Applied Animal Behaviour Science 298 (2026) 106935

Contents lists available at ScienceDirect

Applied Animal Behaviour Science

journal homepage: www.elsevier.com/locate/applanim

Weather and seasonal effects in behavioural patterns for grazing cattle

Gustavo Paixão [a,b,c,d,*], Fernando Mata [a,e], Joaquim Cerqueira [a,b,c], José Pedro Araújo [a,c,f]

[a] Center for Research in Agrifood Systems and Sustainability, Instituto Politécnico de Viana do Castelo, Viana do Castelo 4900-347, Portugal
[b] Veterinary and Animal Research Centre, Universidade de Trás-os-Montes e Alto Douro, Vila Real 5000-801, Portugal
[c] Escola Superior Agrária, Instituto Politécnico de Viana do Castelo, Viana do Castelo 4900-347, Portugal
[d] Escola Superior Agrária, Instituto Politécnico de Bragança, Bragança 5300-253, Portugal
[e] Estação Zootécnica Nacional, Instituto Nacional de Investigação Agrária e Veterinária, Vale de Santarém 2005-424, Portugal
[f] Mountain Research Centre, Instituto Politécnico de Viana do Castelo, Viana do Castelo 4900-347, Portugal

ARTICLE INFO

Keywords:
Cow
Heat stress
Minhota breed
Precision livestock farming
Seasonality
Temperature humidity index

ABSTRACT

Weather conditions influence grazing cattle behaviour, affecting activities like grazing, ruminating, and resting. Understanding these behavioural responses to temperature, humidity, wind, and solar radiation is essential for managing livestock welfare and productivity amid changing climate patterns. The study monitored 20 Minhota breed cattle year-round, from January 1 to December 31, 2024 using GPS-accelerometer collars in Northern Portugal. Behaviour and weather data were analysed via canonical correlation and Kruskal-Wallis tests to assess seasonal impacts on activity patterns and environmental influences. Significant differences ($p < 0.001$) were found between all the analysed behaviours between the seasons. Grazing and walking peaked in spring and summer, following greater pasture availability. Conversely, resting and rumination increased in autumn and winter, reflecting lower energy demands and greater reliance on roughage. All recorded behaviours were influenced by the temperature indexes and solar radiation ($p < 0.001$) and the temperature-humidity-sun-wind index correlated most strongly with resting time reductions (-0.62). Surprisingly, moderate heat stress did not suppress grazing and other behaviours like eating or playing. Rainfall negatively affected grazing while increasing rumination and resting ($p < 0.001$). Canonical correlation revealed strong links between behaviour and environment, and the two canonical covariate pairs (CCP) explain 79.9 % of the variation between the two sets of variables. Seasonal and heat-related factors shaped distinct activity-rest patterns, highlighting cattle's adaptive strategies and the importance of climate-aware livestock management. These findings highlight the need for climate-adaptive livestock management, including strategic feeding, shelter provision, and flexible grazing practices to mitigate climate change impacts.

1. Introduction

Environmental conditions and changes in climate patterns can significantly influence animal behaviour (Lamanna et al., 2025). The impact of weather on grazing animals such as cattle and sheep behaviour can be observed through metabolic behaviours: eating, playing, ruminating, grazing, resting, walking, and daily movement. Exposure to cold, wet, and windy climatic conditions can negatively affect the behaviour of cattle (Schütz et al., 2010; Hendriks et al., 2020; Neave et al., 2022), forcing them to spend most of their time sheltered (Cartes et al., 2021) under such conditions.

With increasing temperatures, more variable precipitation patterns and more frequent extreme events are expected. Thus, climate change is already negatively affecting livestock production (Cheng et al., 2022). Direct effects such as reduced productivity and heat stress (Thornton et al., 2022; North et al., 2023) or indirect effects like changes in feed availability and disease patterns (Ali et al., 2020), are already impacting animals (Ali et al., 2020). The impacts of these changes are primarily caused by behavioural and physiological responses to climatic conditions, which act as early indicators of climatic stress. Therefore, it is essential to understand the etiological relationships with the different meteorological events.

The Temperature-Humidity Index (THI) is a widely used metric to assess heat stress in cattle, combining air temperature and relative

* Corresponding author at: Center for Research in Agrifood Systems and Sustainability, Instituto Politécnico de Viana do Castelo, Viana do Castelo 4900-347, Portugal.
E-mail address: gustavopaixao@esa.ipvc.pt (G. Paixão).

https://doi.org/10.1016/j.applanim.2026.106935
Received 22 May 2025; Received in revised form 6 September 2025; Accepted 30 January 2026
Available online 6 February 2026
0168-1591/© 2026 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

humidity to evaluate weather conditions (Parrini et al., 2022; Nam et al., 2024). It was historically categorised into ranges to indicate varying levels of increasing heat stress; however, recently, a review combining multiple THI studies found that the median threshold for the onset of negative impacts was 68.8 (North et al., 2023). Wind speed and solar radiation have been integrated into newer indexes (Wang et al., 2018) with the possibility of more accurately assessing animal discomfort (Mader et al., 2006) such as the comprehensive climate index (Mader et al., 2010).

Innovative computer technologies that monitor animal behaviour have been developed, enabling their application in pastures and providing farmers with alarms (Dominiak and Kristensen, 2017), and real-time information for better decision-making (Tzanidakis et al., 2023). Wearable IoT devices such as activity monitors, calving detectors, and rumination trackers are one of the most used tools in modern livestock management (Lee and Seo, 2021). While these equipment's of Precision Livestock Farming (PLF) remain with high costs and some technological vulnerabilities, its potential for real-time monitoring, methane reduction, and more sustainable herd management, make them an excellent tool for climatic adaption strategies (Lamanna et al., 2025). Sensor-based systems in pasture-based livestock settings generally show accuracy rates ranging from 80 % to 95 % depending on the sensor type and placement (Asmare, 2022). Grazing, ruminating, and resting are the most studied behavioural activities in precision livestock farming (Decandia et al., 2018). The impact of climatic factors, including temperature, humidity, wind speed, and solar radiation on animals, must be studied within a broader context. Therefore, this study aimed to evaluate the effect of weather and seasonal factors on the behaviour of grazing cattle.

2. Material and methods

The study was conducted in a beef sucker herd farm located in Northern Portugal (41°47'01.4" N; 8°35'51.0" W). Calving occurs year-round. Calves are fed naturally by their mothers, supplemented with concentrated feed in selective feeders. The grazing system is rotational, and cows enter a new plot depending on the availability of grass. The animals were supplemented with grass hay-silage between November/December and February/March composed of *Lolium perenne*, *Festuca L.*, *Dactylis glomerata*, *Trifolium repens*, *Trifolium pratense*, and *Lotus corniculatus*.

