Associations between space-use behaviour and temperature-humidity index in barn-housed dairy cows

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Abstract

Cattle may modify their space-use behaviour as thermal conditions change within their environment. Here we examined the relationship between the temperature-humidity index (THI) and various space-use metrics in a UK barn-housed dairy cow herd. Using a real-time local positioning system, as part of a precision livestock farming (PLF) approach, we continuously tracked the spatial position and activity of cows at high temporal resolution from 1st June to 1st December 2024. Localised ambient barn temperature and relative humidity were also continuously monitored within the barn. We assessed the amount of time individuals spent in key resource areas, their activity levels, distance travelled, and z-axis values, as well as bunching behaviour based on four metrics: range size (individual and herd), intercow distance (ICD) and nearest neighbour distance (NND). Cows spent more time near water troughs and fans as THI increased, and less time in the feeding zone under higher THI, except during early morning hours. Time spent in the cubicle area varied by time of day. Activity increased with rising THI except during the late evening. When high sensor-recorded activity values were recorded, cows travelled further with increasing THI during the day. Additionally, z values increased with increasing THI during the day, suggesting cows spent more time standing. Bunching behaviour also changed with increasing THI: ICD decreased and individual range size increased. Patterns for NND were unclear. Monitoring space-use metrics such as proximity to resources and bunching behaviour, alongside activity levels, may provide early behavioural indicators of heat stress in livestock. Further research is needed to assess the generality of these indicators across different barn environments, to help inform welfare and production management.

Keywords: Dairy cow; Heat stress; Space use; Temperature-humidity index

1. Introduction

Heat stress occurs when animals cannot adequately dissipate body heat (Wang et al., 2020), and is commonly assessed using the temperature-humidity Index (THI) (Thom, 1959; Tresoldi et al., 2019; Tsai et al., 2020). Under heat stress, cattle show reduced feed intake and milk yield (Becker et al., 2020; Bernabucci et al., 2014), increased respiration rate (Idris et al., 2024), and impaired immunity and fertility (Joo et al., 2021; Schüller et al., 2016). These impacts are likely to worsen as global climate change increases the prevalence and severity of heat stress (Becker et al., 2020; Carvajal et al., 2021; Liu et al., 2025).

Cattle modify their behaviour under heat stress, such as increasing standing (Allen et al., 2015) and drinking (Tsai et al., 2020), reducing feeding (Idris et al., 2024), and changing their social dynamics and grouping (Chopra et al., 2024; McDonald et al., 2020). Behavioural responses may vary by individual, housing and management (Calegari et al., 2014; Galán et al., 2018; Niu and Harvatine, 2018), underscoring the need to study behavioural responses to heat stress across systems.

While studies have examined specific behaviours in relation to heat stress (Cook et al., 2007; Mader et al., 2002; Ranzato et al., 2023), few have explored how cattle reposition themselves within their environment. Existing studies that do explore changes in space use in response to heat stress, such as proximity to shade (e.g., Tucker et al., 2008; Schütz et al., 2010) or water sources (e.g., Pontiggia et al., 2024), rely on short, low-resolution in-person observations. More recently, McDonald et al. (2020) used electronic ear tags to track cow proximity to water bins over 59 d, but relied on off-site environmental data. Moreover, most studies exploring resource-based positioning do not account for localised indoor microclimates (Bouraoui et al., 2002; McDonald et al., 2020; Morton et al., 2007), and few link high-resolution tracking data with localised environmental data.

One cattle spatial behaviour recently receiving research attention is bunching, where individuals in a herd closely group together. Bunching is shown to increase with increasing ambient temperatures in indoor (Chopra et al., 2024; Erbez et al., 2012; Mader et al., 2002) and outdoor-housed cattle

(Lefcourt and Schmidtmann, 1989). Bunching may reflect efforts to access shade, water, or good airflow for cooling (Giro et al., 2019; Kendall et al., 2006; Tsai et al., 2020), or serve as a defensive aggregation against heat or flies (El Ashmawy et al., 2019; Foster and Treherne, 1981; Schmidtmann and Berkebile, 1985). However, bunching may be maladaptive under certain conditions, restricting airflow and increasing localised temperatures, especially in confined areas. Most previous studies on cattle bunching relied on in-person observations (El Ashmawy et al., 2019; Lefcourt and Schmidtmann, 1989), videos (Erbez et al., 2012) or photographs (Javorová et al., 2014).

Monitoring activity could further contribute to understanding changes to cattle space use under heat stress. Several studies report increased overall activity (Chopra et al., 2024; Ramón-Moragues et al., 2021; Ranzato et al., 2023) or locomotion (Endres and Barberg, 2007; Heinicke et al., 2019) with increasing THI, possibly reflecting discomfort or restlessness (increased movement or frequent changes in behaviour), or efforts to access cooler areas or resources. Conversely, reduced overall activity and reduced locomotion with increasing THI has been observed (Herbut and and Angrecka, 2018; Leliveld et al., 2025), perhaps due to heat-induced fatigue or energy-conservation. Overall activity may include grooming, feeding, or other behaviours, though definitions vary by study and sensor placement. Nonetheless, both hyper- and hypoactivity under heat stress may compromise welfare and productivity, particularly if essential activities are disrupted. A more nuanced understanding of how heat stress impacts activity may complement our understanding of space-use patterns.

Precision livestock farming (PLF) technologies enable detailed cattle tracking, overcoming the limitations of time-consuming, subjective direct observations (Gygax et al., 2010; Tullo et al., 2016). We have used local positioning system (LPS) technology to study cattle time budgets, space-use patterns, and social interactions (Barker et al., 2018; Chopra et al., 2020; Vázquez Diosdado et al., 2018). In this study, we aim to use LPS technology to explore how THI is associated with proximity to resources, activity, and bunching behaviour in a UK-housed dairy cow herd, with the potential to improve welfare and productivity under rising temperatures.

2. Methods

2.1. Animals and Housing

The animal study was reviewed and given ethical approval by the University of Reading under the unique reference code DAS/CZBHeatStress.

