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The diversity in dairy cattle reticulorumen temperature: Identifying water intake events

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ABSTRACT

Climate change and associated weather variability across the Australian landscape has lent themselves to an increased incidence of cattle heat stress. Water consumption can have a sizeable, sustained impact on reticulorumen temperature readings, thereby impacting our interpretation of an individual's underlying physiological response to changing environmental conditions. To distinguish drinking events, we developed a drinking event detection model based on observed drinking events (video recording) from 28 dairy heifers, alongside sensor-derived reticulorumen temperature (smaXtec Animal Care GmbH) profiles. The optimised model identified drinking events with high accuracy (F-score = 0.99), as predicted when the average reticulorumen temperature declined by at least 0.5°C per 10-minutes, over a 10-, 20-, or 30-minute period. To account for differences in rapidity of decline, smaller reductions of 0.25°C per 10 min were considered valid indicators of a drinking event, provided the 0.5°C per 10-minute threshold was also met in a consecutive observation period. The temporal variability in drinking behaviour for 1,429 lactating dairy cattle across three dairy farms was then determined. Daily drinking events were greater in summer (mean 4.1) than winter (mean 3.3), while the change in reticulorumen temperature with each drinking event was smaller in summer (mean 3.7°C) than winter (mean 4.9°C). Drinking-recovery duration averaged 97.8 min/event. By revealing temporal differences in drinking behaviour for pasture-based dairy cattle, this work provides the basis for an improved understanding of core body temperature diversity.

1. Introduction

Dairy farming in Australia is primarily pasture-based and occurs across a wide range of environments (Cheruiyot et al., 2019). As such, Australian dairy cattle are increasingly exposed to climate variability and with more frequent, intense heat events the associated risk of cattle heat stress (HS) also increases (Blunden and Boyer, 2022; Cowley et al., 2015). Climate change is of particular importance for high-yielding dairy cows as they already experience an elevated internal heat load compared to lower producing individuals (Pryce et al., 2022), and as a result, the impact of heat accumulation is exacerbated for these cows (Bernabucci et al., 2015; West, 2003). As a response to escalating global temperatures, there is an increasing need to understand the role of climate factors and their impact on the prediction and assessment of HS for dairy cattle (Yan et al., 2020). Several thermal indices are used by livestock industries (Wang et al., 2018a) including the temperature humidity index (Mader et al., 2006), heat load index (Gaughan et al., 2008), comprehensive climate index (Mader et al., 2010), index of thermal stress for cows (Da Silva et al., 2015), dairy heat load index (Lees et al., 2018), and equivalent temperature index for cattle (Wang et al., 2018b), among others. However, the success of a thermal index is intimately linked with its ability to predict animal responses to heat (Hahn et al., 2009). As most thermal indices predictions are at a herd-level, methods to determine individual animal responses to HS are required.

An animal's primary response to a challenging thermal environment is the alteration of its physiology and/or behaviour (Ji et al., 2020; Polsky and von Keyserlingk, 2017; West, 2003). Cattle response to HS can appear in a variety of forms, however each response aims to reduce metabolic heat production and enhance heat dissipation into the environment (Islam et al., 2021; West, 2003). Due to advances in precision livestock farming, the use of objective technology is enabling

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identification of changes to individual animal health at a rate much higher than possible with traditional human observation (Barkema et al., 2015), reducing labour requirements whilst increasing efficiency. Reticulorumen boluses for the measurement of deep core body temperature (CBT) have gained traction in both research and commercial industries (AlZahal et al., 2011; Bewley et al., 2008a; Hicks et al., 2001; Sievers et al., 2004; Small et al., 2008). Using an intraruminal device has many advantages over alternative external sensors, as they are independent from exterior disturbing factors and less likely to be lost (Sievers et al., 2004), whilst still retaining continuous data collection through instant wireless transmission (AlZahal et al., 2011) or data storage (Koltes et al., 2018). Nevertheless, a limitation of reticulorumen sensors is the influence that diet and drinking events can have on the readings, with a drinking bout shown to decrease reticulorumen temperature up to 9.2°C for up to three and half hours (Ammer et al., 2016; Bewley et al., 2008b). By accounting for this water intake, reticulorumen temperature has been shown to be a successful proxy indicator of CBT to in turn measure and quantify the impact of HS on dairy cattle.

Commercial bolus systems that identify and remove drinking events from raw reticulorumen temperature data are available, however, algorithm transparency is not always evident. Limited studies have developed their own methods to eliminate drinking events from raw data. Research has suggested that recording the temperature of drinking water will allow for separation of the effect of consumed water on reticulorumen temperature (Dye and Richards, 2008). Timsit et al. (2011) pre-processed raw reticulorumen temperature data to eliminate drinking events using an autoregressive process of order 4 alongside adaptive filtering, as described by Blanchet and Charbit (2006). Vázquez-Diosdado et al., (2019) compared a general-fixed threshold algorithm (single temperature threshold) and cow-day specific threshold algorithm (accounting for mean and standard deviation of the temperature of individual cows), finding the latter performed best. Presenting an overview of the development of a new sensor, Vakulya et al. (2024) described a system that will measure rumen temperature every five minutes, with a drinking event detected when there is a decline in temperature of at least 2°C between consecutive readings. This threshold can be adjusted to account for variations in water temperature (within limits). Additional studies are required to determine the best method of drinking event isolation to enable individual health monitoring.

