

Supplementary Material 2. Additional space-use metrics and models

Here we present further analyses that extend our main findings by examining additional space-use metrics in relation to THI. In Section 2.1, we use two methods to calculate the time cows spent near fans. Additionally, we calculate mean individual full range (Section 2.2.1), herd range size (Section 2.2.2), nearest neighbour distance (NND) (Section 2.2.3), distance travelled during high activity (Section 2.2.4), variance in bunching metrics (Section 2.3), and between-month variability in all dependent variables (Section 2.4).

2.1. Time near fans

2.1.1. Proximity methods

As described with water troughs in Section 2.4.1 of the main paper, the key areas around fans were defined as regions within 3 m radius from the centre of any fan (refer to Fig 1A in main paper). The time spent within these areas was summed across each time period, and a mean was calculated across cows.

As mean THI increased, the mean time spent near the fans significantly increased (except during P1, where the trend is non-significant) (Fig S1.A, Table S1). However, fan and water trough areas largely overlap, making resource-specific preferences difficult to isolate (refer to Fig 1A in main paper). Moreover, this simple proximity-based method does not consider the direction of airflow from the fans, so a secondary method was used to estimate the actual area influenced by fan airflow (Section 2.1.2. below).

2.1.2. Directional method

To quantify the geometry of the airflow zone, a shape was defined for each fan. Each shape comprises of a central rectangle extending 5 m outward from the base of the fan in the direction of air movement, flanked by two right-angled triangles with internal angles of 60 °, 90 °, and 30 ° (Fig S1.B). This method provides a simplified approximation of the area of fan airflow rather than an accurate measurement. As

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with the proximity method, the time spent within these areas was summed across each time period, and a mean was calculated across cows.

Using this directional method, the time spent in areas around the fans decreased with increasing THI during P1, P2 and P5, but increased during P3 and P5, and these trends are significant for P2, P3 and P5 (Fig S1.C). This directional method requires more complicated geometric assumptions than the proximity-based method, and does not account for variations in fan speed, environmental interference (barn layout or obstacles), or variations in airflow across distances.