An indoor-housed dairy cow herd was monitored continuously at the University of Reading's Centre for Dairy Research (CEDAR) in Southern England, UK, from 1st June 2024 to 1st December 2024. The total number of different individual animals within the cubicle yard monitored over this period was 188, and the minimum and maximum numbers of unique cows with sensors present per day during the study period were 85 and 107, respectively. The herd were continually housed in a yard containing 119 usable cubicles (approximate stocking density: feed space = 0.79m to 0.99m per cow, lying space = 1.11 to 1.40 cubicles per cow) with free access to the feeding zone and water troughs. Figure 1A shows the barn layout- the study cows were housed in the cubicle yard. The herd were milked twice daily (between approximately 04:00 h and 06:00 h, then between 14:00 h and 16:00 h; see Supplementary Material 1, Section 1.1), and were fed a total mixed ration at approximately 20:00 h daily (placed at the feed face at approximately y = 22 m, refer to Fig 1A).

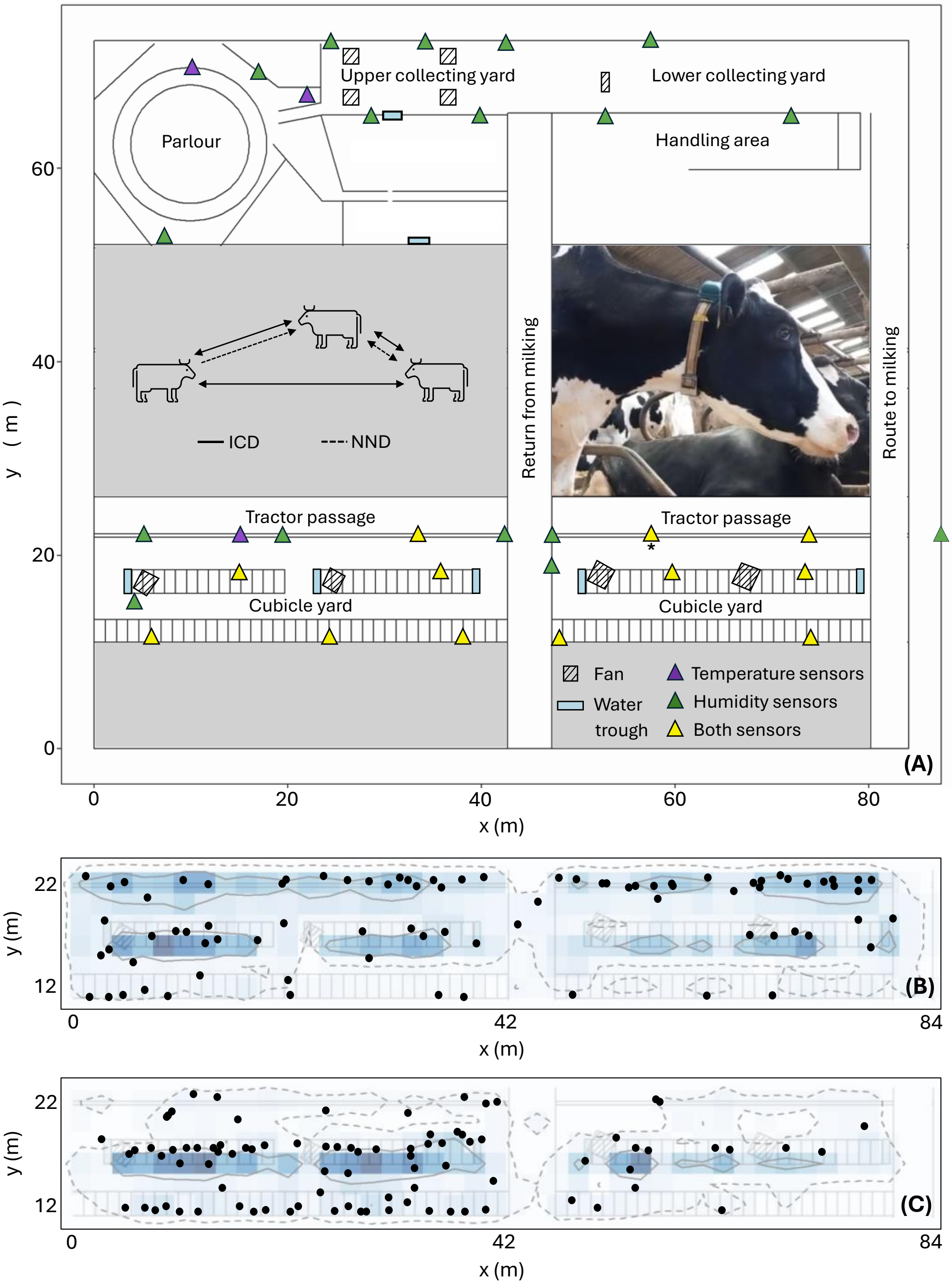

Figure 1. (A) Barn layout of the research farm in Reading, UK. The study cattle were housed in the cubicle yard. 'Both sensors' refers to ambient barn temperature and relative humidity sensors. The temperature sensor positioned at approximately x = 15 m and y = 18.5 m was installed after 5th June 2024. Two humidity sensors were located where an asterisk (*) appears next to a triangle. Data from sensors outside the cubicle yard were excluded from analyses. The grey-shaded areas and the section containing the inserted photo (below the milking areas and below the cubicle yard) were not used by this group of cows during the study period. The infographic (on the left, below the parlour) shows the calculation of intercow distance (ICD) and nearest neighbour distance (NND). Example plots showing space-use distributions in the yard are: (B) space-use distribution on 12th

October 2024, time period 5 (20:00 h to 23:59 h) where herd core range (CR, 50 %, solid grey boundary) = 51 virtual cells of 4 m^2 and herd full range (FR, 95 %, dashed grey boundary) = 188 virtual cells of 4 m^2, mean ICD = 29.68 m, mean NND = 1.73 m, THI = 52.57. Points show the positions of cows at a snapshot on 12th October 2024 at 22:05:44. (C) space-use distribution on 11th August 2024, time period 4 (16:00 h to 19:59 h) where herd CR = 28 virtual cells of 4 m^2, herd FR = 154 virtual cells of 4 m^2, mean ICD = 23.10 m, mean NND = 1.58 m, THI = 76.38. Points show the positions of cows at a snapshot on 11th August 2024 at 16:38:41.

