Revealing and exploiting the diversity in dairy cattle reticulorumen temperature data for heat stress amelioration

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A thesis submitted in fulfilment of the requirements

for the degree of Doctor of Philosophy

2025

To the place that started it all:

30°35.205'S, 149°56.525'E

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ABSTRACT

Dairy farming in Australia occurs across diverse environments that are increasingly affected by climate variability and the resulting risk of heat stress. Cattle response to heat stress takes on a variety of forms, each aiming to return the animal to thermal stability. Driven by the potential to improve cattle welfare under increasingly challenging climatic conditions, this thesis aims to reveal and exploit the diversity in dairy cattle reticulorumen temperature data for heat stress amelioration. The literature review (Chapter 2) sequentially explores animal responses to heat stress, methods of monitoring, and heat amelioration techniques, revealing the benefits of a data-driven amelioration approach. A critical review of key heat abatement terminology (Chapter 3) establishes clear and precise definitions for the terms 'tolerance', 'resistance', 'resilience', and 'susceptibility'. By providing clarity for this terminology, research objectives and industry needs are elucidated. Development of a drinking event detection model (Chapter 4) provides algorithm transparency in the isolation of drinking behaviour using reticulorumen boluses. Exploration of temporal variability in drinking behaviour of pasture-based dairy cattle confirms seasonal variation in drinking frequency, reticulorumen temperature change, and drinking-recovery duration, improving our understanding of core body temperature diversity. Time series and mixed model analysis are used to link the reticulorumen temperature response of pasture-based dairy cattle to variations in temperature humidity index (Chapter 5). Results indicate significant variability in sensitivity to thermal change among individuals alongside the importance of baseline temperature humidity index levels in determination of this response. The association between three phenotypic indicators for heat tolerance (reticulorumen temperature, milk yield, and drinking frequency) are then assessed (Chapter 6). All traits reveal significant individual animal diversity in response to thermal deviations. Analysis of slopes confirms important inter-trait relationships for heat stress response, in particular highlighting the potential for drinking frequency to be monitored on farm as a proxy for heat stress. This work contributes to enhanced welfare and productivity across the dairy cattle industry, supporting progress towards a climate-smart, sustainable future.

ACKNOWLEDGEMENTS

As I scientist, I find this part of my thesis quite difficult to write without using graphs and statistics. How do I accurately depict the impact of all those who have contributed, possibly unknowingly, to the completion of this body of work? This section is both the hardest to write, and the most important, yet 'thank you' seems so inadequate. Although, with that said, there are a number of people I must thank.

To my supervisory team, Doctor **Anna Chlingaryan**, Professor **Cameron Clark**, and Associate Professor **Peter Thomson**, for your support, knowledge and guidance over the years. Your expertise, patience, and insightful feedback have been instrumental in shaping both this research and my own personal development. I am profoundly grateful for your leadership.

To Doctor **Sabrina Lomax** and Associate Professor **Russell Bush** for your ongoing mentorship. You might not have been directly involved in my project but you each set a standard to strive for in my academic career.

To **my fellow PhD candidates** at both CCWF and beyond, it was a great comfort knowing there were others undertaking the same experiences. Thank you for sharing with me your own achievements and challenges. For when the time is right, congratulations.

To **Dairy UP** for the support of myself and this research through the provision of a primary and supplementary scholarship, I greatly appreciate the opportunity to be a part of such an impactful project and directly see the effect of this research on farm.

To my **family**, who helped more than they know, even without a full understanding of my research. Your belief in my goals and steady reassurance has been invaluable.

To **Kira** (Aussie), **Kira** (Norwegian), and **Alana** – who would have thought we would be here now?! Thank you for getting me through undergrad to even have the chance to complete this thesis. Your friendship has been unwavering, even if video calls are not.

To **Steve**, who was by my side through it all. Your comfort and steady companionship kept me grounded. Thank you for being the best boy.

Finally, to the **musical stylings of Luke Combs** that provided a steady soundtrack to this work, the **team at Loaf** who consistently fed my chai addiction, and those I might not have mentioned by name but still assisted. Thank you.

PREFACE

This thesis is presented in the format of ‘thesis with publications’ and is written in Australian English. For e-readers, hyperlinks have been enabled for ease of navigation.

Some of the chapters comprising this thesis have either been published or are under review for publication. The work of this thesis has also formed the basis of presentations at scientific and institutional research showcases, seminars, and symposiums.

STATEMENT OF ORIGINALITY

This thesis is submitted to The University of Sydney in fulfilment of the requirements for the degree of Doctor of Philosophy. This thesis has not been submitted for any degree or other purposes.

I certify that the intellectual content of this thesis is the product of my own work and that all assistance received in preparing this thesis and sources have been acknowledged.

Alice Kathryn Shirley

1 May 2025

LIST OF PUBLICATIONS AND ACHIEVEMENTS

Publications in peer-reviewed journals

Shirley, A. K., Thomson, P.C., Chlingaryan, A., and Clark, C.E.F. (2024). Review: Ruminant heat-stress terminology. *Animal, 18*(9). https://doi.org/10.1016/j.animal.2024.101267

Shirley, A. K., Thomson, P.C., Chlingaryan, A., and Clark, C.E.F. (2025). The diversity in dairy cattle reticulorumen temperature: Identifying water intake events. *Computers and Electronics in Agriculture*, *235*, 110357, https://doi.org/10.1016/j.compag.2025.110357

Hendriks, S. J., Edwards, J.P., **Shirley, A.K.**, Clark, C.E.F., Schütz, K.E., Verhoek, K.J., and Jago, J.G. (2025). Heat stress amelioration for pasture-based dairy cattle: challenges and opportunities. *Animal Frontiers*, *15*(2), https://doi.org/10.1093/af/vfae043

Abstracts and oral presentations

Shirley, A. K., Thomson, P.C., Chlingaryan, A., and Clark, C.E.F. (2024). The diversity in dairy cattle reticulorumen temperature: Correlation with drinking event activity. *Australasian Dairy Science Symposium*, Christchurch, New Zealand.

Shirley, A. K., Thomson, P.C., Chlingaryan, A., and Clark, C.E.F. (2024). The diversity in dairy cattle reticulorumen temperature: Identifying water intake events. *11th European Conference on Precision Livestock Farming*, Bologna, Italy.

Shirley, A. K., Thomson, P.C., Chlingaryan, A., and Clark, C.E.F. (2024). The diversity in dairy cattle reticulorumen temperature: Exploring the influence of temperature humidity index. *75th European Federation of Animal Science Annual Meeting*, Florence, Italy.

Shirley, A. K., Thomson, P.C., Chlingaryan, A., and Clark, C.E.F. (2024). The diversity in dairy cattle reticulorumen temperature: Identifying variability in drinking behaviour. *9th International Conference on the Welfare Assessment of Animals at Farm Level*, Florence, Italy.

Shirley, A. K., Thomson, P.C., Stephenson, S., Garcia, S., Clark, C.E.F. (2024) Heat stress – findings and considerations for design. *Raising the Roof*, Hunter Valley, Australia

Shirley, A. K., Thomson, P.C., Chlingaryan, A., and Clark, C.E.F. (2023). Development of a threshold model to isolate and investigate water intake in dairy cattle fitted with a reticuloruminal sensor. *Dairy Research Foundation Symposium*, Camden, Australia. **Winner of Emerging Scientist Competition.**

Shirley, A. K., Thomson, P.C., Chlingaryan, A., and Clark, C.E.F. (2023). An exploratory analysis of rumen temperature for three dairy herds in Australia: a potential path for GHG emission reduction. *11th International Symposium on the Nutrition of Herbivores*, Florianopolis, Brazil.

Shirley, A.K., Chlingaryan, A., and Clark, C.E.F. (2022). Revealing and exploiting the diversity in dairy cattle core body temperature data for heat amelioration. *School of Life and Environmental Sciences Higher Degree Research Showcase*, Sydney, Australia.

Scholarships

Postgraduate Research Scholarship in Dairy Science (Dairy UP)

Postgraduate Research Supplementary Scholarship in Dairy Science (Dairy UP)

Australian Government Research Training Program (RTP) Offset Scholarship

Awards

Dairy Research Foundation Emerging Scientist Presentation Winner, November 2023

University of Sydney, University Final, Three Minute Thesis Runner-Up, August 2023

University of Sydney, Science Faculty, Three Minute Thesis Runner-Up, July 2023

Related media

Interviews and stories featured in *The Land, The Weekly Times, ABC NSW Country Hour*, and *4BC Brisbane*.

- 'DRF Symposium showcases scientific research and developments in carbon', https://www.theland.com.au/story/8417146/dairy-symposium-gets-farmers-talking-about-carbon/
- 'Dairy Symposium 2023: Alice Shirley on cattle heat stress research', https://www.weeklytimesnow.com.au/dairy/dairy-symposium-2023-alice-shirley-on-cattle-heat-stress-research/news-story/6810307b93a058eba257b70d883b9edb
- 'Hot Cows for Cool Solutions', https://www.abc.net.au/listen/programs/nsw-country-hour/nsw-country-hour/103057354
- 'Cooler water to combat heat stress in cattle', https://www.4bc.com.au/podcast/cooler-water-to-combat-heat-stress-in-cattle/

AUTHOR ATTRIBUTION STATEMENT

This thesis contains five research chapters which are the result of my own investigations.

Chapter 2 presents a review of published literature. Alice Shirley (AS) conducted investigation and preparation of the original draft under the supervision of Peter Thomson (PT), Anna Chlingaryan (AC), and Cameron Clark (CC). All authors devised conceptualisation and contributed to the review and editing process.

Chapter 3 has been published in *Animals* and is titled 'Review: Ruminant heat-stress terminology'. Alice Shirley conducted investigation and preparation of the original draft under the supervision of PT, AC, and CC. Data visualisation was conducted by AS and PT. All authors devised conceptualisation and contributed to the review and editing process.

Chapter 4 has been published in *Computers and Electronics in Agriculture* and is titled 'The diversity in dairy cattle reticulorumen temperature: Identifying water intake events'. All authors contributed to methods conceptualisation. Data curation, validation, and formal analysis was conducted by AS under the supervision of PT and AC. The original draft was written by AS and reviewed and edited by PT, AC, and CC.

Chapter 5 is under consideration with an international journal and is titled 'Probing the diversity in dairy cattle reticulorumen temperature for adaption selection'. All authors contributed to methods conceptualisation. Data curation, formal analysis, and data visualisation was conducted by AS and PT. The original draft was written by AS and reviewed and edited by PT, AC, and CC.

Chapter 6 has been prepared for submission to an international journal and is titled 'Determining the association among three phenotypic indicators for heat tolerance in dairy cattle'. All authors contributed to methods conceptualisation. Data curation, formal analysis, and data visualisation was conducted by AS under the supervision of PT. The original draft was written by AS and reviewed and edited by PT, AC, and CC.

Generative AI Statement

During the preparation of the thesis the author used Microsoft Copilot to assist in the understanding of data analysis methods. The author confirms no text was modified by generative AI during the preparation of the thesis. The author takes full responsibility for the submitted thesis, ensures the work is their own, and has used generative AI in accordance with University guidelines and policies (refer to the University of Sydney generative AI guide for researchers).

Alice Shirley

1 May 2025

Supervisor Statement

As primary supervisor for the candidature upon which this thesis is based, I can confirm that the authorship attribution statements above are correct.

Anna Chlingaryan

1 May 2025

ABBREVIATIONS

Below is a list of alphabetised abbreviations used throughout this thesis. Abbreviations are also defined at first use within respective chapters.

BOM	Bureau of Meteorology
BST	Body surface temperature
CBT	Core body temperature
DMI	Dry matter intake
GPS	Global positioning system
HS	Heat stress
HSP70	Heat shock protein 70
HVLS	High-volume, low-speed
ID	Identification
IRT	Infrared thermography
SE	Standard error
THI	Temperature humidity index

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CHAPTER 1

General Introduction

INTRODUCTION

The Australian dairy industry, one of the nation's most important agricultural industries, attained a farm gate production value of $A6.2 billion in 2023-24 (Dairy Australia, 2024). Additionally, Australia is a significant exporter of dairy products, holding four percent of world dairy trade, valued at $A3.6 billion (Dairy Australia, 2024). The structure of the Australian dairy industry has changed markedly over previous decades, driven by a range of external factors including deregulation, market structure, and prolonged droughts (Ashton et al., 2014).

The Australian dairy processing industry has traditionally been highly regulated by both State and Commonwealth Governments, with the intention of securing the domestic supply of fresh milk, while promoting export of manufactured milk products (Doucouliagos & Hone, 2000; Sheng et al., 2020). Deregulation of the dairy industry involved abolishment of marketplace regulations (Productivity Commission, 2001), increasing the exposure of both processors and farmers to market forces (Doucouliagos & Hone, 2000; Sheng et al., 2020). Deregulation, coupled with an ongoing drought, facilitated product market integration and triggered more rigorous resource allocation between farms, providing an indirect channel for industry level productivity growth (Sheng et al., 2020). In the decades following deregulation, the number of dairy farms in Australia decreased from 12,960 to 5,700, the total area used for dairying halved, the average farm size doubled, and the milk processing and distribution sectors significantly downsized (Ashton et al., 2014; Kompas & Che, 2006; Sheng et al., 2020). Despite this resource reallocation, the industry restructuring promoted a more efficient industry and has led to considerable improvements in farm productivity (Ashton et al., 2014; Doucouliagos & Hone, 2000).

The concentration of Australian milk production shifted, with northern states reducing their share hold whilst southern states have seen significant expansions (Ashton et al., 2014). These shifts reflect regional factors such as climate and landscape, farm location, proximity to processing plants, and milk supply contracts that vary across regions and impact the profitability and productivity of individual properties (Ashton et al., 2014). Although well developed in eastern states, Victoria remains dominant, accounting for 63% of milk production, 66% of dairy farms and 62% of cow numbers, as of 2023-24 (Dairy Australia, 2024). Ongoing adjustment pressures resultant from industry restructuring have forced dairy farmers to continue to find productivity improvements to remain profitable within the industry, often involving technology adoption to reduce labour requirements and optimise animal health and welfare.

The Australian dairy industry, like agriculture more generally, faces strong incentives to innovate and invest in new technology to increase productivity and profitability (Ashton et al., 2014; Kompas & Che, 2006; Sheng et al., 2020). Automation has become both a consequence, through deregulation and structural changes, and a driving force in the contemporary dairy industry (Buller et al., 2020; Min et al., 2016; Sheng et al., 2020). As the industry intensifies and specialises, so too does the need to intensify efficiency and reduce the reliance on a diminishing labour force (Ashton et al., 2014). Initially developed for cropping and viticulture sectors (Bramley, 2009), there are high expectations for the use of precision livestock farming in animal-based agriculture (Rose & Chilvers, 2018; Shepherd et al., 2018). Precision livestock farming is associated with a reduction in human-animal interactions, and encourages the use of automated, mechanised technologies to refine management, procedures, and information collection (Bewley, 2016; Buller et al., 2020; Eastwood et al., 2012). As technical efficiency in the industry is furthered, it will more greatly contribute to growth in total factor productivity for individual producers (Doucouliagos & Hone, 2000). Technology will enable management practices to be refined, as producers strive to improve on-farm performance (Borchers & Bewley, 2015). Success of technology adoption is often attributed to the hybrid model in which producers' knowledge of the land and industry is combined with output from smart farming technologies (Eastwood et al., 2018; Rose et al., 2018). Precision livestock farming presents a value-add opportunity within farm management, working to optimise efficiency through improvements across data processing, decision making, and general herd management (Borchers & Bewley, 2015; Rojo-Gimeno et al., 2019). It is through this optimised management of on-farm systems that producers can achieve productivity gains (Ashton et al., 2014).

Of late, consumers have shown greater interest in milk safety and quality, alongside the health and welfare of cattle (Drake, 2007; von Keyserlingk et al., 2009). Automation has decreased regular human surveillance of cattle and there has been a resultant transition to technology to counterbalance this revolution (Montalván et al., 2024). Advances in precision livestock farming offer new opportunities for monitoring and ensuring animal welfare across the dairy industry (Bewley, 2016; Maroto Molina et al., 2020), aligning with modern ethical values. Objective technology enables identification of animals requiring attention at a rate much higher than possible with traditional human observation (Barkema et al., 2015), working to reduce labour requirements and increase efficiency. Through timelier identification of lapses in animal health and behavioural changes, made possible through sensor technology, management decisions can be implemented earlier, in a manner beyond conventional monitoring. This holistic, continuous welfare assessment presents reasons for optimism regarding an improvement in both cattle and producer wellbeing.

The decision to both purchase and implement on-farm technology is a significant investment and should be approached cautiously to avoid negative financial consequences (Borchers & Bewley, 2015; Steeneveld et al., 2015). Further, there is a wide range of technologies available on the market, many of which are unknown to producers, and the merits of each individual system should be considered when purchasing for an individual property (Borchers & Bewley, 2015). Some of these tools require ongoing training and support to enable adequate competency; therefore, preparation might be required for effective use and interpretation of generated data (Borchers & Bewley, 2015; Eastwood et al., 2018). The continued expansion of technology use on farm, requires new data monitoring and management skills that might be as equally demanding as the physical labour it is replacing (Hostiou et al., 2017). With that in mind, the utilisation of generated data for health and welfare benefits of livestock is largely unrealised.

THESIS OUTLINE AND OBJECTIVES

Motivated by the potential benefits to cattle welfare in changing climatic conditions, this thesis looks to reveal and exploit the diversity in dairy cattle reticulorumen temperature data for heat stress amelioration. In accordance with this aim, the specific objectives of this thesis are to:

1. Understand the current state and gaps in knowledge regarding heat stress specific to dairy cattle and the effective use of data-driven methods for heat amelioration

2. Address the current gaps of knowledge specific to ruminant heat stress terminology
3. Develop a novel drinking event model for dairy cattle and from this model, determine the temporal variability in drinking events for individual pasture-based dairy cattle
4. Reveal the impact of changing thermal conditions, using temperature humidity index, on reticulorumen temperature
5. Evaluate the associations among three phenotypic indicators of heat tolerance and assess their suitability as practical heat stress indicators on-farm.

This thesis is composed of a review of published literature (Chapter 2), review of heat stress terminology (Chapter 3), three independent experimental studies (Chapter 4, Chapter 5, Chapter 6), and a general discussion and conclusion (Chapter 7). Experimental chapters are presented as stand-alone scientific manuscripts, containing an abstract, introduction, materials and methods, results, discussion, and conclusion, with any additional information presented as supplementary material in the appendix.

The research in this thesis contributed to Dairy UP, a collaborative research, development and extension program led by the University of Sydney's Dairy Research Foundation to unlock the potential of the NSW dairy industry.

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CHAPTER 2

Literature Review

With the impacts of climate change being felt worldwide, the requirement to de-risk the dairy industry is ever-present. Chapter 2 sequentially explores animal responses to heat stress, methods of monitoring, and heat amelioration techniques with an emphasis on the use of data-driven amelioration methods. The literature reviewed in this chapter draws together current knowledge in the field of dairy cattle heat stress, suggesting several avenues for further research.

ABSTRACT

Global temperature increases maintain heat stress (**HS**) as a key issue for the dairy industry, impacting cattle health, welfare, and productivity. Thermal indices are used as a primary indicator of HS, but are predominantly used as a herd level predictor, rather than accounting for the singular impact on an individual animal. Reliance on individual animal behavioural and physiological responses might, therefore, be more appropriate to gauge coping ability. Monitoring of such responses, each with their own benefits and limitations, has been better enabled through the increased use of sensor technology. Effective monitoring technology to capture nuanced responses can be further developed and should be maintained as an industry wide investigative focus, especially regarding the transition of smaller scale research technology into commercial practice. Alongside increasing technology use, comes the collection of significant data that must be efficiently exploited. Development of sophisticated data analysis approaches are required to ensure data usage is optimised. Investigation into the suitability of hybrid approaches, to overcome limitations from more traditional analysis methods, might aid in on-farm decision making. Knowledge progression in this field will enable improved understanding of diversity in response to heat for individual cattle, contributing to the advancement of associated selection tools. This review draws together the latest research in the field of dairy cattle HS, highlighting the role data-driven methods of heat amelioration have in an industry that is increasingly reliant on technology.

INTRODUCTION

Dairy farming in Australia occurs across a wide range of environments, which are increasingly exposed to climate variability and the associated risk of cattle heat stress (**HS**). Heat stress occurs when any combination of environmental conditions cause the effective environmental temperature to rise above that of the animals thermoneutral zone (Armstrong, 1994). At this stage, the animal is unable to sufficiently dissipate heat, resulting in an increase in body temperature, affecting the animal's homeostasis and overall health (Gaughan et al., 2012; West, 2003). The degree of stimulation of the neuronal and neuro-hormonal systems determines the intensity of the stress response enacted and resultant consequences to the individual organism (Herbut et al., 2018). Maintenance within the thermoneutral zone is critical for productivity and health. If adaptive mechanisms fail to maintain thermal stability, the animal might enter a stage of either hypo- or hyperthermia, both of which can be potentially fatal (Herbut et al., 2018). Periods of HS might vary from a single day to an extended time period. Minimising both the number of HS events and their duration is critical; however, achievement of this is made difficult with escalating climate variability.

Future changes in temperature and rainfall patterns will likely result in more frequent, severe weather events (Blunden and Boyer, 2022). Consequently, there is an increased requirement for livestock breeds highly tolerant to their local climatic conditions to reduce the impact of temperature stress, thereby maintaining production outputs. Climate change is of particular importance for high yielding cattle as they hold an elevated internal heat load resultant from high milk yields and dry matter intake (**DMI**), and as a result, the impact of heat accumulation is exacerbated with increasing temperature and humidity (Bernabucci et al., 2015; Pryce et al., 2022; West, 2003). As such, the combination of escalating global temperatures and production intensification has resulted in HS becoming a key issue for the dairy industry worldwide.

HEAT STRESS AND DAIRY CATTLE

Predicted climatic changes will increase animal heat exposure even in moderate zones (Gauly et al., 2013). Prolonged HS exposure negatively affects cattle health, welfare, and productivity, highlighting the urgency to mitigate HS on a broad scale. By accounting for the effects of environmental factors, thermal indices provide a quantification estimate to both predict and assess the impact of HS on dairy cattle.

Thermal indices

Several thermal indices are used through the livestock industry (Wang et al., 2018a), each producing an index value which represents the effect produced by the heat exchange process, seen as an impact on animal performance, health, and well-being. Thermal indices that combine the effects of various environmental factors have been shown to represent heat transfer more accurately between an animal and its environment than air temperature alone (Hahn et al., 2009; Mader et al., 2010). Yet, there remains a lack of consensus among researchers at present as to the specific threshold within each of these indices at which HS begins and/or intensifies.

Initially developed from the human discomfort index (Thom, 1959), the temperature humidity index (**THI**) combines ambient temperature and relative humidity into a single value to estimate head load. The THI is used extensively throughout the livestock industry. While this thermal index includes ambient temperature and relative humidity, it omits solar radiation and wind speed. To overcome these limitations, Gaughan et al. (2008) developed the heat load index for feedlot cattle, incorporating the effects of ambient temperature, relative humidity, solar radiation, and wind speed, on feedlot cattle. Similarly, the comprehensive climate index (Mader et al., 2010) and index of thermal stress for cows (Da Silva et al., 2015) were developed, encompassing both hot and cold environmental conditions and specifically for use in inter-tropical regions, respectively. The dairy heat load index (Lees et al., 2018c) filled a void for dairy cattle, developed based on the physiological responses of lactating dairy cows. Wang et al. (2018b) then developed the equivalent temperature index for cattle, incorporating not only the four key environmental variables but their interaction effects. Most recently, the grazing heat load index (Bryant et al., 2023) has been developed for dairy cattle managed predominately on pasture. While developed and validated, experimental application of these models in a wide range of settings is still required to ensure their effectiveness in assessing the thermal environment.

Due to the variations in success of different thermal indices in diverse environments, not all thermal indices are always appropriate for use. Numerous indices exist because each performs better under different conditions; however, inconsistencies arise between thermal indices due to cow-based factors that are not considered in indices based solely on environmental variables (Atkins et al., 2018). Further, there are currently no guidelines available to determine the most appropriate thermal index for use. The success of a thermal index lies primarily in its ability to link important animal responses to an appropriate index which can reflect the heat exchange taking place (Hahn et al., 2009). As most thermal indices are herd level predictions and do not account for individual animal responses, the behavioural and physiological responses exhibited by individual animals in a herd as an indicator of HS should be determined. Therefore, priority should remain on development and testing of a thermal index for dairy cattle that accounts for individual variability between animals. Given the parameters that environmental thermal indices do not account for, a more accurate manner of measuring HS might be obtained by looking to the physiological and behavioural parameters exhibited by animals in response to HS.

Physiological and behavioural response

An animal's primary response to a suboptimal thermal environment is the alteration of their physiology and/or behaviour. 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., 2021b; West, 2003).

Physiological responses

Body temperature

Body temperature is an excellent indicator of an animal's susceptibility to HS and the individual's consequent health and productivity, as it is a summary of all thermoregulatory events. Cattle body temperature can increase due to metabolic heat production, solar radiation, reflected radiation from environmental structures, and from the surrounding air, if at a temperature greater than the animal's body surface (Islam et al., 2021a). Core body temperature maintenance between 38-39 ˚C is critical to ensure body cells and tissues are functioning at an optimal level (Liu et al., 2019). In hot conditions, the core body temperature (**CBT**) of an animal rises higher than the surrounding environment to allow for heat dissipation across a gradient. Breakdown of this heat production and heat loss pathway might prolong the time spent above a tolerable CBT, which might have dire consequences (Islam et al., 2021a).

Environmental temperature, humidity, and other thermal events can fluctuate markedly across a 24-hour period; therefore, cattle can experience varying levels of HS across such times. Research has shown distinct diurnal fluctuations, with minimum body temperature identified in early morning and maximum body temperature in the late afternoon (Islam et al., 2021a). Such fluctuations facilitate body heat dissipation primarily during the night, alongside cooler parts of the day. If ambient temperature and humidity are maintained at high levels over extended durations, heat dissipation will be insufficient, and the animal will remain in a state of HS. The overall heat balance of an animal, therefore, depends on the level of accumulated heat load maintained over this time.

Respiration rate and panting

An increase in respiration rate enables greater heat dissipation and provides an early warning sign for the onset of HS (Ji et al., 2020). Monitoring the degree of panting, respiration, or both, is a viable alternative to monitoring body temperature as an assessment of HS. Respiration rate begins to increase above 50 to 60 breaths per minute at an ambient temperature of 25°C (Berman et al., 1985). If respiration rate increases to above 120 breaths per minute, the cow is deemed to be under severe stress (Hahn, 1999). However, a decrease in respiration rate is not necessarily indicative of an animal coping; it might instead reflect a transition from rapid open mouth panting to a slower, deep phase open mouth panting (Gaughan et al., 2000). Additionally, Lanham et al. (1986) found that respiration rate can decline significantly after drinking water, which can work to reduce internal body temperature through conductive cooling, but might only be a short-term effect. More recently, Luo et al. (2021) detailed various physiological indicators that might genetically identify animals more effective in coping with HS events, providing a scale of respiration rate that ranges from lowly visible chest movement to clear chest movement and open-mouthed respiration.