The region experiences a warm and temperate climate with distinct seasons characterised by mild temperatures and significant yearly rainfall. The area averages about 1886 mm of rainfall annually, with July being the driest month (39 mm) and October the wettest (246 mm); it also enjoys an average of 10.4 h of sunshine in July, while temperatures range from lows around 5 °C in January to highs of about 26 °C in August.

According to the national (Ministério da Agricultura, 2019) and European (Comission, 2010) regulations on animal welfare in experimental research, no animals were used or intended to be used in any experimental procedures. Data were obtained from a previously fitted, commercially available GPS monitoring system for cattle, and therefore, ethical approval was waived.

2.1. Animals

A total of 20 animals (2 male and 18 female), all purebred Minhota cattle, a Portuguese autochthonous breed, were used in this study. The group of animals was on average 4-year-old and had 2.6 parities at the beginning of the study; all cows and heifers were pregnant or became pregnant during the study period (supplementary table). Animals were equipped with a 3-axis accelerometer GPS RUMI collars (https://innogando.com/rumi/) to monitor behaviour 24 h/day. Validation experiments for the RUMI device demonstrated robust performance in activity estimation, with accuracy values ranging from 80 % to 86 % for different behaviours (Ariztimuño, 2024). The animals did undergo an adaptation period of 30 days to ensure that the recorded behaviours were not influenced by initial discomfort or adjustment to the device. Activity data of the animals, measured in hours per day and number of steps per day, were recorded from January 1 to December 31, 2024. It must be noted that the registration of activities is exhaustive and the behaviours are independent, without overlaps. Per hour of registered activities, there are exactly 60 min of activities divided by those being registered. The prerequisites for the construction of an ethogram are, therefore, met. The different activities, registered in minutes per hour, are defined as follows:

- Resting – the animal is inactive (standstill), not ruminating, standing or lying down.
- Grazing – The animal browses and eats grass in the field. It may also be walking; however, the activity is registered as grazing.
- Walking – The animal is walking with its head standing, therefore not grazing.
- Ruminating – The animal is chewing the cud. The animal may be lying down, however, the activity is not registered as resting. Also, it is worth noting that chewing while eating is not registered as rumination.
- Other – The animal eats concentrate or roughage from the feeder/trough or drinks water from water troughs. The animal can also explore, play or engage in other uncategorized activities (e.g., keeping the flies away).

In addition, the number of steps counted was also registered.

2.2. Climatic parameters

Data from the meteorological station of ESA-IPVC (Davis Instruments: Mod. Vantage Pro2 Plus. Company: Wise Secrop - Wise connect SA) were collected every 15 min from January 1 to December 31, 2024. The retrieved parameters were temperature (minimum, maximum, and mean), humidity, wind (speed, direction, and high), rainfall (sum and rate), atmospheric pressure, solar radiation, and UV index. The heat index (HI) and Temperature-humidity-sun-wind index (THSW) are two indices that reflect the "real-feel" temperature. The THSW index is calculated as:

$$THSW = T + f(RH, SR, WS)$$

Where T is air temperature, RH is relative humidity, SR is solar radiation, and WS is wind speed. f(H, SR, WS) is a function that adjusts the temperature based on humidity, solar radiation, and wind speed (Davis Instruments, 2011). The HI index was calculated based on the methodology developed by Steadman (1979) as:

$$\begin{aligned} HI = & -42.379 + 2.04901523T + 10.14333127RH - 0.22475541T \\ & \times RH - 0.00683783T^2 - 0.05481717RH^2 \quad + 0.00122874T^2 \\ & \times RH + 0.00085282T \times RH^2 \quad - 0.00000199T^2 \times RH^2 \end{aligned}$$

Where T is air temperature and RH is relative humidity.

The THI was determined using the prediction model based on the NRC method (Council, 2001). The THI was calculated using the following formula:

$$THI = (1.8 \times T + 32) - [(0.55 - 0.0055 \times RH) \times (1.8 \times T_{db} - 26.8)]$$

Where T is temperature, RH is relative humidity, and T_{db} is dry-bulb temperature.

For the purposes of this study, the seasons were defined according to the conventional calendar as follows: winter (December 21 to March 19), spring (March 20 to June 20), summer (June 21 to September 20), and autumn (September 21 to December 20).

2.3. Statistical analysis

We started the statistical analysis by performing a canonical correlation between the two groups of variables (behaviours and environment). The two sets of variables include behaviours (resting, grazing, walking, ruminating, other and steps), and weather indices (HI, THI, and THSW). The prerequisites of the canonical correlation analysis, namely the multivariate normal distribution of the two sets of variables considered, were checked for multivariate normal distribution with Mardia's multivariate normality test. Multivariate normal distribution was confirmed ($p > 0.05$).

Following the canonical correlation, each behaviour variable was tested for significant differences using 'season' as a factor. Initially, ANOVA models were implemented, but data failed the prerequisites of homogeneity of variances (Levine's test $p > 0.05$) and normal distribution of the residuals (Kolmogorov-Smirnov $p > 0.05$). Consequently, a non-parametric approach was implemented, and data were analysed via Kruskal-Wallis tests followed by asymptotic significance post hoc tests adjusted by the Bonferroni correction.

Data cleaning and preparation were performed in Microsoft Excel for Microsoft 365 MSO, version 2204 Build 16.0.15128.20240, 64-bit. The canonical correlation analysis was performed using R Cran for Windows® version 4.4.2 (2024–10–31ucrt) – "Pile of Leaves"© 2024 The R Foundation for Statistical Computing, platform: x86_64-w64-mingw32/x64. The remaining statistical analysis was performed using the package IBM® SPSS® Statistics, Version 29.0.2.0 (20).

3. Results

The results of the canonical correlation (CC) analysis (presented in Table 1) determined that two canonical covariate pairs (CCP) are found to be significant. These explain 79.9 % (〚CC〛 _1^2 + 〚CC〛 _2^2) of the variation between the two sets of variables: behaviour (resting, grazing, walking, ruminating, other, and steps), and weather (HI, THI, and THSW). The standardised canonical correlation coefficients for the two sets of variables can be consulted in Table 2.

The intensity of the correlation between the individual variables within each of the two datasets analysed, together with the canonical correlations between these two datasets, are represented in Fig. 1.