Water is essential for all major physiological processes in the body, and as such, its deprivation can have negative impacts on animal health, behaviour, and performance (Cardot et al., 2008; Golher et al., 2021). Therefore, the tracking of individual drinking behaviour can be a form of health monitoring, used to predict disease and assess physiological state (Vázquez-Diosdado et al., 2019). Daily water intake between dairy cattle ranges from an average of two to four drinking events per day (maximum of 11) (Campbell and Munford, 1959; Castle et al., 1950; Chiy et al., 1993), up to an average of seven (Cardot et al., 2008). However, there are several influencing factors that impact water intake on an individual level, including dry matter intake, stage of lactation, and climate conditions (Gonzalez Pereyra et al., 2010; Jensen and Vestergaard, 2021; Singh et al., 2022). The consumption of water at varying temperatures and volumes can have a sizable, sustained impact (Bewley et al., 2008b) and as such may be indicative of individual coping strategies dictated by external climatic conditions. Previous studies exploring the impact of water intake on CBT were conducted on a small scale, using nine animals over two three-day periods (Bewley et al., 2008b) or over six days (Boehmer et al., 2009), both in controlled conditions. Most recently, Vázquez-Diosdado et al. (2019) validated two threshold algorithms in field conditions using 16 animals over four days. The most successful model was then used on a further 54 animals to investigate different factors associated with reticulorumen temperature drop characteristics for individual cows. As such, large scale analysis in field conditions is yet to be conducted. Whilst reticulorumen temperature monitoring is well-established, the isolation of drinking events for accurate CBT interpretation has remained problematic. This research introduces a novel algorithm to address this gap.

To the best of our knowledge, the use of threshold algorithms to detect and isolate the impact of water intake using a reticulorumen bolus has not been done to this scale in field settings. The objective of this study was to develop a novel drinking event detection model for dairy cattle and from this model, determine the temporal variability in drinking events for individual pasture-based dairy cattle.

2. Materials and methods

We conducted two experiments to 1) develop and validate a method to detect drinking events and 2) assess temporal variability in water intake in field settings. In both experiments all cattle had previously been orally administered with a bolus (smaXtec Animal Care GmbH, Graz, Austria), that naturally transports to the reticulorumen. Data obtained from the smaXtec bolus included raw reticulorumen temperature data (‘temp’), which was the temperature as it arrives from the sensor, with no alterations, alongside additional parameters including activity (‘act’) and rumination (‘rum_index’). Collection was enabled through wireless transmission with observation periods every 10 min, 24 h a day. Product specification states temperatures between 20°C and 60°C can be measured with an accuracy of ±0.01°C (SmaXtec, 2024). As this study focused on the impact of drinking events on reticulorumen temperature, only the ‘temp’ data was utilised. Python script was developed to automatically download the raw bolus data through a provided application programming interface. All data processing and model development were completed using RStudio (v2023.09.1).

2.1. Experiment 1: Model development and validation

The use of animals was approved by the Animal Ethics Executive Committee of the University of Sydney (2023/2370).

Drinking behaviour of 28 mixed-breed (primarily Holstein-Friesian) heifers on a dairy farm in the Macarthur region of New South Wales, Australia was filmed from 25 October to 31 October 2023. Heifers were selected over cows to avoid drinking events being impacted by daily milking practices, with these animals remaining in a single paddock throughout the study duration. Animals had *ad libitum* access to pasture, supplementary forage, and water. A motion sensor camera (32 MP, 20 m 46 IR LED) was mounted directly in front of the single concrete water trough. The camera was set to record at high quality (video format: AVI, 1080P, 10 frames/s) for a 10 s duration with a five second lag-time, saving to an installed SD card. Video data were downloaded mid-way and at the conclusion of the seven-day period. A single observer scored the video recordings retrospectively to determine the drinking event start time to the nearest minute. Footage of up to six hours per day between morning to midday was reviewed. Individuals were identified on the basis of their farm identification tag; when number identification was not possible, identification was on the basis of coat patterns. Drinking event start time was defined to be the time at which the first sip of water was undertaken (introduction of cow nose to water). Due to the five second lag-time between video recordings as per camera capabilities, this may have been the first time a sip was identified on camera. A second drinking event was not distinguished from the first if it occurred within 30 min of the initial event. From video analysis, the start times of all drinking events were identified.

2.1.1. Data processing

Drinking event start times were synchronised with raw reticulorumen ‘temp’ data. Video data were aligned with sensor data by matching time stamps of the first observed drinking event (from video analysis) with deviations in reticulorumen temperature data (from sensors). True drinking events, identified from video analysis, were labelled as such to enable testing of threshold algorithms during validation.

2.1.2. Model development

To account for variations in both water temperature and water volume across drinking events, the algorithm was developed to identify instances of abrupt cooling – distinguishing between a marked drop in reticulorumen temperature within a single 10-minute interval or a more moderate initial rate of temperature decline over up to three consecutive 10-minute intervals. Three series of differences in temperature observations (1) and time intervals (2) were calculated, between every consecutive, second, and third observation. Reticulorumen temperature changes were then standardised (3), noting the multiplier of 600 to account for the number of seconds in a 10-minute observation period. To formally define the model, suppose there is a series of n consecutive reticulorumen temperature observations $\mathrm{RT}_1, \mathrm{RT}_2, \ldots, \mathrm{RT}_n$ at times $t_1, t_2, \ldots, t_n$. The following calculations are then made on the series:

$$\Delta RT_{ij} = RT_{i+j} - RT_i, i = 1, 2, \cdots, n-j; j = 1, 2, 3 \tag{1}$$

$$\Delta t_{ij} = t_{i+j} - t_i, i = 1, 2, \cdots, n-j; j = 1, 2, 3 \tag{2}$$

$$RateRT_{ij} = \Delta RT_{ij}/\Delta t_{ij} \times 600, i = 1, 2, \cdots, n-1; j = 1, 2, 3 \tag{3}$$

where i represents the index of the drinking event, j denotes the time interval between the two observations being compared, and n represents the total number of observations in the series. As time intervals are fixed, $\Delta t_{i1} = 10$ min, $\Delta t_{i2} = 20$ min, and $\Delta t_{i3} = 30$ min, with RateRT_{ij} the rate of temperature change per 10-minutes.