While respiration rate increases with ambient temperature, there is an approximate one-hour lag time behind solar radiation (Brown-Brandl et al., 2005), with some studies suggesting a delay up to four hours (Gaughan et al., 2000). Acknowledgement of a respiration rate ‘ceiling’ or maximum level is not uncommon, but there is variation as to the point this takes place, ranging from under 100 breaths/min up to 200 breaths/min (Gaughan et al., 2000; Spiers et al., 1994). However, this concept of a maximum level is not universally agreed upon throughout research, with many studies not supporting this theory at all (Brown-Brandl et al., 2005; Hahn, 1999; Spain and Spiers, 1996). Ultimately, the disagreement regarding standard respiration rate levels reinforces the variability in response of ambient temperature on respiration rate between animals, suggesting a herd level assessment might not be indicative of how animals are coping at an individual level.

Sweating

Sweating is one of the primary evaporative cooling mechanisms invoked by cattle in response to high ambient temperatures. Sweating takes place when moisture is evaporated from the skin surface, thereby cooling the animal through evaporative heat transfer. Increased water loss through the skin, alongside respiratory evaporation (panting), might disturb body water levels and mineral concentrations, which ultimately interfere with the individual's ability to maintain osmotic balance (Bernabucci et al., 2010). Accounting for up to 80% of total evaporative heat loss (Robertshaw, 1985), sweating rate is highly dependent on both blood flow rate and the number of sweat glands per unit of skin area (Blazquez et al., 1994). The effectiveness of sweating reduces in high ambient temperature and with increased relative humidity (Sparke et al., 2001); therefore, alternative physiological responses are relied upon more heavily in such conditions.

Milk production

Lactating dairy cattle have a high sensitivity to HS due to the elevated metabolism associated with milk production (Neves et al., 2022), which is further challenged by the high production levels seen today. During a HS event, there is a reduction in DMI and subsequent reduction in nutrients available to maintain milk synthesis (Rhoads et al., 2009; West, 2003). The animal's stage of lactation plays an important role in HS severity and the amount of milk lost (Tao et al., 2018). As such, the first 60 days of lactation are critical to minimise HS exposure due to the associated heightened metabolic heat load. Further, with an increase in standing behaviour, blood flow to the udder is limited as compared to a lying position, thereby restricting nutrient uptake in the mammary gland (Delamaire and Guinard-Flament, 2006), contributing to the reduction in milk yield.

There are a variety of factors that influence the magnitude of the milk yield response to HS, the most significant of which is metabolic heat production (Fuquay, 1981). There is a 17% higher metabolic rate displayed in dairy cows with a higher milk production (31.6 kg/d) than a lower milk production (18.5 kg/d) (Purwanto et al., 1990), and as such, high producing dairy cattle have more difficulty maintaining a thermal equilibrium during HS and are, therefore, more susceptible (Tao et al., 2020). Suggested by Berman (2005), a decrease in air temperature threshold of 5 ˚C is seen with an increase in milk yield from 35 to 45 kg/d in Holstein cows. More specifically, Bernabucci et al. (2010) reported with each THI unit increase, there is an associated loss of 0.27 kg of milk. However, literature has shown that there is typically a lag between warmer temperatures and milk yield decline (Polsky and von Keyserlingk, 2017), implying milk yield only indicates that the animal has been under HS and not whether it is still being experienced. As such, research suggests milk composition changes, rather than volume, as a more reliable indicator (Hu et al., 2016), depending on lagged response times, unless alternative physiological or behavioural responses are used.

Reproductive performance

Dairy cow fertility is shown to be influenced by a multitude of factors, including hormonal levels, nutrition, and general management, though environmental factors appear to have the highest impact (Dash et al., 2016). Heat stress influences reproductive performance at all stages. A single day of HS conditions is enough to negatively impact conception rates of dairy cows, as well as that of long-term periods (Morton et al., 2007; Schüller et al., 2014). As compared to winter conditions, HS in summer has shown a 20-30% reduction in conception rate, declining below the average conception rate of 35% seen in high producing cows today (Lucy, 2001; Rensis and Scaramuzzi, 2003). During artificial insemination, Pereira et al. (2013) found a rectal temperature above 39.1 ˚C causes conception rates to drop further, by up to 6%.

With an increase in ambient temperature, displays of natural mating behaviour are reduced (Orihuela, 2000). As such, a greater reliance is placed on sensor technologies to detect oestrus behaviours to ensure artificial insemination is not conducted at suboptimal times. Though conception rates increase with timed artificial insemination, success rates in summer compared to winter (De Rensis et al., 2017), or in individuals with high rectal temperatures (Zubor et al., 2020), are not comparable. A study by Morton et al. (2007) found a decline in conception rates from cows experiencing HS three to five weeks prior, and one week post day of service. Schüller et al. (2014) identified a THI threshold of 73 at which conception rate is negatively affected, with cows exposed to a THI of 73 for nine hours or more experiencing a 26% decline in conception rate as compared to cattle exposed to the same THI for a lesser time. While HS has a clear influence on reproductive performance, due to the often-long-term nature of reproductive impact, alongside the potential influence of other contributing factors, alternative measures of HS are often relied upon for more timely management decisions.

Behavioural responses

Standing and lying

Measures of lying behaviour are important indicators of cow comfort, with the duration and frequency of lying bouts used as a welfare indicator. Anderson et al. (2013) has shown that cattle under varying levels of HS will have distinct differences in the frequency, duration, and position of lying behaviours. On average, lactating cows spend eight to 13 hours per day in a recumbent position (Tucker et al., 2021); however, with an increase in ambient temperature, lying time is reduced by up to 30% (Cook et al., 2007; Schütz et al., 2011). Cattle subjected to a greater number of cooling treatments in a study by Honig et al. (2012) spent more time lying down than those undergoing fewer cooling treatments, with more of their time spent resting and ruminating. Fewer than 50% of lying bouts are initiated when CBT is above the thermoneutral zone, at 38.8 ˚C (Allen et al., 2015). As such, an increase in CBT decreases length of lying bouts and simultaneously increases standing duration.

Standing assists cooling efficiency by increasing the available surface area for heat abatement, evaporation, and convective cooling through ventilation. Maintenance diet requirements might increase with longer standing times, due to higher energy expenditure and a change in nutrient utilisation (West, 2003). Extended periods of standing are a major risk factor for lameness (Allen et al., 2015), with an increase in claw capsule pressure linked with reduced oxygen and blood supply (Grandin, 2016). However, it is yet unknown if this association is in fact due to increased time standing or as a result of reduced DMI (Cook et al., 2004). Standing time has been shown not to increase linearly with THI, instead peaking at a THI of 80 to 89 (Galán et al., 2018). This is suggested to be a direct result of fatigue accumulated by long standing bouts as external temperature rises (Allen et al., 2015). Therefore, care must be taken with using standing time as an indicator of HS under high THI conditions.

Shade seeking

Cattle experiencing HS have been shown to actively seek shade in an attempt to reduce their internal body temperature, even at the expense of lying down (Finch, 1986; Schütz et al., 2008). Shading has been shown to be effective in reducing negative behavioural and physiological effects associated with HS. When provided with shade, heat stressed cattle undergo more time ruminating (Blackshaw and Blackshaw, 1994), have a higher milk yield (West, 2003), and reduced body temperatures in comparison to unshaded cattle also under HS (Kendall et al., 2006). Shade use is seen to increase with an increase in ambient air temperature and solar radiation intensity (Kendall et al., 2006; Tucker et al., 2008). Exploring the effects of shade provision at pasture, Palacio et al. (2015) identified cows with shade access decreased the quantity of drinking events, increased the number of lying events, and grazed at a higher rate than their non-shaded conspecifics. Cows have also been shown to increase their use of shade as heat load increases, with shade tempering the impact on physiological HS indicators (respiration, rectal temperature, faecal cortisol metabolites) (Veissier et al., 2017). Shade seeking behaviour can be hard to monitor due to dynamic environmental factors and behavioural variation within a herd.

Feed and water intake

The causative effects of increasing environmental temperature on DMI reductions have been well established. Demonstrating the inverse relationship of DMI with elevated temperature, Spiers et al. (2004) simulated a four-day heat wave that suppressed feed intake within one day of the initial temperature rise. Of particular concern in high producing dairy cattle is the associated reductions in rumination and nutrient absorption alongside increased maintenance requirements, ultimately declining available energy. This negative energy balance occurring when feed intake is under that of energy demands can contribute to significant body weight losses during severe HS events (Rhoads et al., 2009; Shwartz et al., 2009) and increase susceptibility to rumen acidosis (Bernabucci et al., 2010; Kadzere et al., 2002). Further, both frequency and duration of eating events shift during a HS event. Dry matter intake decreases to reduce diet induced thermogenesis, which contributes to metabolic heat load (DeShazer et al., 2009). Bernabucci et al. (2010) reported eating frequency per day declines from 15 meals to three meals during HS. This alteration in eating behaviour is also characterised by larger meal sizes (Bernabucci et al., 2010) with animals eating more during the early morning and late afternoon to avoid consumption at the hottest parts of the day (Ramon-Moragues et al., 2021).

Supply of fresh water is said to be the most important resource for a dairy cow experiencing HS (Polsky and von Keyserlingk, 2017). To maintain evaporative water loss, heat-stressed cattle have been seen to increase their average water intake, at volumes of up to 1.2 kg/˚C above minimum ambient temperature (West, 2003). Provision of chilled water (10 ˚C) is found to both lower body temperature and respiration rates (Wilks et al., 1990), though Gonzalez Pereyra et al. (2010) did not identify a preference for water temperature of dairy cattle during HS conditions. Demonstrating the poor water retention abilities of dairy cattle compared with other ruminants, heat-stressed Holstein heifers have been found to have a water intake 2.84-fold higher than Sardinian female lambs under similar conditions (Bernabucci et al., 1999; Bernabucci et al., 2009), reinforcing the importance of fresh water supply.

With distinct changes in the above physiological and behavioural responses under HS conditions, monitoring such reactions is critical to provide an early indicator of animal distress. By doing so, the impact on animal welfare, alongside producer productivity and profitability can be minimised.

MONITORING HEAT STRESS

Both monitoring and mitigation of cattle HS has traditionally been based on visual monitoring or through thermal indices. However, producers are experiencing the impracticalities of visual appraisal, alongside a lack of consideration for the individual response within a herd from thermal indices. As such, the requirement for automation is increasing and several developments throughout both on- and off-animal monitoring devices have been explored, demonstrating various levels of potential for continuous livestock monitoring.

Off-animal monitoring

Climate data

Predictive, accurate weather forecasts can be of great benefit for producers throughout their management calendar. Contrastingly, an inaccurate forecast directly impacts the success of resource management and by extension, animal welfare. Increasing value is being placed on localised weather prediction systems to optimise accuracy for local application (Hewage et al., 2020). At a farm level, climatic data provided from on-site weather stations enables more accurate, continuous monitoring, provided the stations are properly maintained and calibrated to ensure data reliability. Smart-phone applications combining current and forecasted weather information are being developed (Spiers et al., 2012), intending to aid producers in on-farm management decisions through alerts-based messaging. A study by de Oliveira Júnior et al. (2018) developed a portable, low-cost computational system to provide, *in loco*, the thermal condition of an environment. The application used alongside a portable device that measures temperature, relative humidity, and black globe temperature provides an alternative for calculation of thermal comfort indexes and has showed promise in the two tested locations, though additional validation is required before widespread use. Regardless, the application of climate-based assessments remains an indirect measure of HS response, with the provision of a threshold index not accounting for individual animal response to climate.

Video surveillance

Computer vision offers a non-contact, stress-free, cost-effective technology to record and recognise animal behaviours. Legrand et al. (2011) utilised 13 video cameras to observe the physiological and behavioural responses of dairy cattle to hot weather, demonstrating high individual variability between animals in their utilisation of cow showers. Jaddoa et al. (2021) proposed a new thermal imaging method for automatic eye localisation in cattle using Multiview face detection and automatic thresholding. Although the proposed method is effective, more studies are now required to both validate and enhance algorithm performance. While there are some exceptions, most monitoring videos across the industry are captured using ordinary RGB cameras, though the use of depth cameras and imaging would provide advanced recognition and abilities. Some automated imaging techniques have had success, though they typically focus on a key behaviour, which requires complex, manual engineering designs.

The deep learning space has seen new tools and algorithms developed to enable enhanced data analysis through artificial intelligence. Successfully detecting changes in physiological parameters in individual animals, Jorquera-Chavez et al. (2019) developed and validated computer vision algorithms to determine eye and ear base temperature, respiration rate and heart rate. While these methods ranked higher than traditional measures, further work is required to investigate the feasibility of implementation on an extensive scale. Guzhva et al. (2018) proposed a flexible, non-invasive computer system for tracking and identifying individual animals, currently successful for 20-minute durations. Wu et al. (2021) constructed a bidirectional long short-term memory classification model that recognised a single cow's behaviour to an average accuracy of 0.976, but high computing hardware was required. Most recently, Dac et al. (2022) presented a high accuracy, portable facial-recognition pipeline for dairy cattle. Advances in computer vision and deep learning side by side with reducing technology costs, align with the potential for computer vision to be increasingly utilised on-farm; however, these developing techniques are costly both in the way of computational skills and hardware requirements.

Infrared thermography

Infrared thermography is a measure of radiated heat, used broadly to remotely measure the surface temperature of an object, converting heat emissions into a thermal image. Corrections are required to account for the impact of external factors affecting the actual temperature, as compared to the infrared sensor that determines the surface temperature based on total radiative heat (Wang et al., 2021) The use of infrared thermography in animal production has proven popular due to its low cost, speed, efficiency, and remote abilities. Measurements of respiration rate by infrared thermography imaging has a good agreement between live and video recorded measurements (Stewart et al., 2017). Utilised for stress assessments through eye temperature (Jerem et al., 2019) and nose temperature (Cho et al., 2019) across various species, infrared thermography has shown promise in the evaluation of breathing patterns (Milan et al., 2016), overcoming the traditional methods of flank movement observation. Concluding with 76% accuracy, Kim and Hidaka (2021) utilised sequence temperature data alongside RGB images to determine cattle breathing patterns. The method utilised was not labour-intensive, could handle big data, and had a high accuracy, demonstrating promise for future use. Salles et al. (2016) examined 24 Jersey heifers, finding infrared thermography forehead temperature had the highest association with rectal temperature, and forehead, right flank, and left flank temperatures to be strongly associated with THI. Cuthbertson et al. (2019) aimed to utilise infrared thermography to measure cattle temperature under commercial settings. Results showed large variability, highlighting the requirement of extensive pre-processing and algorithms to obtain applicable statistics under commercial conditions. Further, correlation was impacted by frame rate, image resolution, and accuracy of cameras used, reinforcing the potential of variability in collected data between devices. Contrasting results between studies, calls into question the ease of results analysis implied in some papers and by extension the likely success of commercial application of such methods.

On-animal monitoring

Respiration rate monitors

Respiration rate is the first visible response of cattle to HS, oscillating with the thermal environment and providing an easily observable measure of an animal's thermal state (Eigenberg et al., 2000; Milan et al., 2016). However, respiration rate is a non-linear measure of HS increasing more rapidly than ambient temperature beyond a threshold (Eigenberg et al., 2000). Traditionally, visual identification of flank movement is the primary method of breathing rate measurement, during sampling intervals at discrete time points. While this omits the requirement for costly equipment, this method is time-consuming, labour intensive, susceptible to short-term variability, and does not allow for continuous measurement. Additionally, it is challenging to maintain measurement accuracy at a distance required to minimise observer influence on the animal (Eigenberg et al., 2000; Islam et al., 2021a). As a response, automation of respiration rate monitoring has been investigated, through the utilisation of pressure changes associated with muscle tone, chest movement, and/or exhaled air. This is beneficial to increase measurement frequency, provide a more robust application of time series techniques, and reduce labour requirements.

Various remote devices have been developed over previous decades for respiration rate monitoring. Eigenberg et al. (2000) developed a system utilising a thoracic belt to retain position of the transducer; however, the equipment was cumbersome, potentially impacting normal behavioural exhibition, and not appropriate for long-term use. Following this, Pastell et al. (2006), developed a contactless laser for use in a milking robot but was unable to account for variations in animal characteristics (not capable of use on black cattle). Additional approaches included spirometry masks (Maia et al., 2014), chest belts (DeShazer, 2009) and surgical implants, though each had their own drawback whether it be training requirements, potential interference from conspecifics, signal transmission, or ongoing restraint for application (Milan et al., 2016). Monitoring changes in temperature near the nostril with a thermistor, successfully enabled continuous respiration rate recording, but relied on temperature difference to the surrounding air for calculation, which might diminish (Milan et al., 2016). In a pilot study, Strutzke et al. (2019) utilised a differential pressure sensor fixed on the cow's jaw, but the respiration rate sensor had limitations of battery life and requirements to adjust device attachment to minimise losses. Pulse oximetry application across livestock is not commercially common but has been seen in research (Grubb and Anderson, 2017; Salzer et al., 2021). No commercial devices are yet available that enable practical measurement of peripheral oxygen saturation in livestock. Salzer et al. (2022) formulated a custom-made nose ring device that can evaluate heart rate, breathing rate, and oxygen saturation in a more precise manner than flank movement counts. Though, the pilot study requires testing at a greater sample size ($n=4$) to confirm statistically significant results and ensure suitability of the innovation for commercial application.

Accelerometers

Automatic monitoring of animal behaviour through accelerometers provides not only a valuable research tool but an early warning instrument for optimised management. Accelerometers measure static and dynamic acceleration in a two- or three-dimensional space, working to precisely determine animal movement to a higher sensitivity and specificity compared with visual observation. Acceleration data is converted through a range of algorithms to determine object state for core behaviour classification. Developments have ensured accelerometers are primarily small, lightweight apparatus that will maintain minimal interference to natural behaviour exhibition (Yang and Hsu, 2010). Current commercially available accelerometers have the capacity to classify behavioural states minute-by-minute (Bar et al., 2019), contributing to the systems gaining popularity for both research and commercial use (Islam et al., 2021b; Molfino et al., 2017). Various accelerometer systems have been developed over previous decades, each requiring validation under different farming and ambient conditions.

To address the lack of technologies monitoring multiple behaviours in a practical manner, Bikker et al. (2014) introduced the Cow Manager SensOor system that enables real-time quantification of multi-point behaviour and activity on dairy cows. Wolfger et al. (2015) progressed this work to validation in a beef cattle system, suggesting the promise of the tool in measuring beef cattle feeding behaviour but highlighting algorithm optimisation would be required to differentiate rumination and feeding behaviours. Exploring its application in a grazing dairy herd, Pereira et al. (2018) suggests accurate monitoring of rumination and eating behaviours; however, aligns with previous suggestions that active behaviours might be less accurately recorded. The RumiWatch noseband, developed and validated for monitoring eating and rumination in stable fed dairy cows (Braun et al., 2013; Zehner et al., 2017), has seen great interest across literature. Looking to validate this technology, Li et al. (2021) found the device useful to monitor jaw movements for prehension bites, eating chews, and rumination chews and performing at an acceptable level with small random and systematic errors for mastication chews. Comparatively, Norbu et al. (2021) found the RumiWatch system more accurate for both prehension bites and total jaw movements than mastication chews in both grazing and housed cattle. This conflicting success suggests that before widespread use, the accuracy of the device will have to improve. Other research has explored the use of neck-mounted accelerometers in dairy cows (Benaissa et al., 2017), electronic rumination- and activity-monitoring tags (Molfino et al., 2017), accelerometer-based neck tags (Bar et al., 2019) and various devices for respiration monitoring (Davison et al., 2020; Islam et al., 2020).

Global positioning systems

Tracking of free-range animals has previously shown low predictability of animal location across time, relying on human observations but yielding issues with observer fatigue, physical limitations, external weather factors, and impacts of observer proximity (Turner et al., 2000). The Global Positioning System (**GPS**) was developed from improvements originating from very high frequency technology, that in turn became the ARGOS Data Collection and Location System. Development of GPS allowed for 24-hour monitoring of livestock movement patterns (Bailey et al., 2018), providing users with position fixes through a constellation of earth-orbiting satellites. Today, GPS is primarily used in extensive grazing systems. Through the importation of GPS data into a geographic information system, animal behaviour characteristics and pasture utilisation can be assessed (Islam et al., 2021a). Shade seeking preferences have been mapped through GPS data in grazing livestock (Bailey et al., 2018), which can enable improvements across shade and water provision management, particularly through HS periods. Forecasting of cattle behaviour has also been completed using GPS locations, detecting the transition between walking, grazing, and resting states (Williams et al., 2016). Neck-mounted GPS based virtual fencing technologies are emerging (Colusso et al., 2020; Lomax et al., 2019) with the potential for targeted heat amelioration for cattle through individual animal isolation. While success has been had in the utilisation of the systems, their carry over capabilities from an extensive system into a barn system might not be feasible, though research into the use of real-time location systems is being explored. While GPS employs state of the art electronics, there are limitations to the system inclusive of satellite clock and position errors, receiver and atmospheric errors, and selective availability (Turner et al., 2000). Notably for both GPS and real-time location systems, as precision requirements increase, so too does the burden on data storage, yet this is required, as the alternative is a decline in predictive power (Swain et al., 2008).

Body surface temperature

A primary response to heat is vasodilation, which enables blood diversion from the core to the skin, increasing body surface temperature (**BST**), and encouraging additional environmental heat exchange. Importantly, measurement of BST is aligned with modern animal welfare requirements within the precision livestock farming sector, contributing to its recent focus through literature. One of the most popular methods of BST measurement is infrared thermography, an off-body measurement technique discussed earlier in this paper. Body surface temperature can also be measured using on-animal technology, utilising wearable devices equipped with wireless transmission, though method of device attachment varies. A study by Bach et al. (2015) evaluated the agreement between four skin temperature devices at rest, during exercise in the heat, and through recovery, finding thermistors and data loggers to have very good agreement. However, attachment of BST measurement devices is limited by their ability to adhere to the skin, inclination for movement, and impact from surrounding hair and wind (Iwasaki et al., 2019). In efforts to address the influence of wind and hair, Kou et al. (2017) developed a special shell designed to align with the anatomy of a cow's hind leg. This anatomical position has less hair that can impact measurement, proving to be an accurate and reliable method to detect body temperature. Now, studies are prioritising the use of non-contact, infrared devices (Bakony et al., 2023).

To enable a more time efficient identification of HS, research has focused on the development of thresholds relative to BST. As BST does not reach a plateau as seen with CBT, focus is instead given to the stage BST begins to rapidly increase (Shu et al., 2021). In a study of 488 Holstein dairy cows, Peng et al. (2019) measured BST across seven locations to better understand the inflection point of rectal temperature and BST. Results demonstrated that BST was impacted by temperature and humidity conditions, in a manner more sensitive to that of rectal temperature. Mean and maximum forehead temperatures began to increase rapidly at a condition lower than where rectal temperature began to rapidly increase (Peng et al., 2019). Temperature humidity index thresholds between 65 (eyes) to 70 (hindquarters) were identified as the point in which BST exceeds that of CBT, for Hanwoo heifers (Kim et al., 2020). Conducting a similar study in Holstein calves, Dado-Senn et al. (2020) found no detectable breakpoints in BST in either treatment (chronic HS vs continuous cooling), instead identifying a strong linear relationship to THI. As such, additional research is required to identify if the BST breakpoint could sit at a different range of THI in dairy cattle as compared to beef.

Core body temperature

Core body temperature monitoring yields a direct and precise measure of an animal's thermal conditions. Given its importance, this section explores CBT monitoring as a primary focus.

Rectal temperature

Measurement of rectal temperature offers advantages of speed, low cost, and easy interpretation. Shown to be an important indicator of thermal balance, an increase in rectal temperature as minimal as 1 ˚C can be sufficient to reduce production outputs in dairy cattle

(McDowell et al., 1976). Traditional manual measurement of rectal temperature involves insertion of a digital thermometer into the rectum at 9 cm for calves and 15 cm for cows (Piccione et al., 2003); however, this procedure is both time and labour consuming. Additionally, rectal measurements in this manner require animal restraint which in addition to adding time and labour costs, involves significant stress to the animal which might bias results. Rectal temperature has been found to be more variable than alternatives (i.e. vaginal temperature) (Lees et al., 2018a), with reading accuracy dependent on operator consistency, type of thermometer, and depth of insertion (Burfeind et al., 2010).

Regardless, multiple indwelling rectal thermometers have been utilised across literature in research settings. Gaughan et al. (2000) continuously monitored rectal temperature using a temperature data logger to clarify the relationship between environmental conditions and respiratory response. Spiers et al. (2004) recorded rectal temperature using a stainless-steel thermistor probe attached to a recorder, finding no alternative measurement of respiration rate was superior to rectal temperature in the prediction of production changes during a HS event. Additionally, many studies have focused on developing and testing rectal thermometers that address traditional shortcomings in the lack of continuous measurement ability and requirement for repeated handling and restraint of animals (Shu et al., 2021). To automate rectal temperature measurement in cattle, Reuter et al. (2010) designed an indwelling data logger that was supported by an aluminium tail harness. The device was found to remain in place for several days; however, due to potential tail damage and influence of faecal temperatures, limited uptake was achieved. A real time measurement of rectal temperature in dairy cattle using a radiofrequency based digital thermometer as opposed to a mercury bulb thermometer was achieved by Debnath et al. (2017). While results were promising with the radiofrequency based digital thermometer successful in recording and monitoring real time rectal temperature in cattle, this method did not reduce requirement for cattle restraint nor manual labour. Showing encouraging results for long-term monitoring, Lees et al. (2018a) developed an intra-rectal device for 23-hour continuous measurement in beef cattle. However, while results demonstrated a strong relationship between rectal and vaginal temperature, vaginal temperature appeared to be a more reliable estimate of CBT, requiring additional research as to the implications in dairy cattle specifically. Overall, while rectal temperature is more objective than traditional visual observation, significant limitations are present; therefore, resultant data should be utilised with careful consideration. Overall, rectal probes appear more applicable in research settings as compared to commercial sites at this stage.

Vaginal temperature

The vagina is a common location of deep body temperature measurement across livestock species, with traditional vaginal temperature measurement very similar to that of rectal temperature. Due to abundant blood flow to the area, the vagina is more sensitive to changes in CBT than the rectum. High correlation of vaginal temperature with rectal temperature has been identified (r = 0.97) (Burdick et al., 2012). Correlation strength is improved with simultaneous measurement, though accuracy is primarily linked to individual device precision (Tresoldi et al., 2020; Vickers et al., 2010). Readings can; however, fluctuate relative to insertion depth and cow position (Vickers et al., 2010). To reduce some of these impacts, Hillman et al. (2009) introduced a plastic anchor to hold data loggers inside the vagina. These support devices could be moulded to a desired structure for optimal control and were subsequently validated in a study by Lee et al. (2015). Similar methods involve the use of a modified vaginal controlled internal drug release insert, within which a data logger is placed for insertion into the vagina (Burdick et al., 2012; Kendall et al., 2008; Vickers et al., 2010). However, as data loggers, these setups store data without the ability for real-time transfer of information, limiting potential impact in a commercial setting. Recent advances have enabled wireless transmission in various forms. Achieving wireless transmission using WiFi, Sakatani et al. (2018) found success in continuous measurement of vaginal temperature to predict calving time, with similar methods likely able to be utilised for HS prediction. Through a wireless measuring system composed of an indwelling device, temperature sensor, data collector and computer, Wang et al. (2020) measured alterations in vaginal temperature in response to environmental variations; however, additional validation is required with larger animal numbers in a variety of housing conditions.