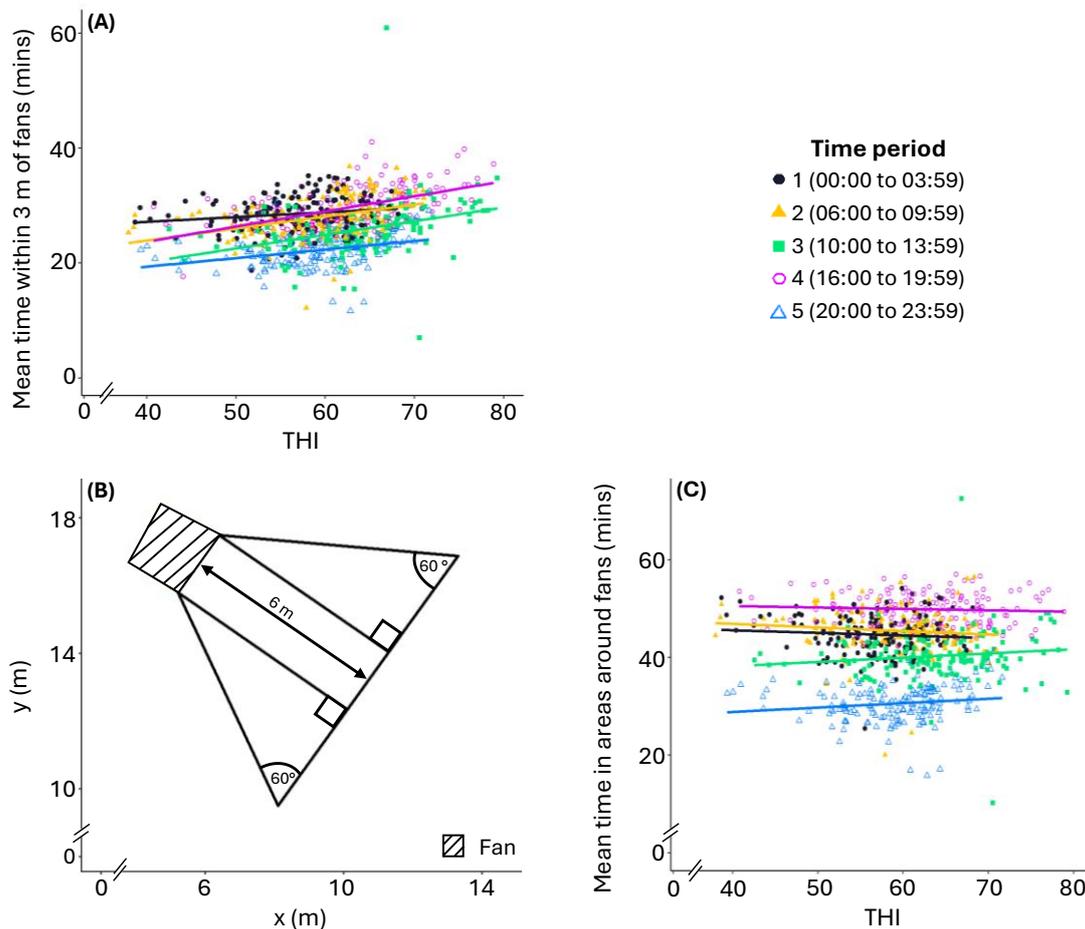


Fig S1. (A) Mean time individuals spent around fans (proximity method) against THI. (B) Example of shape drawn around a fan (directional method), and (C) mean time individuals spent in areas around fan shapes (directional method) against THI. Time periods (P) shown are: P1 (00:00 h to 03:59 h; n = 160 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).

2.2. Additional bunching metrics

2.2.1. Mean individual full range

Following Section 2.4.4.1 in the main paper, here we show the results for full range size (highest density cells produced from cell count method cumulatively summing to 95%).

As mean THI increases, mean individual FR increases across each time period, and this trend is significant during P2 and P4 (Fig S2.A; Table S1). These results are qualitatively similar to those for mean individual core range.

2.2.2. Herd range size

We analyse the relationship between herd range size and mean THI for completeness, despite the limitations due to the varying herd size throughout the study (refer to Section 2.4.4.1 in the main paper).

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 (Fig S2.B-C, Table S1).

2.2.3. Nearest neighbour distance

At a given time point, the nearest neighbour distance for a given individual is the distance (in metres) to its closest neighbour in the herd (i.e., the smallest ICD when considering all dyad pairs involving that individual). A mean value can then be determined across the full herd for each time period (which we define as **NND**, measured in metres):

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

where j indexes all possible dyad pairs for i across the N individuals in the herd.

The pattern between NND and THI is unclear (Fig S2.D, Table S1).

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2.2.4. Distance travelled during high activity

High activity periods were defined as times when the mean activity level exceeded 2.15 g, corresponding to the overall average activity measured across the entire study and for each month. During these high activity periods, the distance travelled by each cow was calculated for each time period, then a mean was calculated for each time period.

Mean distance travelled during high activity periods significantly increases with increasing mean THI during P2 to P4 whereas significantly decreases during P5 (Fig S2E, Table S1).