2.2. Local Positioning System and Data Preprocessing

Each cow was equipped with a combined real-time local positioning sensor, temperature sensor, and accelerometer, Omnisense 500 (Omnisense Ltd, 2022), mounted on a weighted neck collar. The Omnisense positioning sensors form a localised radio network which triangulates signals between all (fixed and cow-equipped) sensors to determine the spatial position of each individual animal. Animal positions were typically recorded at 0.125 Hz/every 8 s, although sometimes less regularly due to signal interference. The commercially advertised 50 % circular error of probability (CEP) measurement of the sensor system is 20 cm (50 % of all recorded locations lie within a 20 cm radius of the mean location of static sensors), an improved accuracy compared to earlier studies using a previous version of the sensor system (Barker et al., 2018; Chopra et al., 2024; Vázquez Diosdado et al., 2018).

All data processing and analysis was conducted in R version 4.4.2 with RStudio (Posit Team, 2025; R Core Team, 2024). Extended system interruption occurred on 23 of the study days (05/06/2024, 09/07/2024, 19/07/2024, 22/07/2024 to 26/07/2024, 12/08/2024 to 24/08/2024 and 27/10/2024 to 28/10/2024) due to technical or operational issues; these were excluded from the subsequent analysis. A total of 142,580,048 location data points were collected from all the study cows.

For the analysis, we excluded hours when most cows were in the milking parlour or collecting yard (04:00 h to 05:59 h and 14:00 h to 15:59 h; refer to Supplementary Material 1, Section 1.1) because their behaviour was constrained by farm staff during these periods. A total of 125,567,618 data points remained after removing milking periods (herein referred to as the 'original data'). Details of subsequent data pre-processing steps are outlined in Supplementary Material 1, Section 1.2 and in the Supplemental Material (Data Sheet 2) of Chopra et al. (2020), where a similar approach was used (note that data in the current study were not smoothed due to the improved accuracy of the Omnisense positioning system).

2.3. Environmental Data

Temperature and humidity were recorded by shed-mounted wireless sensors, which formed part of an environmental monitoring sensor system developed and provided by Smartbell (Smartbell, 2025). These sensors were attached to fixtures within the cubicle yard, milking parlour, and collecting yard to maximise coverage (Fig 1A). For this analysis, data from 16 temperature sensors (height of 1.3 m) and 20 humidity sensors in the cubicle yard (height of 2.3 m except for one placed at 3.3 m above another) were used (Fig 1A). Temperature and humidity sensors automatically and continuously recorded ambient barn temperature (BT) and relative humidity (RH), respectively, every 10 minutes throughout the study period. A mean THI measurement was calculated across all sensors for each time period, given the minor variance in values across sensors (mean variance across the study = 1.00 °C^2 for BT, and 2.84 %^{2} for relative humidity). We calculated THI using the equation from Kibler (1964) (Equation 1):

Equation 1. $1.8 \times T - (1 - RH)(T - 14.3) + 32$,

where BT = ambient barn temperature (°C), and RH = relative humidity (%)

2.4. Data analysis

For analysis, the data were split into five equal four-hour time periods, to explore the presence of diurnal patterns, and to account for deterministic events at certain points of the day including milking (04:00 h to 05:59 h and 14:00 h to 15:59 h; refer to Supplementary Material 1, Section 1.1), fresh feed placement (approximately 20:00 h), and irregular closing of a gate which restricted movement within the cubicle yard (P2 to P4). Periods considered were: P1 (00:00 h to 03:59 h; n = 160 days/data points), P2 (06:00 h to 09:59 h, n = 160 days/data points), P3 (10:00 h to 13:59 h, n = 161 days/data points), P4 (16:00 h to 19:59 h, n = 160 days/data points) and P5 (20:00 h to 23:59 h, n = 159 days/data points).

Between-month variability was calculated across dependent metrics (outlined below in Sections 2.4.1 to 2.4.3) (refer to Supplementary Material 2, Section 2.4).

2.4.1. Time spent near resources

To gain insights into how THI may influence cow behaviour, the total time each individual spent near key resources was calculated for each time period. These key resource areas were defined as regions within a 3 m radius from the centre of any water trough (Fig 1A), or within the feeding zone. This 3 m threshold was chosen to account for both potential sensor error and the typical size of a dairy cow. The feeding zone was where cows accessed their feed by dipping their heads under the feed face (at approximately y = 22 m), while facing the tractor passage, and was defined as 3 m below the feed face (refer to Fig 1A). The time spent within these areas was summed across each time period, and a mean was calculated across cows. Similarly, the mean time individuals spent within 1 m of the cubicles was calculated (Fig 1A). In addition, the mean time individuals spent near fans was calculated using a similar approach, and a secondary method accounting for the direction of airflow (see Supplementary Material 2, Section 2.1).

2.4.2. Activity

Activity data were recorded by the accelerometers (every 10 minutes) within the Omnisense sensors and determined overall activity by computing the mean of a filtered VeDBA (Vectorial Dynamic Body Acceleration). This measure was derived by taking the square root of the sum of squares of the dynamic x, y, and z acceleration values (as described in Qasem et al. (2012)). The mean was then calculated using a sliding window of 32 data points for each sensor. The data underwent filtering both before and after the sum of squares calculation, to account for low-frequency components, including gravity. To account for varying recording frequencies (i.e., recordings were often less frequent than every 10 minutes), the mean and variance in activity was calculated across the herd for each time period.

To gain further insight into how changes in activity relate to THI, we calculated the distance cows travelled during high activity periods (refer to Supplementary Material 2, Section 2.2.4).

2.4.3. Z values

The z values recorded by the positional part of the Omnisense sensors were also considered, as they serve as a proxy for a cow's height above the ground (and hence lower values may indicate lying behaviours whereas higher values may indicate standing behaviours). Since the raw z-axis readings had an initial offset that did not correspond to floor level, we adjusted the data so that zero represents the approximate floor level. Mean z values were calculated across the herd for each time period.

2.4.4. Bunching metrics

There is no universally accepted definition of 'bunching' behaviour within the context of PLF. However, a range of different metrics are available to measure spatial aggregation, spatial clustering, or social proximity from positional data. Previous studies have used direct observations or basic nearest neighbour aggregation indices to measure bunching, the latter of which would provide a distorted score if cows tend to form dyad pairs (El Ashmawy et al., 2019; Erbez et al., 2012; Lefcourt and Schmidtmann, 1989; Mader et al., 2002). Following the approach in Chopra et al. (2024), we consider four complementary 'bunching metrics', which directly measure the level of spatial separation (i.e., the inverse of bunching), each measured for each time period: mean individual range size (CR and FR), mean intercow distance (ICD), and mean nearest neighbour distance (NND). The results for mean individual FRand mean NND are in Supplementary Material 2 (Section 2.2.1 and Section 2.2.3 respectively).