Limitations as to uptake of vaginal temperature measurements over alternatives are likely due to extensive limitations. Owing to the inherent nature of the device, vaginal temperature can only be taken in female animals and should also consider reproductive cycle phase for optimal accuracy. Although Lees et al. (2018a) has suggested the potential for a direct comparison between genders, there is a high likelihood of error resultant from incorrect estimation of individual variables. Prices of vaginal temperature devices show considerable variation, with distinct failures in classification occurring with inexpensive tools (Tresoldi et al., 2020). Further, only short-term monitoring is recommended for indwelling devices due to the increased risk of irritation and infection (Burdick et al., 2012; Shu et al., 2021), reinforcing the ineffectiveness of such devices in a commercial setting.

Tympanic temperature

Tympanic (ear) temperature is measured through the placement of data loggers into the ear canal. Measurement of tympanic temperature has been reported to be of high accuracy, as the tympanic membrane has a similar blood supply to the hypothalamus and is overall sheltered from external heat influences. Of particular note, measurement of tympanic temperature is the only validated indicator of CBT in dairy calves (Woodrum Setser et al., 2020).

Initial trials to compare two devices in dairy cattle by Myers and Henderson (1996) found tympanic temperature to be lower than rectal temperature for all animals across both devices, likely reflecting the normal temperature for this site. Further studies by Bergen and Kennedy (2000) looked to determine the relationship between vaginal temperature and tympanic temperature in beef heifers, concluding a close relationship, though highlighting tympanic temperature might be preferred for identification of acute responses to short-term environmental fluctuations. This study also emphasised difficulties of recording tympanic temperature for more than a few days due to thermistor dislocation and infection potential. A study by McCorkell et al. (2014) tested a commercialised tympanic temperature tag for the detection of diseased calves, but found tag placement, probe displacement, and a high activation threshold contributed to a lack of reliability. Jara et al. (2016) reported a high association of tympanic temperature with thermal indices (especially comprehensive climate index) in Holstein Friesian dairy cows yet provided no threshold value.

Though the use of tympanic temperature has been seen across species in literature, its measurement has several limitations, including poor acceptance of the foreign object within the ear canal itself, resultant in changes to behavioural expression (Shu et al., 2021). Ear infections are not uncommon post installation, especially during long-term use (Bergen and

Kennedy, 2000). Additionally, placement of the data logger must be retained near the tympanic membrane, with any movement impacting reading accuracy and consequent data validity (McCorkell et al., 2014).

Subcutaneous temperature

In cattle under high heat conditions, approximately 15% of endogenous heat is directly lost from the body core through the respiratory tract (McDowell et al., 1976), with the remainder transferred to the skin for dissipation through alternative mechanisms (Finch, 1986; Kadzere et al., 2002). As such, subcutaneous temperature is a promising candidate to represent CBT. However, only in recent years have developments in wireless technology made the reliable measurement of subdermal or skin temperatures possible, through the implantation of sensors. As subcutaneous temperature can vary significantly depending on anatomical location, varied efforts have been made to determine the most appropriate, accurate location on the body (Iwasaki et al., 2019; Lee et al., 2016; Reid et al., 2012). Additional considerations include ability to recover the implant prior to introduction into the food chain, alongside ease of use in a commercial setting without detriment to animal welfare.

Earlier studies recommended a range of implantation sites across livestock species including subcutaneous at either the neck, front of head or base of ear, intramuscularly in the neck, or under the scutiform cartilage of the ear (Fallon and Rogers, 1999; Hasker et al., 1992; Nakamura et al., 2019; Reid et al., 2012). Based on such recommendations, a more recent study by Reid et al. (2012) used implantable radio frequency identification microchips at three different anatomical sites: subcutaneous at the base of the ear, posterior to the poll, and beneath the umbilical fold. Measurements at each site were positively correlated with rectal temperature in a controlled, thermal environment but the overall correlations were not strong ($r = 0.43$-0.53), with the highest correlation being between rectal temperature and base of the ear. Using button-shaped data loggers in the lateral neck, upper scapula, and lower scapula of Holstein steers, Lee et al. (2016) found subcutaneous temperature a reliable reference of CBT; however, the devices required experimental removal for access to data. While this and similar methods are successful in measuring subcutaneous temperature, the infrequency of data accessibility decreases the feasibility of their use in commercial settings. Iwasaki et al. (2019) developed implantable wireless thermometers and tested them across 10 different sites. Among subcutaneous sites, the tail base demonstrated the highest reception rate for continued wireless transmission (97.6%) while retaining a good correlation with rectal temperature. Measuring subdermal temperature at the base of the ear in dairy cows across a five-day period, Chung et al. (2020) demonstrated the feasibility of automatic monitoring of physiological data. A correlation of 0.58-0.85 between ear base and vaginal temperature was shown, advanced by involvement of a machine learning algorithm to predict current CBT information. However, contrary to the aforementioned studies, Woodrum Setser et al. (2020) used a microchip to measure body temperature in dairy calves. While microchip readings were highly correlated with the rectal thermometer in the ex vivo trial, rectal temperature was not significantly correlated with ear, upper scapula, neck, or tympanic temperature for the daily and hourly studies. This suggests that although temperature microchips are effective themselves, temperature is dependent on anatomical location in calves and at this stage, temperature measured at the ear, upper scapula, and neck cannot be used for CBT estimation in calves.

To date overall, limited studies have utilised subcutaneous temperature as a sensitive gauge of HS in dairy cattle (Shu et al., 2021). It is thus unclear the role of long-term sensor implants as to potential health implications on the animal, nor the impact on the food chain, with very few studies yet to make observations over a longer time scale. From this, it is clear the cost and complexities associated with implantable sensor use limits their application to a research setting, reinforcing additional studies are required before they can be practically implemented at a commercial level.

Ruminal and reticular temperatures

Being part of the internal environment, the rumen and reticulum are locations of interest for CBT measurement. They are isolated from external factors while still enabling continuous measurement as an in vivo location. As such, use of intraruminal boluses for the measurement of deep CBT has gained traction through both research and commercial industries. Transported naturally to the rumen/reticulorumen once orally administered, temperature loggers typically consist of a chip, antenna, battery and temperature sensor built into a small bolus. Initial studies measuring ruminal temperature required a fistula (Hicks et al., 2001), as compared to modern devices that are overall non-invasive and administered through the oesophagus with the use of either a customised bolus applicator or a balling gun. Once ingested, the devices remain in the reticulum or near the junction between the rumen and reticulum (Koltes et al., 2018). Using an intraruminal device has many advantages over alternative external sensors, as they are independent from external disturbing factors and less likely to be lost. Enabling real time, continuous data collections through instant wireless transmission (AlZahal et al., 2011) or data storage (Koltes et al., 2018), reticulorumen boluses remove the need for additional handling post insertion. Various studies have revealed a correlation between reticulorumen temperature and ambient thermal environment (Ammer et al., 2016b; Bewley et al., 2008a; Liang et al., 2013; Stone et al., 2017). Correlations of ruminal temperature and rectal temperature show great variations, with correlation coefficients between 0.34 (Prendiville et al., 2002) to 0.92 (Sievers et al., 2004). Similarly, correlation coefficients between reticular temperature and rectal temperature range from 0.50 (Burns et al., 2002) to 0.645 (Bewley et al., 2008a). Of note, reticulorumen temperature is approximately 0.5 ˚C higher than CBT, likely due to rumen microorganism activity (Bewley et al., 2008a; Hicks et al., 2001; Prendiville et al., 2002).

Earlier studies looked to develop an intraruminal device for measuring fermentation parameters, temperature included, with periodic data transmission to a receiver unit (Sievers et al., 2004). In vitro experiments indicated positive recording capabilities for temperature, conductivity, and pressure, encouraging further development. Looking to confirm abilities of capsule based wireless technology in cattle, Ipema et al. (2008) conducted a pilot study that found data transmission was affected by behavioural activity, specifically finding data losses high when cattle were lying down, suggesting more attention was required for aspects of signal propagation through body tissue. With water temperature known to temporarily decrease rumen or reticular temperatures, Bewley et al. (2008b) looked to further assess the impact of ingested water intake on reticular temperatures in lactating dairy cattle. The simple ingestion of water was found to have minimal impact on reticular temperature, but it was the temperature of said consumed water that determined the magnitude of reticular temperature decrease, as well as time to return to baseline. Following this, Bewley et al. (2008a) assessed the dynamics of the relationship between reticular and rumen positioned sensors. Both locations were subject to greater measurement error and variation than was expected, likely influenced by feed and water intake, and emphasising that additional research is needed to ensure feasibility of such devices. With a penultimate focus on detecting ruminal pH, AlZahal et al. (2009) compared a telemetric monitoring system to an existing in situ methodology to monitor ruminal temperature. While this method is non-invasive compared to alternative cannulations, further system improvements are required for the detection of more subtle changes in temperature. This study also suggested the utilisation of roaming boluses for future research as to better understand the impact that diet type and intake has on rumen temperature (AlZahal et al., 2009). Reinforcing the potential ability of rumen temperature boluses in detecting temperature changes as a result of adverse health events, Rose-Dye et al. (2011) found a high correlation between rumen boluses and rectal temperature. While validated in beef cattle as an effective measure of CBT in both thermoneutral and thermally stressful environments (Boehmer et al., 2015), ruminal temperature in the same circumstance in dairy cattle had yet to be confirmed. Following this, Ammer et al. (2016b) investigated if reticular temperature could be used as an indicator of HS under moderate climatic conditions, finding reticular temperature increased at a THI greater than 65, further increasing if THI was greater than or equal to 70. This was extended upon in the same year, when Ammer et al. (2016a) confirmed a correlation, be that lower than rectal temperature and vaginal temperature alone, between rectal temperature, vaginal temperature, and reticular temperature. This reduction in correlation is likely due to the limiting factor of feed and water intake yet still encouraging for the utilisation of this newly developed technology for CBT monitoring. Lees et al. (2018b) reinforced the requirement to account for breed, ambient conditions, and shade availability in the assessment of rumen temperature, highlighting that *Bos indicus* and *Bos taurus* cattle regulate ruminal temperature in different manners – a factor likely consistent across all cattle. A further study within the same group, emphasised that additional studies are still required to more accurately detail the relationships between rectal and ruminal temperature, though still noting the potential for ruminal temperature to be used as a proxy of CBT (Lees et al., 2019).

While reticulorumen temperature has shown great promise across a multitude of studies in the continuous monitoring of deep CBT, there are a range of identified limitations. Initial studies discussed concerns as to device cost, battery life, device retrieval at the abattoir, and potential misplacement into the trachea during administration (Flattot, 2022). With continued advancements in wireless and battery technology, the latest bolus devices have a usage of approximately five years (Hajnal et al., 2022), which will only improve in coming years, likely hand in hand with price decline per unit. Additionally, reticulorumen temperature can be influenced by diet and drinking events (AlZahal et al., 2011; Bewley et al., 2008a; Lees et al., 2019), with a drinking bout seen to decrease reticulorumen temperature by up to 9.2 ˚C for three and a half hours (Ammer et al., 2016b; Bewley et al., 2008b). However, statistics such as described in Timsit et al. (2011), can eliminate water drinking events from the raw data to remove the influence of drinking bouts on reticulorumen temperature. Alternatively, the temperature of water consumed can be measured to allow for separation of the effect of drinking water on reticulorumen temperature (Dye and Richards, 2008). Even with these identified limitations, the aforementioned studies highlight that reticulorumen temperature has the potential to be used as a proxy indicator of CBT to in turn measure and quantify the impact of HS on dairy cattle. While there are several ways to monitor animals' behavioural and physiological responses to HS conditions, practical short- and long-term mitigation strategies are required in response.

DAIRY CATTLE HEAT AMELIORATION

Various management approaches to ameliorate HS in dairy cattle are available, each with differing efficacy, reflective of the surrounding climatic conditions. With dairy farms varying in intensity, breed selection, feed utilisation, mechanisation, and animal welfare indicators (Ruban et al., 2020), the most appropriate route to alleviate HS impact will be determined on an individual farm basis. These options to reduce the effects of HS fall into three distinct management strategies: genetic development of resistant breeds, nutritional management, and physical modification of the environment (Beede and Collier, 1986; Johnson, 2018). Irrespective of chosen amelioration technique, there are ongoing calls to select animals that are either resilient or tolerant to heat, yet clarity among the definition of these terms (among others) remains lacking. To ensure research efforts reflect industry goals, it is crucial that ambiguity surrounding HS terminology is addressed (see Chapter 3).

Genetic development of resistant breeds

Genetic selection of cattle is a permanent, cumulative management strategy that provides a long-term solution to HS (Pryce et al., 2022). Herd improvement has been taking place for decades, with the intention of improving subsequent generations of animals. In particular, dairy herd improvement has historically concentrated on milk recording traits (Newton et al., 2021), to the detriment of heat tolerance ability (Carabaño, 2016). Breeding objectives play a key role in determining the direction of genetic changes in traits. Efficient multiple-trait selection is typically achieved through clearly defined breeding objectives alongside the development of appropriate selection indexes for a specific production system. The genetic development approach, with a focus on genes responsible for heat tolerance processes, will enable breeding of cattle with prioritised thermoregulatory traits.

There are various phenotypic characteristics that influence the suggested heat tolerance capabilities both between and within breeds. Collier et al. (1981) found that Jersey cows have increased heat tolerance over Holstein cows. This was extended upon by Muller and Botha (1993), suggesting the variation in tolerance is reflective of respiratory rate capacity alongside physical surface area ratio. Hansen (1990) found that predominately white coated, lactating Holsteins had lower rectal temperatures and respiration rate while maintaining a more consistent daily milk production, as compared to those with a predominately black coat in an unshaded environment. However, a low sample size of 20 cows suggests further research should be undertaken before coat colour as a primary genetic selection tool is widely adopted. Bernabucci et al. (2010) have reported animals with lighter, shorter hair have a greater tolerance for high heat conditions, with Collier et al. (2008) conveying the density of both hair coat and sweat glands, alongside hair length, and coat and skin colour impact the animals evaporative heat loss ability. Cattle hair density has a direct influence on the number of sweat glands per animal, with a single apocrine sweat gland present per hair fibre (Gebremedhin and Wu, 2001; Olson et al., 2006). Horses, who also have apocrine sweat glands, have a sweating rate 10x that of a cow (Berman, 2005; McCutcheon and Geor, 2000), suggesting room for evaporative heat loss improvement.

The slick hair gene (*slick hair*) is one of limited specific genes identified to control heat tolerance in cattle (Dikmen et al., 2008). Controlling hair length, this gene was originally identified in Senepol, then Carora cattle (Olson et al., 2003) before being introduced into Holsteins through selective breeding (Dikmen et al., 2008). Responsible for a very short, sleek coat, this gene controls hair length and density, thereby regulating thermoregulation by evaporation. Dikmen et al. (2008) confirmed earlier findings by Olson et al. (2003) that slick-haired cattle had better body temperature regulation with an increased sweating rate, lower rectal temperature, and lower respiration rate than wild-type cattle under conditions greater than 15 ˚C. Mariasegaram et al. (2007) presented findings from a genome scan of the *slick* hair coat in Senepol-derived cattle, and was able to further localise the *slick* locus to the *DIK4835-DIK2930* interval. Further research has been directed to improve the annotation of the bovine sequence assembly and better understand the functionality of the coding genes to enable further development in this field.

To combat HS, cells have specific proteins, known as heat shock proteins, involved in the protection of cellular proteins from denaturation. Specifically, heat shock protein 70 (**HSP70**) have been identified to have a key role in maintaining thermal tolerance. While most cellular proteins are affected by HS, HSP70 exhibits increased expression under HS across a variety of livestock species. Singh et al. (2014) found the expression of HSP70 is enhanced in zebu cattle, with Kim et al. (2017) finding the gene in African cattle breeds as well. This suggests HSP70 might be utilised for breeding heat tolerant cattle, particularly in tropical conditions. Pathirana and Garcia (2022) optimised an ELISA system to quantify HSP70 levels in cow milk, having success with this non-invasive method of detection. Future work should extend this method across various seasons and herds to ensure its validity.

Nguyen et al. (2016) put forth genomic selection as a promising approach to accelerate genetic gains for heat tolerance in dairy cattle. The study combined milk production data, climate data, and dense single-nucleotide polymorphism markers to derive genomic predictions for heat tolerance to an accuracy of 0.57 in Holsteins and 0.61 in Jerseys. While falling short of alternative production traits that are achieving accuracies up to 0.8 (Wiggans et al., 2011), findings remained equal to that of DMI (de Haas et al., 2012). Desirable, are higher accuracies which will in turn lead to an increase in genetic gain over shorter generations. This can be achieved, primarily, by a greater pool of predictor animals available in a reference population, from which to derive the heat tolerance phenotype. The availability of high density single-nucleotide polymorphism genome sequencing is increasing, enabling the efficient selection of candidate genes for genomic selection (Zeng et al., 2022).

Research by Nguyen et al. (2018) presents the development, validation, and implementation of a genomic breeding value for heat tolerance, specifically for dairy cattle in Australia. The study combined temperature and humidity data with milk production records over a 13-year period, across 509,242 Holstein and Jersey cattle, to formulate a genomic prediction equation. This equation was then validated across 390 Holstein heifers with the predicted heat tolerant group demonstrating a reduction in rectal and intra-vaginal temperatures, alongside a smaller decline in milk production, compared to those in the heat susceptible group. Currently, the mean reliability of this breeding value is moderate, but improvements are expected with an increase in reference population in coming years.

The impacts of genetic gain are often not seen for several years, reflective of its cumulative nature alongside genetic lag (Newton et al., 2021). Therefore, investments into herd improvement will not be shown on farm for several years, a characteristic often putting producers off. Further, the success of genetic gain is driven by the accuracy, intensity and variation of selection, reinforcing the impact of appropriate selection at the outset. With this in mind, producers often rely on short-term solutions to see an immediate impact of animal response to HS mitigation.

Nutritional management

Nutritional management strategies offer the flexibility of nutrient manipulation across varied contexts. Nutrient acquisition begins at diet consumption, includes diet digestion and ends with nutrient absorption, all of which can be impacted by HS conditions. During a HS event, both the frequency and duration of DMI is altered (Bernabucci et al., 2010; DeShazer et al., 2009), contributing to a decline in overall productivity. In lactating dairy cattle, this DMI decrease typically begins at an average daily temperature of 25-27 ˚C but is influenced by diet composition (Beede and Collier, 1986). For example, grazing animals exhibit a higher impact of HS on DMI intake due to reduction in grazing activity, as opposed to barned conspecifics. As this reduction in feed intake results in less consumption of essential nutrients and metabolisable energy, nutrient and energy uptake must be otherwise increased. Rhoads et al. (2009) found the DMI reduction might only account for 36% of the milk production decline; therefore, production losses might be recuperated with suitable nutritional management.

Protein

Sufficient protein provision is required in hot conditions to maintain both rumen microbial function and adequate amino acid flow to the intestines (Bergen, 2021). However, with the reduced daily feed intake typical of a cow experiencing HS, rumen microbial function might be compromised and as such the quantity of consumed nutrients, including crude protein, declines. While increasing the percentage of protein supplied in the diet might appear advantageous, as it counteracts the decline in physical intake, there is an energetic cost associated with such a change. As additional energy is required for conversion (Conte et al., 2018), supply of excess rumen degradable protein in a HS event results in both DMI and milk production decline (Huber et al., 1994). As such, literature suggests in its place, that protein quality rather than yield should be optimised during the hot season, focusing on the supply of bypass protein sources which are less likely to be digested by rumen microbes, improving milk production (Tandon and Siddique, 2016). Soybean meal (a high-quality protein source) has been tested in the diet of Holstein cows to evaluate changes in the rumen microbiome and milk composition (Amin et al., 2022). Results demonstrated the inclusion of fermented soybean meal into the diet increased milk urea nitrogen, milk protein yield, fat corrected milk, and milk fat yield while decreasing somatic cell count. Beneficial changes to the rumen microbiome were also identified (Amin et al., 2022); however, the retention of these changes under HS conditions are yet to be tested. While high producing dairy cattle do require at least some rumen-undegradable protein in their diet (Moran, 2005), an increase in rumen-undegradable protein in dairy cows' diets has not seen consistent lactation improvements in literature (Santos et al., 1998) and as such must be carefully managed.

Fibre

As energy is often the limiting nutrient, a common dietary approach is to reduce forage content, while simultaneously increasing concentrate matter in a ration (Conte et al., 2018; Sammad et al., 2020). While a reduced forage-to-concentrate ratio enhances nutrient density and supports heightened DMI, ruminal conditions must be considered. If fibre content is compromised, ruminal pH might drop, which can result in acute ruminal acidosis and lead to the associated production and health consequences. As such, concentrate feeding during HS conditions is beneficial at amounts no greater than 65% of the diet (Coppock, 1985). This is where fibre quality becomes key; a high-quality fibre will tend to improve feed digestibility and palatability, while maintaining rumen stability without significant contribution to metabolic heat (Conte et al., 2018; Min et al., 2019). Contrastingly, low-quality forage provides unwarranted bulk to the diet without provision of adequate nutrition. Thereby, while a lower fibre, high grain diet might work to reduce metabolic heat production, reducing impact during HS conditions, fibre of adequate quality must still be provided to ensure ruminal pH and overall animal health. Feeding a low fibre diet during hot weather has seen heightened daily milk production concurrent with lower body temperature and respiration rates (West, 1999; West et al., 2003). Halachmi et al. (2004) replaced roughage neutral detergent fibre with soy hulls in hot climate conditions returning higher average milk yield, milk fat, and 4% fat-corrected milk. Completed entirely under HS conditions, Naderi et al. (2016) replaced corn silage with shredded beet pulp, finding the replacement beneficial at up to 12% of dry matter. Opposingly, Gonzalez-Rivas et al. (2018) established that a total mixed ration plus crushed corn ration ameliorated HS responses indicated by a reduction in rectal temperature and improved milk production. Variation in type and quantity of fibre utilised between studies demonstrates deviation in nutritional management can be successful for the short-term management of HS.

Fats

Typical of a HS event due to DMI reduction, a negative energy balance results when energy intake is unable to meet lactation requirements. Addition of fat to the diet of lactating cattle is common, working to increase net energy intake due to the high energy density of fat supplements, alongside the potential to reduce thermogenesis owing to a lower metabolic heat production as compared to fibre, starch, or protein. In particular, rumen-protected fats can lower metabolic heat increments (Conte et al., 2018) and as such, commercial bypass products are commonplace. However, further feed intake depression can be experienced if excessive fat is supplied, instead, interfering with microbial digestion and milk yield; therefore, caution must be taken. As with fibre, the addition of fat to the diet in various forms and quantities has been explored in research. Palmquist and Jenkins (1980) identified that 3-5% fat might be added to a ration to increase energy intake of high producing cows without toxic effects to rumen microflora. This was supported by Drackley et al. (2003), reporting 3% supplemental fat should be used during hot weather to maintain energy. Providing a supplemental rumen inert fat in the form of a saturated free fatty acid, Warntjes et al. (2008)

found intestinally absorbed C16:0 has the greatest positive impact on milk production for cattle with a lower volume, increasing milk yield and true protein content. Evaluating the effectiveness of physical and nutritional HS alleviation, Serbester et al. (2005) identified that applying sprinklers and fans has a greater impact on milk yield than nutritional manipulation through the supplementation of either fish meal or protected fat. Interestingly, the success of protected fat over fish meal supplement was influenced by the level of dietary protein (Serbester et al., 2005), reinforcing the requirement to assess the diet as a whole when manipulating nutrition for success. Wang et al. (2010) identified that metabolic heat can be minimised by replacing fermentable carbohydrates with supplemental saturated fatty acids. This study demonstrated saturated fatty acids worked to increase milk yield, milk fat content, and total milk solids, without impacting DMI, body condition score, or energy balance. More recently, Melo et al. (2016) determined supplementation with fat from palm oil increased feed efficiency while reducing signs of HS. Behzad et al. (2019) compared the supplementation of calcium salts of fatty acids and high-palmitic acid in the diets of dairy cows under HS. Cattle fed calcium salts were seen to have both greater digestibility and milk fat content regardless of the lesser energy supplied by calcium salts compared to palmitic acid, likely due to compensation from heightened digestibility. Thereby, it is evident that with a reduction in DMI intake across high heat periods, various forms and quantities of fibre supplementation can assist with the management of HS.

Feed additives

Utilisation of feed additives in various forms has been explored for the management of HS, including rumen modifiers and nutritional additives such as yeast, betaine, vitamins, and minerals. Rumen modifiers have been used as early as the 1950s (Beeson and Perry, 1952), working to modify the balance of rumen microbes and as such, the proportion of produced volatile fatty acids. These feed additives might be classified as ionophores and non-ionophores, dependent on their action mechanism. Used commonly as growth promoters for ruminants, monensin is the most widely employed (Silva et al., 2021). Monensin has been well studied in beef cattle, working to increase propionate production (Schelling, 1984) and decrease the acetate to propionate ratio in the rumen, enhancing energy metabolism efficiency (Duffield et al., 2008), though its successful utilisation in dairy cattle is still being confirmed. Across literature, varied success as to monensin supplementation has been seen, with some studies reporting an increase in milk yield and/or DMI (Ghizzi et al., 2018; Grigoletto et al., 2021), with others reporting minimal impact (de Moura et al., 2021; Duffield et al., 2008). A meta-analysis by Rezaei Ahvanooei et al. (2023) confirmed an increase in production with monensin supplementation up to 23 ppm. Alternative doses; however, can significantly decrease DMI, milk protein, milk fat, and milk fat yield (Rezaei Ahvanooei et al., 2023), reinforcing that dosage is critical in maintaining benefits during a HS event. Further, the use of monensin has been linked to bacterial resistance; therefore, its use might be considered a public health concern (Vendramini et al., 2016) and alternative strategies should be prioritised.

Microbial additives including yeast and yeast cultures have been used widely in the dairy industry to maintain and/or increase milk yield through improved feed intake, feed efficiency, rumen fermentation, and digestibility (Min et al., 2019). With the supplementation of yeast to attenuate reductions in ruminal pH, digestion and performance, benefits are typically resultant (Perdomo et al., 2020). Conducted in climate chambers, Shwartz et al. (2009) found cattle fed a novel yeast culture retained a slightly reduced body temperature but were unable to ward off the negative effects of HS, including impacts on feed intake and milk production. Finding greater success, Liu et al. (2014) supplemented multiparous lactating Holstein cows with either common yeast culture or glycerol-enriched yeast culture and saw partially mitigated HS effects – glycerol-enriched yeast returned beneficial energy status and gene expression results. Perdomo et al. (2020) explored the impact of feeding two dosages of live yeast on performance and feeding behaviour of Holstein cows under HS. While treatment did not impact rectal temperature or DMI, 1 g of live yeast (maximum dosage) increased yield of energy-corrected milk, improved digestibility, and increased rumen pH. Focusing specifically on the benefits of chromium yeast, Shan et al. (2020) demonstrated an increase in DMI, reduction in both rectal temperature and respiration rate, alongside a promotion of immune function in mid-lactation Holstein cattle under HS. Most recently, Li et al. (2023) investigated the impact of live yeast on lactation performance and bacterial composition and function in the rumen and hindgut of Holstein cattle under HS. Live yeast supplementation decreased rectal temperature and respiratory rate while increasing DMI and the yield of milk, milk fat, milk protein, and milk lactose. Rumen and hindgut bacterial composition was altered, typically enriching the pathways for carbohydrate and protein metabolism. However, as highlighted by Perdomo et al. (2020), it is as yet unclear if the positive responses to yeast are evident from direct effects of the yeast on microbial activity in the rumen or due to improved DMI and/or digestibility.