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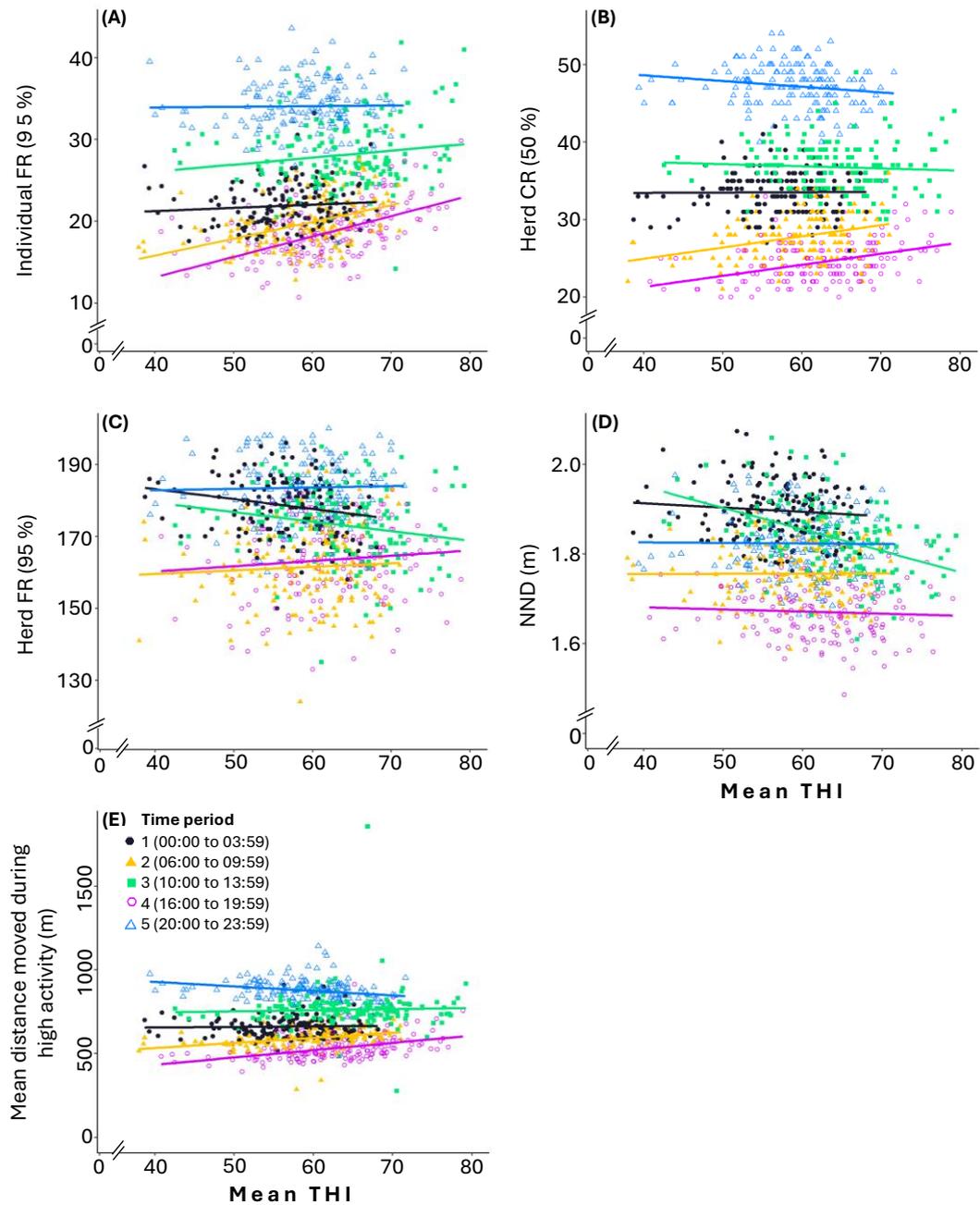


Figure S2. Relationship between mean THI and (A) mean individual full range (FR) (B) herd core range (50 %) (C) herd full range (95 %), (D) nearest neighbour distance, and (E) distance moved during high activity, for each time period. Time periods (P) shown are: P1 (00:00 h to 03:59 h), P2 (06:00 h to 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). A singular data point represents one day (P1: n = 160 days, P2: n = 160 days, P3: 161 days, P4: 160 days and P5: 159 days).

2.3. Variance in bunching metrics and activity

Inter-cow variance in individual range size refers to the differences in range size *between* cows and was calculated to determine whether some cows had much smaller or larger range sizes compared to others, and how this changed with THI. The relationship between inter-cow variance in (individual) range size and mean THI is unclear (Fig S3.A-B, Table S1).