As can be observed, the correlations are evident in both datasets, and particularly within the dataset with the environmental variables, the correlations are very strong. In the cross-correlation, there is also evidence of correlation between the variables in the sets of data.

In Fig. 2, we can observe the projection of the variables on the bidimensional space created by the two significant canonical covariate pairs (dimensions).

As observed, the weather variables have a strong and positive correlation. In contrast, in the group of behavioural variables, there is a negative correlation between the behavioural variables, implying spatial activity (steps, walking and grazing) and the others. As expected, the ruminating activity, as well as resting, are observed, while the animals are not spatially active. Therefore, these two behaviours can be understood as forming a group of spatially inactive behaviours in opposition to spatially active behaviours, to form the first dimension. Nevertheless, as explained in the methodology, it must be noted that if the animal is lying down and ruminating, the activity registered is rumination. No overlaps of behaviours are registered. The same is observed, for example, for walking and grazing; the animal may be walking without grazing, and the activity registered is walking. However, the animal may also be walking and grazing, and in such cases, the activity registered is grazing.

3.1. Season effects

Each first canonical covariate reveals a good discrimination of both sets of variables, behavioural and environmental, according to the seasons, winter, spring, summer and autumn. The representation of this discrimination can be found in Fig. 3. As can be observed, in both the behavioural and the weather variables, winter and summer have higher levels of opposition, while spring and autumn reveal an intermediary positioning. The spread observed in the environmental indices in the spring has the same impact in terms of the behavioural pattern spread observed. The higher concentration in the environmental indices observed in the autumn also results in a higher concentration of behavioural patterns in the same season. Fig. 4 represents the projection of the observations in the first canonical covariate pair, and the discrimination of seasons observed before is confirmed. Overall, the summer is the season with the best discrimination from all the other, as the degree of overlap between winter, spring, and autumn is higher when compared to that of the summer and the other seasons.

The analysis of the individual behaviours function of the different seasons is presented in Table 3. As can be observed, significant differences ($p < 0.001$) were found between all the analysed behaviours between the seasons. Individual behavioural differences between seasons can also be seen in Fig. 5. The number of steps is higher in the spring and lower in the autumn and winter, which correlates perfectly with walking activity. Grazing increases during spring, reaching its peak in summer, then decreases in autumn, reaching its minimum in winter. Conversely, the resting and ruminating behaviours increase during the autumn and winter.

3.2. Weather effects

The THI values exceeded the threshold value of 68.8 during 51 days (maximum: 77.71), the majority occurring during the summer. In contrast, the THI reached its minimum value of 37.02 during the winter.

All recorded behaviours were influenced by the HI, THI, THSW and solar radiation ($p < 0.001$) (Fig. 6). In the case of rainfall, only walking ($p = 0.186$) and, consequently, the number of steps were not significantly ($p = 0.120$) affected by rainfall. For wind, no correlations were found with resting ($p = 0.379$) and ruminating ($p = 0.933$). Resting was negatively correlated with HI (-0.60), THI (-0.58), THSW (-0.62), and solar radiation (-0.54) and positively with rainfall (0.22). Ruminating followed a similar pattern, being negatively correlated with HI (-0.43), THI (-0.44), THSW (-0.48) and solar radiation (-0.59), and positively with rainfall (0.35). Grazing, walking, and other behaviours exhibited moderate positive correlations with THI (0.46, 0.35, and 0.58), THSW and solar radiation (0.50, 0.54, and 0.64). Rainfall negatively influenced grazing (-0.38; $p < 0.001$) and other activities (-0.15; $p = 0.052$), but had no significant effect on walking. The wind showed the lowest correlations among the parameters analysed. In summary, negative correlations are more strongly associated with resting and rumination, except in the case of rainfall and wind during grazing (Fig. 6). These results

Table 1
Canonical covariates extracted from the canonical correlation analysis between the behavioural (resting, grazing, walking, ruminating, other and steps) and environmental variables (heat, temperature-humidity, and temperature-humidity-sun-wind indices).

CCP	CC	CC^2	Eigenvalue	Wilks Λ	F	Num df	Den df	p-value
1	0.825	0.681	2.124	0.282	31.691	18	1010	< 0.001
2	0.344	0.118	0.134	0.881	4.703	10	716	< 0.001
3	0.040	0.002	0.002	0.998	0.147	4	359	0.964

CCP – Canonical covariate pairs, CC – Canonical correlation, Num – numerator, Den – denominator, df – degrees of freedom

Table 2
Standardised canonical correlation coefficients for the two sets of variables.

Behaviour variables				Environmental variables			
Variable	1	2	3	Variable	1	2	3
Resting	0.576	-0.948	-2.265	HI	-0.782	11.082	2.444
Grazing	0.051	-0.991	-2.149	THI	2.383	-6.727	-7.420
Walking	-0.054	0.549	-2.108	THSW	-2.530	-4.323	4.597
Ruminating	0.521	-0.323	-2.314				
Other	-0.501	.0018	-1.808				
Steps	0.360	-1.392	1.338				

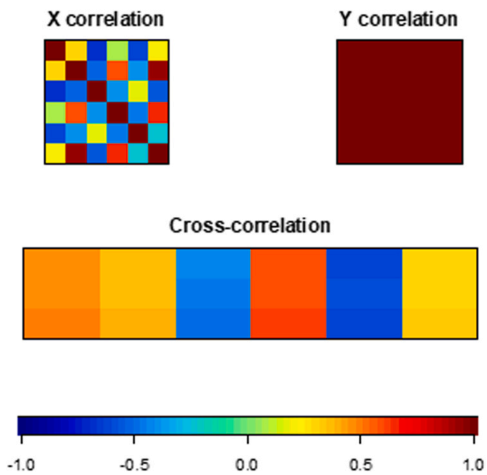

Fig. 1. View of the overall correlation structure within and between the two datasets analysed. X represents the dataset with the behaviour (resting, grazing, walking, ruminating, other, and steps), and Y represents the environment variables (heat, temperature-humidity, and temperature-humidity-sun-wind indices).

