the sheep and the second-lowest average temperature recorded by the nearest weather station. One limitation of this study was the inability to obtain meteorological data from a location close to the study area and at a comparable altitude, which may have impacted the accuracy of meteorological factor analyses related to sheep activity and energy expenditure. Additionally, the temperature measured at the sheep's surface may not provide a highly accurate value. This measurement could be affected by factors, such as the proximity of sheep to one another, which can lead to heat retention, as well as variations in posture, and exposure to direct sunlight. These variables may introduce inaccuracies in interpreting the relationship between temperature and energy expenditure. Access to local meteorological data could provide more precise insights into how weather conditions affect livestock behavior in mountain pastures.

4.2. Daily Flock Activity Patterns

In the present study, a bimodal pattern of daily activity of the flock was found. Movement activity began early in the morning, with a peak around 7 a.m., where the average speed reached 13 $m.min^{-1}$. This coincided with a significant increase in grazing behavior during the same period. The synchronization between movement and grazing activities suggests that sheep prioritize early morning foraging, likely to exploit the cooler temperatures and the moisture from morning dew. In addition, in the morning and evening, the light is dimmer, providing better camouflage from predators [57]. Moreover, the midday decline in both movement and grazing activities, particularly between 11 a.m. and 3 p.m. suggests that sheep reduce their activity during the hottest parts of the day to avoid heat stress and additionally take the opportunity to rest and ruminate. The resumption of movement and grazing activities in the late afternoon, with another peak in speed at around 6 p.m. (14 $m.min^{-1}$) and grazing activity between 3 and 7 p.m., reflects a bimodal grazing pattern. During the nighttime, both movement and grazing activities are significantly reduced, with speeds dropping below 2.5 $m.min^{-1}$ from 10 p.m. to 6 a.m. This low level of activity aligns with the natural resting phase observed in sheep, although on certain days, the livestock exhibit minimal nocturnal activity. These daily behavioral patterns of sheep demonstrate rhythms that are consistent with the findings of previous studies [58,59]. Plaza et al. [47] found that the flock activity fit a circadian rhythmicity influenced by day length and temperature. Sheep spend the majority of their time grazing, with grazing activity peaks in the early morning and late evening, with a bimodal distribution pattern [58–62].

In our study, the results showed that sheep spent 55% of daylight time grazing and 12% at nighttime. This value aligns with those found by Ikurior [15], who found, using a triaxial accelerometer, that sheep spent 64% of daylight time grazing, with grazing at night reduced to 14%. When sheep are not grazing, they spend their time in a variety of behaviors classified under the "non-grazing" category. These activities primarily include resting, during which the animals lie down or stand in a stationary position, often ruminating to process the forage consumed earlier. Additionally, sheep may move without grazing, transitioning between grazing areas or exploring their environment. Other behaviors include social interactions within the flock and occasional vigilance, where they raise their heads to scan their surroundings for potential threats.

The methodology using accelerometers and GPS devices provided valuable insights into the activity patterns of the sheep. The accelerometer data allowed for the classification of grazing activity based on vertical head movements, while GPS data were used to monitor movement. Synchronizing these data sources enabled a detailed understanding of the sheep's behavior. However, other methodologies have allowed for the differentiation of more specific activities. García-Gonzalez et al. [63], through direct observation, identified five types of activities: Stationary grazing, where sheep graze in specific areas with minimal movement; grazing while moving, where sheep feed while moving from one area to another; movement, where sheep move without grazing; resting, during which the flock rests, either standing or lying down, typically at night or during midday hours; and night activity, which includes both grazing and movement. Further research is needed to use accelerometers to distinguish additional activities.

4.3. Body Condition

Our results show a significant loss of body condition score during the summer season in mountain pastures. This result aligns with Revilla et al. [64], who studied the BCS at the beginning of spring grazing and summer mountain pasturing in the Pyrenees. The results of this work showed increases of BCS during spring grazing and BCS losses in the summertime.

Despite an average loss of 0.65 points in BCS for the whole summer stay in the mountain pastures, the mean value obtained at the end of each of the 3 summer seasons indicates an optimal body condition, as it fell within the range of 2.5 to 3.5 [30]. Sheep can lose 0.5 to 1 point in BCS depending on their starting point, with minimal impact on productivity [31].

The differences in body condition loss observed in 2019 could be attributed to the extended grazing period in the mountain pastures, as part of the flock remained there until late October. During this extra time, temperatures dropped, and pasture availability became increasingly scarce. In contrast, the descent occurred about one month earlier in 2020 and 2 weeks earlier in 2021. This may also explain the lack of differences in energy expenditure on locomotion among the three years, as the calculation was only based on the free-grazing period and free-grazing areas, which were similar across all years. In contrast, the body condition was assessed at the end of the whole summer grazing period, with some sheep grazing for a longer duration and in different areas, particularly in 2019, potentially influencing their final body condition. Sheep initially classified as 'fat' experienced a significantly greater loss in body condition compared to those classified as 'normal'. Despite this, both groups maintained an average nutritional state within the optimal range. Thinner sheep showed an increase in BCS, although they did not, on average, reach an optimal condition during their time in the mountain pastures. Among age groups, older and younger sheep exhibited the greatest body condition losses, but all remained within an optimal range. Although sheep in advanced gestation showed greater losses in body condition score, they generally remained within the optimal range.

This suggests that grazing on mountain pastures does not result in a relevant loss of body condition. Even if some age classes and sheep in certain initial conditions experience a significant loss during the stay in mountain pastures, they have the capacity for recovery quickly afterwards. Adequate nutrition and management practices are essential to support body condition recovery. Maintaining an optimal body condition is crucial for maximizing reproductive performance and overall health. However, based on the results of this study, it may be advisable for farmers to consider the body condition score of sheep when deciding which animals to send to the mountain pastures. Young and old ewes with a BCS below around 3.25 points might require additional evaluation to determine whether they are well-suited for grazing in such grasslands. For adult ewes aged 1 to 6 years, a slightly lower threshold, around 3 points, could be considered appropriate. Given the average BCS variation of −0.82 points, it could be prudent to avoid sending sheep in advanced gestation with an initial BCS below approximately 3.25 points to mountain pastures, as their condition could further decline to suboptimal levels.

5. Conclusions

This study provides valuable insights into the energy expenditure of locomotion, daily activity patterns, and body condition changes in sheep grazing freely at mountain pastures. Sheep traveled an average of 9.6 km per day, and the average daily energy expenditure due to locomotion was found to be 3.20 MJ. This study demonstrates that sheep in mountain pastures exhibit substantial energy expenditure and cover extensive distances daily, influenced by the rugged terrain and seasonal resource availability. The combination of GPS and accelerometer data provided valuable insights into sheep daily activity patterns, which followed a bimodal diurnal rhythm with grazing peaks during cooler periods in the morning and late afternoon and reduced activity during midday and nighttime, reflecting adaptive strategies to minimize heat stress. Body condition changes were moderate, with an average loss of 0.65 BCS points but maintenance within optimal ranges (2.5–3.5). Vulnerable groups, such as younger and older ewes or those in advanced gestation, exhibited higher body condition losses, highlighting the importance of targeted management to ensure recovery and welfare. Future research should focus on the effects of environmental factors, terrain, and forage quality to refine grazing strategies and improve livestock management in mountainous regions.

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Informed Consent Statement: We obtained consent from the four farmers whose animals were included in our study by explaining the purpose of the research and ensuring they fully understood the implications of their participation.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

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