Betaine is a naturally occurring extract from sugar beet that has been explored for its ability to reduce the effect of HS across livestock species. Shown to mitigate against HS in sheep (DiGiacomo et al., 2016), chickens (Shakeri et al., 2018), and beef cattle (DiGiacomo et al., 2014), the effects on lactating dairy cows have been equivocal. Addition of betaine to the diet of animals is suggested to assist in HS through several mechanisms, primarily related to betaine being an osmolyte (Hammer & Baltz, 2002), methyl donor (Cronje, 2018), and a molecular chaperone (Dunshea et al., 2019; Sharma et al., 2009). In thermoneutral conditions, betaine has been shown to increase milk production and reduce feed and water intake; however, the effect on milk production was lost during HS at high doses (Hall et al., 2016). A study by Shah et al. (2020) highlighted the ability of betaine supplementation to increase milk yield, rumen fermentation, and apparent digestibility for dairy cows under HS, concluding 15g of betaine per day could optimise production performance. Two individual meta-analyses both found dietary betaine to increase feed intake with Malik et al. (2024) identifying positive influences on milk fat yield, milk lactose yield, and milk protein yield while results from Abhijith et al. (2024) found milk composition to be minimally impacted. Ongoing research is required to confirm these findings and develop optimal implementation conditions.

As vitamins are essential for the normal growth and development of multi-cellular organisms, and minerals retain an important role in the maintenance of normal physiological function, their addition to the diet during a HS event might be warranted to alleviate adverse HS effects. Vitamin and mineral requirements of dairy cattle fluctuate depending on their physiological and management conditions. Identifying the ideal quantity presents a challenge for producers. Supplementation at levels greater than required is recommended by dairy nutritionists to promote adequate absorption at the intestinal level (Andrieu, 2008), with some research suggesting long-term supply at these heightened levels increases productivity during physiological stress (Kincaid and Socha, 2004; Rensis and Scaramuzzi, 2003), such as that experienced during a HS event. Khorsandi et al. (2016) explored the provision of a sustained-release multi-trace element/vitamin ruminal bolus during HS conditions to Holstein dairy cows. Results demonstrated that cattle with the slow-release bolus tended to maintain a higher milk yield, milk fat, protein, and solid non-fat percentage than the control group, supporting the use of this method for mitigating HS effects for high producing cows. Vitamin and mineral supplementation should be seen as a management strategy to buffer the effects of diet and climate as a whole, rather than specific to individual nutrient turnover (Calamari et al., 2007). Research has shown that supplementing specific nutrients - such as rumen-protected niacin, which reduces CBT and vaginal temperature (Zimbelman et al., 2013), and selenium, which enhances immune function, milk quality, and overall health (Sejian et al., 2012) – can be effective. However, it is important to consider the complex interactions and balance of all nutrients within the body, rather than attributing beneficial effects solely to the supplementation of a single vitamin or mineral.

As nutritional supplementation has seen both varied methods and results across literature, it can be surmised that no single dietary manipulation will be suitable for all individuals across all conditions. Instead, nutrient management must be managed on a per herd basis at minimum, to enable peak production in line with HS management.

Physical modification of the environment

Shade provision

Provision of natural or artificial shade is a means of protection from solar radiation, shown to be effective in reducing negative behavioural and physiological traits resultant from HS (Marcillac-Embertson et al., 2009; Mitlohner et al., 2001). Cattle actively seek shade when access is possible (Kendall et al., 2006; Widowski, 2001), with shaded cattle experiencing lower respiration rates and CBT compared with unshaded conspecifics (Blackshaw and Blackshaw, 1994). Heightened ambient air temperature and solar radiation intensity increases the utilisation of shade by cattle (Kendall et al., 2006; Tucker et al., 2008).

The utilisation and benefits of shade for pasture based dairy cattle is of particular importance, but further research is required to evaluate the effectiveness of trees in providing quality shade. Legrand et al. (2009) reported that with an increasing THI, dairy cattle showed a preference for a free-stall barn environment over pasture. This could be a reinforcement of the findings by Tucker et al. (2008), demonstrating dairy cows actively seek shade offering the most protection from solar radiation, such as that offered by a barn. Cattle in this study were twice as likely to utilise shade providing 99% protection from solar radiation as opposed to 25% protection. Cattle experiencing this greater shelter from solar radiation maintained lower minimum body temperatures with less marked increases in average body temperature on warmer days (Tucker et al., 2008), suggesting a contribution of solar radiation exposure to heat accumulation. Kendall et al. (2007) studied the effects of shade and sprinklers, both alone and in combination, finding that although shade alone did reduce respiration rate and body temperature, sprinklers had a greater effect on respiration rate reduction, while also providing relief from insects. The sprinklers also had a longer-term effect, retaining lower body temperatures of cattle for several hours. These findings were extended upon by Schütz et al. (2011), including the influence of cattle preference in resource selection. Cattle showed preference for shade over sprinklers, with this inclination upheld with increasing air temperature, solar radiation, and wind speed. However, respiration rate and BST declined most by sprinklers, along with the added benefits of insect avoidance behaviours declining. Therefore, while shade holds value to dairy cattle and is beneficial, HS mitigation with water is more efficient, leading producers to continue exploration of supplementary mitigation methods.

Bedding material

Modern housing of dairy cattle exposes the animals to a variety of bedding materials and designs. As lying accounts for up to 16 hours of daily activity (Tucker et al., 2003), maintaining the integrity of this period is key to the animal's health. Free stall comfort reflects stall size alongside type and quality of bedding material. Bedding material is multi-purpose, providing durability, friction, thermal comfort, and softness all while aiming to reduce daily labour requirements for cleaning (van Gastelen et al., 2011). Dairy cow free stalls are typically bedded with a variation of organic or synthetic products, reflective of availability in price within the surrounding region. Cows show a preference (through increased lying time) for materials that are soft, dry, and well-bedded (Chaplin et al., 2000; Tucker and Weary, 2004). By utilising a bedding material that encompasses these factors, alongside thermoregulatory benefits, the impact of HS can be accounted for. However, little research has been conducted into the thermal comfort of various flooring surfaces used for indoor dairy housing.

Lendelová et al. (2010) highlighted the requirement for bedding to have a low thermal effusivity to restrict heat conduction between bedding and animal. The study evaluated the properties of various organic matters in comparison to rubber mats and rubber foam mattresses, finding dry straw most appropriate compared to other organic products. Thermal effusivity of rubber foam mattresses was slightly better than dry straw, but all tested products performed advantageously over bare concrete. Overall thermal comfort can be increased on synthetic products through the addition of some organic material coverage (Lendelová et al., 2010). A study by Dimov et al. (2017) compared the use of rubber mats and straw, rubber mats alone, and compost and straw, finding rubber mats alone resulted in the highest bedding surface temperature. Dairy cows showed preference for a cooler surface, of which was found in the compost and straw bedding, including consideration of the concrete alleyways. The rubber mat alone failed to provide heat dissipation opportunities, with cattle opting to stand at higher ambient temperatures, impacting not only their duration under HS but also contributing to a decrease in milk production. Radoń et al. (2014) developed a computational model for heat exchange between a dairy cow and her bedding. This model extended upon that of McGovern and Bruce (2000), which did not account for transient heat exchange between the animal's surface area and bedding. However, Radoń et al. (2014) acknowledged the complexity around determining thermal conditions and the requirement for various estimations for use within a computational model, for example, real heat flux and lying time patterns. As such, focus was primarily given to two bedding types (straw or sand) and should be extended upon in future research.

Fans

Cooling strategies adhere to the four thermodynamic principles of heat transfer: conduction, convection, evaporation, and radiation. Improvements in cow comfort and milk production have been shown through supplemental mechanical cooling systems in barned dairies (Beede and Collier, 1986). Combining fans alongside sprinklers and/or foggers to utilise both convection and evaporative cooling methods has been shown as the most effective heat abatement method (Worley and Bernard, 2008). In particular, cooling should be maximised in areas where cow retention will be beneficial to production levels, such as feeding and rest areas, within which maintenance of air velocity should be a focus.

The introduction of high-volume, low-speed (**HVLS**) fans offer an alternative to the conventional fan utilised across the industry. The HVLS fan system proposes a replacement ratio requirement of 8:12, utilising less electrical energy and working at a lower noise level (Worley and Bernard, 2008). An early study by Kammel et al. (2003) employed HVLS fans and used anecdotal evidence from producers to assess their impact on cow HS abatement. All farmers surveyed acknowledged a noticeable air quality improvement in their barns. Some producers noted a reduction in milk losses, as well as a faster recovery timeframe upon return to climate averages, following intense heat and humidity periods, as compared to natural ventilation systems. Worley and Bernard (2008) extended upon this study to address the lack of evaluation concerning cooling effectiveness of the HVLS fan system. While they agreed with the reduction in noise of the HVLS system, the authors found air speeds averaged 50-60% below that of recommended industry standards. Further, the average body temperature of animals undergoing the HVLS fan treatment were higher than those under conventional settings by 0.2 ˚C, suggesting that the use of conventional fans provided more effective HS abatement. However, the study did not acknowledge that with changes to external ambient temperature and humidity, the cooling method utilised might alter. With increasing ambient temperatures, non-evaporative cooling reduces in effectiveness. As such, the efficiency of a mixed cooling system is dependent on relative humidity (Xie et al., 2017). Conducting further research on the adoption of HVLS fans, Das et al. (2021) compared the cooling effects of HVLS fans with high-speed conventional fans in a simulated space using computer fluid dynamic models. While the average velocity of the HVLS fans was not better than the conventional fans, they did maintain a more uniform airflow at breathing height. Overall, the operational output of the HVLS fans was similar to conventional fans, but the improvement in energy efficiency markets well in an industry looking to improve sustainability.

Evaporative cooling

To enable sufficient heat dissipation, it is necessary to understand the interactions between temperature, airflow, and moisture gradients. Wetting the coat of the animal to the skin surface, followed by the introduction of air movement, utilises the principles of evaporative cooling and lowers the body temperature of cattle. While wetting the coat alone can have heat dissipation effects, coupling it with air movement is more effective (Lin et al., 1998). Dampening the skin surface removes the presence of an insulating air layer that can limit cooling effectiveness, with circulating air working to enhance evaporation rate and reduce HS more efficiently. Moisture on the surface absorbs heat conducted through the skin, cooling the skin in turn, and enabling it to take up more body heat internally, repeating this cycle. Gebremedhin and Wu (2001) developed a model that predicts evaporative, convective, and radiant heat fluxes from the skin surface and coat. They identified the dominant role of evaporative cooling as a heat mitigation technique for cattle experiencing HS, which increases with an increasing percentage of wetness. However, evaporative heat loss declines with a simultaneous increase in relative humidity because of water-vapor concentration deficit between the skin surface and surrounding ambient air. Though developed, the simulated results from this model are yet to be experimentally validated.

Cooling by surface is typically conducted in the feeding and milking parlour holding areas of the barn, in which the wetting of animals and by extension their surrounding environment, has limited negative health consequences. Contrastingly, this system in the resting area can increase the bacterial load of the bedding surfaces, increasing the risk of environmental mastitis (De Palo et al., 2006) and results in animals standing in other barn areas, counteracting HS dissipation methods conducted when lying and resting (Barbari et al., 2010; Frazzi et al., 2000). With this said, studies have shown that cooling the feed area alone will not eliminate the effects of HS (Calegari et al., 2005; Frazzi et al., 2002). Cooling by surface in the feeding area, coupled with forced ventilation in the resting area, works well to mitigate HS effects (Calegari et al., 2015). Comparatively, evaporative cooling in the resting area has no impact on physiological markers but has a behavioural impact with cattle showing an increased preference to lay down in the free stall area. However, the negative impacts of heightened somatic cell count, alongside clinical mastitis across some of the herd, suggest caution in the adoption of this method.

Evaporative cooling was identified to be more effective than spray and fan systems on Holstein cattle in a hot-dry climate (Ryan et al., 1992). This is similarly seen across literature, with the use of sprinkler systems typically investigated in hot-dry climates (Avendaño-Reyes et al., 2012; Chen et al., 2015; Correa-Calderon et al., 2004), proving the cooling system to be effective in mitigating HS. Comparatively less common are the same studies conducted in a hot-humid climate (Calegari et al., 2012; Honig et al., 2012; Khongdee et al., 2006), demonstrating a requirement for further research to ensure the efficacy of these systems are not negated by increasing humidity. D'Emilio et al. (2017) investigated if HS can be mitigated using evaporative cooling in an open barned system. Exposed to the same microclimate, those undergoing sprinkler treatment had a moderate, positive effect on rectal temperatures. Higher respiratory rates were recorded for cattle within the control group, suggesting HS was mitigated for those in the treatment group.

With an overall agreement across literature regarding the effectiveness of evaporative cooling, a hand in hand consideration is the amount of water required to retain this efficacy. Chen et al. (2016) determined a 73% reduction in water usage could result in equivalent reductions in body temperature and retention of milk yield. This was furthered by Tresoldi et al. (2018), finding that an increase in frequency but consistency in water volume, appeared to reduce respiration rate by seven breaths per minute. Spraying cows for longer, or reducing the time with the water turned off, reduced the ambient temperature surrounding the animal’s leg and improved overall cow cooling. Importantly, all treatment groups regardless of the spray strategy were relatively cool at the end of treatment (Tresoldi et al., 2018), indicating that improving water efficiency does not necessarily compromise HS mitigation. However, a study comparing sprinkler flow rates found that rates below 0.5 L/min were associated with higher respiration rates and reduced daily milk yield (Bah et al., 2021), suggesting there might be a minimum water flow threshold for effective cooling. Optimising water use in heat mitigation stragies – one of the top three uses of potable water in commercial dairies – can significantly enhance the sustainability of the industry.

When it comes to heat amelioration, whether it be through genetic development, nutritional management, or physical modification of the environment, technology can aid in each decision. With the continued development of precision livestock farming, we should be looking to these tools to aid in on-farm management, using them to optimise productivity, profitability, and welfare. Thereby, the utilisation of a data-driven approach might be appropriate for use now, more than ever before.

DATA DRIVEN METHODS OF HEAT AMELIORATION

The increasing challenges of climate change and resulting rise in HS among dairy cattle necessitate innovative approaches to maintain and improve animal welfare and productivity. Automation and the use of on animal sensors have emerged as transformative tools in this domain, providing real-time insights and facilitating the development of effective heat amelioration techniques. However, with the advent of modern technology allowing collection of immense amounts of data at decreasing acquisition cost, there comes the challenge to effectively exploit these records (Morota et al., 2018). At this stage, data primarily remains underutilised in the dairy industry. Evidently, growing sophistication in the types of data analysis approaches used for application is required, to ensure that data usage is optimised.

Trending use of machine learning methods in heat stress research

While statistical analysis has played a significant role in HS research, there has been a growing shift towards machine learning approaches. Machine learning algorithms present a solution to the analysis of large datasets, with the capabilities to handle non-linear relationships and complex interactions more appropriately than classical statistical methods (Cockburn, 2020). Through self-learning practices, potential bias can also be reduced through their use (Gorczyca and Gebremedhin, 2020). Employing a data-driven approach, machine learning models, and by extension deep learning models, have the power to analyse large datasets that statistical models alone might not be capable of (Fatima and Pasha, 2017; Mota et al., 2021). As the volume of recorded dairy farm data continues to increase, machine learning presents an opportunity to surpass linear relationships and other more simplistic models, improving decision support systems for on-farm productivity and animal wellbeing (Cockburn, 2020; Morota et al., 2018; Neves et al., 2022). Table 1 presents a review of studies that have employed the use of machine learning techniques for the prediction of various HS parameters in dairy cattle.

Table 1: Publications employing machine learning techniques for the prediction of various heat stress parameters in dairy cattle.

Paper	Predictive Model	Machine Learning Algorithms	Optimal Model	Comments
(Hernández-Julio et al., 2014)	Rectal temperature, respiration rate	Artificial neural networks, neurofuzzy networks	Artificial neural networks	Models based on neurofuzzy networks and regressions performed similarly.
(Hempel et al., 2019)	Heat stress risk	Artificial neural networks, random forest regression, support vector regression models	Artificial neural networks	Further development and refinement of indoor climate models is necessary.
(Gorczyca and Gebremedhin, 2020)	Respiration rate, skin temperature, vaginal temperature	Random forest, gradient boosted machine, artificial neural networks	Artificial neural networks	Nonlinear machine learning algorithms consistently most accurate in predicting physiological response.
(Pacheco et al., 2020)	Rectal temperature, respiration rate	Artificial neural networks	Artificial neural networks	Utilised linear regression to enhance parameter choices prior to model development.
(Becker et al., 2021)	Heat stress severity	Logistic regression, Gaussian naïve Bayes, random forest	Random forest*, logistic regression**	Benefit seen in using a combination of precision technologies.
(Bovo et al., 2021)	Milk yield trends as they relate to environmental conditions	Random forest	Random forest	Random forest models can represent a reliable, viable tool for production evaluation.
(Shu et al., 2023)	Respiration rate, vaginal temperature, eye temperature	Random forests, gradient boosting machines, artificial neural networks, regularised linear regression	Artificial neural networks	Addition of predictors other than meteorological parameters into training might increase predictive power.
(Chapman et al., 2023)	Heat stress	Long-Short Term Memory networks	Long-Short Term Memory networks	Deep learning model found more accurate than traditional statistical methods and climate indices.

(Brezov et al., 2023)	Rectal temperature	WeightedEnsemble_L2, NeuralNetTorch, XGBoost, CatBoost	WeightedEnsemble_L2	Demonstrates advantages of multimodal machine learning.
(Inadagbo et al., 2024)	Behavioural phenotypes relevant to thermotolerance	YoloV8, convolutional neural network, DeepSORT	Convolutional neural network***	Required development of a user-friendly interface to aid in interpretability for producers.
(Li et al., 2024)	Core body temperature	Elastic net, artificial neural networks, random forests, extreme gradient boosting, light gradient boosting machine, CatBoost	Grey wolf optimisation-optimised extreme gradient boosting	Utilisation of optimisation algorithms contributed to improved model performance.
(Woodward et al., 2024)	Heat stress events	Random forest, cubist, gradient boosted machine, support vector machine with radial basis, k-nearest neighbors	Cubist	Linear heat indices are not sufficiently discriminating for the purpose of heat stress prediction.

*Prediction of sprinkler group with respect to accuracy and precision.

**Prediction of heat-stressed cows in control, shade, and combined.

***Highest accuracy, models built upon each other.

While these studies have demonstrated the power of machine learning in prediction and monitoring of HS for dairy cattle, further optimisation of these methods is still necessary. As highlighted by Morota et al. (2018), utilisation of machine learning techniques requires ongoing efforts to prevent overfitting (regularisation), alongside integration of diverse datasets to expand training samples. Issues of bias, fairness, and explainable artificial intelligence are often highlighted when considering machine learning shortcomings (Barbierato and Gatti, 2024; Tufail et al., 2023); therefore, continuous discussion and transparency are key. The potential benefits of using a hybrid model to mitigate these limitations is gaining traction.

Towards a hybrid approach

Researchers are now integrating various analytical methodologies to overcome individual limitations, creating a 'hybrid vigour' in the realm of statistics. The hybrid approach integrates techniques from different domains to enable performance improvement over a single method. Classification of hybrid approaches varies across literature, with some categorising the technique as a combination of parametric (knowledge based) and non-parametric (data-derived) models (Schweidtmann et al., 2024) while others classify three principal structures of hybrid modelling, namely statistical-dynamical, serial, and coupled/parallel (Slater et al., 2023).

Regardless of the combined approach, hybrid modelling is continuing to show potential across literature. Modelling complex, high-dimensional, or computationally expensive systems benefits from the integration of more fundamental methods to manage dimensionality, balance performance and effort, and enhance computational efficiency (Schweidtmann et al., 2024). Adoption of hybrid forecasting approaches have shown improvements in accuracy, prediction, and resilience (Agarwal et al., 2025; Mathonsi and van Zyl, 2021). Greater dependability of predictions has been identified (Küçüktopcu et al., 2023), with nonlinear combinations shown to improve accuracy in some contexts (de Mattos Neto et al., 2022). While used successfully for weather forecasting (Das et al., 2024; Slater et al., 2023), the classification of growth for crops under drought and HS conditions (Xing et al., 2023; Zhang et al., 2022), and for optimised selection of crop genotype by environment selection (Khalilzadeh et al., 2024), to our knowledge there remains a paucity of hybrid model use for HS predictions of livestock. However, using transferable insights from successful application in other areas suggests promising potential. As reviewed by Ellis et al. (2020), the current niche occupied by data driven approaches in animal production are classification or clustering, prediction, and dimensionality reduction problems. Hybridisation, particularly used within the realm of precision agriculture, offers substantial opportunity to expand the value of collected data.

The value of big data relies on accessibility and accuracy. Difficulties remain balancing privacy and anonymity of data sources with the need for locally generated, on-farm information to enable informed decision making (Neethirajan and Kemp, 2021; Wolfert et al., 2017). Incorporation of cloud services offers new opportunities for holistic decision making, benchmarking, and scalability, yet issues of intellectual property, data ownership and interoperability challenges must first be addressed (Bhaskaran et al., 2024; Wolfert et al., 2017). Regardless, future integration of hybrid methodologies in-line with increasing industry automation is promising and should be explored in future research.

CONCLUSION

Increasing global temperatures have highlighted HS as a critical issue worldwide. Quantification of cattle HS has primarily been based on thermal indices at a herd level, rather than accounting for individual animal impact. As such, effective monitoring methods that capture the diverse behavioural and physiological responses to HS enacted by individuals are critical. Numerous strategies for both individual monitoring and subsequent amelioration methods are available, each with their contextual benefits and limitations. Further research should prioritise the exploration of more novel sensor technologies that are robust to outside climatic conditions (i.e. reticulorumen boluses), to best understand their effectiveness as proxy indicators of CBT. As precision livestock farming tools continue to evolve, it is essential to explore optimal methods to best utilise these tools for on-farm management, requiring in particular, sophisticated data analysis approaches to enhance timely decision-making. Progression of knowledge in this field will enable advancement of the selection of heat tolerant individuals.

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CHAPTER 3

Review: Ruminant heat-stress terminology

Despite the growing global requirement for heat stress research, there remains a paucity of consistent definitions for common heat abatement terminology, highlighting the requirement for a dedicated terminology evaluation. As such, Chapter 3 presents a critical review of key terminologies across literature, encompassing both their historical and contemporary use. This review seeks to establish clear and precise definitions for terms relevant to ruminant heat stress.

Animal (2024) 18, 101267

PUBLISHED MANUSCRIPT

The published version of this manuscript is included on the following pages.

Animal 18 (2024) 101267

Contents lists available at ScienceDirect

Animal
The international journal of animal biosciences

Review: Ruminant heat-stress terminology

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ARTICLE INFO

Article history:
Received 21 March 2024
Revised 11 July 2024
Accepted 12 July 2024
Available online 18 July 2024

Keywords:
Resilience
Resistance
Ruminants
Susceptibility
Tolerance

ABSTRACT

With increasing climate variability, there is a rise in the exposure to, and incidence of, ruminant heat stress (**HS**), increasing the requirement for focused research. As such, precise terminology is crucial to maintain effective communication and knowledge advancement. Despite this, several key terms are currently defined inconsistently, leading to confusion and misinterpretation. This paper examines the historical and contemporary use of the terms 'resistance', 'tolerance', 'resilience', and 'susceptibility' across various disciplines, revealing significant ambiguities that hinder both research and practice. Through this comprehensive review, we propose new definitions for each term as they are used relating to HS, with a focus on ruminant production. Proposed definitions align with current scientific understanding, providing a robust framework for future research and application. As further research is conducted, we hope these definitions can be improved through the inclusion of quantitative measures which align with these classifications. This present review provides definition clarity for common heat abatement terminology, enabling consistency and from this, progress in the field to ameliorate HS for ruminants.

Implications

The exposure of livestock to climate variability and the associated risks of heat stress is increasing, warranting the development of heat abatement techniques. Whilst various mitigation strategies have been identified, poor clarity and consistency across heat tolerance terminology remain. This review provides definition clarity for common heat abatement terminology, enabling consistency and from this, progress in the field to ameliorate heat stress.

Introduction

Ruminant production in Australia occurs in a wide range of environments, with most livestock exposed to climate variability and the associated risk of heat stress (**HS**) (Cowley et al., 2015; Cheruiyot et al., 2019). Alongside these climate changes has been production intensification, compounding the impact of HS worldwide (Renaudeau et al., 2012; Polsky and von Keyserlingk, 2017; Islam et al., 2021). High-producing animals are particularly vulnerable to HS due to their greater metabolic rates and energy requirements as compared to lower−producing contemporaries (Ravagnolo and Misztal, 2000; Collier et al., 2019). With global projections requiring milk production to double in the next five decades (Britt et al., 2018) and the World Health Organization recognising a notable rise in the demand for animal-derived protein in all regions (Henchion et al., 2021), investigation of heat abatement techniques is vital to minimise and ameliorate heat stress and with this, maintain or enhance animal welfare standards and production outputs.

To ameliorate HS in ruminants, there are three management strategies: genetic development of resistant breeds, nutritional management, and physical modification of the environment (Beede and Collier, 1986; Johnson, 2018). Irrespective of strategy, the identification of an individual animal's ability to cope under HS conditions is essential for effective implementation. Despite this, there is poor clarity across heat tolerance terminology, leading to ambiguity. Ambiguity with regard to HS terminology is problematic due to resulting confusion and miscommunication among researchers, disciplines, and industries. For instance, the terms 'resistance', 'tolerance', 'resilience', and 'susceptibility' are used interchangeably despite their distinct meanings.

Resistance is typically viewed as an innate ability that enables an organism to defend itself from disease agents (Best et al., 2008; Schneider and Ayres, 2008), though variability in the classification of this term remains. Tolerance is primarily associated with a degree of endurance, defined by the slope of a reaction norm (West-Eberhard, 2008), but has other interpretations. Definitions of resilience primarily account for an encapsulation of change and ability to recover at speed (Gunderson and Holling, 2002;

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https://doi.org/10.1016/j.animal.2024.101267
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Colditz and Hine, 2016), though are often presented with a dual interpretation. Various concepts of susceptibility are presented including the ability of an individual to resist harm, the probability of a reaction due to exposure, or variation in levels of vulnerability within a population (Parkin and Balbus, 2000). To ensure that research efforts align with targeted industry expectations and desired outcomes, it is crucial to establish clear definitions for these terms. Here, we provide definition clarity for common heat abatement terminology through an analysis of current dictionary definitions, portraying the terms' current societal use, alongside an interdisciplinary analysis of peer-reviewed literature.

Resistance

For the term resistance, we first explore existing definitions. Oxford Languages (n.d-a.) defines resistance as 'the refusal to accept or comply with something'. This is a concise, straightforward definition, suggesting that the 'something' attempting to alter, will fail in this effort. This contrasts with the longer, more elaborate definition from Merriam-Webster (n.d-a.) being 'the power or capacity to resist: such as (a) the inherent ability of an organism to resist harmful influences (b) the capacity of a species or strain of microorganism to survive exposure to a toxic agent formerly effective against it'. This classification details the 'power or capacity' of resistance, providing examples specific to toxic organisms/agents and suggests resistance does not require a lack of impact, rather survival is the defining feature. This is similarly described by Collins English Dictionary (n.d-a.) as 'the capacity to withstand something, especially the body's natural capacity to withstand disease', implying survival is more important than a lack of change to the focal entity. The definition by Cambridge Dictionary (n.d-a.) highlights the active nature of resistance in its fight, identified as the 'act of fighting against something that is attacking you, or refusing to accept something; a force that acts to stop the progress of something or make it slower'. This is reinforced by Encyclopaedia Britannica (n.d-a.) as the 'refusal to accept something new or different; the ability to prevent something from having an effect'. Again, it is implied that no changes can occur otherwise the external force would '[have] an effect', deeming the entity non-resistant. These definitions all encompass the idea of an external force acting upon an entity and the capacity of that entity to withstand such force. Whilst an overall concept of 'refusal' is maintained across each definition, the surrounding descriptive language varies. This lack of definitive clarity is maintained as we explore resistance across agricultural industries.