The start of a drinking event at time t is defined as the time point t_i when.

$$(\mathrm{RateRT}_{i1} \leq -0.5) \text{ OR}$$

$$(\mathrm{RateRT}_{i1} \leq -0.25 \text{ AND } \mathrm{RateRT}_{i2} \leq -0.5) \text{ OR}$$

$$(\mathrm{RateRT}_{i1} \leq -0.25 \text{ AND } \mathrm{RateRT}_{i2} \leq -0.25 \text{ AND } \mathrm{RateRT}_{i3} \leq -0.5) \tag{4}$$

These constants (−0.5, −0.25) were chosen based on the minimisation of false positives and false negatives. The reticulorumen temperature drop associated with a drinking event, at time t_i, $\Delta\mathrm{RT}_i$, is calculated as the sum of drops associated with up to three-time intervals starting at times t_i, t_{i+1}, and t_{i+2}. The negative sign is applied to return a temperature drop as a positive value, for ease of subsequent analysis. This is calculated as

$$\Delta\mathrm{RT}_i = -(\Delta\mathrm{RT}^*_{i1} + \Delta\mathrm{RT}^*_{i2} + \Delta\mathrm{RT}^*_{i3}) \tag{5}$$

where

$$\Delta\mathrm{RT}^*_{ij} = \begin{cases} \Delta\mathrm{RT}_{ij} & \Delta\mathrm{RT}_{ij} < 0 \\ 0 & \text{otherwise.} \end{cases}$$

2.1.3. Performance of the validation

From the synchronisation of raw sensor data and daily video annotations for 28 heifers over seven days, 177 drinking events were available for analysis. Algorithm performance was evaluated by the following metrics: precision (‘Pre’; proportion of predicted events that were positive events according to the data, also known as positive predictive value), recall (‘Rec’; proportion of positive events that the model predicted correctly, also known as sensitivity), and F-score (harmonic mean of precision and recall, evaluates overall performance) (Branco et al., 2015). The formulae for these metrics are

$$\text{Precision} = \frac{\mathrm{TP}}{\mathrm{TP} + \mathrm{FP}}$$

$$\text{Recall} = \frac{\mathrm{TP}}{\mathrm{TP} + \mathrm{FN}}$$

$$\text{F-score} = \frac{2 \times \mathrm{Pre} \times \mathrm{Rec}}{\mathrm{Pre} + \mathrm{Rec}}$$

where TP, FP, and FN are the number of true positives, false positives, and false negatives, respectively.

2.2. Experiment 2: Drinking event temporal variability

Reticulorumen temperature data from 1,429 mixed-breed (primarily Holstein-Friesian) dairy cattle across three dairy herds in Victoria, Australia were collected across four years with a data download cut-off for ease of analysis in February 2023 (Table 1). To retain anonymity, specific farm locations are withheld. All farms are primarily pasture-based, with animals varying in age and parity. No alterations to typical farm management were dictated by us throughout the duration of data collection to ensure standard conditions were maintained. Animal ethics approval was not required as the data were already being recorded by the farms for their own use.

These data were processed and analysed as per Experiment 1, with the addition of the analysis described below.

To determine the length of a drinking event inclusive of recovery, the initial temperature was taken at the time at which the start of a drop was recorded. Then, the time to return to 100 k% of the difference from the initial temperature was determined. In this analysis, time to 90 % return was calculated ($k = 0.9$). This time, labelled $t_i^{(k)}$, was taken at the first time t_j, $j = i+1, i+2, \ldots, m$ when

$$RT_j \geq RT_i - (1-k)\Delta RT_i$$

where m is the number of observations before the next drinking event. If the next drinking event started before the reticulorumen temperature had returned to this value, the last time in this series, $t_m = t_i^{(k)}$, was recorded as a censored observation. As a measure of overall heat loss during a drinking event, the ‘area under the curve’ between drinking start time t_i and $t_i^{(k)}$ using reticulorumen values over this interval is calculated using a simple trapezoidal method (Appendix A). These areas will also be censored if $t_i^{(k)}$ is censored.

The number of predicted drinking events each day by individual animals was analysed to investigate seasonal changes as well as any difference between the three farms. For this, a term labelled ‘YM’ was formed which was a combination of the year and month of the drinking event. A Poisson generalised linear mixed model was then fitted to the count data using ASReml-R in the R environment (Butler et al., 2023). Fixed effects were YM, farm, and their interaction and a random effect for the individual animal within the farm was included. Wald tests were used for significance testing.

For the analysis of reticulorumen temperature drop, the average of drops on each data for each animal was calculated and then analysed. A linear mixed model was then fitted to these temperature drop data with the same fixed and random effects as were used for the analysis of number of drinks. To meet model assumptions, the temperature drop data were first log-transformed, and model-based means then reported in the back-transformed scale.

The association between the number of drinking events per day and average temperature drop was assessed graphically and tested using a Spearman’s correlation coefficient, separately for each farm.

Time to 90 % recovery of the reticulorumen temperature drop and

Table 1
Individual farm statistics.

	Farm A	Farm B	Farm C
Number of animals	659	426	344
Start date	8 June 2021	28 March 2019	7 March 2019
End date	2 February 2023	2 February 2023	2 February 2023

total temperature drop over a drinking event were analysed using individual drinking event data, not daily averages, and only uncensored values were included in the analyses. Values for both response variables were log-transformed to meet model assumptions, and the same fixed and random effects as used in the previous mixed models were included.