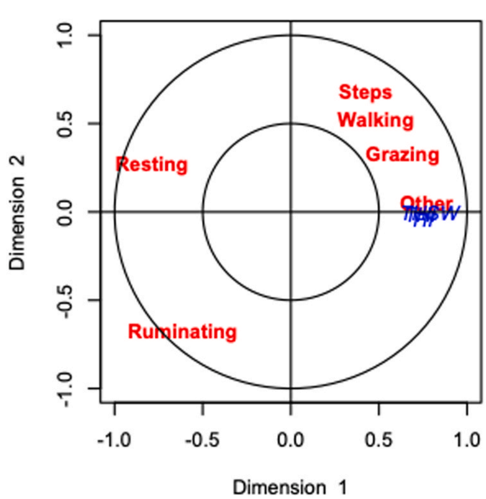

Fig. 2. Canonical correlation circle plot on the space created by the two significant canonical covariate pairs (dimensions), where the maximised correlations between the transformed variables of the behavioural and environmental variables' datasets. To note the overlap between the variables of the environmental dataset: heat (HI), temperature-humidity (THI), and temperature-humidity-sun-wind (THSW) indices (in blue).

suggest that adverse weather conditions negatively affect grazing activity. Conversely, higher weather indices and increased sunshine are linked to less active behaviours, such as resting and ruminating, while the opposite trend is observed for more active behaviours, including walking and grazing.

4. Discussion

4.1. Seasonal effects on behaviour

Seasonality has a significant impact on cattle behaviour. Winter and summer exhibited the most distinct behavioural and environmental patterns, whereas spring and autumn were intermediary seasons. The number of steps taken was highest in spring and lowest in autumn and winter, mirroring walking activity. Grazing increased during spring, peaked in summer, and declined during autumn and winter. In contrast, resting and ruminating behaviours were most prominent in colder seasons, suggesting an impact of changes in forage availability. Spring and summer seasons coincide with the pastures' vegetative activity; therefore, the availability of grazing pastures is higher in these seasons. On the other hand, in the autumn and winter, pastures enter dormancy and their grazing availability decreases.

The annual reproductive cycle favours summer mattings, aiming for spring calving. As a result, autumn and winter coincide with lower nutritional requirements, while spring and summer coincide with the suckling period, where the demand for nutrients is higher (Briggs et al., 2022; Yu et al., 2024).

These seasonal variations can, therefore, be explained by the physiological and metabolic adaptations of cattle to temperature fluctuations. Increased grazing activity in warmer months likely corresponds to higher nutritional requirements, forage availability and longer daylight hours, while elevated resting and ruminating behaviours during colder months align with previous findings that suggest cattle reduce movement to minimise energy expenditure in low temperatures combined with windy conditions (Bargeman, 2017).

4.2. Effects of environmental variables

Heat stress in cattle occurs when they cannot effectively dissipate body heat, leading to increased body temperature and physiological stress (Brown-Brandl, 2018; Habimana et al., 2023). This condition can result in reduced feed intake, decreased milk production, impaired fertility, and increased susceptibility to diseases, significantly impacting the health, welfare, and productivity of dairy and beef cattle (Oliveira et al., 2025). Changes in their behaviour will accompany these physiological effects (Leliveld et al., 2023). Studies have demonstrated behavioural coping strategies, such as increased water intake, reduced feed intake, longer standing periods (Lovarelli et al., 2020), and decreased rumination (Jurkovich et al., 2024). In our study, we evaluated rumination, and the result was similar to those of previous studies. Rumination time is negatively affected by increased temperature, humidity, and solar radiation.

The impact of climatic factors was particularly evident in response to temperature humidity-based indices and solar radiation. The correlations were higher in the THSW, which combines temperature, humidity, sun and wind. However, the difference to the other indices, HI and THI, is minor, proving that THI is still a reliable animal production indicator, even in outdoor settings. In our study, the THI exceeded the stress threshold of 68.8 (North et al., 2023) on 51 days. Maximum THI values consistently reached and exceeded 77, the upper end of a range that

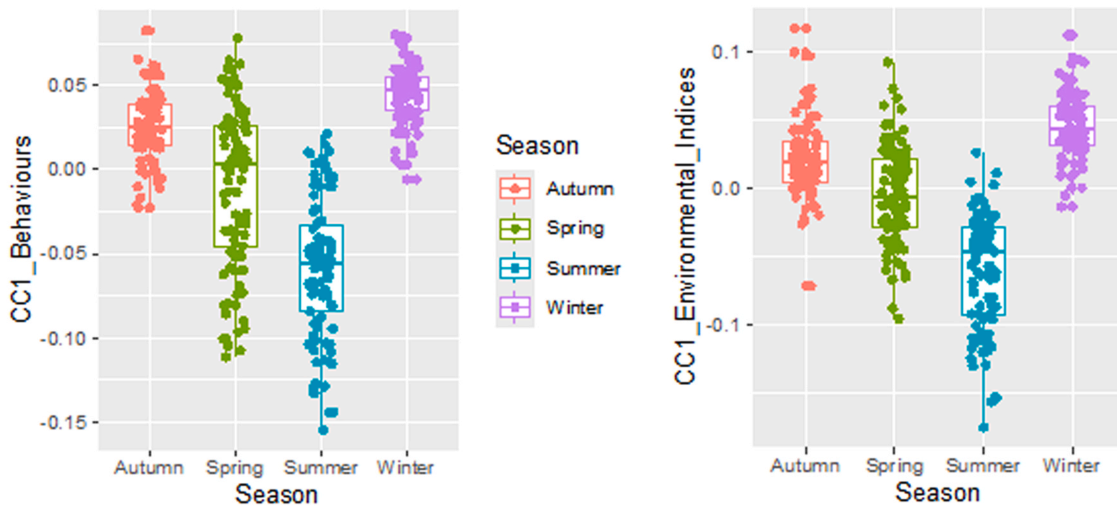

Fig. 3. Quartiles of the seasonal discrimination obtained by the first individual canonical covariate. Left – Behavioural variables; Right -Environmental variables.

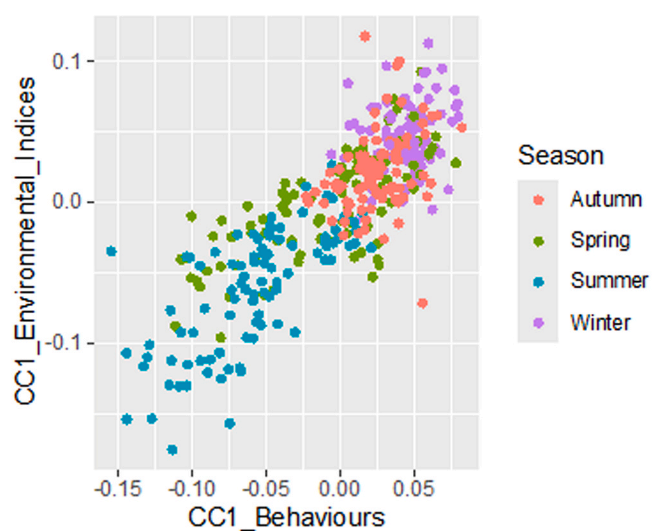

Fig. 4. Seasonal discrimination obtained by the first canonical covariate pair explaining 68,1 % of the variability within the variables.