Resistance related to disease is said to be well characterised in both animal and plant breeding, with several reviews conducted comparing disease resistance and tolerance (Baucom and de Roode, 2011; Detilleux, 2011). Resistance by plant and animal hosts is the active reduction of parasite and pathogen burden through direct inhibition of infection and reduction of pathogen growth rate (Best et al., 2008; Doeschl-Wilson et al., 2012). As such, genes related to resistance display negative feedback on their own fitness. This is supported by Detilleux (2011), stating resistance is the hosts' ability to reduce infection success or increase pathogen clearance rate. In this interpretation, it can be assumed that changes to the host are allowed to be displayed whilst the host is still deemed resistant overall. This concept is also seen in pesticide resistance, where resistance is 'a genetically based, statistically significant increase in the ability of a population to tolerate one or more pesticides' (Tabashnik and Johnson, 1999). Identified as a defence trait, Baucom and de Roode (2011) state that resistance can both reduce and alleviate a decline in fitness owing to parasite infection, without an impact on the parasite itself. These definitions each imply that the impacted entity can have a decline in fitness without being deemed non-resistant, opposing previously presented definitions by Cambridge Dictionary (n.d-a.) and Encyclopaedia Britannica (n.d-a.). Rupp and Boichard (2003) acknowledge that resistance can be defined for individual traits, suggesting clarification may be required at each use.

Resistance is presented as an inclusive disjunction by Cloete (2003) as the 'temporary or permanent ability of an organism and its progeny to remain viable and/or multiply under conditions that would destroy or inhibit other members of the strain'. Extending this definition to apply to ruminants, it is unreasonable to define an animal as resistant solely based on reproductive ability, irrespective of other effects. The nature of resistance as an absolute term is expressed by Cerf et al. (2010) as an entity that either possesses resistance or does not. Different viewpoints can influence interpretation, such as resistance to treatment in clinical settings compared to the use of wild-type or non-wild type (i.e., resistant) as used in epidemiology (Cerf et al., 2010). Therefore, caution is required when interpreting terms across sectors without the provision of a sector–specific definition. Considering Encyclopaedia Britannica (n.d-a.) and Cerf et al. (2010), for an animal to be classified as resistant to heat, there must be no or at most negligible change in its behaviour and/or physiology associated with the climate in which it is located. Therefore, resistance related to climate can be defined as the innate ability to maintain state despite varying environmental conditions (Fig. 1).

Tolerance

Tolerance, as per resistance, has varying interpretations. Oxford Languages (n.d-b.) defines tolerance as 'the capacity to endure continued subjection to something such as a drug or environmental conditions without adverse reaction'. This emphasises the ability to endure continued subjection without an adverse reaction but does not specify the nature of the subjection (positive or negative). Providing greater detail, Merriam-Webster (n.d-b.) accounts for a waning response with maintained exposure, defining tolerance as 'the capacity of the body to endure or become less responsive to a substance or a physiological insult especially with repeated use

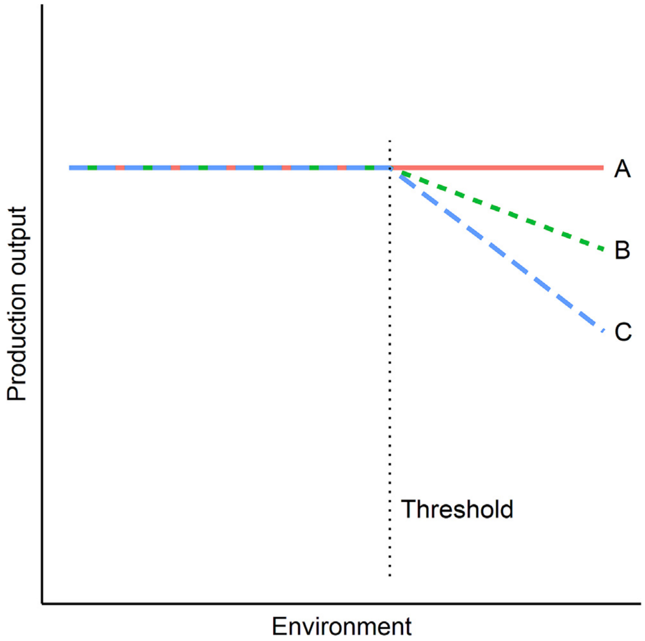

Fig. 1. Illustration of resistance (A), greater degree of tolerance (B), and lower degree of tolerance (C) for ruminants under environmental heat load.

or exposure; relative capacity of an organism to grow or thrive when subjected to an unfavourable environmental factor'. As such, the entity can develop coping strategies to maintain fitness during unfavourable conditions. Emphasising the length of endurance, Cambridge Dictionary (n.d-b.) describes 'the ability to deal with something unpleasant or annoying, or to continue existing despite bad or difficult conditions; an animal's or plant's ability not to be harmed by a drug or poison over a long period of time'. Unlike prior definitions, this suggests the negative nature of the influencing entity as a 'drug or poison', as per the Collins English Dictionary (n.d-b.) definition being the 'capacity to endure something, especially pain or hardship'. Defined to be 'the ability to accept, experience, or survive something harmful or unpleasant', Encyclopaedia Britannica (n.d-b.) includes a psychological dimension in the concept of acceptance whilst maintaining the negative connotation. These definitions all maintain a focus on the capacity or ability to endure something, typically adverse conditions or substances. Contextually this endurance is maintained over time, with either repeated exposure or continued subjection. This lack of clarity is maintained throughout other industries.

Reinforcing the need for a re-assessment of heat abatement terminology, Ferrar (1976) critiques the way in which tolerance is discussed in sociology, suggesting it is often oversimplified and lacks clarity, despite its consistent application across studies. This problem is maintained across other fields – the struggle to find a common definition of tolerance in psychological literature has been identified by Williams and Jackson (2015) and earlier by Witenberg (2007). Whilst a plethora of research into tolerance in plants has been conducted over the past few decades (Baucom and de Roode, 2011), a strict definition of tolerance is also absent. Defined by some as the ability of a plant to grow and produce optimal financial return under exposure to high temperature (Hasanuzzaman et al., 2013), the definition of heat tolerance has been adapted by others to be a deviation from an expected reaction during stressful conditions, as compared to non-stressed circumstances (Lemerle et al., 2006; Dolferus et al., 2019). Though unable to agree on the definition itself, many authors provide a distinguishable feature when referring to tolerance as opposed to other terms. Guy et al. (2012) argues tolerance primarily differs from resistance in the lack of host-pathogen interaction that occurs. A consideration of genotype-by-environment interaction is noted to be of importance (Freitas et al., 2021), with various literature confirming a genetic component in heat−tolerant species, confirming it is a heritable trait (Carabaño et al., 2017; Misztal, 2017; Zhang et al., 2019). Importantly, genetic variability for livestock heat tolerance has been identified (Ravagnolo and Misztal, 2000), reinforcing the individual nature of this trait. Freitas et al. (2021) has also suggested the potential benefits of a selection sub-index to allow accurate breeding choices due to the low to moderate genetic correlations between various heat tolerance traits. As such, a developed method of genetic selection for heat tolerance must account for and quantify the varying levels of heat tolerance that are displayed by individuals.

As plants are sessile, they must cope with various forms of stress at the same time and have evolved intricate molecular networks to enable rapid cellular metabolism adaptation when required (Bokszczanin et al., 2013; Haider et al., 2021). Whilst Larcher (2003) classified plant species into three groups dependent on heat tolerance abilities, namely heat sensitive, relatively heat resistant, or heat tolerant, others such as Haider et al. (2021) noted the three documented responses for plants under HS as basal thermotolerance, acquired thermotolerance, and programmed cell death. Applying such terminology between species, Papanastasiou et al. (2016) studied HS levels in sheep and classified four HS categories (absence, moderate, severe, extreme severe) on the basis of temperature humidity index. The intricate nature of individual animal responses to HS poses a significant challenge, and the absence of a precise definition in each study, particularly across species, amplifies the lack of clarity seen industry wide.

Tolerance in terms of an environmental factor is defined by Simms (2000) as 'the ability to maintain fitness in the face of stress imposed by that factor'. Emphasised here is that measurement of fitness must be undertaken across environmental extremes – from a benign environment to one with higher influential potential (Simms, 2000). Many definitions of heat tolerance have been proposed for use in animals (Carabaño et al., 2019; Collier et al., 2019), with the resultant consensus that heat tolerance is the ability to endure environmental heat and regulate body temperature at an optimal rate in suboptimal conditions. In principle, a heat−tolerant animal may still exhibit behavioural and physiological changes to cope with increasing temperatures, but they retain a core body temperature within the thermoneutral zone i.e., maintain homeothermy (Carabaño et al., 2019). However, to think of an animal as either tolerant or not is a false dichotomy that needs instead to be viewed as a continuity. Whilst the epitome of tolerance is to maintain thermal stability with a rising environmental temperature (i.e., be resistant), it is in fact the slope of the reaction norm (West-Eberhard, 2008) that defines an organism's degree of tolerance. As such, if an animal is unable to maintain thermal stability through behavioural and physiological means, thereby breaching the upper limit of core body temperature homeostasis, we would suggest that it is still considered tolerant but to a much lesser degree (Fig. 1).

Resilience

Again, there are varied resilience definitions. Oxford Languages (n.d-c.) defines resilience as 'the capacity to withstand or to recover quickly from difficulties; toughness', providing a dichotomous definition. Merriam-Webster (n.d-c.) highlights adaptability in the recovery and/or adjustment, defining resilience as 'an ability to recover from or adjust easily to misfortune or change'. Cambridge Dictionary (n.d-c.), however, places more emphasis on efficiency, classifying resilience to be 'the quality of being able to return quickly to a previous good condition after problems'. Presenting an ecological view, Collins English Dictionary (n.d-c.) defines resilience as 'the ability of an ecosystem to return to its original state after being disturbed' but does not stipulate if that prior state was good or bad to begin with – what Cambridge Dictionary (n.d-c.) states to be previously 'good'. 'The ability to become strong, healthy, or successful again after something bad happens' is provided as a more holistic view of recovery by Encyclopaedia Britannica (n.d-c.), however this use of the term 'or' can contribute to confusion if only one or two of these factors has been achieved. Each of these definitions implies a negative interaction occurring with an entity that must be overcome. However, only three out of the five definitions acknowledge speed of return; the recovery must be either 'quick' (Oxford Languages, n.d-c.; Cambridge Dictionary, n.d-c.) or 'easy' (Merriam-Webster, n.d-c.), though no timeframe for recovery is provided.

Resilience is often used to describe mental health. Southwick et al. (2014) stresses that context is critical to avoid misunderstanding when referencing resilience as it can be viewed in various manners. By one definition, resilience is characterised as a stable trajectory of health functioning that is maintained after undergoing an adverse event (Bonanno, 2004; Bonanno et al., 2011). Supporting this, Masten (2014, 2015) refers to resilience as the capacity of adaptation to disturbance that would otherwise threaten the viability of a system functioning. These definitions are challenged by Yehuda and Flory (2007) and Yehuda et al. (2010), who propose that resilience should instead be characterised by undergoing adversity with adept recovery, emphasising the concept of moving forward postadversity, without regression.

Similar concepts are explored within the plant sector – an early definition of resilience by Westman (1978) portrays the necessity of restoration after disturbance, in terms of reinstating original structure and function. This is further broken down into two types of resilience by Grubb and Hopkins (1986). '*In situ*' is where all plant species retain a presence of reasonable size in a particular location, though their levels of abundance and representation may change as a result of disturbance and the following recovery. In comparison, '*by migration*' is where all plant species may be killed in a community, with resilience reliant on re-establishment through dispersal. Whilst the ecological space defines resilience as the absorption of disturbance such that change is resisted (Holling, 1996), an engineering review explores resilience as the recovery process after a disturbance (Pimm, 1984). Whilst Capdevila et al. (2021) suggests these contrasting views of resilience highlight the requirement for a unified understanding of the terms across systems, we instead reinforce the requirement for a strict definition of terminology prior to use, to ensure relevance within one's discipline and avoidance of misunderstandings.

For some in the agricultural sector, resilience encapsulates change, uncertainty, and the requirement for adaptation (Gunderson and Holling, 2002) whilst others use the term to describe the ability of a system to minimise the impacts of a disturbance, i.e., maintaining production under novel conditions (Walker et al., 2002; Walker et al., 2004; Folke, 2006; Biggs et al., 2012). Such classification aligns with resilience in animal health, deemed the maintenance of production, regardless of the level of pathogenic infection (Albers et al., 1987). Often reinforced is that to mitigate the impacts of HS, selection of resilient (or robust) animals is required to maintain performance across changing environmental conditions (Lourenco, 2018). Given the tight link between resilience and changing conditions, its use is prevalent when referencing HS in ruminants. As such, an unambiguous definition of the term is required to ensure consistency and provide clarity in both literature and research.

Resilience is defined for livestock within the heat abatement field as the capacity of an animal to be minimally affected by a disturbance, or to rapidly return to its status before exposure to disturbance (Colditz and Hine, 2016). However, a resilient animal should be primarily defined by its ability to recover from a stressor after the challenge has subsided, more so than how it copes during the actual event (Fig. 2). As such, an animal with low tolerance may still be deemed resilient, as although it may be affected by heat in a production sense, its capacity to return to a prechallenge state may be rapid. In contrast, a highly tolerant animal may not be resilient due to the speed at which it returns to a prechallenge baseline, although, the requirement for resilience in this sense is minimised as production outputs will be negligibly impacted regardless of the rapidity of return. Thus, resilience can be best defined as the capacity of an animal to rapidly return to its status prior to exposure to disturbance.

Susceptibility

Oxford Languages (n.d-d.) defines susceptible as being 'likely or liable to be influenced or harmed by a particular thing', suggesting a level of predisposition in the emphasis of likelihood or liability of harm. Defined by Merriam-Webster (n.d-d.) as being 'capable of submitting to an action, process, or operation', there is a focus on the act of submission as opposed to vulnerability implied by Cambridge Dictionary (n.d-d.), classifying susceptible as being 'easily influenced or harmed by something'. Collins English Dictionary (n.d-d.) furthers this concept of readily yielding, with an indication of willingness or ease of influence in its definition as 'yielding readily (to); capable of'. Encyclopaedia Britannica (n.d-d.), as does Merriam-Webster (n.d-d.), implies a level of voluntary risk by the entity being 'capable' of either submitting or being affected, in its definition as 'capable of being affected by a specified action or process'. Each definition describes the capacity of a particular entity to be influenced, harmed, or affected without a great degree of difficulty, implied through the use of terms such as 'easily', 'yielding readily', and 'capable'.

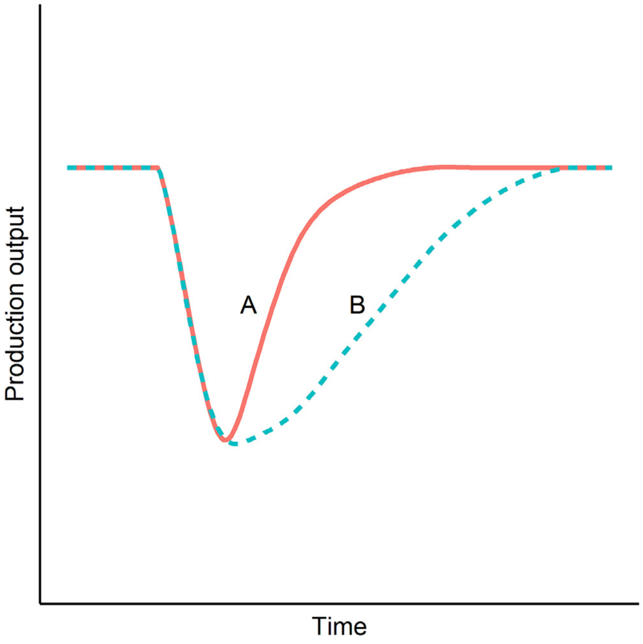

Fig. 2. Illustration of a greater degree of resilience (A) contrasted with a lower degree of resilience (B) for ruminants under environmental heat load.

The need to differentiate between ease and likelihood of influence is critical when using the term susceptible across disciplines (Laursen and Faur, 2022). Whilst ease of influence suggests minimal effort is required by the influencer, likelihood of influence suggests a heightened prospect that an influencer, regardless of effort, will have an impact on the influencee. As such, an article exploring peer conformity defines susceptibility as 'conformation in response to the behaviour of peers' whereby if one is not influenced by their peers, they are deemed resistant (Laursen and Faur, 2022). Considering the 'influencer-influencee' relationship in a similar manner is an ecological dictionary that instead describes this affiliation as the 'host-agent' relationship. This definition states susceptibility to be 'the degree to which an organism is prone to infection by a particular disease or is sensitive to a particular drug or poison' (Art, 1993). Both definitions account for a response by the host (or influencee) to an external factor; however, the extent of this response in a measurable form is not discussed by either.

According to the Centers for Disease Control and Prevention (2022), something susceptible is 'a living being that [is] at risk of contracting a disease'. This concept of risk implies a negative connotation that is intermittently used interchangeably with vulnerability. An example of this in conservation literature states implications of vulnerability and susceptibility are equal and the use of such terminology in this context is simply preference (Royce et al., 2023). Contrastingly, 'susceptibility' and 'vulnerability' are used distinctly for the identification of populations at varying levels of risk for air-pollutant-related health implications (Kleeberger and Ohtsuka, 2005; Sacks et al., 2011). The distinction here, is that biological or intrinsic factors relate to susceptibility, whilst vulnerability is characterised by non−biological or extrinsic factors.

Disagreement is also evident in natural hazard terminology. Some acknowledge susceptibility in relation to the ‘tendency of an area to undergo the effects of a certain hazardous process’, discounting the impact of exact timing or resultant effects (victims, economic losses) (Domínguez-Cuesta, 2013) whilst others use the term as an identification of likely locations for landslide damage to occur (Guzzetti, 2006; Reichenbach et al., 2018). This is similarly seen by some authors defining wildlife susceptibility to be the likelihood of fire occurring in a particular location, based on predisposing terrain characteristics (Leuenberger et al., 2018), others consider factors beyond intrinsic terrain features, accounting for the geographic likelihood of harm (Cao et al., 2017). Several approaches to the assessment of wildlife susceptibility are also available (Di Gregorio et al., 2013; Chhetri and Kayastha, 2015; Jaafari et al., 2019), further reinforcing the lack of consistency in nomenclature. Accounting for exposure level, Murray (1986) states that with an exposure of great enough quantity, everyone is susceptible and may be dubbed ‘hypersusceptible’ dependent on their reaction norm. However, there is minimal agreement as to the suitable distinction between such categories, with terms such as hyper-susceptible, high risk, sensitive, and hyper-sensitive often used interchangeably (Reisher, 1995). Clarity as to both the definition of susceptibility itself, as well as the potential categories of susceptibility, are therefore critical.

Poor clarity for susceptibility also exists in the ruminant heat abatement space. Whilst many suggest heat susceptibility refers to the reduced ability of an animal to cope with increasing temperature, we suggest susceptibility to climate is a risk rather than a result. Susceptibility is a dynamic state, with an individual’s level of susceptibility variable throughout time (Parkin and Balbus, 2000). Various biological determinants have been found to influence heat tolerance capabilities both between and within breeds including relative body surface area (Berman, 2003), sweating rate, coat characteristics (Hansen, 1990; Dikmen et al., 2008; Bernabucci et al., 2010), and expression of heat shock proteins (Chughtai et al., 2001; Mayer and Bukau, 2005). Susceptibility can thus be defined as the sum total of genetic and/or phenotypic characteristics that an individual may or may not possess. Importantly, one may be deemed susceptible to heat, based on the combination of aforementioned traits they possess, but could still maintain a great degree of tolerance in the right environment, as tolerance does not equate to a lack of susceptibility.

Discussion

The diversity of definitions across the literature has led us to propose the use of the following definitions for common heat abatement terminology:

Resistance: innate ability of an animal to maintain its physiological state despite changing thermal environmental conditions.
Tolerance: the degree to which an animal can retain thermal stability with changing thermal environmental conditions.
Resilience: the capacity of an animal to rapidly return to its prior status after exposure to an altered thermal environment.
Susceptibility: sum of genetic and/or phenotypic heat tolerance attributes possessed by an individual animal; risk factor.

The following three scenarios provide examples of ruminants in various situations or production systems that these livestock are managed within, that encompass the above definitions.

1. In a mixed herd of beef cattle, an F_1 hybrid such as a Brangus (cross between a Brahman and Angus) will likely exhibit more tolerance to heat stress than a purebred animal. Hybrid animals are known for the production improvements that arise from heterosis (Beatty et al., 2006; Dikmen et al., 2018; Davila et al., 2019). With the heat tolerance of *Bos indicus* combined with the productivity of *Bos taurus*, an F_1 hybrid would be expected to maintain good health and performance in a hot climate.
2. Merino sheep, known for their high-quality wool, are more susceptible to heat stress as compared to other breeds, such as the Namaqua Afrikaner (Hopkins et al., 1980; Molotsi et al., 2019). If both breeds were moved from a temperate climate to a tropical environment, one would expect the Merino would exhibit poorer tolerance to the high heat conditions, exhibited as reduced growth performance and feed intake (Zhang et al., 2021).
3. Holstein Friesian dairy cattle, known for their high milk production, are particularly susceptible to heat stress. Holstein cows experience greater heat stress than Jerseys, resulting from a difference in metabolic heat production according to their relative milk production capacity (Lim et al., 2021). In a herd of Holstein dairy cattle that have experienced a period of high heat and had a reduction in milk production as a result, the most resilient individual will return to its pre-event level of milk production at the fastest rate.

This review presents highly complex traits that are governed by numerous biological and environmental mechanisms. Categorisation of ruminants on the basis of their response to heat stress conditions requires a comprehensive and situationally specific understanding. There is an ongoing desire to understand what makes an individual’s phenotypic response to heat stress unique, and the extent to which it is under genetic control. Typically, a phenotypic trait and its observable characteristics are not regulated by a single gene (Orgogozo et al., 2015) – more likely it is an output from the effect of multiple genes and how they interact with the environment, both internal and external. Phenotype plasticity, the ability of a genotype to express varied phenotypes dependent on the residing environment (Dellasala and Goldstein, 2018) alongside the degree of acclimation (Collier and Gebremedhin, 2015), must also be considered. Kültz et al. (2013) describe three principal factors that define an organism’s phenotype, namely genotype, environment, and life history (age, development, experiences, previous exposure). A thorough understanding of these influencing factors will enhance the accuracy and/or effectiveness of short-term heat mitigation strategies or long-term breeding decisions that may be employed, dictating improvements in animal health and welfare.

Whilst the impact of heat stress during and immediately proceeding a heat stress event has been widely studied, long-term impacts have not received the same attention. Directly proportional to the length and severity of a heat stress event, milk production may be permanently reduced for the remainder of an individual’s lactation (Ravagnolo and Misztal, 2000; Lees et al., 2019). Heat stress on a calf *in utero* retains long−lasting effects on that animal’s performance over time, impacting growth, performance and health (Cartwright et al., 2023). There is no certainty that an animal will retain its production capabilities following a period of high heat load, however, the exact degree and length of impact requires further research to accurately quantify, noting this will likely differ between individuals. Future research should continue to explore these long-term impacting factors to further refine our understanding and management of heat stress in diverse animal groups across various ruminant systems.

To ensure accurate and meaningful classification of animals at the individual level, especially within a reasonably homogeneous group, intensive measurement and/or well-founded knowledge of critical measurement timepoints is required. Initially developed for cropping and viticulture sectors (Bramley, 2009), there are high expectations for the integration of precision-livestock farming (**PLF**) in animal-based agriculture (Rose and Chilvers, 2018; Shepherd et al., 2018). Advances in PLF offer new opportunities for monitoring and ensuring animal welfare (Bewley, 2016; Maroto Molina et al., 2020) with continued development of on-animal and in-animal devices providing access to previously unseen information in a non-biased manner. Objective technology enables the identification of animals that require attention – such as those experiencing heat stress – at a rate much higher than possible with traditional human observation (Barkema et al., 2015). Data monitoring and management skills are now vital, with the continued expansion of technology use on farm (Hostiou et al., 2017). As such, our ability not only to procure these data, but also to exploit these records efficiently and effectively is a necessity.

Conclusion

Through an interdisciplinary review of heat abatement vocabulary, this work has confirmed a lack of consistency in the use and definition of various terms. We have defined key terms within the heat tolerance domain for use pertaining to ruminant management. The newly proposed heat tolerance definitions provided here align with current scientific understanding, providing clarity and consistency for future work and application. We hope that future research can explore the inclusion of quantitative measures for accurate categorisation of individuals, likely through the adoption of assistive technology. Through this comprehensive review, we hope to see further progress in the field to ameliorate HS for ruminants.

Ethics approval

Not applicable.

Data and model availability statement

Not applicable for this review. Information can be made available from the authors upon request.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

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Declaration of interest

None.

Acknowledgements

None.

Financial support statement

This research was supported by Dairy UP, a collaborative RD&E program for New South Wales, Australia (www.dairyup.com.au) through the provision of an academic scholarship to Alice Shirley.

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CHAPTER 4

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

Having established definitions for heat stress terminology in Chapter 3, evaluation of individual animal responses to changing environmental conditions using reticulorumen sensors is better enabled. However, due to the position of internal sensors in the reticulorumen, there is an ongoing influence of drinking events on temperature readings that must be accounted for. While commercial bolus systems have their own algorithms, transparency regarding their development is limited. Chapter 4 explores the development and use of a drinking event detection model to assess the temporal variability in drinking behaviour of pasture-based dairy cattle. By revealing variation in drinking behaviour, this chapter aims to provide an improved understanding of core body temperature diversity, better positioning us to investigate an individual's underlying physiological responses to climate, exclusive of the influence of water consumption.

Computers and Electronics in Agriculture (2025) 235, 110357

PUBLISHED MANUSCRIPT

The published version of this manuscript is included on the following pages.

Computers and Electronics in Agriculture 235 (2025) 110357

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

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

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

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ARTICLE INFO

Keywords:
Heat stress
Drinking behaviour
Sensors
Threshold algorithm
Precision agriculture

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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https://doi.org/10.1016/j.compag.2025.110357
Received 22 November 2024; Received in revised form 15 March 2025; Accepted 26 March 2025

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.

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

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

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

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

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

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

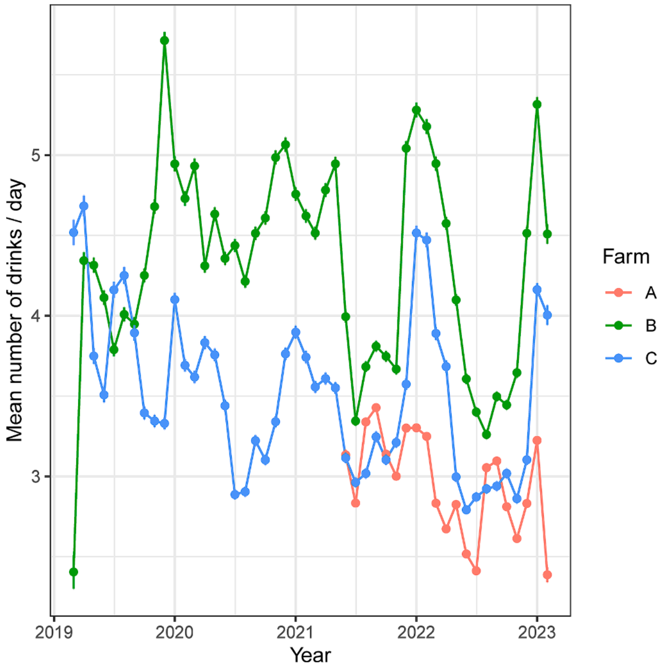

Fig. 2. Mean number of drinks per day over time for each of the three properties.