To calculate variance in ICD, a mean distance was calculated for each timestep across cows, then the variance of these values was calculated for each time period. Low variance in ICD indicates relatively consistent group spacing whereas high variance indicates less consistent group spacing, during a time period. Similarly, variance in NND was calculated as the variance in all NND values for each time period. Variance in ICD and variance in NND increase with increasing mean THI (Fig S3.D-E, Table S1).

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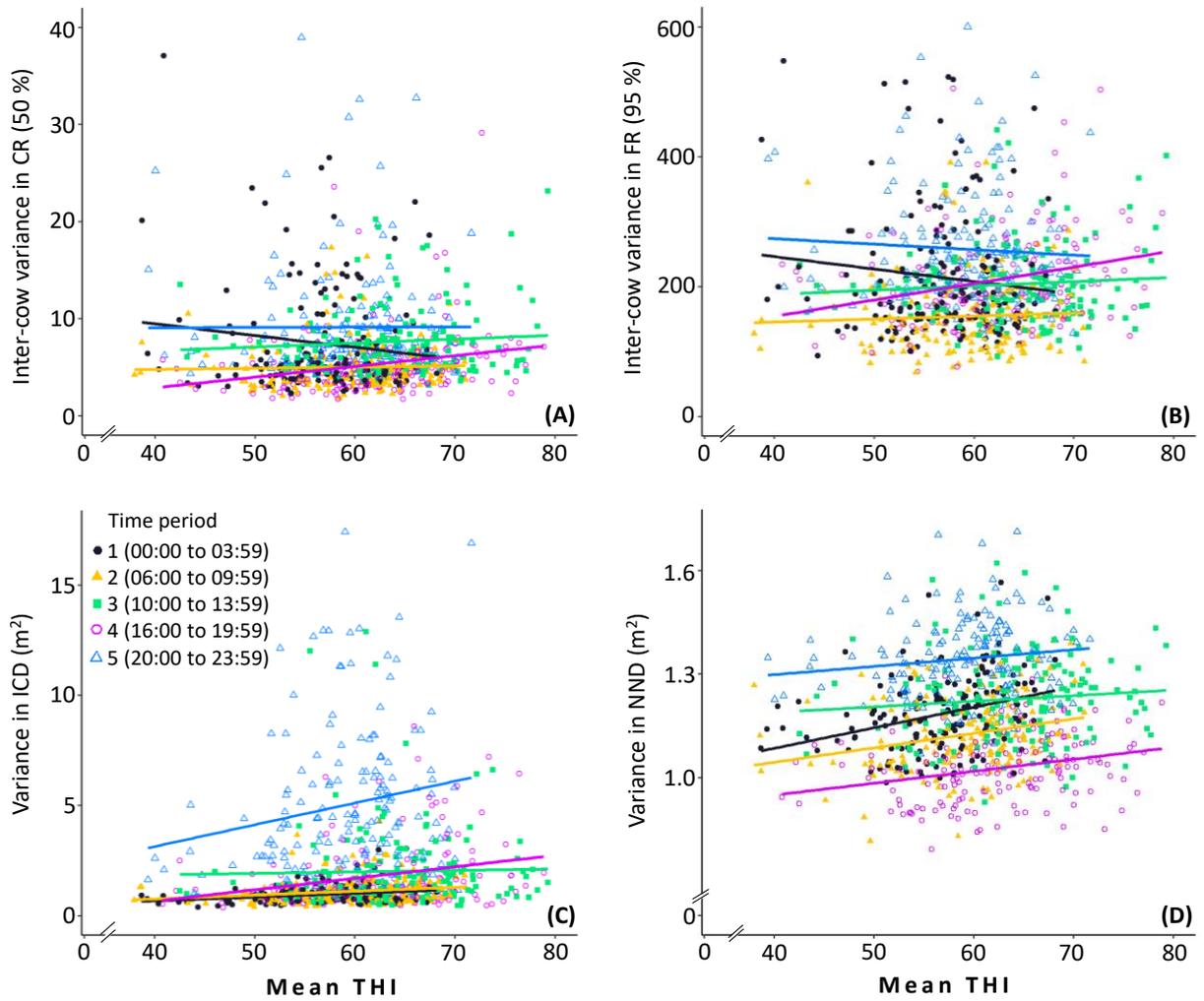