3. Results

3.1. Experiment 1: Model development and validation

Synchronisation of raw sensor data and manual video annotations for 28 heifers over seven days resulted in 177 drinking events for analysis. Out of these events, 173 were true positives, three were false negatives and one was a false positive. As such, the final threshold model provided a precision of 0.99, recall of 0.98 and F-score of 0.99. Visualisation of raw sensor data with identification of drinking event start times is shown in Fig. 1.

3.2. Experiment 2: Drinking event temporal variability

3.2.1. Number of drinking events

The median number of drinking events per day was 4.00 with a mean value of 3.66. There was a greater quantity of cattle drinking events per day across summer periods (mean 4.07, SE 0.003) compared to winter (mean 3.31, SE 0.003) (Table 2). Here and elsewhere seasons are defined conventionally, treated as equal periods of three months each, with summer defined as December-January-February, autumn as March-April-May, winter as June-July-August, and spring as September-October-November (for the Southern Hemisphere). Farm B retained consistently higher average drinks per day for each season, with the seasonality of drinking frequency over time shown in Fig. 2.

We identified a significant difference between farms ($p < 0.0001$), over time ($p < 0.0001$), as well as a time by farm interaction ($p < 0.0001$) (Table 3). There was significant variation in the frequency of drinking events between individual animals, as indicated by the animal variance of 0.03 ± 0.001 ($p < 0.0001$). This variability within each farm is visualised in Fig. 3.

3.2.2. Reticulorumen temperature change

The median drop in reticulorumen temperature with each drinking event was 4.12°C with a mean of 4.25°C. The change in reticulorumen temperature with each drinking event was smaller in summer (mean 3.71°C, SE 0.002°C) with the highest drop occurring in winter (mean 4.86°C, SE 0.004°C) (Table 4). Farm B retained the lowest change in reticulorumen temperature during summer and autumn, whilst Farm C retained the lowest change in reticulorumen temperature during winter

Table 2
Mean number of drinks per day.

	Farm A	Farm B	Farm C	Overall
Summer	3.34	4.98	3.85	4.07
Autumn	3.04	4.56	3.62	3.85
Winter	3.10	3.70	3.06	3.31
Spring	3.20	3.91	3.15	3.45

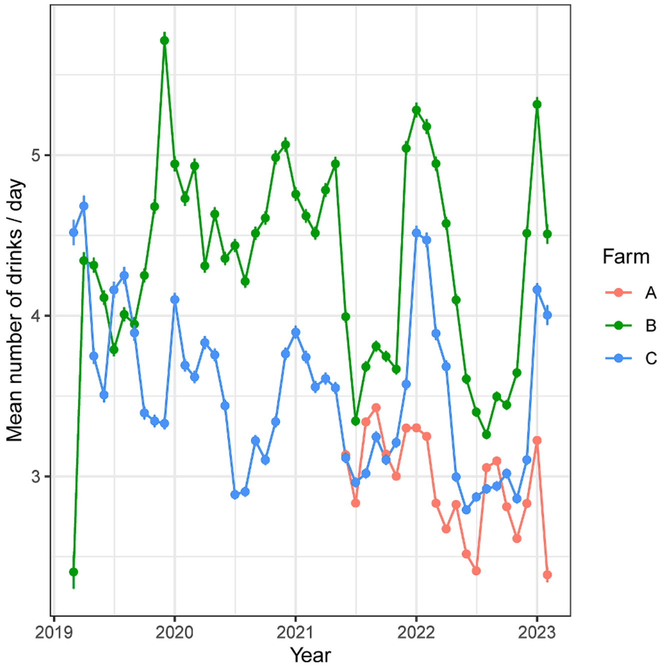

Fig. 2. Mean number of drinks per day over time for each of the three properties.

Table 3
Wald test for fixed effects; response = number of drinks.

	Num. DF	Den. DF	*F*-statistic	*P*-value
Farm	2	1404	600	< 0.0001
YM*	47	865,230	2,074	< 0.0001
Farm × YM	67	865,298	664	< 0.0001

* YM is the combination of year and month.

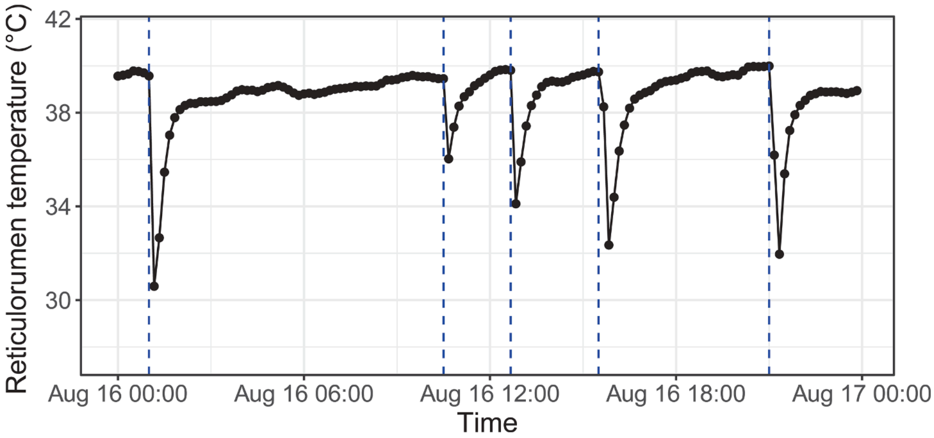

Fig. 1. Synchronisation of raw sensor data (black dots indicate 10-minute interval reticulorumen temperature readings) and manual video annotations (dashed blue lines indicate observed drinking events).