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.

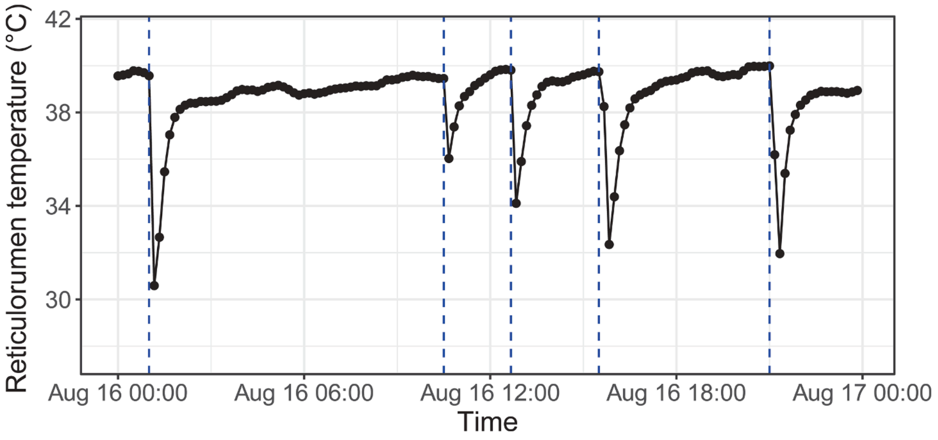

Fig. 1. Synchronisation of raw sensor data (black dots indicate 10-minute interval reticulorumen temperature readings) and manual video annotations (dashed blue lines indicate observed drinking events).

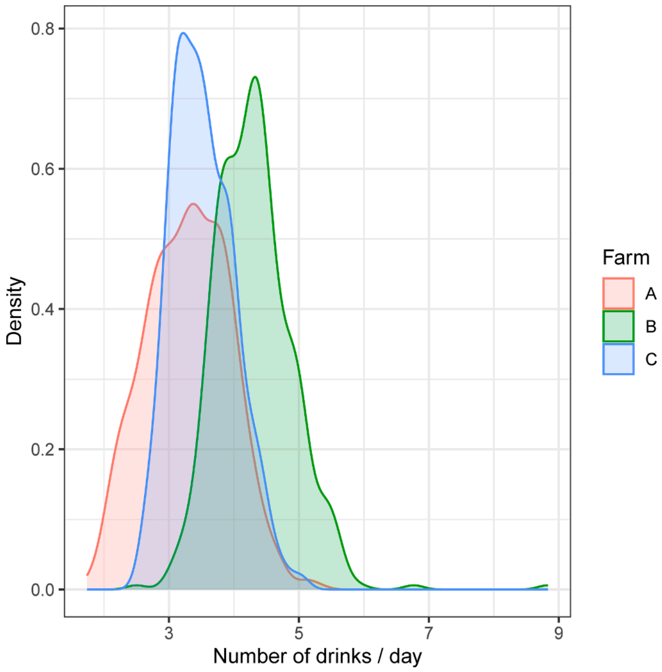

Fig. 3. Variability in number of drinking events for individual animals on each of the three properties.

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

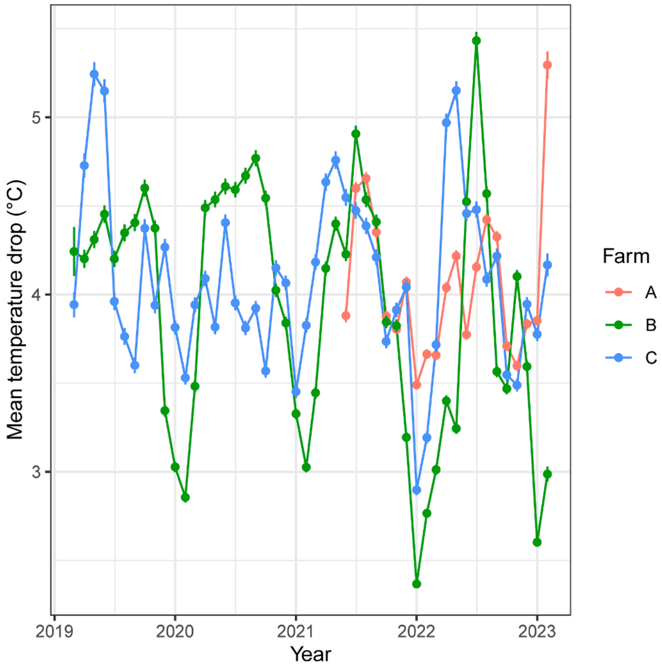

Fig. 4. Mean reticulorumen temperature (°C) drop over time for each of three properties.

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.

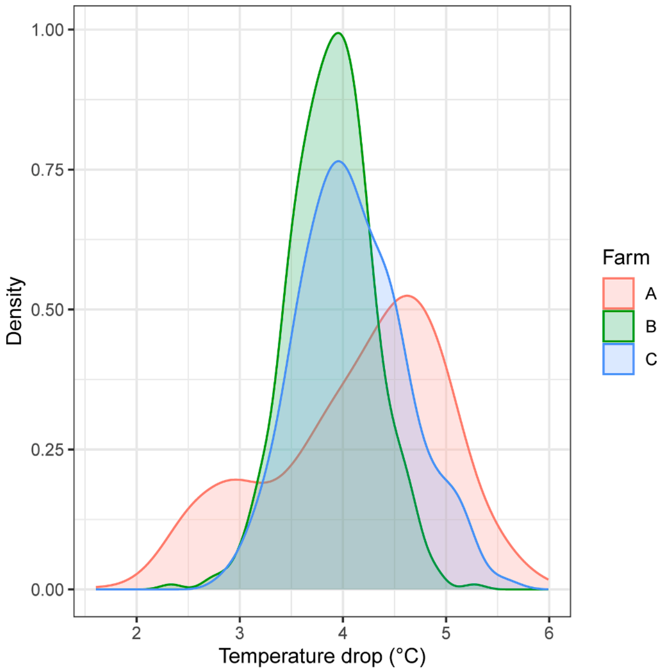

Fig. 5. Variability in reticulorumen temperature drop for individual animals on each of the three properties.

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-

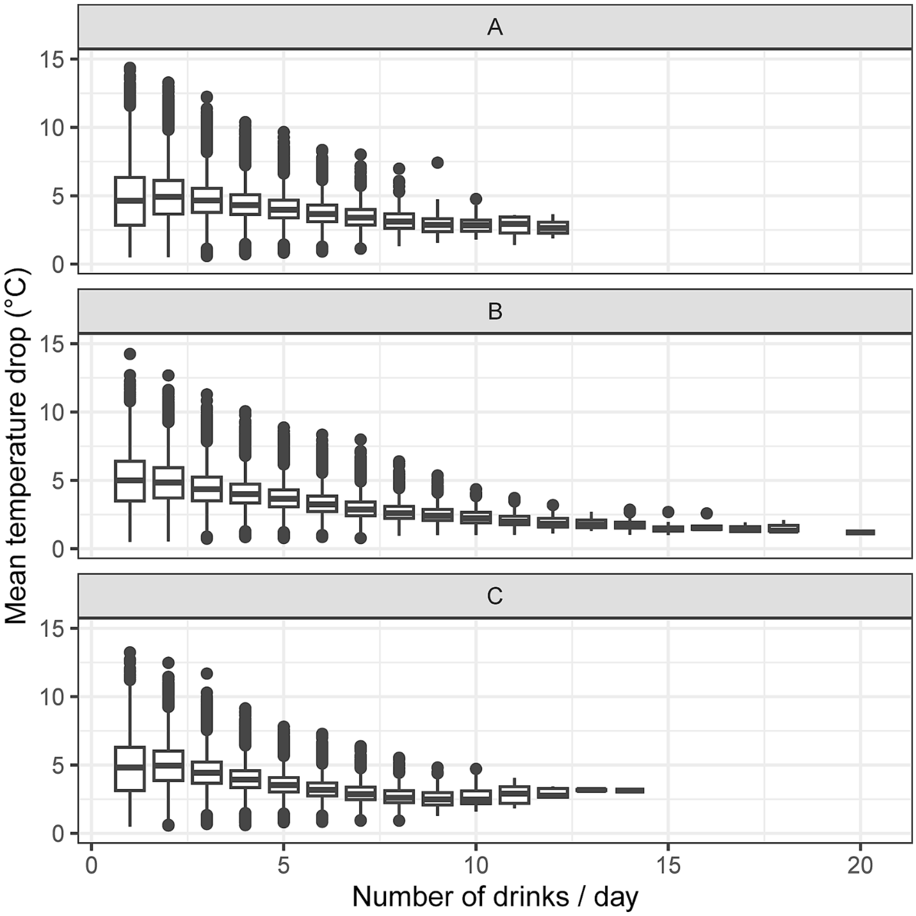

Fig. 6. Association between number of drinks per day and average drop in reticulorumen temperature (°C).

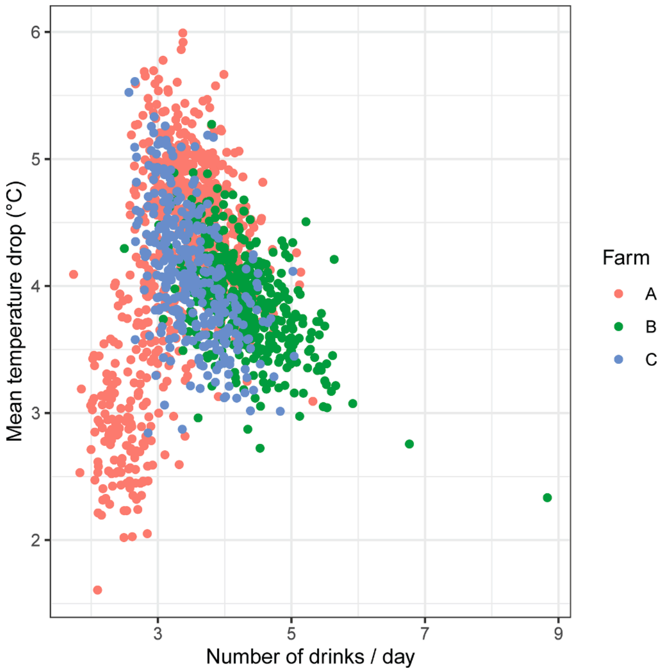

Fig. 7. Individual animal effect on the association between number of drinks per day and average drop in reticulorumen temperature (°C). Each point represents an individual animal average.

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

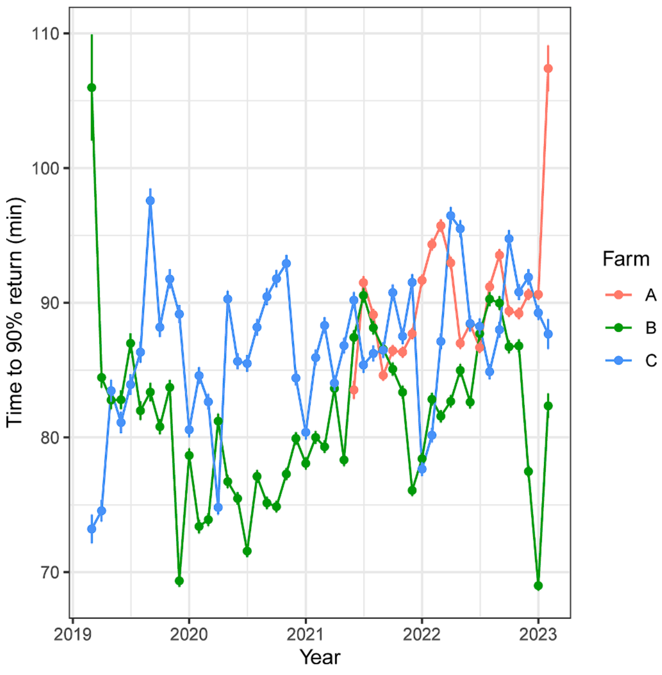

Fig. 8. Average drinking event duration based on time at 90% temperature recovery.

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

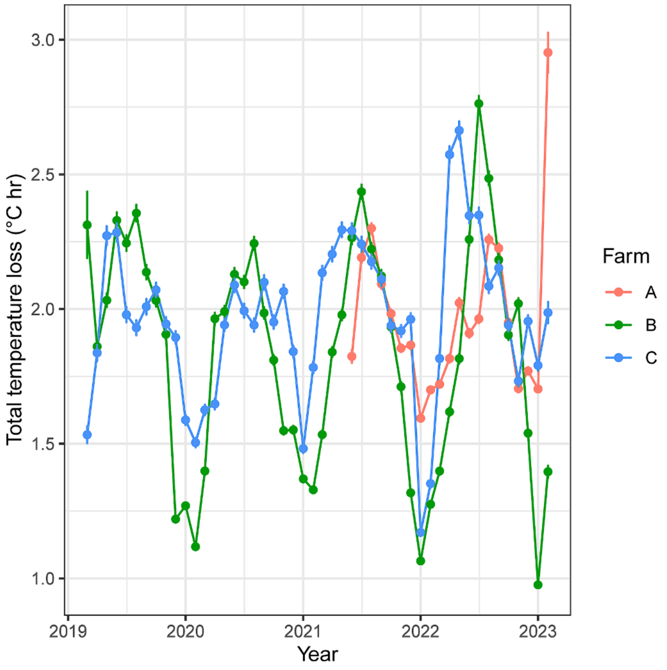

Fig. 9. Total temperature loss per event (°C hr) over drinking event duration.

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.

Acknowledgements

This research was supported by Dairy UP, a collaborative RD&E program for New South Wales (www.dairyup.com.au). The authors would also like to thank smaXtec, distributed in Australia by Lallemand Animal Nutrition, for the support received for the duration of this research.

Funding

This research was funded by Dairy UP, grant number BIP - SDG – 132, 2021- 2026.

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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CHAPTER 5

Probing the diversity in dairy cattle reticulorumen temperature for adaption selection

In the development of a novel drinking event detection model, Chapter 4 provided an opportunity to improve our understanding of individual animal response to climate factors. Here, Chapter 5 reveals the impact of reticulorumen temperature (exclusive of drinking events) in response to temperature-humidity index, using a time series and mixed model analysis. The link between variation in dairy cattle reticulorumen temperature and changes in climate factors is explored, retaining a focus on phenotype development for heat tolerance selection.

The following chapter is a manuscript under consideration with *Scientific Reports*. Journal-specific formatting is retained, with minor edits made for consistency.

ABSTRACT

There remains a paucity of literature investigating the direct link between variability in dairy cattle core body temperature response to thermal indices, despite advances in precision livestock monitoring through sensor technology. Here, we decomposed thermal indices and reticulorumen temperature data for 1,429 dairy cattle across three dairy farms in Victoria, Australia to investigate the variability in individual response to climate at different temperature humidity index (**THI**) thresholds. We revealed an overall positive association between THI and reticulorumen temperature deviation, with significant variability in sensitivity to thermal change among individuals. Increases in reticulorumen temperature are evident at a THI_{max} of 65, indicating a review of industry-established THI thresholds are required. Baseline THI levels are shown to be a major influencing factor for animal response. From these insights, our work is now focused on the development of a core body temperature derived phenotype for the selection of heat-tolerant animals.

INTRODUCTION

Heat stress (**HS**) poses a significant challenge for dairy cattle welfare and with increasing global temperatures the prevalence and severity of HS among dairy herds is expected to increase. Dairy cattle, particularly in pasture-based systems, face direct exposure to solar radiation (Tucker et al., 2008) and fluctuating environmental conditions (Woodward et al., 2024), making them vulnerable to climate factors. While environmental indices such as the temperature-humidity index (**THI**) are widely used to predict HS, they represent an external measure of heat load. More importantly, we must account for individual variability in response among animals. This inter-animal variability is increasingly recognised as a key influencing factor in the effectiveness of heat mitigation strategies (Islam et al., 2023; Nguyen et al., 2016).

Monitoring reticulorumen temperature offers a promising method to supervise internal heat load in dairy cattle, providing a direct, continuous measure of the body’s response to environmental stress (Shu et al., 2022; Sievers et al., 2004). By capturing real-time data on an individual level, reticulorumen temperature can reveal cattle response to HS under varying THI thresholds, providing insights into individual heat tolerance. Despite its potential, little is known about the extent to which THI correlates with reticulorumen temperature across individual animals. A THI threshold of 72 is commonly cited as a critical value, above which production decline will occur (Bohmanova et al., 2007; Hahn et al., 2009; Ravagnolo & Misztal, 2000; Smith et al., 2013), yet such generalities do not capture the nuanced response of individual cattle.

Understanding the relationship between THI and reticulorumen temperature is essential for improving HS management strategies. Identification of individual variability in response to heat might allow for more tailored interventions in the short-term, and dedicated breeding strategies in the long-term, ensuring that heat mitigation efforts are both effective and efficient. While there is extensive research on the general effects of HS on dairy cattle (Giannone et al., 2023; Polsky & von Keyserlingk, 2017), understanding the interplay of individual animal variability in reticulorumen temperature and THI deviation is less explored, particularly in pasture-based systems where cattle experience a high degree of environmental variation.

In this work, we have continuously recorded reticulorumen temperature data (smaXtec Animal Care GmbH) from 1,429 dairy cattle across three farms in Victoria, Australia. Drinking events were isolated and removed, with climatic data for the same period interpolated from surrounding weather stations to calculate THI. The association of reticulorumen temperature with simultaneously collected THI was explored with raw data and after removing diurnal patterns and long-term trends from the time series to investigate the variability in HS response at different THI thresholds. This work has the potential to contribute to the development of proactive and individualised strategies to enhance dairy cattle welfare and productivity in increasingly challenging conditions.

RESULTS

Overall positive association between THI and reticulorumen temperature deviation, with notable variability in individual sensitivity. Following de-trending of both THI_{max} (deviation; irrespective of baseline) and reticulorumen temperature time series, the association between THI_{max} and reticulorumen temperature deviations (˚C) was assessed (Fig.

1). An overall positive association was observed at both the farm and individual levels. Farm B depicted greater sensitivity as indicated by the overall steeper slope compared to Farms A and C, acknowledging its geographical location further north (southern hemisphere). At the individual level, the visualisation highlights significant variability in sensitivity to thermal change among individuals (Supplementary Table 2), with individual variability less pronounced for animals from Farms A and C. Cross-correlation analyses (Supplementary Fig. S1**)** confirm correlation is highest on Day 0, although significant positive associations were detected for the next two days following a change in THI_{max}. A Wald test indicated significant differences between farms ($p = 0.0057$), THI_{max} (deviation) ($p < 0.001$), as well as a farm by THI_{max} (deviation) interaction ($p < 0.0001$) (Supplementary Table 1). Differences in individual sensitivity to a change in reticulorumen temperature per unit change in THI were evident, as estimated by the random slopes in the mixed model (Fig. 2). All animals maintained an average reticulorumen temperature change below 0.035 ˚C/THI unit, ranging from below 0 to 0.030.

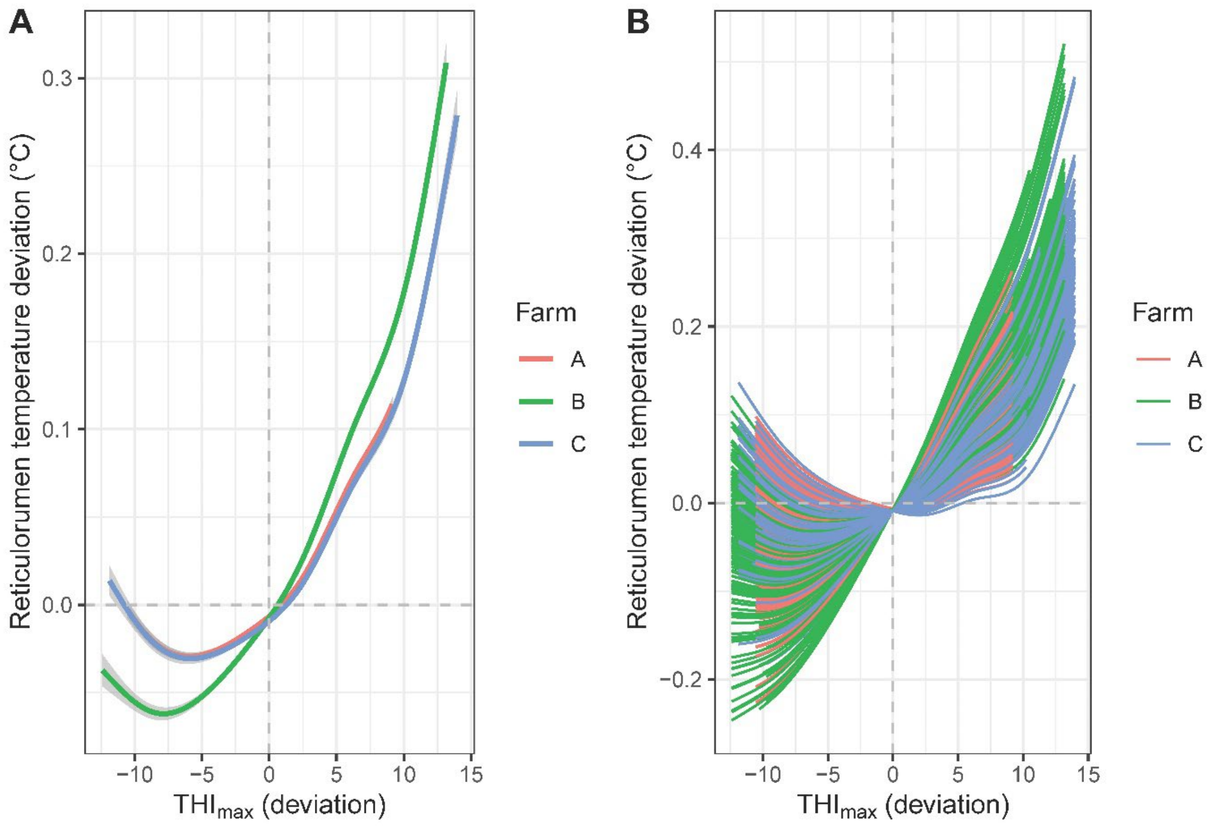

Fig. 1 | Association between THI$_{max}$ (deviation) and reticulorumen temperature deviation (˚C). Association depicted at both the **A** farm and **B** individual level. THI$_{max}$ (deviation) is the effect of THI deviation regardless of baseline. Truncation applied to display only THI ranges experienced by the farm and/or individual.

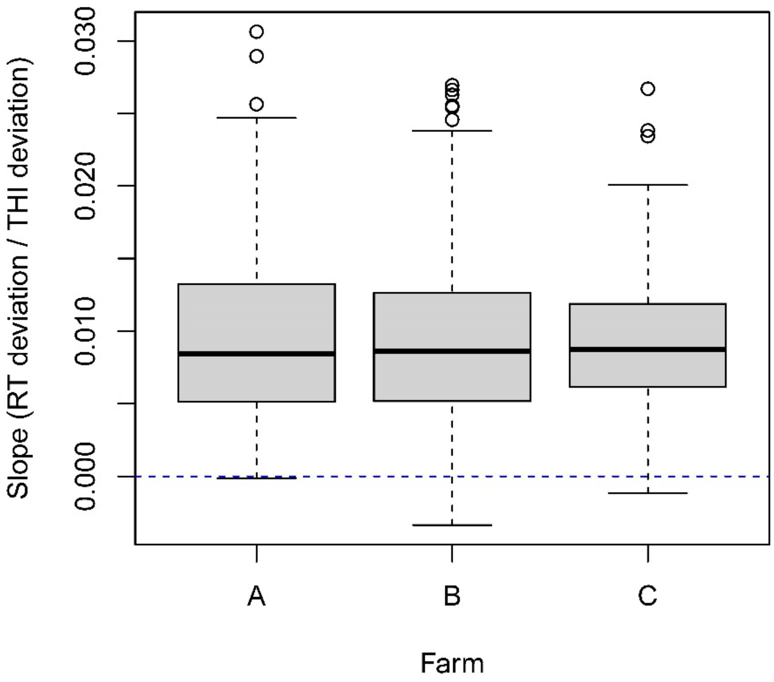

Fig. 2 | Sensitivity of reticulorumen temperature (RT) deviation on THI deviation for each animal. Slopes of the individual animal reticulorumen response per change in THI deviation, for each animal.

Baseline THI levels are a major influencing factor for animal response. The association between $\mathrm{THI}_{\mathrm{max}}$ (smooth; accounting for the initial THI baseline) and reticulorumen temperature deviation (˚C) at both the farm and individual levels was assessed (Fig. 3). The data revealed an increase in reticulorumen temperature at a $\mathrm{THI}_{\mathrm{max}}$ (smooth) of approximately 65, followed by a second, more marked increase at a $\mathrm{THI}_{\mathrm{max}}$ (smooth) of approximately 75. Based on Wald tests, there were significant differences between farms ($p < 0.0001$), $\mathrm{THI}_{\mathrm{max}}$ (smooth) ($p < 0.0001$), and farm by $\mathrm{THI}_{\mathrm{max}}$ (smooth) interaction ($p < 0.0001$) (Supplementary Table 3). The individual animal plot closely mirrors the farm-level plot, indicating minimal detectable variation at the individual level. This lack of variation is confirmed by the estimated variance components in the mixed model (Supplementary Table 4).

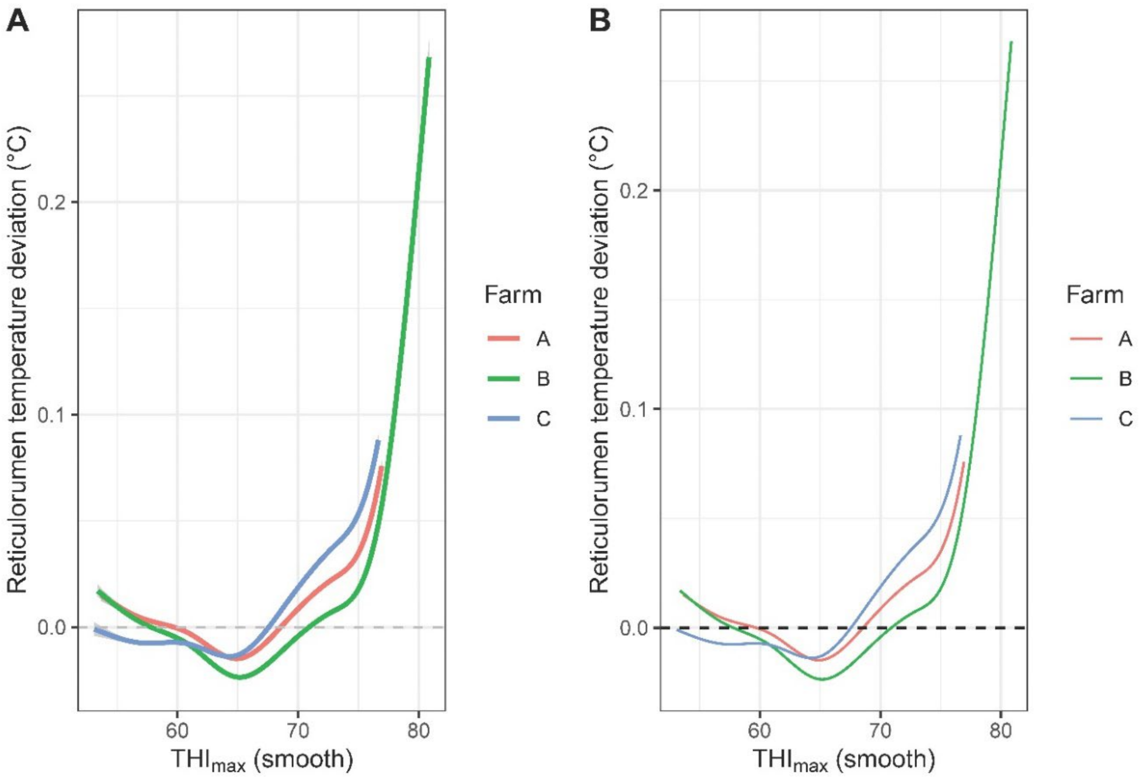

Fig. 3 | Association between THI$_{max}$ (smooth) and reticulorumen temperature deviation (˚C). Association depicted at both the **A** farm and **B** individual level. THI$_{max}$ (smooth) is the effect of THI deviation accounting for baseline value. Truncation applied to display only THI ranges experienced by the farm and/or individual.