Figure S3. Relationship between mean THI and (A) inter-cow variance in core range (50 %) and (B) inter-cow variance in full range (95 %), (C) variance in inter-cow distance, and (D) variance in nearest neighbour distance, for each time period. Time periods (P) shown are: P1 (00:00 h to 03:59 h), P2 (06:00 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). A singular data point represents one day (P1: $n = 160$ days, P2: $n = 160$ days, P3: 161 days, P4: 160 days and P5: 159 days).

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Table S1. Results of **robust regression models** using the predictor variable mean THI for each of the additional 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			Summary
		<i>(p-values)</i>			
S_1 : time within 3m of fans (proximity method)	1	$a_0 = 24.54$	$a_1 = 0.07$	$(p = 0.05)$	Time spent near fans increases with increasing THI, and this is significant during P2 to P5.
	2	$a_0 = 16.00$	$a_1 = 0.20$	$(p < \mathbf{0.001})$	
	3	$a_0 = 10.40$	$a_1 = 0.24$	$(p < \mathbf{0.001})$	
	4	$a_0 = 13.59$	$a_1 = 0.26$	$(p < \mathbf{0.001})$	
	5	$a_0 = 12.31$	$a_1 = 0.17$	$(p < \mathbf{0.001})$	
S_2 : time in areas around fans (directional method)	1	$a_0 = 49.12$	$a_1 = -0.08$	$(p = 0.17)$	Time spent near fan shapes decreases during P1, P2 and P4 whereas increases during P3 and P5, and this is significant during P2, P3 and P5.
	2	$a_0 = 52.79$	$a_1 = -0.12$	$(p = \mathbf{0.002})$	
	3	$a_0 = 33.64$	$a_1 = 0.10$	$(p = \mathbf{0.03})$	
	4	$a_0 = 51.64$	$a_1 = -0.03$	$(p = 0.48)$	
	5	$a_0 = 24.19$	$a_1 = 0.11$	$(p = \mathbf{0.04})$	
S_3 : mean individual full range (FR)	1	$a_0 = 20.05$	$a_1 = 0.03$	$(p = 0.45)$	Individual FR increases with increasing THI, and this trend is significant for P2, and P4.
	2	$a_0 = 8.16$	$a_1 = 0.19$	$(p < \mathbf{0.001})$	
	3	$a_0 = 24.88$	$a_1 = 0.05$	$(p = 0.34)$	
	4	$a_0 = 3.25$	$a_1 = 0.25$	$(p < \mathbf{0.001})$	