(Gaughan et al., 1999) identified as indicative of moderate heat stress in livestock. Surprisingly, these periods coincided with increased grazing and other activities such as eating or playing behaviours, suggesting that cattle remained active under moderate heat stress. In fact, the overall animal activity (n° of steps) was positively correlated with temperature, humidity and solar exposure. These results contradict the published literature and might be explained by the moderately higher values. The observed behavioural persistence under moderate THI values suggests behavioural resilience, though physiological markers would be required to confirm adaptive capacity. High-yield dairy cattle are more susceptible to heat stress than low-producing cows (Gaughan et al., 2018). More extreme THI values would have impacted the feeding activities (Bargeman, 2017; Parrini et al., 2022; Thornton et al., 2022), and therefore reduced the time spent grazing.

Nonetheless, these results are consistent with the findings of Idris (Idris et al., 2023), which demonstrated that cattle exhibited increased movement (walking activity) under hot conditions. This finding can also be the result of animals seeking tree cover shade or because forage allowance was lower (Sawalhah et al., 2016).

Rain can influence cattle behaviour. Most of the literature focuses on lying time, which, similarly to temperature-humidity, seems to reduce it (Lovarelli et al., 2020; Schütz et al., 2010; Tullo et al., 2019). In this study, daily rainfall influenced cattle behaviour, with a negative relation to grazing, reflecting cattle's tendency to reduce foraging during wet conditions (Hessle et al., 2008). However, to a lesser extent, rainfall also appears to be related to increased resting and rumination time.

4.3. *Implications for livestock management*

The findings highlight the importance of climate-adaptive management strategies in livestock farming. Given the expected increase in extreme weather events due to climate change, farmers must implement mitigation strategies to support cattle welfare. Providing natural or artificial shelter (Van laer et al., 2014), optimising nutrition (Most and Yates, 2021) and water troughs availability, and monitoring heat stress indices (Islam et al., 2021) can help reduce the adverse effects of high temperatures.

The integration of wearable sensors and machine learning into cattle management systems creates a comprehensive approach and enables

Table 3
Medians of the different behavioural variables across the different seasons. The significant differences were tested with a Kruskal-Wallis test, and asymptotic significance post hoc tests were adjusted by the Bonferroni correction.

Variable	Units	Test statistic	df	p-values	medians			
					Winter	Spring	Summer	Autumn
Resting	Hours/day	146.33	3	< 0.001	6.42^{c}	5.45^{b}	3.24^{a}	5.35^{b}
Grazing	Hours/day	101.93	3	< 0.001	3.19^{a}	5.91^{b}	6.95^{c}	5.18^{b}
Walking	Hours/day	56.79	3	< 0.001	0.26^{a}	0.48^{c}	0.39^{b}	0.30^{a}
Ruminating	Hours/day	109.55	3	< 0.001	9.14^{c}	6.57^{a}	7.05^{b}	8.55^{c}
Other	Hours/day	68.71	3	< 0.001	4.46^{b}	$4.95^{b,c}$	5.30^{c}	4.01^{a}
Steps	Number/hour	74.33	3	< 0.001	148.89^{a}	219.46^{c}	181.24^{b}	142.49^{a}

Different letters in superscript in the same row are indicative of significant differences ($p < 0.05$).

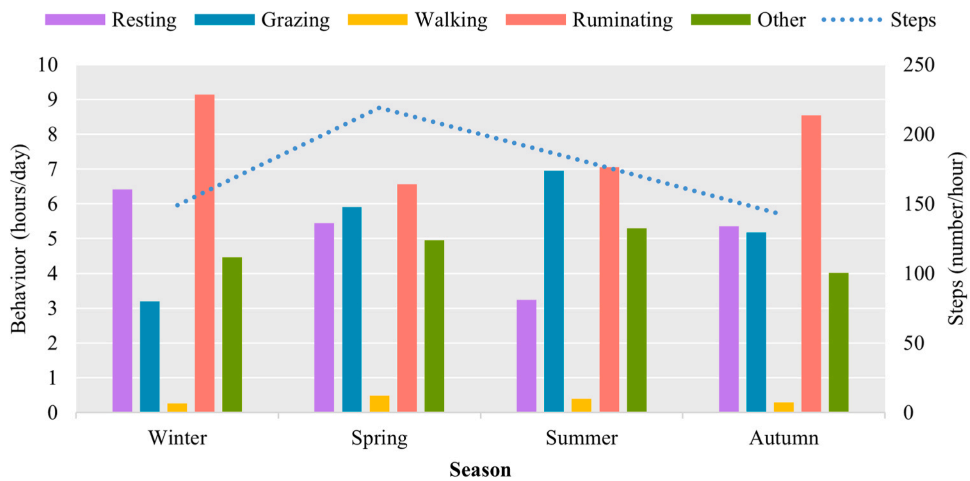

Fig. 5. Medians of the different behaviours of the whole herd by season.