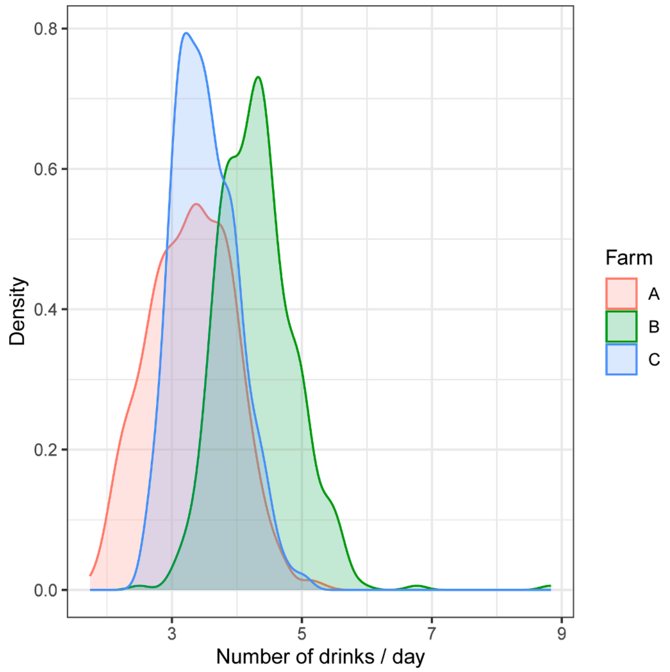

Fig. 3. Variability in number of drinking events for individual animals on each of the three properties.

Table 4
Mean reticulorumen temperature drop (°C).

	Farm A	Farm B	Farm C	Overall
Summer	4.18	3.16	3.82	3.71
Autumn	4.57	3.80	4.56	4.25
Winter	5.10	4.83	4.64	4.86
Spring	4.52	4.15	4.09	4.27

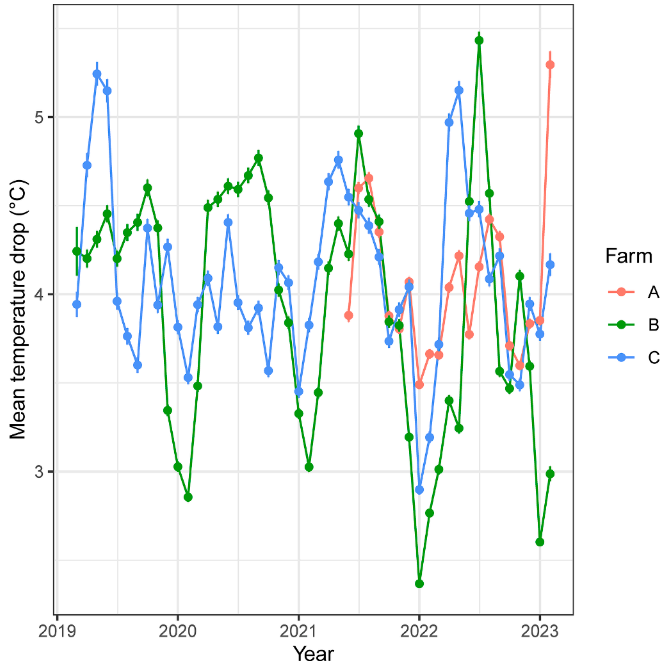

Fig. 4. Mean reticulorumen temperature (°C) drop over time for each of three properties.

and spring. Fig. 4 demonstrates the seasonal variation in reticulorumen temperature across farms.

A Wald test indicated significant differences between farms ($p < 0.0001$), over time ($p < 0.0001$), as well as a time by farm interaction ($p < 0.0001$) (Table 5). There was also significant variation in temperature drops between animals, where the animal variance was estimated as 0.03 ± 0.001 ($p < 0.0001$). This variability in individual animal temperature drops for each farm is shown in Fig. 5.

3.2.3. *Correlation of drinking event frequency and reticulorumen temperature change*

With an increased number of drinking events occurring per day, the average temperature drop per drink was reduced (Fig. 6). Farm B retained the strongest negative association between number of drinks per day and reticulorumen temperature decline (Spearman's correlation: A $r_s = -0.18$, B $r_s = -0.41$, C $r_s = -0.38$). The individual animal effect on the association between number of drinks per day and average drop in reticulorumen temperature is visualised in Fig. 7.

3.2.4. *Recovery time*

The cumulative drinking-recovery duration (i.e. time below baseline), based on time until 90 % temperature recovery, had a median of 90 min, with a mean of 97.73 min. Recovery time remained consistent across seasons with little variation from summer (mean 95.46 mins, SE 0.06 mins) to winter (mean 98.66 mins, SE 0.07 mins). Farm B consistently had a faster recovery time (Table 6), with the duration over time visible in Fig. 8.

Based on Wald tests, there were significant differences between farms ($p < 0.0001$) and over time ($p < 0.0001$) (Table 7).

3.2.5. *Total temperature loss*

Accounting for cumulative reticulorumen temperature loss during a drinking event, the median total temperature loss per event was 2.07°C with a mean of 2.33°C. The greatest loss occurred in winter (mean 2.81°C, SE 0.003°C), as compared to the smallest loss in summer (mean 1.93°C, SE 0.002°C) (Table 8). Seasonality of the total temperature loss over time can be seen in Fig. 9.

We identified a significant difference between farms ($p < 0.0001$), over time ($p < 0.0001$), as well as a time by farm interaction ($p < 0.0001$) (Table 9).

4. Discussion

The present study completed validation under standard farm management with 28 animals across a seven-day period. Acknowledging differences in study design, the model developed here performed better than the cow-day specific threshold presented by Vázquez-Diosdado et al., (2019), which retained an optimal performance of F-score = 0.74 (threshold factor = 10). This model is distinct from others in that it looks at the rapidity of a drop within a timeframe, rather than being based on a set temperature, in the way of a general fixed threshold. In this manner, it considers individual animal variation. By accounting for a level of variability in individual animal response, the dynamic nature of this algorithm makes it more capable of identifying drinking events across various individuals in a herd. The success of our drinking event algorithm for use in farm conditions, at a large scale, is promising, providing the basis for an improved understanding of dairy cattle drinking event

Table 5
Wald test for fixed effects; response = reticulorumen temperature.