	5	$a_0 = 32.90$	$a_1 = 0.02$	$(p = 0.63)$	
S_4 : nearest neighbour distance (NND)	1	$a_0 = 1.93$	$a_1 = -0.001$	$(p = 0.54)$	Unclear relationship between NND and THI (only significant during P3).
	2	$a_0 = 1.75$	$a_1 = 0.0001$	$(p = 0.95)$	
	3	$a_0 = 2.12$	$a_1 = -0.005$	$(p < \mathbf{0.001})$	
	4	$a_0 = 1.70$	$a_1 = -0.001$	$(p = 0.45)$	
	5	$a_0 = 1.81$	$a_1 = 0.0001$	$(p = 0.85)$	
S_5 : distance travelled during high activity	1	$a_0 = 673.05$	$a_1 = -0.33$	$(p = 0.66)$	Distance travelled during high activity increases with increasing THI during the day (significant during P2 and P4) whereas decreases during the night (significant during P5).
	2	$a_0 = 411.07$	$a_1 = 3.08$	$(p < \mathbf{0.001})$	
	3	$a_0 = 725.32$	$a_1 = 0.45$	$(p = 0.46)$	
	4	$a_0 = 304.69$	$a_1 = 3.44$	$(p < \mathbf{0.001})$	
	5	$a_0 = 1033.41$	$a_1 = -2.70$	$(p < \mathbf{0.001})$	
S_6 : inter-cow variance in CR	1	$a_0 = 5.04$	$a_1 = 0.001$	$(p = 0.97)$	Relationship between inter-cow variance in range size and THI is unclear.
	2	$a_0 = 2.67$	$a_1 = 0.03$	$(p = 0.17)$	
	3	$a_0 = 7.76$	$a_1 = -0.02$	$(p = 0.56)$	
	4	$a_0 = -0.51$	$a_1 = 0.08$	$(p < \mathbf{0.001})$	
	5	$a_0 = 3.75$	$a_1 = 0.06$	$(p = 0.11)$	
S_7 : inter-cow variance in FR	1	$a_0 = 202.85$	$a_1 = -0.33$	$(p = 0.70)$	
	2	$a_0 = 88.70$	$a_1 = 0.92$	$(p = 0.09)$	
	3	$a_0 = 195.07$	$a_1 = -0.01$	$(p = 0.99)$	
	4	$a_0 = 66.81$	$a_1 = 2.16$	$(p = \mathbf{0.004})$	
	5	$a_0 = 288.13$	$a_1 = -0.81$	$(p = 0.51)$	
S_8 : variance in ICD	1	$a_0 = 0.35$	$a_1 = 0.01$	$(p = \mathbf{0.009})$	Variance in ICD increases with increasing THI, and this is significant for P1 to P3, and P5.
	2	$a_0 = 0.06$	$a_1 = 0.02$	$(p = \mathbf{0.006})$	
	3	$a_0 = 0.02$	$a_1 = 0.02$	$(p = \mathbf{0.02})$	
	4	$a_0 = 0.38$	$a_1 = 0.01$	$(p = 0.08)$	
	5	$a_0 = -0.43$	$a_1 = 0.08$	$(p = \mathbf{0.003})$	
	1	$a_0 = 0.86$	$a_1 = 0.006$	$(p < \mathbf{0.001})$	
	2	$a_0 = 0.87$	$a_1 = 0.004$	$(p = \mathbf{0.009})$	