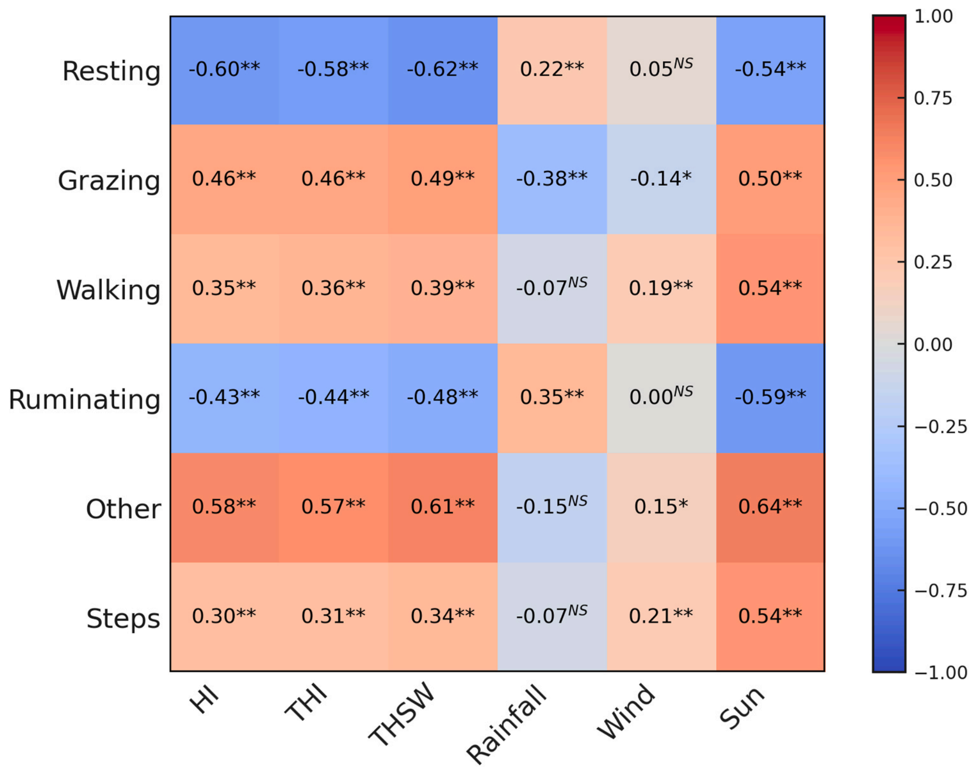

Fig. 6. Correlation heatmap between behaviour and weather parameters.

continuous monitoring of animal stress indicators, allowing for timely and informed decision-making (Han and Lin, 2022).

The seasonal variations in behaviour indicate that livestock management strategies must be adapted to suit the differing needs of cattle across the seasons. The increased grazing and walking activity observed in spring and summer agrees with higher forage availability, and this should coincide with greater nutritional requirements during the suckling period; most extensive systems in Northern Portugal, however, have all-year-round breeding (Araujo et al., 2014), which may pose limitations on taking ad-vantage of this aspect. During spring, pasture management should focus on ensuring optimal grass growth and production of conserved forages (hay and silage). Supplementation with concentrate feed may be necessary to meet the heightened nutritional requirements.

On the other hand, should calving spring be targeted, the autumn and winter months are characterised by reduced activity and increased resting and ruminating behaviours, which should reflect a shift to maintenance-level nutrition and a greater reliance on conserved forages such as hay and silage. During this period, feeding strategies could focus on maintaining body condition without overfeeding, ensuring sufficient roughage intake to support rumination and digestive health. Shelter provision and bedding may also become more critical to support the animals' comfort and minimise energy expenditure in response to lower temperatures and adverse weather conditions.

Heat stress may present a growing challenge, as climate change is expected to increase the frequency of extreme weather events. While the animals used in this study appeared to maintain eating, grazing and social behaviour during periods of moderate heat stress, it remains essential to provide strategies to mitigate its impact. These may include access to shade, improved ventilation in housing systems, and ensuring a continuous water supply to support thermoregulation.

Rainfall was also found to influence behaviour, particularly reducing grazing activity and increasing time spent resting and ruminating. This suggests the need for flexible grazing plans and potentially providing sheltered areas or covered feeding stations during wet weather to maintain consistent intake and reduce discomfort.

4.4. Study limitations

The accuracy of motion sensors used in livestock is greatly evolving (Biszkup et al., 2024). Nevertheless, these accelerometer-based devices still have room to improve, as reported accuracies in the literature vary (González et al., 2015; Andriamandroso et al., 2016; Giovanetti et al., 2017). Therefore, some behaviour misreading may have been registered. The motion sensors used in this study do not differentiate between lying and standing time, which would have been further interesting in analysing the cattle's behaviour in relation to the weather experienced. In addition, the study was restricted to a single breed and geographic location, which may limit the generalizability of the findings to other cattle breeds or agroclimatic regions

5. Conclusions

The canonical correlation analysis identified strong associations between behavioural and environmental variables, with two canonical variate pairs explaining most of the variation. Climatic factors (HI, THI, THSW) exhibited strong internal correlations, while behavioural variables followed distinct activity-rest patterns influenced by seasonal and weather effects. Winter and summer showed the most distinct behavioural and environmental profiles, while spring and autumn served as transition periods. Walking and grazing activities peaked in spring and summer, whereas resting and ruminating dominated in autumn and winter, suggesting adaptive thermoregulatory strategies. Weather variables played a key role, with heat indices and solar radiation reducing resting and ruminating but increasing foraging activities, particularly in summer. Rainfall suppressed grazing and other activities, while wind had minimal impact. This study emphasises the nexus interplay between behaviour and environmental conditions, highlighting the need for seasonal and weather-driven adaptations. Further research should explore individual variability and long-term climatic impacts to improve animal welfare and productivity.

CRediT authorship contribution statement

José Pedro Araújo: Writing – review & editing, Validation, Data curation. **Joaquim Cerqueira:** Writing – review & editing, Supervision. **Gustavo Paixão:** Writing – original draft, Methodology, Conceptualization. **Fernando Mata:** Writing – original draft, Formal analysis.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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

Acknowledgments

The authors sincerely thank NaturalMinho for supporting the field work and Innogando for providing the GPS collars. Centre for Research and Development in Agrifood Systems and Sustainability is supported by Fundação para a Ciência e a Tecnologia (FCT, Portugal) (UIDB/05937/2020 DOI:10.54499/UIDB/05937/2020 and UIDP/05937/2020 DOI:10.54499/UIDP/05937/2020).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.applanim.2026.106935.

Data availability

The data supporting this study's findings are available from the corresponding author upon reasonable request.

References

Ali, M.Z., Carlile, G., Giasuddin, M., 2020. Impact of global climate change on livestock health: Bangladesh perspective. Open Vet. J. 10, 178–188. https://doi.org/10.4314/ovj.v10i2.7.

Andriamandroso, A.L.H., Bindelle, J., Mercatoris, B., Lebeau, F., 2016. A review on the use of sensors to monitor cattle jaw movements and behavior when grazing. Biotechnol. Agron. Soci. été Et. Environ. 20. https://doi.org/10.25518/1780-4507.13058.

Araujo, J.P., Cerqueira, J., Santos Vaz, P., Andrade, L., J, V.-R., Am, R., 2014. Extensive beef cattle production in Portugal. International Worskshop "New updates in Animal Nutrition. Natural Feeding Sources and Environmental Sustainability, Arzachena, Sardinia (Italy).

Ariztimuño, J., 2024. Validación del dispositivo RUMI para la recogida automática de la actividad de pastar en ganado vacuno. Escuela Técnica Superior de Ingeniería Agronómica y Biociencia. Universidad Pública de Navarra.