	Num. DF	Den. DF	*F*-statistic	*P*-value
Farm	2	1415	18	< 0.0001
YM*	47	865,179	2588	< 0.0001
Farm × YM	67	865,223	1145	< 0.0001

* YM is the combination of year and month.

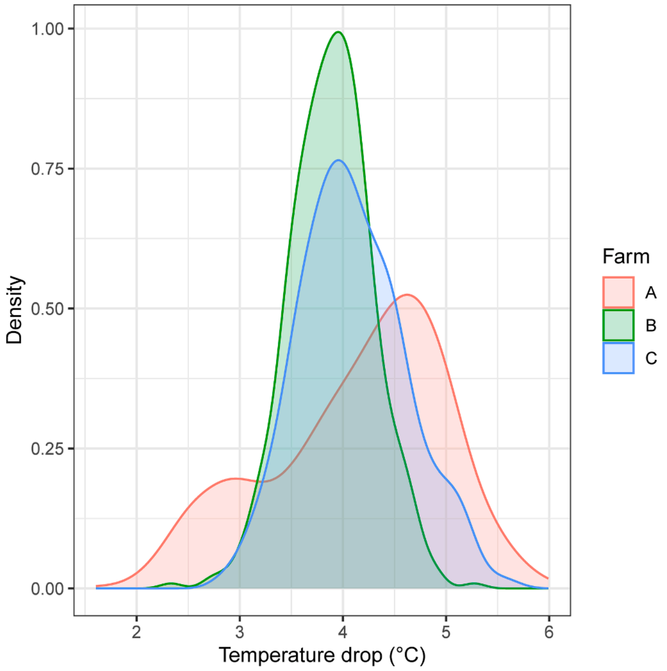

Fig. 5. Variability in reticulorumen temperature drop for individual animals on each of the three properties.

detection and behaviour.

The temporal variability in water intake for 1,429 cattle (mixed breeds) on three dairy farms was determined using this drinking event model across four years. Aligning with seasonal variation, the average number of drinking events per day across summer, autumn, winter, and spring were 4.07, 3.85, 3.31, and 3.45, respectively. Literature has shown variation in daily water intake, ranging from an average of two to four drinking events per day (maximum of 11) (Campbell & Munford, 1959; Castle et al., 1950; Chiy et al., 1993) compared to a greater average of seven (Cardot et al., 2008). Whilst our overall mean of 3.66 drinks per day is lower than that reported in literature, individual animals did exhibit large variation in the amount of drinking events per day, from one to 20. Previous studies have suggested variation in the frequency of water intake is primarily due to the quantity of water drunk during each event (Cardot et al., 2008) with increases in water intake also identified with increasing parity (Dado and Allen, 1994; Vázquez-Diosdado et al., 2019). Variation in water intake among individuals within a herd can have significant implications in terms of animal health. Summarised by the NRC (2001), several experiments have shown that the physical act of drinking water accounts for 83 % of individual water demand. Tracking of water intake frequency and volume at an individual level may provide an indication of heat tolerance. Further research should focus on distinctive characteristics that vary between individuals which may account for these differences in drinking behaviour.

The average change in reticulorumen temperature with each drinking event was 3.71°C, 4.25°C, 4.86°C, and 4.27°C, across summer, autumn, winter, and spring, respectively. The smallest change occurred in summer, and the highest in winter. This combined average drop of 4.25°C was greater than the 2.30–3.01°C drop observed by Vázquez-