Association between THI$_{max}$ (deviation) and THI$_{max}$ (smooth) on reticulorumen temperature deviation (˚C), for each farm was evaluated (Fig. 4). Reticulorumen temperature exhibited a stronger positive response with increasing THI$_{max}$ (smooth). This effect was more pronounced at higher THI$_{max}$ deviation values, indicating a compounding influence of baseline THI on physiological response to variations. At both positive and negative THI$_{max}$ (deviation) extremes, if THI$_{max}$ (smooth) was low, a paradoxical response of reticulorumen temperature was evident. While the overall trend was consistent across farms, there were subtle differences in the magnitude of response. The standard error of prediction has been accounted for in a complementary surface plot (Supplementary Fig. S2).

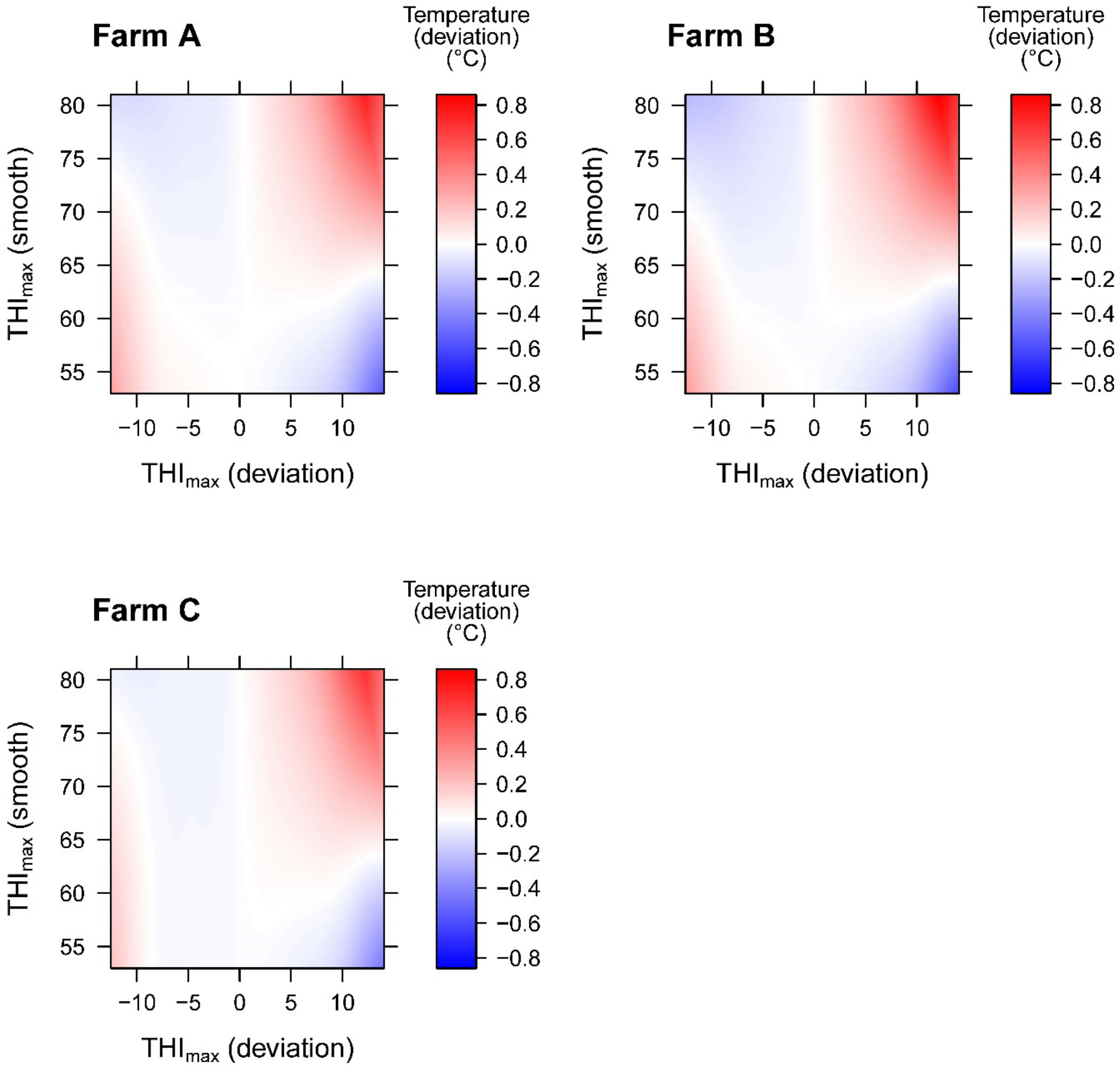

Fig. 4 | Reticulorumen temperature response to THI deviations. Surface plot illustrating the relationship between reticulorumen temperature and two measures of THI deviation (THI_{max} (deviation) and THI_{max} (smooth)). An individual surface plot is displayed per farm alongside a colour legend.

DISCUSSION

Here, we reveal the impact of changing thermal conditions on reticulorumen temperature through time series and mixed model analysis. The decomposition of THI_{max} enabled removal of long-term and seasonal trends, facilitating an assessment of how deviations in THI impact subsequent animal response. With minor deviations in THI_{max}, all cattle were able to maintain similar reticulorumen temperature, suggesting they were operating within their thermoneutral zone. This physiological stability indicates that ambient conditions remained within a range that did not trigger thermoregulatory responses. Different overall levels of temperature change were evident at the farm level in response to larger THI deviations, with individuals shown to vary significantly in their sensitivity. Also conducting a time series decomposition, Islam et al. (2023) presented similar results in feedlot beef cattle, demonstrating an overall increase in core body temperature with increasing THI, identifying a distinction in response between ‘susceptible’ and ‘tolerant’ cattle beyond a THI range of 70-74. Here, at both the farm and individual level, animals on the most northern property were most affected by THI_{max} deviations. Dairy cows retain a known sensitivity to high ambient temperature (Kadzere et al., 2002; Zhou et al., 2022); therefore, temperature deviations might have greater impact for animals experiencing warmer conditions.

Exploration of individual animal slopes suggests that the group as a whole demonstrated a high level of thermoregulatory capacity, though highlights that some individuals still undergo a greater physiological change to rising THI in comparison to others. Analysis of these slopes offers the first step for the development of a core body temperature derived phenotype for the selection of heat-tolerant animals. Other work has separated animals based on their level of susceptibility (Islam et al., 2023), and this concept should be introduced here. Further research should explore the repeatability of these responses, that is, do the same animals consistently demonstrate similar responses across multiple HS events? Rather than singularly exploring how an animal responds to THI deviations, we must consider how consistently that individual can maintain stability in different conditions.

Based on the analysis of THI_{max} (smooth), baseline THI levels are shown to be a major influencing factor for animal response. Variation at the baseline remains significant at the population level. A distinct increase in reticulorumen temperature deviation at a THI_{max} (smooth) of approximately 67 is evident, followed by a second, more marked increase at THI 75. Several studies have confirmed THI predictions are underestimating the physiological impact of HS (Pinto et al., 2020; Zimbelman et al., 2009). This study, therefore, aligns with recommendations by others that heat mitigation should be enacted earlier – upon exposure of THI 65 (at minimum) and above. A review of industry-established THI thresholds is required to better reflect responses of the high-producing dairy cow seen today. Alternatively, acknowledgement that THI thresholds might be most effectively determined for an individual herd (ideally for individuals within this herd), allowing for a more tailored approach that will account for animal factors. Interestingly, minimal detectable variation was evident at the individual animal level for baseline $\mathrm{THI}_{\mathrm{max}}$ (smooth). We propose three hypotheses in response:

1) Environmental conditions exert such a dominant influence at certain thresholds that intrinsic differences are overridden. Yet, this does not explain the maintained lack of variability seen at low thresholds.
2) As all individuals (at the farm level) are experiencing the same macro-environment, long-term times measures will appear to have a near identical impact. Analysis at a more regular time interval (i.e. hourly) might demonstrate differing results.
3) A standardised response is seen at farm level due to environmental acclimation among individuals.

Individual variation in heat tolerance and susceptibility might impact apparent associations between core body temperature and thermal indices over time (Allen, 1962; Heinicke et al., 2019; Islam et al., 2023). Further research should include greater consideration for individual cow-related factors such as breed, age, and parity that might better reveal animal sensitivity and account for the remaining variability in the presented models.

Mixed models using thin-plate splines were employed to produce surface plots that show the overall mean response for each farm, though theoretically, each individual has their own response pattern. A paradoxical response of reticulorumen temperature was evident if $\mathrm{THI}_{\mathrm{max}}$ (smooth) was low, at both positive and negative $\mathrm{THI}_{\mathrm{max}}$ (deviation) extremes. We suggest this might be indicative of:

1) Overcompensation of thermoregulation at large THI deviations.
2) Increased effectiveness of employed thermoregulation efforts at low THI baselines.
3) Carry over effect from temperature extremes (both hot and cold) from preceding days.

Highlighted here is the influence that the starting THI has on the resultant reticulorumen temperature impact. If an animal is positioned at a lower starting THI baseline, it has greater capacity for thermoregulation; therefore, a lower effect on reticulorumen temperature is evident. Conversely, if an animal is exposed to a higher THI baseline, there is reduced ability to buffer an increase in environmental temperature and a greater effect on reticulorumen temperature is seen. Cowan et al. (2024) have identified the requirement for an equivalent HS alert for cattle to the Australian Bureau of Meteorology sheep graziers alert, highlighting the benefits of using multiple thermal stress indices and standardising resultant risk classifications. We emphasise the requirement for all HS alerts to account for the preceding environmental conditions (i.e. starting THI) and not just those predicted, to most accurately forecast the resulting impact on cattle.

METHODS

This research was conducted using historical reticulorumen temperature data from 1,429 dairy cows across three farms in Victoria, Australia from June 2021 ongoing, with a data download cut-off for ease of analysis in February 2023 (Table 1). Animal ethics approval was not required as the data were already being recorded by the farms for their own use.

All farms were primarily pasture-based with animals of varying age, breed (primarily Holstein-Friesian), and parity. Cattle had been previously orally administered with a bolus, that naturally transports to the reticulorumen. Farm management remained under individual producer discretion.

Table 1. Individual farm statistics.

	Farm A	**Farm B**	**Farm C**
Number of animals	659	426	344
Recording start date	8 June 2021	28 March 2019	7 March 2019
Data download cut-off	2 February 2023	2 February 2023	2 February 2023

Reticulorumen temperature data

Reticulorumen temperature data was obtained from the smaXtec bolus (https://smaxtec.com) as raw reticulorumen temperature data (‘temp’) at 10-minute intervals through wireless transmission, enabling initial visualisation of raw data (Supplementary Fig. S3-S4). Product specification states temperatures between 20 ˚C and 60 ˚C can be measured with an accuracy of ± 0.01 ˚C (SmaXtec, 2024). A Python script was used to automatically download the raw bolus data through a provided application programming interface. To maintain a more accurate representation of normal reticulorumen temperature trends, drinking events were identified and isolated as per Shirley et al. (2025) and removed.

Climate data

Climatic data were collected at 3-hourly intervals from the nearest surrounding Bureau of Meteorology (BOM, http://www.bom.gov.au/) weather stations, and the average values of these surrounding stations taken as to best predict on-site weather conditions at each property. From these data, the THI was calculated using the equation from Yousef (1985)

$$THI = T_{air} + 0.36 \times T_{dp} + 41.2$$

where T_{air} is the dry-bulb temperature (˚C) and T_{dp} is the dew point temperature (˚C). The constant (41.2) adjusts the index to a commonly accepted scale. The daily maximum (THI_{max}) was then determined for use in subsequent analysis.

Statistical analyses

To investigate the association of THI_{max} and reticulorumen temperature, the following analyses were conducted. To avoid spurious associations, regardless of underlying functional association, time series trends were decomposed to remove long-term and seasonal trends. The principal behind this is to assess how deviations in THI_{max} affect subsequent deviations in body temperature. For each farm, THI data were extracted and converted into a time series with a yearly frequency, before applying seasonal-trend decomposition using the ‘stl’ function in R.

$$\text{THI}_{\text{max}} = \text{THI}_{\text{max\_seasonal}} + \text{THI}_{\text{max\_trend}} + \text{THI}_{\text{max\_dev}}$$

where $\mathrm{THI}_{\mathrm{max}}$ is the observed value on the day, $\mathrm{THI}_{\mathrm{max\_seasonal}}$ reflects the yearly seasonal trends, $\mathrm{THI}_{\mathrm{max\_trend}}$ captures the long-term trend, and $\mathrm{THI}_{\mathrm{max\_dev}}$ captures short-term residual deviations. Seasonal and trend values were summed to produce a ‘smoothed’ series.

$$\mathrm{THI}_{\mathrm{max\_smooth}} = \mathrm{THI}_{\mathrm{max\_seasonal}} + \mathrm{THI}_{\mathrm{max\_trend}}$$

For each farm, a data set of smoothed $\mathrm{THI}_{\mathrm{max}}$ and $\mathrm{THI}_{\mathrm{max}}$ deviations was created for subsequent analysis. The role of the ‘smoothed’ version of $\mathrm{THI}_{\mathrm{max}}$ is to provide a ‘baseline’ value, free of daily fluctuations.

To analyse the reticulorumen temperature data from each farm, the order of unique identification (ID) levels was randomised and divided into batches (n = 10) for ease of analysis, as all the raw data could not be simultaneously analysed for the decomposition process as described below. For each batch, a mixed-effects model was fitted, using the ASReml package in R.

$$\mathrm{Temp} = \beta_0 + \left(\beta_1 + \beta_1^{(\mathrm{Farm})}\right)\mathrm{cDate} + \mathrm{Farm} + s(\mathrm{cDate}) + \mathrm{ID} + s(\mathrm{cDate}, \mathrm{ID}) + \varepsilon$$

where Temp is the observed body temperature, cDate is the date centred around its mean for computational stability, Farm and their interaction are fixed effects, random effects for animal ID account for individual variability, and a spline for Date, $s(\mathrm{cDate})$, nested within ID, $s(\mathrm{cDate}, \mathrm{ID})$, to capture individual-specific nonlinear temporal trends. From the fitted model, residuals were obtained, as these were the deviations ($\mathrm{Temp}_{\mathrm{dev}}$) with trend removed, and carried forward for analysis. These deviations were appended to the batch data which were then combined for further analysis. The use of ASReml over the ‘stl’ function allowed for simultaneous modelling of fixed effects and complex random effects, providing a more accurate representation of individual differences in the data.

Cross-correlation analysis was conducted to evaluate the temporal relationship between $\mathrm{THI}_{\mathrm{max}}$ deviations and reticulorumen temperature deviations to assess any lagged responses to changes in THI. Mixed effects models were used to explore the associations in more detail, with model fitting conducted using ASReml-R. Fixed effects for the model exploring the relationship between reticulorumen temperature and $\mathrm{THI}_{\mathrm{max}}$ were the interaction between Farm and $\mathrm{THI}_{\mathrm{max}}$ deviation. Random effects were included for ID (nested with $\mathrm{THI}_{\mathrm{max}}$

deviation) and spline smoothing terms for each individual. The specification of the model is as follows:

$$\text{Temp}_{\text{dev}} = \beta_0 + \left(\beta_1 + \beta_1^{(\text{Farm})}\right)\text{THI}_{\text{max\_dev}} + \text{Farm} + s\left(\text{THI}_{\text{max\_dev}}\right) + \text{ID} + s(\text{cDate}, \text{ID}) + \varepsilon$$

where Temp_{dev} is the reticulorumen temperature deviation, after removing the trend, Farm and $\text{THI}_{\text{max\_dev}}$ are the fixed effects, together with their interaction, with random effects for ID to account for individual variability, and a spline for $\text{THI}_{\text{max\_dev}}$ nested within ID to capture individual-specific nonlinear responses to THI deviations. The model for $\text{THI}_{\text{max\_smooth}}$ was fitted in the same manner, with replacement of $\text{THI}_{\text{max\_dev}}$ with $\text{THI}_{\text{max\_smooth}}$.

The Wald test was used to assess the significance of the fixed effects, and the variability between individuals evaluated using estimated variance components. For both models, predicted values were computed from the fitted models, with predictions made over a grid of $\text{THI}_{\text{max\_dev}}$ or $\text{THI}_{\text{max\_smooth}}$ values for each farm, as well as for each individual animal within its farm.

A similar model was developed to investigate the impact of simultaneous effects of deviations and smooth THI_{max}, and their interaction, on reticulorumen temperature deviation. This allows an assessment of how the effect of THI_{max} deviations changes according to its baseline THI_{max}, as given by $\text{THI}_{\text{max\_smooth}}$. The model was specified as:

$$\text{Temp}_{\text{dev}} = \beta_0 + \left(\beta_1 + \beta_1^{(\text{Farm})}\right)\text{THI}_{\text{max\_dev}} + \left(\beta_2 + \beta_2^{(\text{Farm})}\right)\text{THI}_{\text{max\_smooth}} + \text{Farm} + s\left(\text{THI}_{\text{max\_dev}}, \text{THI}_{\text{max\_smooth}}\right) + s\left(\text{THI}_{\text{max\_dev}}, \text{THI}_{\text{max\_smooth}}, \text{ID}\right) + \varepsilon$$

where the term $s\left(\text{THI}_{\text{max\_dev}}, \text{THI}_{\text{max\_smooth}}\right)$ indicates a ‘thin plate’ spline. As above, Wald tests and variance components were evaluated, followed by predicted values being computed from the fitted model and merged with farm-specific THI_{max} limits.

Visualisations of model predictions and the thin-plate spline were obtained using the ggplot2 package and the levelplot function in the lattice package, respectively.

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CHAPTER 6

Determining the association among three phenotypic indicators for heat tolerance in dairy cattle

Confirmation of variability in individual response to climate at varied temperature humidity index thresholds was achieved in Chapter 5. With this knowledge, and in consideration of the need to develop climate-smart strategies to combat heat stress, Chapter 6 explores the potential association of three phenotypic indicators for heat tolerance. As ‘easy to monitor’ indicators of heat stress, confirmation of correlation between these traits will enable practical integration at the farm-level.

ABSTRACT

Heat stress (**HS**) remains a critical challenge in global dairy systems, requiring the prioritisation of climate-smart strategy development. Identification of association among phenotypic indicators of heat tolerance offers opportunities to implement cost-effective monitoring tools at a commercial scale. Here, we investigated the association between reticulorumen temperature, milk yield, and drinking frequency, evaluating their potential to serve as effective proxies of HS. Time series decomposition and mixed model analysis confirmed significant effects of temperature humidity index (**THI**) deviations for all traits. All traits revealed individual animal diversity in response to both THI and reticulorumen temperature deviations. Slopes analysis highlighted opportunities to consider multi-trait heat responses, especially for drinking behaviour. From these insights, progression can be in the preparation of livestock systems for ongoing climate challenges.

INTRODUCTION

As a consequence of global warming and climate change, heat stress (**HS**) remains a critical challenge in dairy production systems globally (Oliveira et al., 2025). The sudden onset and long duration of high heat events can have significant implications on dairy cattle productivity, fertility, and overall welfare (Polsky & von Keyserlingk, 2017; West, 2003). As such, there is a growing need to prioritise the development of climate-smart strategies that will prepare livestock systems for forecasted climate changes. Central to this, is the identification of cost-effective tools to assist in the monitoring and management of animal responses to environmental stressors. Phenotypes, being a set of observable traits, can provide these valuable insights while being easily tracked under routine farm management.

Three phenotypes that are commonly associated with dairy cattle HS are core body temperature, milk yield, and drinking behaviour. Core body temperature provides a direct measure of physiological response to thermal change, typically monitored using rectal (Lees et al., 2018; Piccione et al., 2003), vaginal (Hillman et al., 2009; Lee et al., 2015), or reticulorumen (Koltes et al., 2018; Shirley et al., 2025) measures. Reflective of lesser dry matter intake available for milk synthesis, a lagged reduction in milk yield is typical during a high heat event (Rhoads et al., 2009). Heat-stressed cattle have also been seen to increase their average water intake, with supply of fresh water said to be a critical resource during this time (Polsky & von Keyserlingk, 2017; West, 2003). All three phenotypes have established relationships with thermal changes, but their interrelationships and potential utility in real-world, low-technology commercial application remains underexplored. In Australia, genetic evaluations for heat tolerance are incorporated into the national selection indices as heat tolerance genomic breeding values (Nguyen et al., 2017). Derived from milk yield and its associated characteristics, these (genomic) estimated breeding values provide an optimal measure of an animal in a breeding program for genetic selection, by combining phenotypic ‘clues’ from related animals (Falconer & Mackay, 1996). To expand practical utility of this breeding value, there is an opportunity to identify simple, easy-to-measure phenotypes that retain a high correlation with heat tolerance.

This study investigates the potential associations between reticulorumen temperature, milk yield, and drinking frequency and their use as indicators of heat tolerance in dairy cattle. The aim is to assess whether these traits can serve as effective proxies for HS within the context of climate-smart management, given they are measurable with minimal technological intervention. Through advancement of our understanding of these potential associations, we seek to enhance the preparedness of livestock systems for future climate challenges.

MATERIALS AND METHODS

This study was conducted using historical animal data (reticulorumen temperature, drinking frequency, and milk yield) from 498 animals on a dairy farm in Victoria, Australia. As the data were already being recorded by the farm for their own use, animal ethics approval was not required. Corresponding climate data were collected for the same period, from 1 June 2023 to 31 March 2025.

Animals for this study were kept on pasture, and were primarily Holstein-Friesian, but their breed, age, and parity varied. All cattle had previously been orally administered with a bolus, that naturally transported to the reticulorumen, collecting reticulorumen temperature data at 10-minute intervals through wireless transmission. No alterations to farm management were dictated by us throughout the study duration.

Climate data

Climatic data were collected at half-hourly intervals from the nearest Bureau of Meteorology (BOM, http://www.bom.gov.au/) weather station. From these data, the temperature humidity index (**THI**) was then calculated using the equation from Yousef (1985)

$$THI = T_{air} + 0.36 \times T_{dp} + 41.2$$

where T_{air} is the dry-bulb temperature (˚C) and T_{dp} is the dew point temperature (˚C). The constant of 41.2 adjusts the index to a commonly accepted scale. The daily maximum THI ($\mathrm{THI}_{\mathrm{max}}$) was then determined for use in subsequent analysis. Here and elsewhere, time series trends were decomposed, removing long-term and seasonal trends to avoid spurious correlations, regardless of underlying functional association. Temperature-humidity index data were extracted and converted into a time series with a yearly frequency. Seasonal trend decomposition was then applied using the 'stl' function in R.

$$\mathrm{THI}_{\mathrm{max}} = \mathrm{THI}_{\mathrm{max\_seasonal}} + \mathrm{THI}_{\mathrm{max\_trend}} + \mathrm{THI}_{\mathrm{max\_dev}}$$

where $\mathrm{THI}_{\mathrm{max}}$ is the observed value on the day, $\mathrm{THI}_{\mathrm{max\_seasonal}}$ reflects the yearly seasonal trends, $\mathrm{THI}_{\mathrm{max\_trend}}$ captures the long-term trend, and $\mathrm{THI}_{\mathrm{max\_dev}}$ captures short-term residual deviations. A resultant 'smoothed' series was then produced by summing the seasonal and trend values, providing a 'baseline' value, exclusive of daily fluctuations.

$$\mathrm{THI}_{\mathrm{max\_smt}} = \mathrm{THI}_{\mathrm{max\_seasonal}} + \mathrm{THI}_{\mathrm{max\_trend}}$$

Datasets of $\mathrm{THI}_{\mathrm{max\_dev}}$ and $\mathrm{THI}_{\mathrm{max\_smt}}$ were carried forward for subsequent analysis.

Reticulorumen temperature data

Raw reticulorumen temperature data ('temp') was collated from the smaXtec boluses (http://smaxtec.com) and downloaded using a Python script through a provided application programming interface. Product specification declares a measurement accuracy of ± 0.01 ˚C for temperatures between 20-60 ˚C (SmaXtec, 2024). To better reflect an individual's underlying physiological response to changing environmental conditions, drinking events were identified and isolated as per Shirley et al. (2025) and removed. To align with other data, a daily average reticulorumen temperature for each individual was determined for use in subsequent analysis. Decomposition was conducted using ASReml, allowing for simultaneous modelling of fixed and random effects to better represent individual differences within the data. Due to computational burden, the order of unique identification (ID) levels was randomised and divided into batches (n = 100). Using ASReml in R, each batch had the following linear mixed model fitted:

$$\mathrm{Temp} = \beta_0 + \beta_1\mathrm{cDate} + s(\mathrm{cDate}) + \mathrm{ID} + s(\mathrm{cDate}, \mathrm{ID}) + \varepsilon$$

where Temp is the observed reticulorumen temperature, cDate is the date centred around its mean (computational stability), animal ID is a random effect to account for individual variability, and a spline for Date, s(cDate) was nested within ID, s(cDate, ID), to capture individual-specific nonlinear temporal trends. Reticulorumen deviations with the trend removed ($\mathrm{Temp}_{\mathrm{dev}}$) were obtained from the fitted model and appended to the batch data and combined. As with the above climate data, a ‘smoothed’ series of reticulorumen temperature was developed ($\mathrm{Temp}_{\mathrm{smt}}$). Datasets of $\mathrm{Temp}_{\mathrm{dev}}$ and $\mathrm{Temp}_{\mathrm{smt}}$ were carried forward.

Milk yield data

Daily individual milk yield data (L/day) for all cattle was obtained across the same time period and decomposed. The same form of model for decomposition as used for the reticulorumen temperature data was fitted to the milk yield data (Yield), again in batches of 100 IDs. Milk yield deviations ($\mathrm{Yield}_{\mathrm{dev}}$) were appended to the batch data and combined for further analysis.

Drinking frequency data

Using the model developed by Shirley et al. (2025), daily drinking event frequency (ndrink) was determined for all individuals. As above, decomposition was conducting using ASReml using the same model as used for reticulorumen temperature and milk yield, in batches of n = 100. Drinking frequency deviations ($\mathrm{ndrink}_{\mathrm{dev}}$) were appended, combined, and carried forward.