Asmare, B., 2022. A Review of Sensor Technologies Applicable for Domestic Livestock Production and Health Management. Adv. Agric. 2022, 1599190. https://doi.org/10.1155/2022/1599190.

Bargeman, E.S., 2017. Cows seek tree cover in South American grasslands during hot and windless, and cold and windy conditions. Wageningen University.

Biszkup, M., Vásárhelyi, G., Setiawan, N.N., Márton, A., Szentes, S., Balogh, P., Babay-Török, B., Pajor, G., Drexler, D., 2024. Detectability of multi-dimensional movement and behaviour in cattle using sensor data and machine learning algorithms: Study on a Charolais bull. Artif. Intell. Agric. 14, 86–98. https://doi.org/10.1016/j.aiia.2024.11.002.

Briggs, E.A., Holder, A.L., Gross, M.A., Moehlenpah, A.N., Taylor, J.D., Reuter, R.R., Foote, A.P., Goad, C.L., Lalman, D.L., 2022. Retained energy in lactating beef cows; effects on maintenance energy requirement and voluntary feed intake. Transl. Anim. Sci. 6, txac120. https://doi.org/10.1093/tas/txac120.

Brown-Brandl, T.M., 2018. Understanding heat stress in beef cattle. Rev. Bras. De. Zootec. 47. https://doi.org/10.1590/rbz4720160414.

Cartes, D., Strappini, A., Sepúlveda-Varas, P., 2021. Provision of shelter during the prepartum period: Effects on behavior, blood analytes, and health status in dairy cows in winter. J. Dairy Sci. 104, 3508–3521. https://doi.org/10.3168/jds.2020-19439.

Cheng, M., McCarl, B., Fei, C., 2022. Climate Change and Livestock Production: A Literature Review. Atmosphere 13, 140. https://doi.org/10.3390/atmos13010140.

Comission, E., 2010. Diretiva 2010/63/UE relativa à Proteção Dos. animais Util. Para. fins Cient. íficos.

Council, N.R., 2001. Nutrient requirements of dairy cattle: 2001 (Nutrition, C.o.A., Nutrition, S.o.D.C.). National Academies Press.

Davis Instruments, 2011. Vantage Pro2 Console Manual. Document Part Number: 07395.234. Rev. J, 2/14/11. Davis Instruments, 3465 Diablo Avenue, Hayward, CA, 94545–2778 U.S.A.

Decandia, M., Giovanetti, V., Molle, G., Acciaro, M., Mameli, M., Cabiddu, A., Cossu, R., Serra, M.G., Manca, C., Rassu, S.P.G., Dimauro, C., 2018. The effect of different time epoch settings on the classification of sheep behaviour using tri-axial accelerometry. Comput. Electron. Agric. 154, 112–119. https://doi.org/10.1016/j.compag.2018.09.002.

Dominiak, K.N., Kristensen, A.R., 2017. Review: Prioritizing alarms from sensor-based detection models in livestock production - A review on model performance and alarm reducing methods, 133, 46. https://doi.org/10.1016/j.compag.2016.12.008.

Gaughan, J.B., Mader, T.L., Holt, S.M., Josey, M.J., Rowan, K.J., 1999. Heat tolerance of Boran and Tuli crossbred steers. J. Anim. Sci. 77, 2398–2405. https://doi.org/10.2527/1999.7792398x.

Gaughan, J.B., Sejian, V., Mader, T.L., Dunshea, F.R., 2018. Adaptation strategies: ruminants. Anim. Front. 9, 47–53. https://doi.org/10.1093/af/vfy029.

Giovanetti, V., Decandia, M., Molle, G., Acciaro, M., Mameli, M., Cabiddu, A., Cossu, R., Serra, M.G., Manca, C., Rassu, S.P.G., Dimauro, C., 2017. Automatic classification system for grazing, ruminating and resting behaviour of dairy sheep using a tri-axial accelerometer. Livest. Sci. 196, 42–48. https://doi.org/10.1016/j.livsci.2016.12.011.

González, L.A., Bishop-Hurley, G.J., Handcock, R.N., Crossman, C., 2015. Behavioral classification of data from collars containing motion sensors in grazing cattle. Comput. Electron. Agric. 110, 91–102. https://doi.org/10.1016/j.compag.2014.10.018.

Habimana, V., Nguluma, A.S., Nziku, Z.C., Ekine-Dzivenu, C.C., Morota, G., Mrode, R., Chenyambuga, S.W., 2023. Heat stress effects on milk yield traits and metabolites and mitigation strategies for dairy cattle breeds reared in tropical and sub-tropical countries. Front. Vet. Sci. 10. https://doi.org/10.3389/fvets.2023.1121499.

Han, X., Lin, Z., 2022. AI Based Digital Twin Model for Cattle Caring. Sens. (Basel Switz.) 22. https://doi.org/10.3390/s22197118.

Hendriks, S.J., Phyn, C.V.C., Turner, S.-A., Mueller, K.R., Kuhn-Sherlock, B., Donaghy, D. J., Huzzey, J.M., Roche, J.R., 2020. Effect of weather on activity and lying behaviour in clinically healthy grazing dairy cows during the transition period. Anim. Prod. Sci. 60, 148–153. https://doi.org/10.1071/AN18569.

Hessle, A., Rutter, M., Wallin, K., 2008. Effect of breed, season and pasture moisture gradient on foraging behaviour in cattle on semi-natural grasslands. Appl. Anim. Behav. Sci. 111, 108–119. https://doi.org/10.1016/j.applanim.2007.05.017.

Idris, M., Gay, C.C., Woods, I.G., Sullivan, M., Gaughan, J.B., Phillips, C.J.C., 2023. Automated Quantification of the Behaviour of Beef Cattle Exposed to Heat Load Conditions. Animals. https://doi.org/10.3390/ani13061125.

Islam, M.A., Lomax, S., Doughty, A., Islam, M.R., Jay, O., Thomson, P., Clark, C., 2021. Automated Monitoring of Cattle Heat Stress and Its Mitigation. Front. Anim. Sci. 2. https://doi.org/10.3389/fanim.2021.737213.

Jurkovich, V., Hejel, P., Kovács, L., 2024. A Review of the Effects of Stress on Dairy Cattle Behaviour. Animals (20762615) 14, 2038. https://doi.org/10.3390/ani14142038.

Lamanna, M., Bovo, M., Cavallini, D., 2025. Wearable Collar Technologies for Dairy Cows: A Systematized Review of the Current Applications and Future Innovations in Precision Livestock Farming. Animals 15, 458. https://doi.org/10.3390/ani15030458.