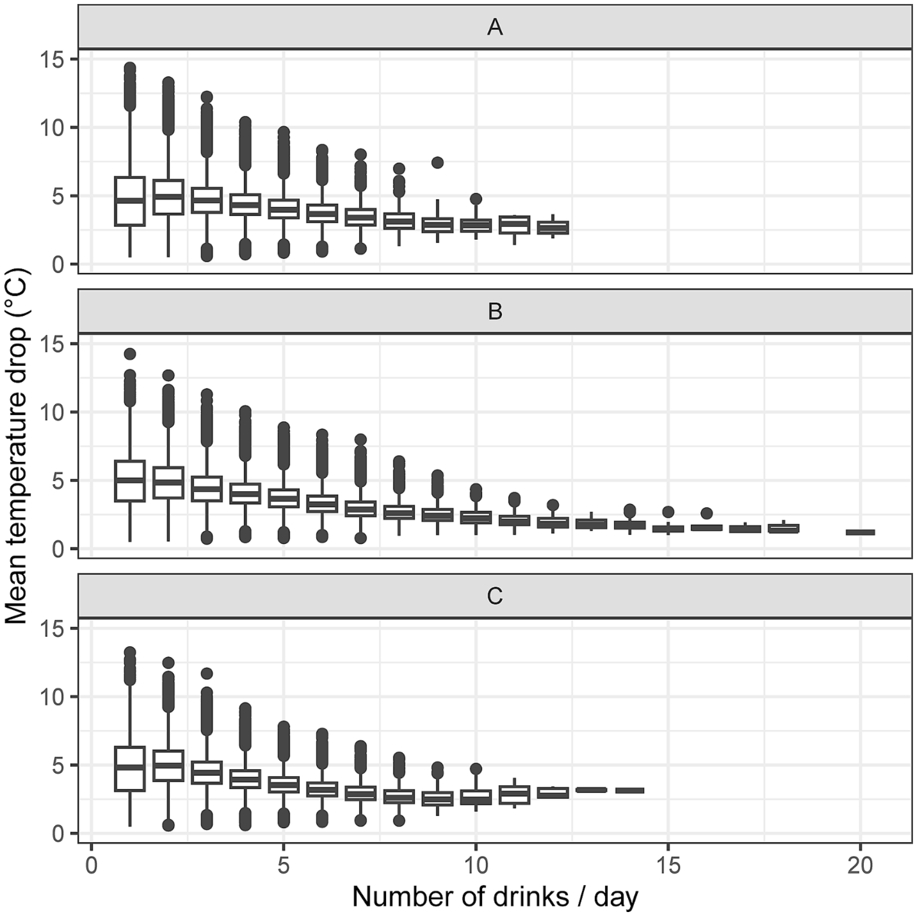

Fig. 6. Association between number of drinks per day and average drop in reticulorumen temperature (°C).

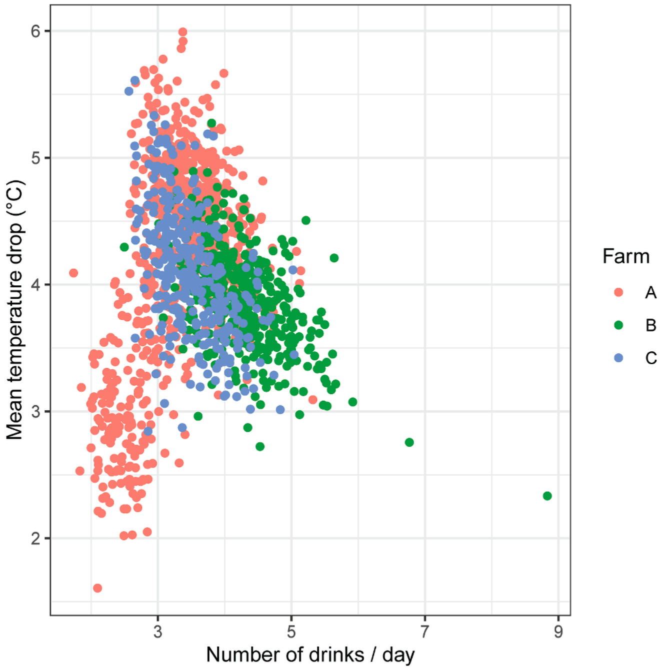

Fig. 7. Individual animal effect on the association between number of drinks per day and average drop in reticulorumen temperature (°C). Each point represents an individual animal average.

Table 6
Mean time to 90% recovery (mins).

	Farm A	Farm B	Farm C	Overall
Summer	103.44	88.24	97.11	95.52
Autumn	104.45	93.67	99.43	97.84
Winter	101.33	96.58	98.75	98.67
Spring	100.64	95.94	102.70	99.32

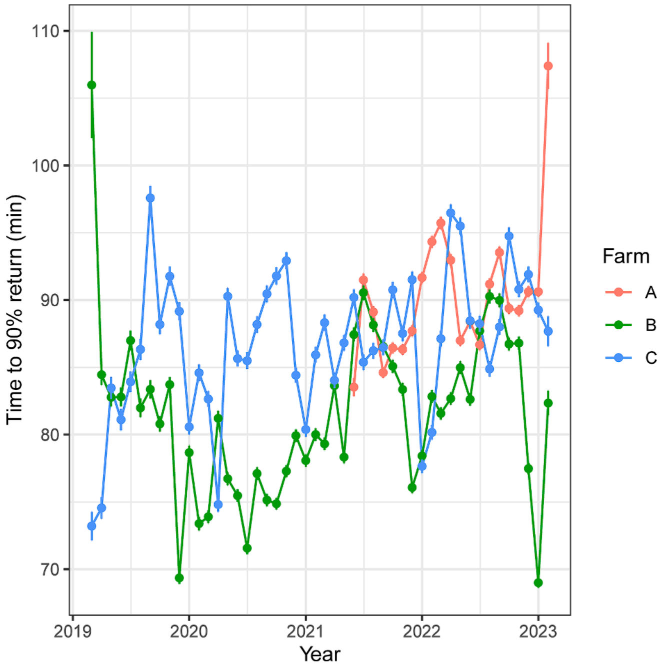

Fig. 8. Average drinking event duration based on time at 90% temperature recovery.

Table 7
Wald test for fixed effects; response = drinking event duration.

	Num. DF	Den. DF	*F*-statistic	*P*-value
Farm	2	1425	129	< 0.0001
YM*	47	2,532,240	256	< 0.0001

* YM is the combination of year and month.

Table 8
Temperature loss over drinking event duration (°C).

	Farm A	Farm B	Farm C	Overall
Summer	2.31	1.62	2.04	1.93
Autumn	2.45	2.10	2.52	2.30
Winter	2.98	2.79	2.67	2.81
Spring	2.69	2.33	2.41	2.47

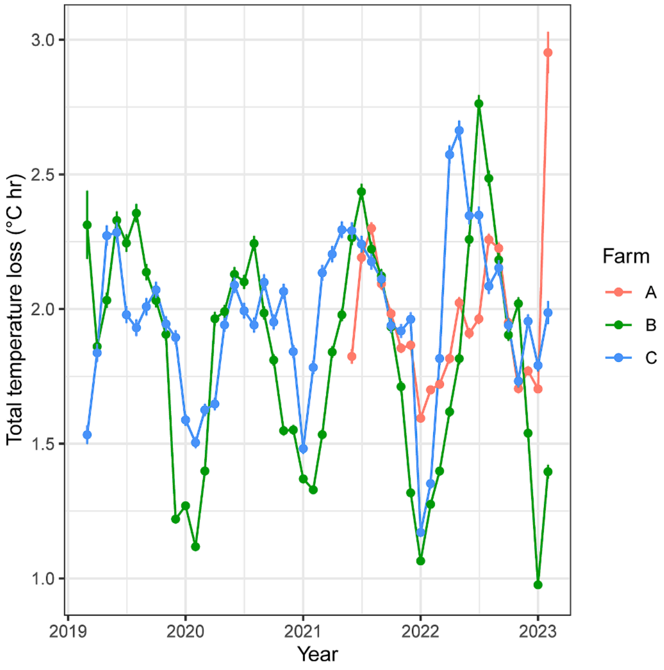

Fig. 9. Total temperature loss per event (°C hr) over drinking event duration.