2.4.4.1. Range size

Range size was calculated by overlaying a virtual grid (2 m × 2 m = 4 m^2 cells) over the barn map (cubicle yard area only; refer to Fig 1A). At each time-step, location data were used to assign each individual cow within the herd to a given cell (or rejected if it lay outside the yard). The respective cell count value was increased to reflect time spent in the area (varying update rates should have minimal impact). Using this simple cell count method, a given matrix can be visualised and is henceforth referred to as 'space-use distribution (plot)'. The highest density cells cumulatively adding to 50 % or 95 % correspond to the core range (CR) and full range (FR) respectively. Range size was calculated for each individual for each time period (P1 to P5) and a mean was calculated across the herd, to account for the varying number of cows throughout the study, henceforth referred to as 'mean individual range size'. It must be noted that range size is somewhat constrained, as the horizontal distance exceeds the vertical distance, resulting in movement that is nearly one-dimensional.

It is important to note that the range size metric used in Chopra et al. (2024) was calculated at the herd level from the onset rather than at the individual level, given the group size remained relatively stable over time. Consequently, trends in mean individual range size cannot be directly compared to those in Chopra et al. (2024), as the two methods capture different aspects of range size e.g., while a herd's range as a whole may become smaller (herd range size), individuals within that range may end up moving more extensively within it (individual range size). However, we do also analyse the relationship between herd range size and mean THI for completeness (Supplementary Material 2, Section 2.2.2). Figure 1B-C shows examples of space-use distribution maps and locations of individuals where herd CR = 51 (Fig 1B) and 28 virtual cells (Fig 1C).

Inter-cow variance in range size refers to the differences in range size *between* cows and was also calculated (results shown in Supplementary Material 2, Section 2.3).

2.4.4.2. Intercow distance

At a given time point, the herd mean intercow distance is the mean distance (in metres) between each of the $(N^2 - N)/2$ possible dyad pairs across a herd with *N* individuals. A value for each time period (which we define as **ICD**, measured in metres) is then calculated as the arithmetic mean of all (*n*) values recorded over that time period (assuming 0.125 Hz sampling frequency, *n* = 1800 (four hours):

$$ICD = \frac{1}{n}\sum_{t=1}^{n}\left(\frac{2}{N^2-N}\sum_{(i,j)\in N}\sqrt{[x_i(t) - x_j(t))^2 + (y_i(t) - y_j(t)]^2}\right), \quad (1)$$

where *(i ,j)* is a given dyad pair and $i \neq j$.

The nearest neighbour distance (**NND**) is the smallest ICD when considering all dyad pairs involving a given individual (refer to Supplementary Material 2, Section 2.2.3 for equation). Variance in ICD and NND were also calculated (Supplementary Material 2, Section 2.3).

Since the recording frequency was not consistently regular, data points were occasionally only available for a small subset of sensors at a given time point and hence ICD and NND would not be truly reflective of the herd's behaviour in such cases. To address this, we applied a threshold requiring at least 75 % of the sensors active on a given day to have data for a given time point. If this condition was not met, the time point was not considered for analysis (a total of 8.63 % of the original data were not considered).

The four bunching metrics measure different aspects of space use and social proximity, but all decrease as spatial clustering increases. Range size is independent of ICD and NND but does not capture short-term proximity changes; a smaller mean individual range size indicates that individuals are on average using less space. ICD and NND are related but measure different aspects; ICD accounts for overall herd distribution and can be skewed by distant individuals, while NND may miss broader bunching patterns.

To gain insight into where cows were positioning across the study period, space-use distribution matrices were generated and visualised using the simple count method (refer to Section 2.4.4.1): across the entire study, during each time period, and during periods of low and high bunching (highest and lowest 10 % of values for each bunching metric combined, respectively) across the entire study and for each time period (refer to Supplementary Material 3, Section 3.1). Additionally, adapting the cell count method outlined in Section 2.4.4.1, sensor temperature data recorded from the Omnisense mobile sensors were used to generate temperature distribution plots across the entire study, for each month and each time period (refer to Supplementary Material 3, Section 3.2).

2.4.5. Models

To test the impact of THI on each metric, regression models were created for each time period. To handle the non-normality of model residuals (tested using Shapiro-Wilks) and heteroscedasticity (tested using non-constant variance, NCV), we used robust regression. Robust regression works by minimising the effect of outliers and providing more reliable estimates under violations of standard linear model assumptions. We used the R package ‘robustbase’ (Meachler et al., 2024), and the function ‘lmrob()’ which computes an MM-type regression estimator, using a bi-square redescending score function (Koller and Stahel, 2011). Outputs from linear regression models show qualitatively similar results.

Previous studies have found changes in behaviour above a certain threshold (Chopra et al., 2024; Erbez et al., 2012; Javorová et al., 2014).). For completeness, we undertook additional analysis that divided the data into THI < 65 and THI ≥ 65. Values above this threshold accounted for 24.44 % of the mean THI values over the study period, and the outputs are qualitatively similar (results omitted).

All data underlying these analyses are accessible through the Essex Data Repository (Chopra and Codling, 2025).

3. Results

3.1. Trends in temperature and space use

During the late morning to early afternoon period, P3 (10:00 h to 13:59 h), barn temperature (BT) peaked, whereas it dropped during P1 and P5 (late evening/night) (Fig 2A). BT generally increased from June to August, then decreased from August to December (Fig 2B). The coolest mean BT over time periods was recorded in November (10.90 °C; n = 30 days) and the hottest in August (20.20 °C, n = 18 days). There is a significant difference in mean BT between the months (F-value = 136.90, $p < 0.001$). Conversely, relative humidity dropped during P3 (10:00 h to 13:59 h) and P4 (16:00 h to 19:59 h) and peaked during P1 and P5 (late evening/night) (Fig 2C), showing less variation and consistently higher values over time (Fig 2D). THI followed similar patterns to BT (Fig 2E-F).

Temperature was relatively evenly distributed across the barn during each time period and month, although the hottest temperatures were recorded toward the centre of the barn (Figs S3-S4 in Supplementary Material 3, Section 3.2).