Lamanna, M., Muca, E., Giannone, C., Bovo, M., Boffo, F., Romanzin, A., Cavallini, D., 2025. Artificial intelligence meets dairy cow research: Large language model's application in extracting daily time-activity budget data for a meta-analytical study. J. Dairy Sci. 108, 10203–10219. https://doi.org/10.3168/jds.2025-26385.

Lee, M., Seo, S., 2021. Wearable Wireless Biosensor Technology for Monitoring Cattle: A Review. Animals 11, 2779. https://doi.org/10.3390/ani11102779.

Leliveld, L.M.C., Finzi, A., Riva, E., Provolo, G., Lovarelli, D., 2023. Effects of cow reproductive status, parity and lactation stage on behaviour and heavy breathing indications of a commercial accelerometer during hot weather conditions. Int. J. Biometeorol. 67, 1263–1272. https://doi.org/10.1007/s00484-023-02496-2.

Lovarelli, D., Tamburini, A., Mattachini, G., Zucali, M., Riva, E., Provolo, G., Guarino, M., 2020. Relating Lying Behavior With Climate, Body Condition Score, and Milk Production in Dairy Cows. Front. Media S. A. https://doi.org/10.3389/fvets.2020.565415.

Mader, T.L., Davis, M.S., Brown-Brandl, T., 2006. Environmental factors influencing heat stress in feedlot cattle1,2. J. Anim. Sci. 84, 712–719. https://doi.org/10.2527/2006.843712x.

Mader, T.L., Johnson, L.J., Gaughan, J.B., 2010. A comprehensive index for assessing environmental stress in animals1. J. Anim. Sci. 88, 2153–2165. https://doi.org/10.2527/jas.2009-2586.

Ministério da Agricultura, 2019. Decreto-Lei n.o 1/2019, de 10 de Janeiro. Diário da República n.º 7/2019, Série I de 2019-01-10, 3.

Most, M.S., Yates, D.T., 2021. Inflammatory Mediation of Heat Stress-Induced Growth Deficits in Livestock and Its Potential Role as a Target for Nutritional Interventions: A Review. Animals 11, 3539. https://doi.org/10.3390/ani11123539.

Nam, K.T., Choi, N., Na, Y., Choi, Y., 2024. Effect of the Temperature–Humidity Index on the Productivity of Dairy Cows and the Correlation between the Temperature–Humidity Index and Rumen Temperature Using a Rumen Sensor. Animals 14, 2848. https://doi.org/10.3390/ani14192848.

Neave, H.W., Schütz, K.E., Dalley, D.E., 2022. Behavior of dairy cows managed outdoors in winter: Effects of weather and paddock soil conditions. J. Dairy Sci. 105, 8298–8315. https://doi.org/10.3168/jds.2022-21819.

North, M.A., Franke, J.A., Ouweneel, B., Trisos, C.H., 2023. Global risk of heat stress to cattle from climate change. Environ. Res. Lett. 18, 094027. https://doi.org/10.1088/1748-9326/aceb79.

Oliveira, C.P., Sousa, F.C., Silva, A.L.D., Schultz, É., B., Valderrama Londoño, R.I., Souza, P.A.R., 2025. Heat Stress in Dairy Cows: Impacts, Identification, and Mitigation Strategies-A Review. Anim. (Basel) 15. https://doi.org/10.3390/ani15020249.

Parrini, S., Sirtori, F., Fabbri, M.C., Dal Prà, A., Crovetti, A., Bozzi, R., 2022. Effects of a Ceiling Fan Ventilation System and THI on Young Limousin Bulls' Social Behaviour. Animals 12, 1259. https://doi.org/10.3390/ani12101259.

Sawalhah, M.N., Cibils, A.F., Maladi, A., Cao, H., Vanleeuwen, D.M., Holechek, J.L., Black Rubio, C.M., Wesley, R.L., Endecott, R.L., Mulliniks, T.J., Petersen, M.K., 2016. Forage and Weather Influence Day versus Nighttime Cow Behavior and Calf Weaning Weights on Rangeland. Rangel. Ecol. Manag. 69, 134–143. https://doi.org/10.1016/j.rama.2015.10.007.

Schütz, K.E., Clark, K.V., Cox, N.R., Matthews, L.R., Tucker, C.B., 2010. Responses to short-term exposure to simulated rain and wind by dairy cattle: time budgets, shelter use, body temperature and feed intake. Anim. Welf. 19, 375–383. https://doi.org/10.1017/S0962728600001858.

Steadman, R.G., 1979. The Assessment of Sultriness. Part I: A Temperature-Humidity Index Based on Human Physiology and Clothing Science. J. Appl. Meteorol. 18 (7), 861–873. https://doi.org/10.1175/1520-0450(1987)026<0322:IOITIT>2.0.CO;2.

Thornton, P., Nelson, G., Mayberry, D., Herrero, M., 2022. Impacts of heat stress on global cattle production during the 21st century: a modelling study. Lancet Planet. Health 6, e192–e201. https://doi.org/10.1016/S2542-5196(22)00002-X.

Tullo, E., Mattachini, G., Riva, E., Finzi, A., Provolo, G., Guarino, M., 2019. Effects of Climatic Conditions on the Lying Behavior of a Group of Primiparous Dairy Cows. Anim. (Basel) 9. https://doi.org/10.3390/ani9110869.

Tzanidakis, C., Tzamaloukas, O., Simitzis, P., Panagakis, P., 2023. Precision Livestock Farming Applications (PLF) for Grazing Animals. Agriculture 13, 288. https://doi.org/10.3390/agriculture13020288.

Van laer, E., Moons, C.P.H., Sonck, B., Tuyttens, F.A.M., 2014. Importance of outdoor shelter for cattle in temperate climates. Livest. Sci. 159, 87–101. https://doi.org/10.1016/j.livsci.2013.11.003.

Wang, X., Bjerg, B.S., Choi, C.Y., Zong, C., Zhang, G., 2018. A review and quantitative assessment of cattle-related thermal indices. J. Therm. Biol. 77, 24–37. https://doi.org/10.1016/j.jtherbio.2018.08.005.

Yu, T., Yan, R., Xin, X., Zhang, X., Yin, G., 2024. Simulation of the nutritional requirements and energy balance of adult cows in a northern temperate grassland. Front. Vet. Sci. 11. https://doi.org/10.3389/fvets.2024.1414096.