Table 9
Wald test for **fixed** effects; response = total temperature loss.

	Num. DF	Den. DF	*F*-statistic	*P*-value
Farm	2	1391	54.9	< 0.0001
YM*	47	1,808,206	2184	< 0.0001
Farm × YM	67	1,808,356	597.9	< 0.0001

* YM is the combination of year and month.

Diosdado et al., (2019). As this experiment was conducted outside in field conditions with animals provided access to open water troughs, water temperatures were likely associated with environmental conditions at the time. Bewley et al. (2008b) drenched cold water at 7.6°C (25.2 kg) or 5.1°C (18.9 kg) into cattle resulting in an average 8.5°C or 9.2°C, maximum temperature decrease, respectively. The greater temperature drop reported here as compared to this study was likely due to the large volume of water drenched in combination with the low temperature. Alongside the greatest frequency of drinking events for cattle on Farm B, these cattle also retained the lowest reticulorumen temperature drop in summer and autumn, likely due to the warmer water ingested. There have been suggestions that providing chilled water to cattle may assist in reducing CBT to assist with HS. Provision of cold water has been shown to reduce respiration rate and retain lower body temperatures, but the effect was not prolonged (Stermer et al., 1986), therefore HS mitigation over a day might only be beneficial if drinking event frequency is high. Further, the energetic cost to the cow proportional to the quantity of chilled water consumed must be considered. Further work is required to isolate the impact of water volume and water temperature on reticulorumen temperature, although such changes are likely to follow thermodynamic laws.

Examining the association between number of drinks per day and drop in reticulorumen temperature, demonstrated that with a smaller number of drinks, there was a greater drop in temperature per event. This suggests that animals undertaking a smaller number of drinking events per day increased their water consumption per event, and vice versa. Heritability for water intake behaviours as high as 0.88 has been identified in feedlot cattle (Dressler et al., 2023). Confirmation of this relationship in pasture-based dairy cattle will enable selection of individuals for feed and water efficiency. We recommend future studies allow for measurement of both water volume and temperature to confirm this relationship and enable further investigation.

We identified an average drinking-recovery time of 97.73 min, based on the time at 90 % temperature recovery. This is slightly shorter than the minimum two-hour recovery period indicated by studies conducted in controlled conditions (Bewley et al., 2008b; Boehmer et al., 2009) but longer than other field condition experiments in dairy cattle that observed a recovery period between 29.98 and 35.55 min (Vázquez-Diosdado et al., 2019). As we did not measure water volume or temperature, we cannot definitively conclude why these differences are evident between animals, but it does highlight variability in recovery time for individual events. Prior studies across species describe great variation in time to recovery, ranging between 20 min to over three hours (Bewley et al., 2008b; Cantor et al., 2018; Cunningham et al., 1964; Dracy et al., 1963; Noffsinger et al., 1961). Slight differences from controlled conditions may be explained by the ad libitum access to feed and water available in the natural field conditions. It might also occur due to the position of the internal bolus for data collection, noting both this and the study by Vázquez-Diosdado et al., (2019) utilised reticulorumen sensors as compared to reticular boluses (Bewley et al., 2008b) and rumen boluses (Boehmer et al., 2009). More knowledge as to the impact of recovery speed following drinking will provide insights into individual animal thermoregulation and overall metabolic health. Further research should be undertaken to explore the difference in recovery time after water consumption in different rumen compartments alongside the influence of body size variation.

Given that water is vital to maintain dairy cattle health and performance (NRC, 2001), ensuring equal access to watering points for all individuals in a herd is essential. With variations in social structure and dominance hierarchies across herds, regulation of resource access can vary. Water consumption typically occurs several times across the day, often associated with feeding or milking activities (NRC, 2001). However, reported rates of water intake can vary significantly. Whilst studies have shown that individuals develop characteristic patterns for feeding and drinking activities (Melin et al., 2005), it is not yet known the influence that hierarchical structure places on drinking event duration or frequency. For example, an animal with a high number of drinking events per day might only have a high frequency as they are consistently bullied away from the watering point prior to quenching their thirst at that time. Whilst local regulations may dictate requirements around watering point size, accessibility, or availability, further work should consider the use of tracking devices (i.e., GPS sensors) to monitor individual animal movement around key resources to ensure accessibility among conspecifics.

5. Conclusions

This work provides the basis for an improved understanding of dairy cattle drinking event detection and behaviour. Our findings now open an area of research focused on the interaction of climate, drinking behaviour, and individual animal CBT diversity. By revealing this diversity, we take the first step towards an improved understanding of CBT diversity. Future work should integrate the impact of climate conditions on individual animal behaviour and explore the genetic basis of drinking behaviour for pasture-based dairy cattle.

CRediT authorship contribution statement

A.K. Shirley: Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **P.C. Thomson:** Writing – review & editing, Visualization, Validation, Supervision, Software, Methodology, Formal analysis, Data curation, Conceptualization. **A. Chlingaryan:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **C.E.F. Clark:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compag.2025.110357.

Data availability

The data that has been used is confidential.

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