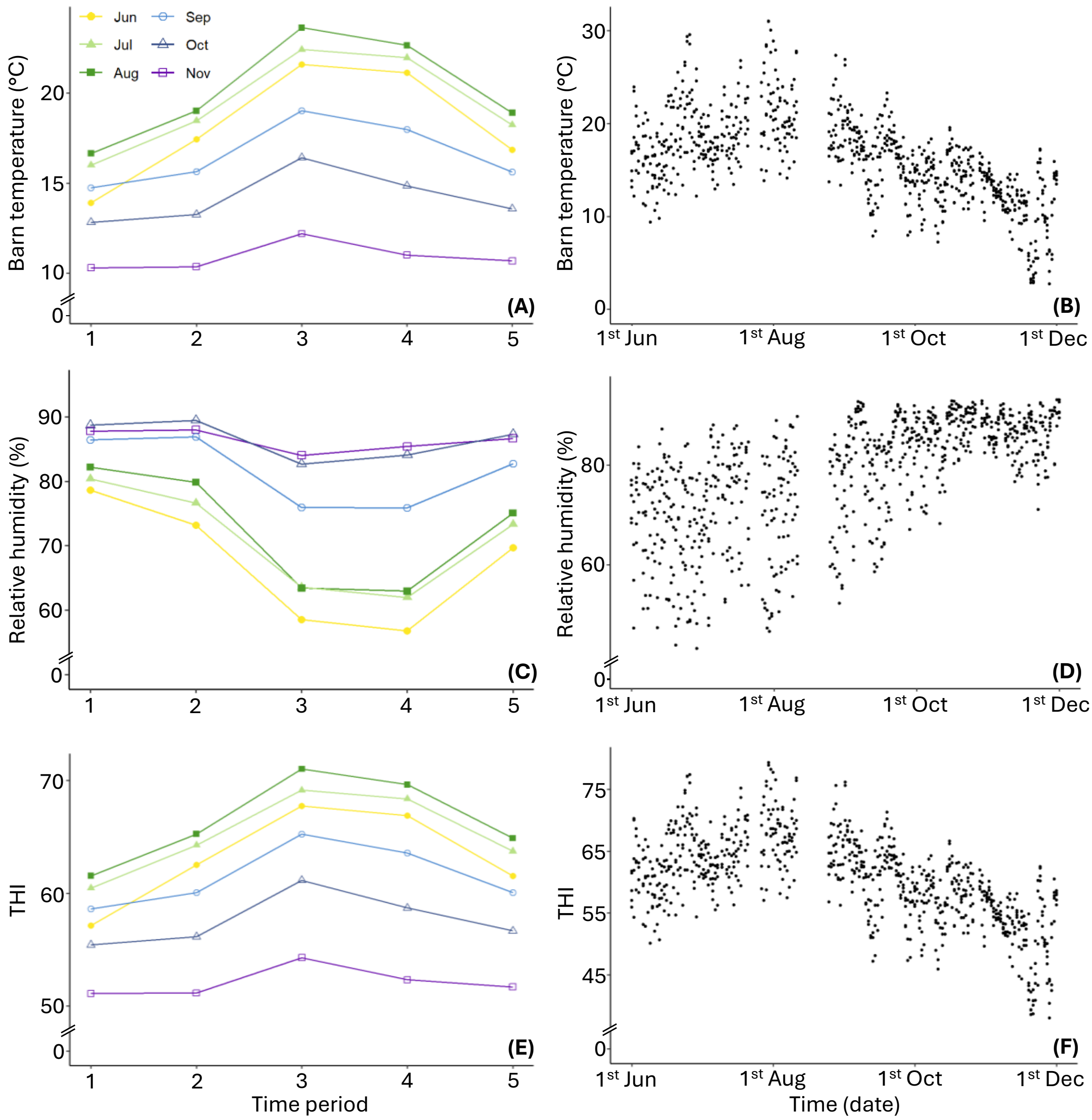

Figure 2. Mean of environmental metrics (A, C, E) over all days per month and time period and (B,D,F) per time period over time. (A-B) ambient barn temperature (°C), (C-D) relative humidity (%), and (E-F) temperature-humidity index (THI). Time periods are: P1 (00:00 h to 03:59 h), P2 (06:00 h to 09:59 h), P3 (10:00 h to 13:59 h), P4 (16:00 h to 19:59 h), and P5 (20:00 h to 23:59 h).

3.2. Time spent near features, activity, z values, and THI

As mean THI increased, the mean time spent near the water troughs significantly increased (Fig 3A, Table 1). There are relatively large differences in the time spent near the water troughs between months, which is associated with THI (mean SD = 0.42; Fig S3.B in Supplementary Material 2, Section 2.3). The mean time spent near cubicles significantly decreases with increasing THI during P2 and P4 whereas significantly increases during P3 and P5 (Fig 3B; Table 1). Cattle spent most of their time in the cubicle area across the entire study, irrespective of time period (refer to Fig S3 in Supplementary Material 3, Section 3.2). The mean time spent near the feeding zone (FZ) decreases with THI across time periods (except P2), and this is significant during P3 to P5 (Fig 3C, Table 1).

Using a simple proximity-based method, the time spent near fans increased across time periods, and this trend is significant during P2 to P4 (Supplementary Material 2, Section 2.1.1). Using a secondary method accounting for fan airflow direction, the time spent near fans significantly decreased with rising THI during P2 but significantly increased during P3 and P5 (refer to Supplementary Material 2, Section 2.1.2).

Mean activity significantly increases as mean THI increases across each time period (except during P5 where the trend is negative) (Fig 3D, Table 1). The variance in activity decreases across each time period (significant for all time periods except P2) (Fig 3E, Table 1). Mean distance travelled during high activity periods significantly increases with increasing mean THI during P2 to P4 whereas significantly decreases during P5 (Supplementary Material 2, Section 2.2.4).

Mean z value significantly increases during the day (P2 to P4) whereas decreases during the night (P1 and P5), significantly during P5 (Fig 3F, Table 1).

3.3. Bunching and THI

Mean individual core range size was lowest during the early morning (P2) and the evening (P4), and highest during the night (P5) (Fig 3G) as cows spent more time in the FZ after fresh feed was delivered (Fig S3 in Supplementary Material 3, Section 3.1). As mean THI increases, mean individual CR increases across each time period, and this trend is significant during P2 and P4 (Fig 3G; Table 1). The results are similar for mean individual FR (Supplementary Material 2, Section 2.2.1). The relationship between THI and herd range size is similar to that for mean individual range size, although there are some differences e.g., for herd CR the trend is significantly negative during P5 (Supplementary Material 2, Section 2.2.2). There is no clear relationship between mean THI and inter-cow variance in range size (Supplementary Material 2, Section 2.3).