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<i>S₉</i> variance in NND	3	$a_0 = 1.08$	$a_1 = 0.002$	$(p = 0.12)$	Variance in NND increases with increasing THI, and this is significant for P1, P2, P4, and P5.
	4	$a_0 = 0.79$	$a_1 = 0.004$	$(p = \mathbf{0.0002})$	
	5	$a_0 = 1.19$	$a_1 = 0.002$	$(p = \mathbf{0.03})$	

2.4. Between-month variability in space-use metrics

To quantify comparison of between-month variability across dependent metrics in Fig S4, with differing units and scales, each variable was standardised (z-score), and the standard deviation across months was calculated for each time period. The mean of these values was used as a unitless measure of between-month variance. Figure S4 reflects seasonality, with the highest mean standard deviations for time spent near water troughs and fans (mean SD = 0.42 and 0.18 respectively; Fig S4.A-B), and ICD (mean SD = 0.22; Fig S4.J).

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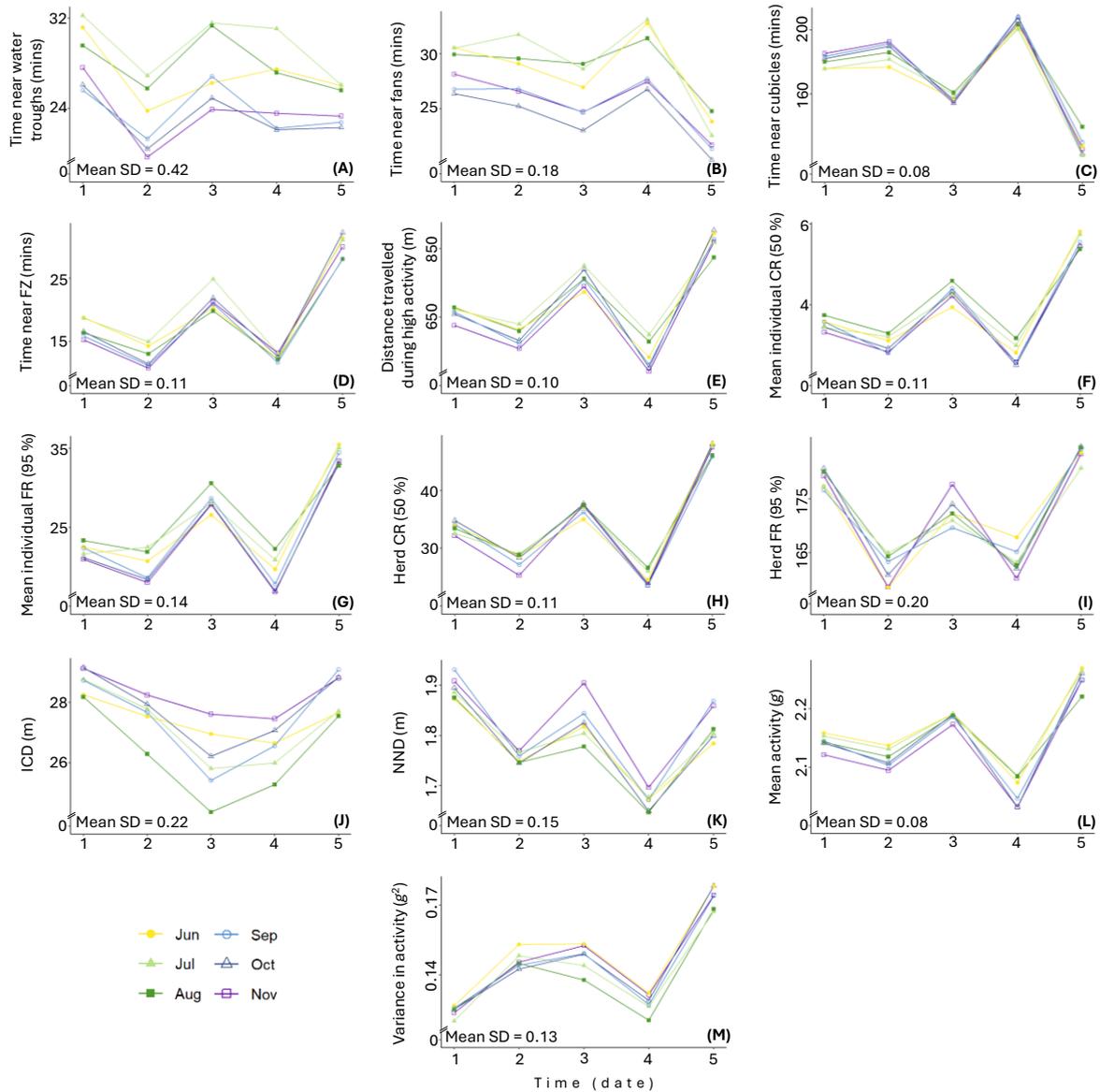


Figure S4. Mean average of dependent variables over all days per month and time period: time near (A) fans, (B) water troughs, (C) cubicles, (D) the feeding zone (FZ), and (E) distance travelled during high activity, (F) individual core range (CR; 50%), (G) individual full range (FR; 95%), (H) herd CR, (I) herd FR, (J) intercow distance (ICD, m), (K) nearest neighbour distance (NND, m), (L) mean activity, and (M) variance in activity. 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). Months are divided as June (dark purple), July (light purple), August (blue), September (turquoise), October (green), November (light green) and December (yellow) 2024. Mean SD = average standard deviation across months (z-scored).