As mean THI increases, mean ICD significantly decreases across each time period (Fig 3H, Table 1). There are relatively large differences in ICD between months, likely driven by THI (Supplementary Material 2, Section 2.4). The pattern between NND and THI does not show a clear pattern (Supplementary Material 2, Section 2.2.3). As mean THI increases, the variance in ICD and the variance in NND appear to increase (Supplementary Material 2, Section 2.3).

During periods of low bunching (time periods corresponding to highest 10 % of each bunching metric combined, n = 203 time periods), cows spent more time in the FZ and less time in the cubicles compared to during periods of high bunching (n = 203 time periods) and the entire study (n = 799 time periods) (Fig S1 in Supplementary Material 3, Section 3.1).

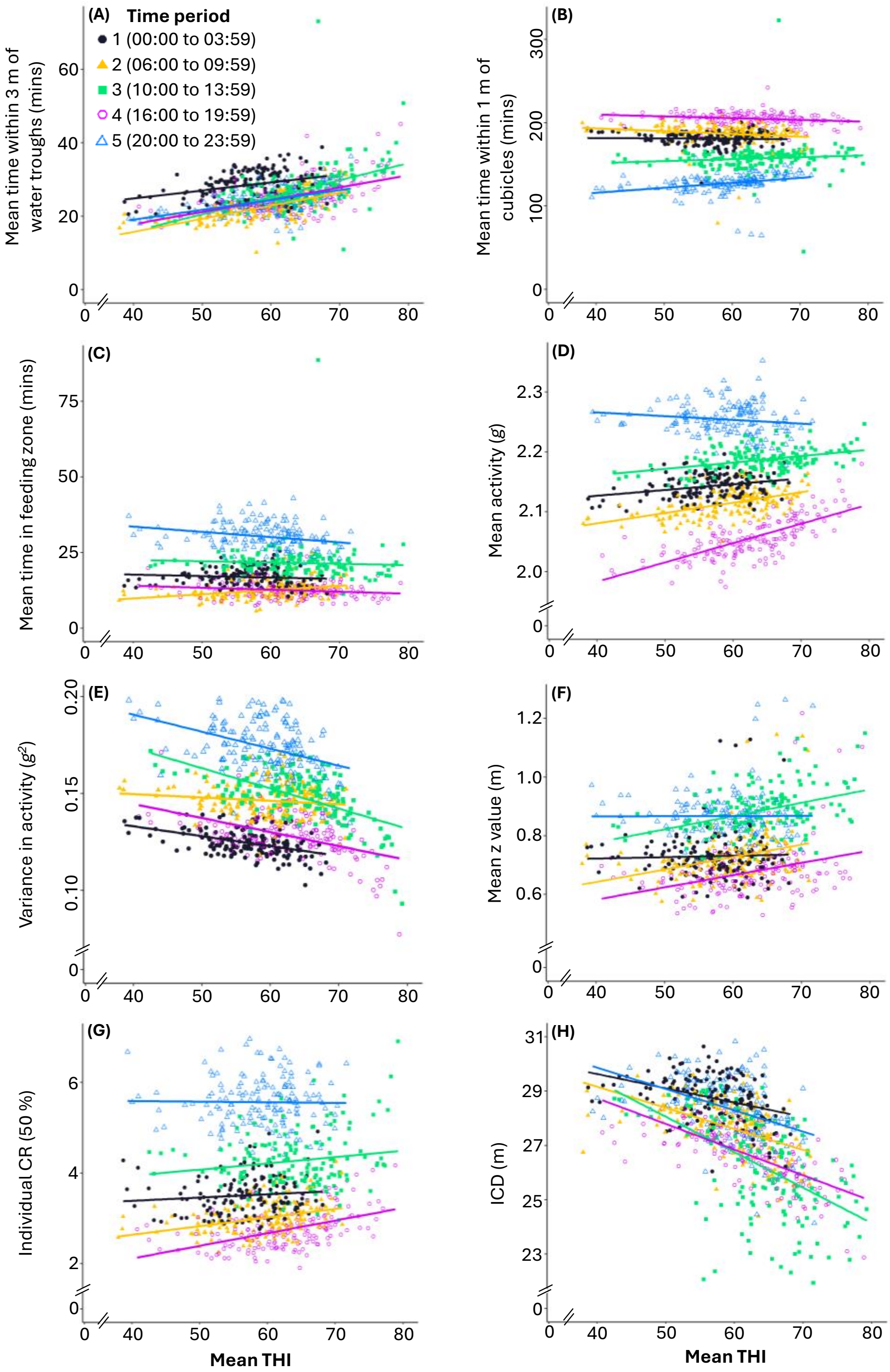

Figure 3. Relationship between mean THI and the mean time individuals spent near (A) water troughs (≤ 3 m), (B) cubicles (≤ 1 m), (C) the feeding zone (≤ 3 m from feed face), (D) mean activity, (E) variance in activity, (F) mean z value, (G) mean individual core range (50 %) and (E) mean intercow distance. A singular data point represents the mean THI and mean y value across a day. Time periods (P) shown are: P1 (00:00 h to 03:59 h; n = 160 days/data points), P2 (06:00 h to 09:59 h, n = 160 days/data points), P3 (10:00 h to 13:59 h, n = 161 days/data points), P4 (16:00 h to 19:59 h, n = 160 days/data points) and P5 (20:00 h to 23:59 h, n = 159 days/data points).

Table 1. Results of **robust regression models** using the predictor variable mean THI for each of the metrics, for each time period. All linear models are in the format $S_x = a_0 + a_1\text{THI}$ where S_x is the dependent variable.

Space-use measure	**Time period**	**Regression coefficient values (*p*-values)**			**Summary**
S_1: time near water troughs	1	$a_0 = 15.69$	$a_1 = 0.23$	**($p < 0.001$)**	Time spent near the water troughs significantly increases with increasing THI, during each period.
	2	$a_0 = 1.58$	$a_1 = 0.36$	**($p < 0.001$)**	
	3	$a_0 = -0.48$	$a_1 = 0.43$	**($p < 0.001$)**	
	4	$a_0 = 7.49$	$a_1 = 0.28$	**($p < 0.001$)**	
	5	$a_0 = 7.86$	$a_1 = 0.28$	**($p < 0.001$)**	
S_2: time near cubicles	1	$a_0 = 185.55$	$a_1 = -0.08$	($p = 0.48$)	Mean time spent near the cubicles significantly increases with increasing THI during P3 and P5 whereas significantly decreases during P2 and P4.
	2	$a_0 = 208.00$	$a_1 = -0.32$	**($p < 0.001$)**	
	3	$a_0 = 136.85$	$a_1 = 0.33$	**($p < 0.001$)**	
	4	$a_0 = 218.08$	$a_1 = -0.21$	**($p < 0.001$)**	
	5	$a_0 = 85.37$	$a_1 = 0.73$	**($p < 0.001$)**	
S_3: time near FZ	1	$a_0 = 19.75$	$a_1 = -0.05$	($p = 0.22$)	Time spent near the FZ decreases with increasing THI (except during P2), and this trend is significant during P2 to P5.
	2	$a_0 = 5.07$	$a_1 = 0.12$	**($p < 0.001$)**	
	3	$a_0 = 25.69$	$a_1 = -0.07$	**($p = 0.02$)**	
	4	$a_0 = 16.26$	$a_1 = -0.06$	**($p = 0.03$)**	
	5	$a_0 = 40.40$	$a_1 = -0.17$	**($p < 0.001$)**	
S_4: mean activity	1	$a_0 = 2.08$	$a_1 = 0.001$	**($p < 0.001$)**	Mean activity significantly increases with increasing THI across periods except P5.
	2	$a_0 = 2.01$	$a_1 = 0.002$	**($p < 0.001$)**	
	3	$a_0 = 2.12$	$a_1 = 0.001$	**($p < 0.001$)**	
	4	$a_0 = 1.86$	$a_1 = 0.003$	**($p < 0.001$)**	
	5	$a_0 = 2.29$	$a_1 = -0.001$	**($p = 0.03$)**	
S_5: variance in activity	1	$a_0 = 0.15$	$a_1 = -0.001$	**($p < 0.001$)**	Variance in activity decreases with increasing THI, and this is significant during each period (except P2).
	2	$a_0 = 0.16$	$a_1 = -0.0002$	($p = 0.04$)	
	3	$a_0 = 0.21$	$a_1 = -0.001$	**($p < 0.001$)**	
	4	$a_0 = 0.16$	$a_1 = -0.001$	**($p < 0.001$)**	
	5	$a_0 = 0.23$	$a_1 = -0.001$	**($p < 0.001$)**	
S_6: z value	1	$a_0 = 0.79$	$a_1 = -0.001$	($p = 0.08$)	Mean z value significantly increases during the day (P2 to P4) whereas decreases during the night (P1 and P5), significantly during P5.
	2	$a_0 = 0.59$	$a_1 = 0.002$	**($p = 0.002$)**	
	3	$a_0 =0.62$	$a_1 = 0.004$	**($p < 0.001$)**	
	4	$a_0 = 0.56$	$a_1 = 0.002$	**($p = 0.007$)**	
	5	$a_0 = 0.99$	$a_1 = -0.002$	**($p = 0.001$)**	
S_7: mean individual core range (CR)	1	$a_0 = 3.19$	$a_1 = 0.005$	($p = 0.43$)	Individual CR increases with increasing THI, and this is significant for P2 and P4.
	2	$a_0 = 2.01$	$a_1 = 0.02$	**($p < 0.001$)**	
	3	$a_0 = 4.04$	$a_1 = 0.003$	($p = 0.69$)	
	4	$a_0 = 1.13$	$a_1 = 0.03$	**($p < 0.001$)**	
	5	$a_0 = 5.52$	$a_1 = 0.001$	($p = 0.94$)	
S_8: intercow distance (ICD)	1	$a_0 = 31.57$	$a_1 = -0.05$	**($p < 0.001$)**	ICD decreases with increasing THI, and this trend is significant across periods.
	2	$a_0 = 32.46$	$a_1 = -0.08$	**($p < 0.001$)**	
	3	$a_0 = 35.28$	$a_1 = -0.14$	**($p < 0.001$)**	
	4	$a_0 = 32.33$	$a_1 = -0.09$	**($p < 0.001$)**	
	5	$a_0 = 32.79$	$a_1 = -0.07$	**($p < 0.001$)**	

4. Discussion

Using a local positioning system to monitor an indoor UK dairy herd over six months, this study finds that increasing THI is associated with marked changes in proximity to key barn features, bunching, and activity. Our findings underscore the value of space-use monitoring for early detection of heat stress, particularly important in the face of climate change.

As THI increased, cows spent more time near the water troughs (Fig 3A, Table 1). This aligns with findings from Pontiggia et al. (2024), who visually observed that cows at pasture were more frequently near water troughs when vaginal temperatures were higher. Similar patterns have been visually observed with indoor cows: Schütz et al. (2010) found increased time near water troughs with increased heat load, while McDonald et al. (2020) reported the same trend in relation to THI using electronic ear tags. This behaviour may reflect a physiological need to offset fluid loss via panting and sweating, to gain from direct cooling (Ammer et al., 2018; Kadzere et al., 2002). Water troughs may also contribute to cooler microclimates via surface evaporation (Schütz et al., 2010). Cows also spent more time near the fans as THI rose (except during the night, P1), with partially consistent results when accounting for airflow direction (Supplementary Material 2, Section 2.1.1 to 2.2.2). Fans increase air speeds supporting greater evaporative cooling, thus creating more favourable microclimates. While temperatures were relatively uniform across the barn (Fig S3-4 in Supplementary Material 3, Section 3.2), other microclimatic factors may have further influenced spatial preferences. Examples of environmental changes outdoors which alter the space use of cows include shade seeking and the avoidance sunlight at high temperatures (Kendall et al., 2006; Schütz et al., 2010).

The time cows spent near the cubicles decreased with increasing THI during the early morning (P1 and P2) and late afternoon (P4), potentially due to increased thirst following milking (P2 and P4) (Fig 3B, Table 1). In contrast, cubicle use increased with rising THI during the hotter midday period (P3) and the night (P5) (Fig 3B, Table 1). Nonetheless, the central cubicles remained the most frequently used area throughout the study (Fig S1-S3 in Supplementary Material 3), potentially in part due to their proximity to key resources including fans and water troughs (refer to Fig 1A). Furthermore, as THI increased, individuals spent less time near the FZ (except during P2), supporting previous studies showing that feeding activity decreased in hotter conditions (Idris et al., 2024; Pontiggia et al., 2024). The increase in time spent in the FZ with increasing THI during P2 may reflect heightened motivation to feed after resting overnight and before morning milking (Iqbal et al., 2023; Sheahan et al., 2013).

Mean activity increased with rising THI across most time periods (Fig 3D), consistent with Chopra et al. (2024), who found a similar trend with ambient barn temperature. Antanaitis et al. (2024) reported cows were 12 % more active when THI exceeded 78 versus below 72. This may reflect restlessness or behavioural thermoregulation as cows seek cooler microclimates and resources. The neck-mounted activity sensors used in this study are sensitive to micromovements of the head and neck, therefore, the increase in activity may also be indicative of general discomfort or of fly-deterrence behaviour (El Ashmawy et al., 2019). During high activity, cows travelled further with increasing THI during the day (P2 to P4), potentially reflecting restlessness or resource-seeking (Supplementary Material 2, Section 2.2.4). Similarly, Lovarelli et al. (2024) reported increased locomotion under heat stress, and Brzozowska et al. (2014) found step counts were higher during hotter than cooler months. During fresh feed placement (P5), activity declined with increasing THI, likely due to reductions in feed intake (Idris et al., 2024). Variance in activity decreased with rising THI, showing more uniformly elevated daytime activity (P1 to P4) and reduced activity at night (P5) (Fig 3D-E). Conversely, at night (P1 and P5), during high activity, cows did not travel as far with rising THI (Supplementary Material 2, Section 2.2.4), possibly reflecting a shift toward rest. Notably, THI and activity are not entirely independent; increased movement can raise thermal load through increased body heat generation. Furthermore, increasing THI was linked to higher z values during daytime periods (P2 to P4), indicating more time spent upright (Fig 3F). Higher z values may reflect standing or other upright behaviours such as walking. Increased standing in the heat agrees with previous findings and may enhance heat loss by increasing exposed body surface area (Cook et al., 2007; King et al., 2016; Tresoldi et al., 2019).

Our finding that ICD decreases with increasing THI (Table 1, Fig 3H) aligns with previous research. Erbez et al. (2012) and Javorová et al. (2014) observed cows bunched more when THI exceeded 70 or temperatures surpassed 19 °C. Additionally, Pontiggia et al. (2024) reported shorter inter-individual distances among cows with elevated vaginal temperatures. These earlier studies assessed bunching through direct observations, by counting individuals in barn segments (Erbez et al., 2012; Javorová et al., 2014), or categorising inter-individual distances into two groups (Pontiggia et al., 2024). Conversely, El Ashmawy et al. (2019), observed reduced bunching with increasing ambient temperature ≤ 30 °C, though their binary infrequent sampling (weekly, twice per day) may explain differences. In contrast, our findings provide a more detailed understanding of cattle bunching behaviour through multiple metrics capturing various aspects of space use and social proximity. Notably, our findings align with those of Chopra et al. (2024), who found ICD decreased with higher ambient barn temperatures. In the present study, the negative relationship between ICD and THI is strongly significant across all periods, with consistently higher ICD values during P1 and P5 (late evening/night) (Fig 3H, Table 1), possibly reflecting cows spreading out to rest. Our results align with previous studies where cows crowded together more in the afternoon than the night/early morning (Chopra et al., 2024; Erbez et al., 2012; Javorová et al., 2014). Additionally, we found that variance in ICD increased with THI across time periods, suggesting less consistent group spacing, particularly during fresh feed placement (P5) (Supplementary Material 2, Section 2.3).

Individual core range size increased with increasing THI, significantly during P2 and P4 (Fig 3G, Table 1), which followed milking. After being subject to increased heat load due to confinement during milking (Liu et al., 2025), cows may move more widely around the yard to seek preferable microclimates or resources under high THI. Individual CR values are higher during P5, likely due to cows spreading out along the feed face, leading to a larger range size (Supplementary Material 3, Section 3.2), also reflected in higher ICD variance during P5 (Supplementary Material 2, Section 2.3). Similar patterns were observed for individual FR (Supplementary Material 2, Section 2.2.1). Trends are somewhat different for herd range size, and although they do not contradict findings from Chopra et al. (2024), some differences are apparent (likely due to management) (Supplementary Material 2, Section 2.2.2). The herd range size results should be interpreted with caution, due to the variable group size. During P5, herd CR decreases with increasing THI (Supplementary Material 2, Section 2.2.2), possibly due to reduced feeding. Consistent with this, cows spent less time in the FZ during high bunching periods compared to low bunching periods (primarily during P5) (Fig S1-S2 in Supplementary Material 3). These patterns reflect how our bunching metrics are highly sensitive to cows spreading out between cubicles and the FZ. Nonetheless, such changes in bunching behaviour may exacerbate localised heat by increasing body heat accumulation and restricting airflow.

No significant relationship was found between NND and THI (except during P3) (Supplementary Material 2, Section 2.2.3). Similarly, Chopra et al. (2024) observed no significant effect of ambient barn temperature on NND. In contrast, Lefcourt and Schmidtmann, (1989), who measured bunching by categorising individuals into nearest neighbour groups, found bunching increased with THI (Lefcourt and Schmidtmann, 1989). In the present study, during P3, we observed a significant decrease in both NND and no significant change in variance in NND with increasing THI (Supplementary Material 2, Section 2.2.3 and Section 2.3). Thus, aspects of bunching linked to heat load may vary by time of day.

Our findings have important implications for dairy farm management, particularly as rising temperatures are predicted to increase the risk of livestock heat stress (Carvajal et al., 2021). Monitoring space use such as time spent near key features, bunching, and activity changes with THI may serve as early indicators of emerging heat stress. Integrating these metrics into PLF systems could support real-time management decisions, such as increasing airflow, adjusting feeding times, repositioning resources, or reducing stocking density. Environmental variables beyond ambient barn temperature and relative humidity, such as ventilation, and air quality, may also impact such behaviour, and future research should incorporate these. Additionally, further research is needed to assess the generality of these indicators across barn environments, and monitor fine-scale microclimatic variations, to inform barn design and resource placement to improve thermal comfort and welfare. These principles are also relevant to other managed animals and wildlife, where understanding microhabitat use under thermal stress is increasingly important under a changing climate.

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