Statistical analysis

To evaluate the temporal relationship between deviations and assess lagged responses, cross-correlation analysis was conducted for the following causal relationships:

$$\mathrm{THI}_{\mathrm{max\_dev}} \rightarrow y_1$$

$$\mathrm{Temp}_{\mathrm{dev}} \rightarrow y_2$$

where y_1 = $\mathrm{Temp}_{\mathrm{dev}}$, $\mathrm{Yield}_{\mathrm{dev}}$, or $\mathrm{ndrink}_{\mathrm{dev}}$ and y_2 = $\mathrm{Yield}_{\mathrm{dev}}$ or $\mathrm{ndrink}_{\mathrm{dev}}$. Lags were applied to outcome variables as required. To explore the associations in more detail, mixed effects models were used, with model fitting conducted using ASReml. The specification of the model is as follows, using each of the above casual pathways:

$$y_{\mathrm{dev}} = \beta_0 + \beta_1 x_{\mathrm{dev}} + s(x_{\mathrm{dev}}) + \mathrm{ID} + b_{\mathrm{ID}} x_{\mathrm{dev}} + s(x_{\mathrm{dev}}, \mathrm{ID}) + \varepsilon$$

where y_{dev} is the respective response variable, after removing the trend, x_{dev} is the fixed effect covariate, with random effects for ID (individual variability, random intercept and slope), an overall spline for x_{dev}, and a spline nested within ID to capture individual-specific nonlinear responses to predictor deviations. This model was replicated using appropriate x_{dev} and y_{dev} terms as defined above.

To assess the significance of fixed effects, a Wald test was conducted for each model. Estimated variance components were evaluated to assess the variability between individuals. From the fitted model, predicted values were determined and merged from farm-specific $\mathrm{THI}_{\mathrm{max}}$ limits. Visualisation of model predictions were computed using the ggplot2 package. Overall linear trend estimates ($\beta_1 + b_{\mathrm{ID}}$) were calculated for each animal, as an overall phenotype measure.

RESULTS

Cross-correlation analysis

Cross-correlation analysis was performed to assess the temporal relationship between deviations of $\mathrm{THI}_{\mathrm{max}}$ and reticulorumen temperature deviations, milk yield deviations, and drinking frequency deviations (Figure 1). Analysis revealed a statistically significant correlation between $\mathrm{THI}_{\mathrm{max\_dev}}$ and $\mathrm{Temp}_{\mathrm{dev}}$ that was highest on Day 0 ($r = 0.204$, $p < 0.001$). Significant positive associations were detected for the first five days for $\mathrm{THI}_{\mathrm{max\_dev}}$ and $\mathrm{Yield}_{\mathrm{dev}}$, with the highest correlation evident on Day 1 ($r = 0.0203$, $p < 0.001$). Similarly, Day 1 presented the peak, statistically significant positive association between $\mathrm{THI}_{\mathrm{max\_dev}}$ and $\mathrm{ndrink}_{\mathrm{dev}}$ ($r = 0.111$, $p < 0.001$). Cross-correlation results were also obtained for the deviations of reticulorumen temperature on milk yield deviations and drinking frequency deviations (Figure 1). While positive associations were detected for the first seven days for $\mathrm{Temp}_{\mathrm{dev}}$ on $\mathrm{Yield}_{\mathrm{dev}}$, the highest correlation was evident on Day 0 ($r = 0.020$, $p < 0.001$). For $\mathrm{Temp}_{\mathrm{dev}}$ on $\mathrm{ndrink}_{\mathrm{dev}}$, Day 1 retained the most significant positive associations ($r = 0.075$, $p < 0.001$). As required, lags were carried through for model analysis.

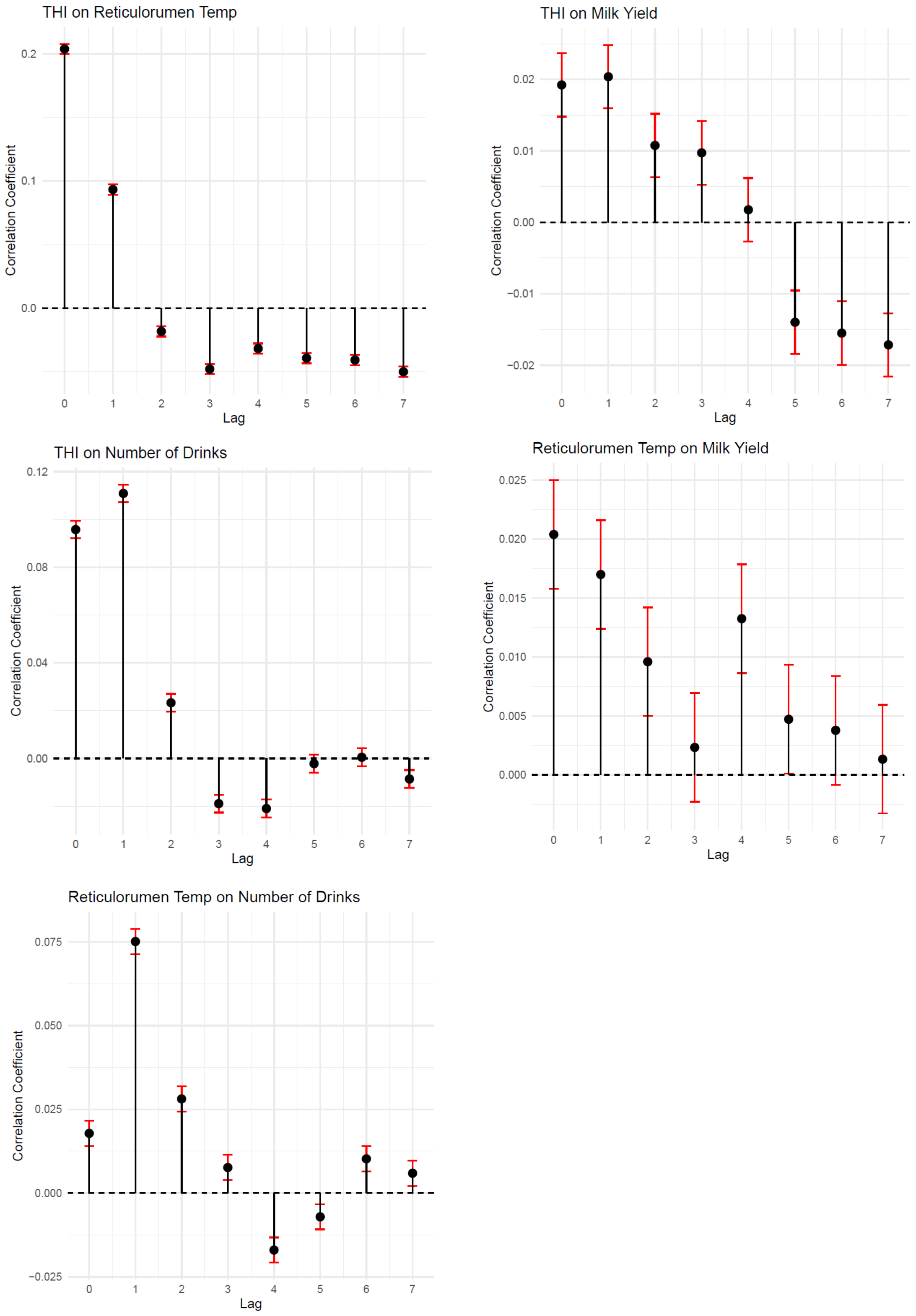

Figure 1. Lagged cross-correlation of $\text{THI}_{\text{max\_dev}}$ and Temp_{dev} on respective traits. Error bars (red) represent 95% confidence interval.

Mixed effects models

Temperature-humidity index on reticulorumen temperature

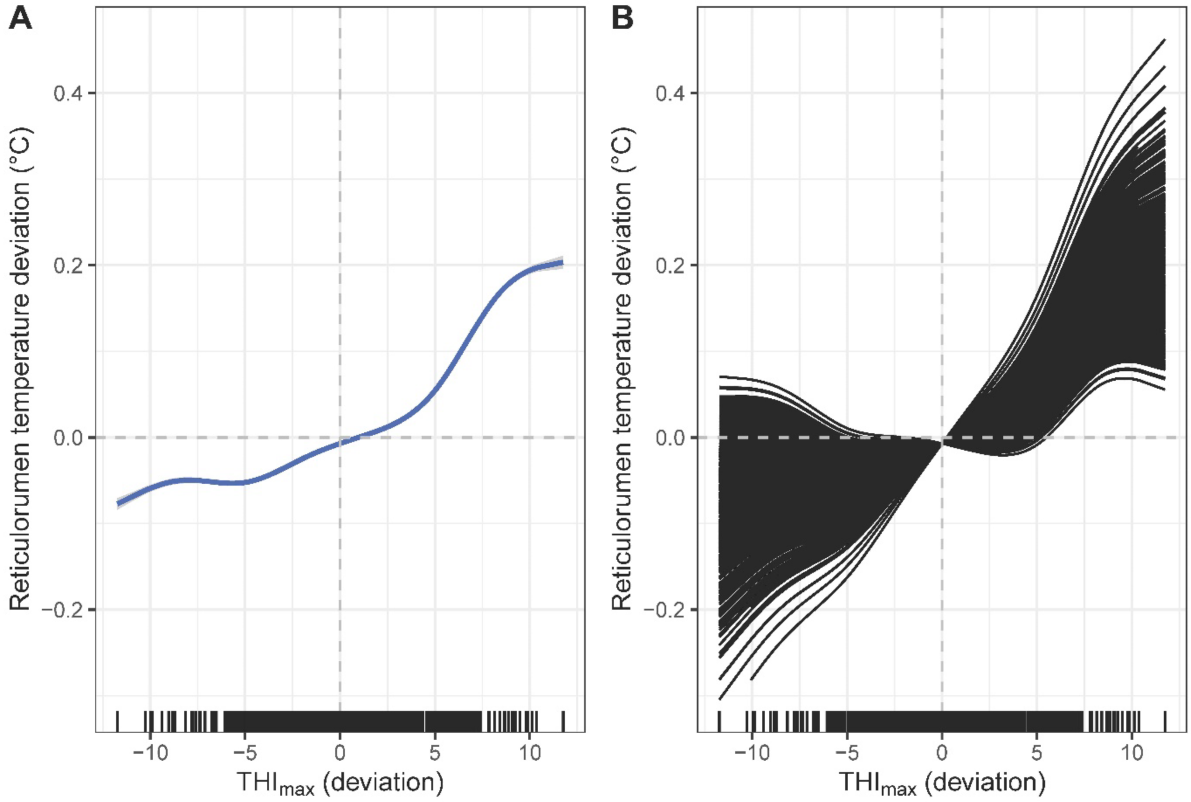

Figure 2. Association between $\text{THI}_{\text{max\_dev}}$ and Temp_{dev} (˚C). Association depicted at both the farm (A) and individual (B) level. Truncation applied to display only THI ranges experienced by the farm and/or individual. The grey band in (A) represents ± 1 standard error (SE), a 'rug plot' is shown on the *x*-axis to indicate observed $\text{THI}_{\text{max\_dev}}$ values.

The association between $\text{THI}_{\text{max\_dev}}$ and Temp_{dev} was analysed using time series decomposition, cross-correlation analysis, and mixed effects modelling. An overall positive association was evident at both population and individual levels (Figure 2). A Wald test indicated the fixed effect of $\text{THI}_{\text{max\_dev}}$ on Temp_{dev} was highly significant ($F_{1,\,1113} = 1{,}098$, $p < 0.0001$). Significant between-animal variability was derived from animal response to $\text{THI}_{\text{max\_dev}}$ (Table 1). As estimated by the animal-specific slopes extracted from the fitted mixed model, differences in individual sensitivity as changes in reticulorumen temperature per unit change in THI were evident (Figure 3). All animals retained an average reticulorumen temperature change below 0.035 ˚C/THI unit.

Table 1. Estimated variance components for the association between $\text{THI}_{\text{max\_dev}}$ and Temp_{dev}.

Source of variation	Variance estimate	Standard Error	*z*-ratio
$s(\text{THI}_{\text{max\_dev}})$	4.01×10^{-3}	2.37×10^{-3}	1.70
ID	4.39×10^{-9}	NA	NA
$\text{ID}\times\text{THI}_{\text{max\_dev}}$	4.11×10^{-5}	2.92×10^{-6}	14.10
$s(\text{THI}_{\text{max\_dev}})\times\text{ID}$	2.77×10^{-10}	NA	NA
Residual	4.34×10^{-2}	1.16×10^{-4}	373.86

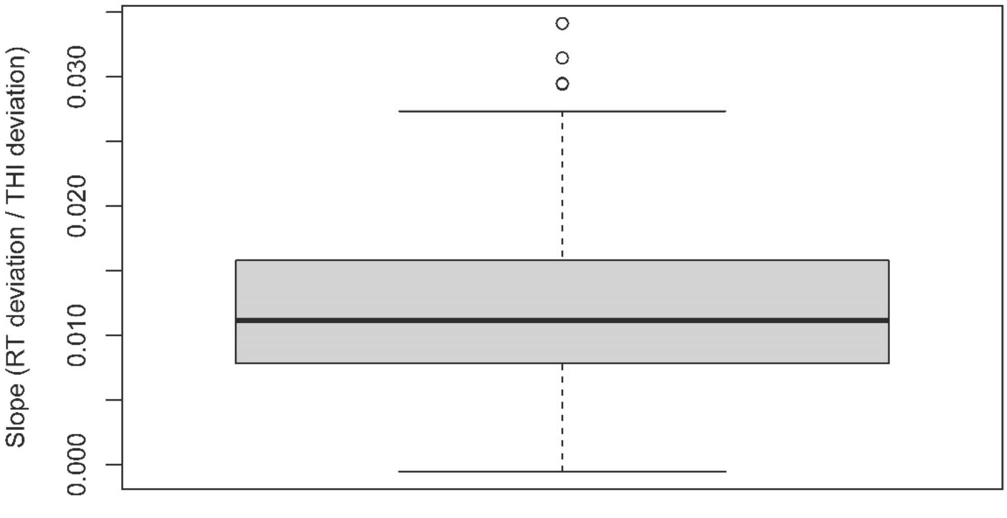

Figure 3. Sensitivity (slope) of Temp_{dev} per change in $\text{THI}_{\text{max\_dev}}$, for each individual.

An assessment of the association between $\text{THI}_{\text{max\_smt}}$ and Temp_{dev} revealed no significant relationship ($F_{1,\,85064} = 2.49$, $p = 0.11$), suggesting short-term deviations in THI are more impactful on reticulorumen temperature than smoothed trends (Supplementary Figure S1). Variance components associated with individual animal ID and its interactions were negligible, indicating minimal between-animal differences (Table 2).

Table 2. Estimated variance components for the association between THI_{max_smt} and Temp_{dev}.

Source of variation	Variance estimate	Standard Error	*z*-ratio
$s(\mathrm{THI}_{max\_smt})$	8.27×10^{-3}	4.82×10^{-3}	1.40
ID	4.65×10^{-9}	NA	NA
$\mathrm{ID}\times\mathrm{THI}_{max\_smt}$	1.86×10^{-11}	NA	NA
$s(\mathrm{THI}_{max\_smt})\times\mathrm{ID}$	2.94×10^{-10}	NA	NA
Residual	4.60×10^{-2}	1.23×10^{-4}	326.10

Temperature-humidity index on milk yield

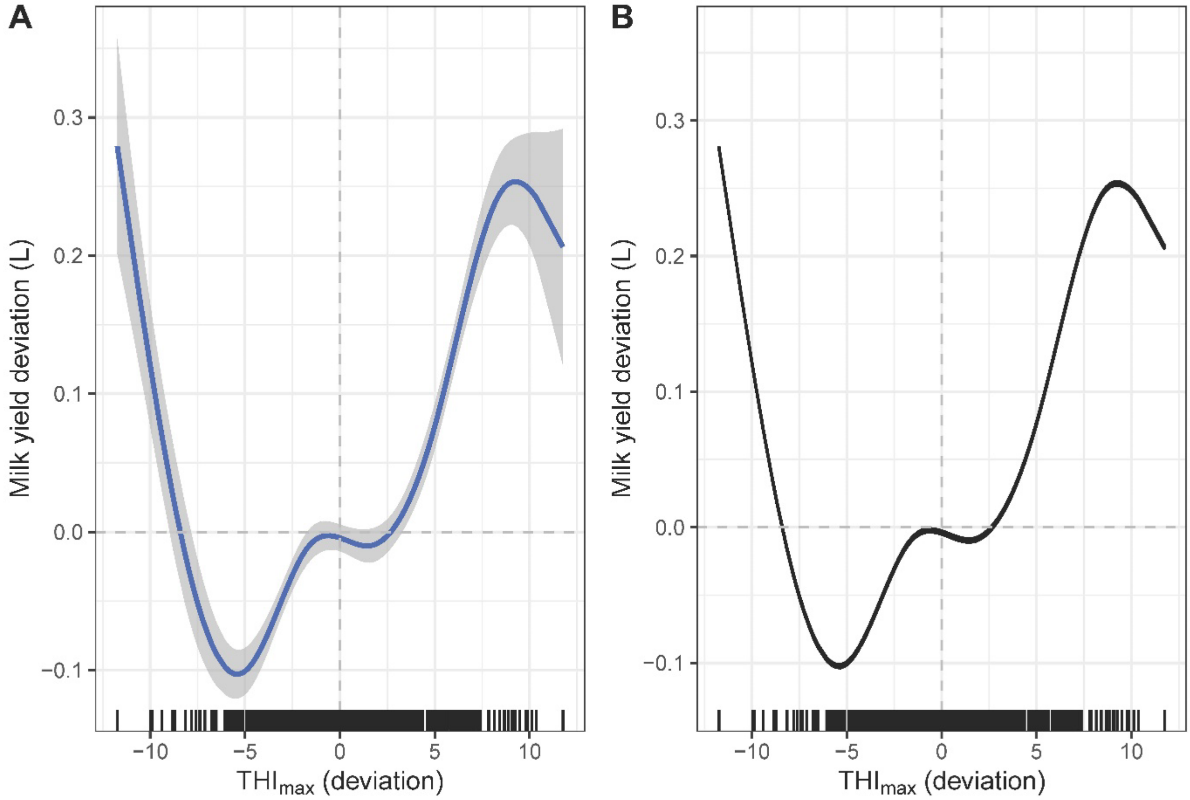

Figure 4. Association between THI_{max_dev} and Yield_{dev} (L). Association depicted at both the farm (A) and individual (B) level. Truncation applied to display only THI ranges experienced by the farm and/or individual. The grey band in (A) represents ± 1 SE, a ‘rug plot’ is shown on the *x*-axis to indicate observed THI_{max_dev} values.

Examining the relationship between THI_{max_dev} and Yield_{dev}, revealed an overall positive trend above a THI_{max_dev} of negative five (Figure 4). Data points observed outside of a positive and negative deviation of 10 were very few, validating why the standard error (SE) fans out at either end of the farm level plot. Wald test results demonstrated significant differences between $\mathrm{THI}_{\mathrm{max\_dev}}$ ($F_{1,\,2642} = 508$, $p < 0.0001$). Variance components for the interaction between individual ID and $\mathrm{THI}_{\mathrm{max\_dev}}$ were statistically significant, though retained a small absolute magnitude of variation (Table 3), contributing to the minimal apparent variation seen in the visualisation. This tight range of individual sensitivity, estimated by the animal-specific slopes in the mixed model, is shown in Figure 5.

Table 3. Estimated variance components for the association between $\mathrm{THI}_{\mathrm{max\_dev}}$ and $\mathrm{Yield}_{\mathrm{dev}}$.

Source of variation	Variance estimate	Standard Error	*z*-ratio
$s(\mathrm{THI}_{\mathrm{max\_dev}})$	3.07×10^{-2}	1.88×10^{-2}	1.63
ID	1.11×10^{-7}	NA	NA
$\mathrm{ID} \times \mathrm{THI}_{\mathrm{max\_dev}}$	8.72×10^{-5}	1.43×10^{-5}	6.12
$s(\mathrm{THI}_{\mathrm{max\_dev}}) \times \mathrm{ID}$	7.02×10^{-9}	NA	NA
Residual	1.10	2.90×10^{-3}	377.82

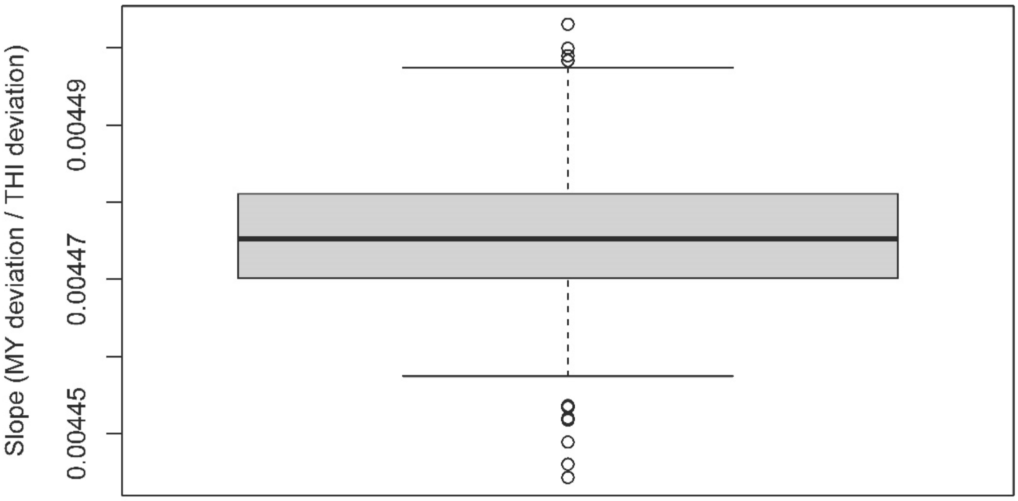

Figure 5. Sensitivity (slope) of $\mathrm{Yield}_{\mathrm{dev}}$ per change in $\mathrm{THI}_{\mathrm{max\_dev}}$, for each individual.

The model of $\mathrm{THI}_{\mathrm{max\_smt}}$ and $\mathrm{Yield}_{\mathrm{dev}}$ demonstrated no significant relationship ($F_{1,\,25} = 1.61$, $p = 0.22$), with minimal individual variation (Table 4). Almost all variance was attributed to residual error. A corresponding model plot is available as Supplementary Figure S2.

Table 4. Estimated variance components for the association between $\mathrm{THI}_{\mathrm{max\_smt}}$ and $\mathrm{Yield}_{\mathrm{dev}}$.

Source of variation	Variance estimate	Standard Error	*z*-ratio
$s(\mathrm{THI}_{\mathrm{max\_smt}})$	7.58×10^{-3}	7.69×10^{-3}	0.99
ID	9.70×10^{-7}	NA	NA
$\mathrm{ID}\times\mathrm{THI}_{\mathrm{max\_smt}}$	5.29×10^{-8}	NA	NA
$s(\mathrm{THI}_{\mathrm{max\_smt}})\times\mathrm{ID}$	8.37×10^{-7}	NA	NA
Residual	8.35	2.56×10^{-2}	326.10

Temperature-humidity index on drinking frequency

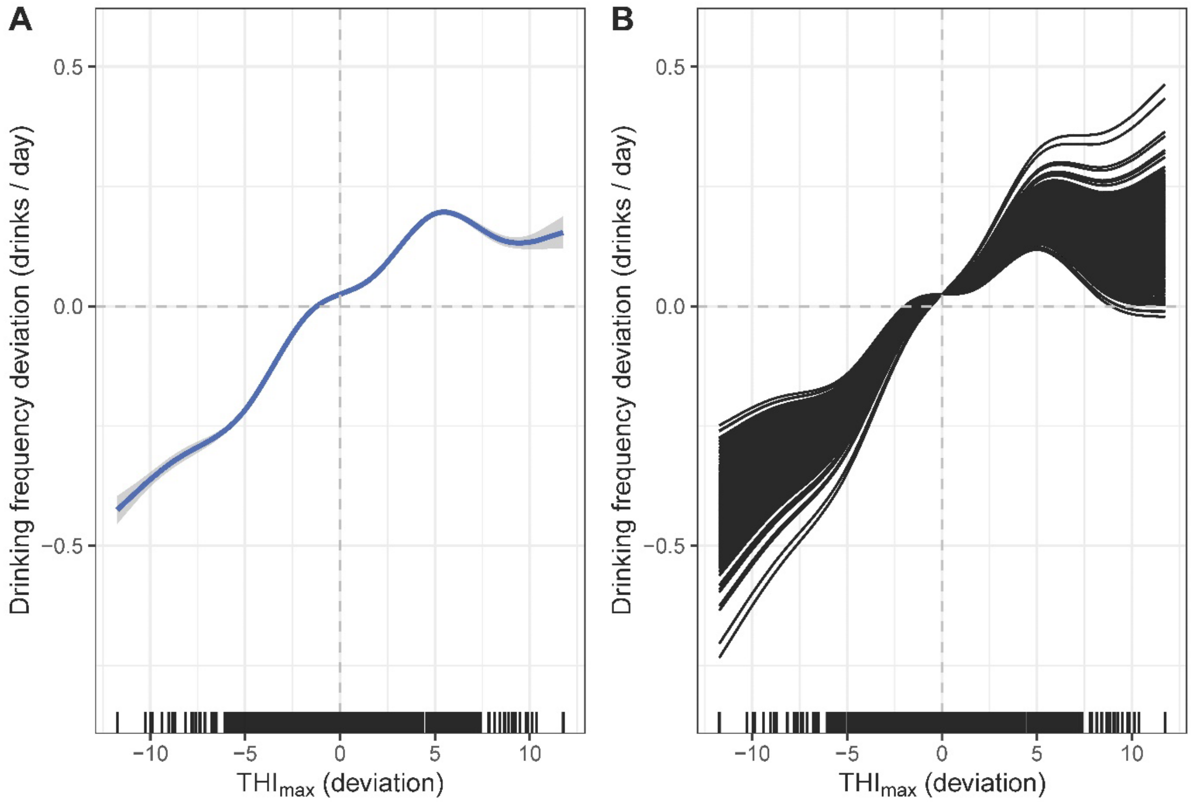

Figure 6. Association between $\mathrm{THI}_{\mathrm{max\_dev}}$ and $\mathrm{ndrink}_{\mathrm{dev}}$ (drinks/day). Association depicted at both the farm (A) and individual (B) level. Truncation applied to display only THI ranges experienced by the farm and/or individual. The grey band in (A) represents ± 1 SE, a 'rug plot' is shown on the *x*-axis to indicate observed $\mathrm{THI}_{\mathrm{max\_dev}}$ values.

Strong positive associations were revealed in the evaluation of $\mathrm{THI}_{\mathrm{max\_dev}}$ and $\mathrm{ndrink}_{\mathrm{dev}}$ (Figure 6), as confirmed from Wald test results ($F_{1,\,2642} = 509$, $p < 0.0001$). While the variance component for intercept variability between cows was negligible, the variance component for slope variability was significant (Table 5). Slopes of drinking frequency deviation per change in THI deviation for each animal (Figure 7) displayed changes between 0 and 0.05 drinks/THI unit.

Table 5. Estimated variance components for the association between $\mathrm{THI}_{\mathrm{max\_dev}}$ and $\mathrm{ndrink}_{\mathrm{dev}}$.

Source of variation	Variance estimate	Standard Error	*z*-ratio
$s(\mathrm{THI}_{\mathrm{max\_dev}})$	3.07×10^{-2}	1.88×10^{-2}	1.63
ID	1.11×10^{-7}	NA	NA
$\mathrm{ID}\times\mathrm{THI}_{\mathrm{max\_dev}}$	8.72×10^{-5}	1.43×10^{-5}	6.11
$s(\mathrm{THI}_{\mathrm{max\_dev}})\times\mathrm{ID}$	7.02×10^{-9}	NA	NA
Residual	1.10	2.90×10^{-3}	377.82

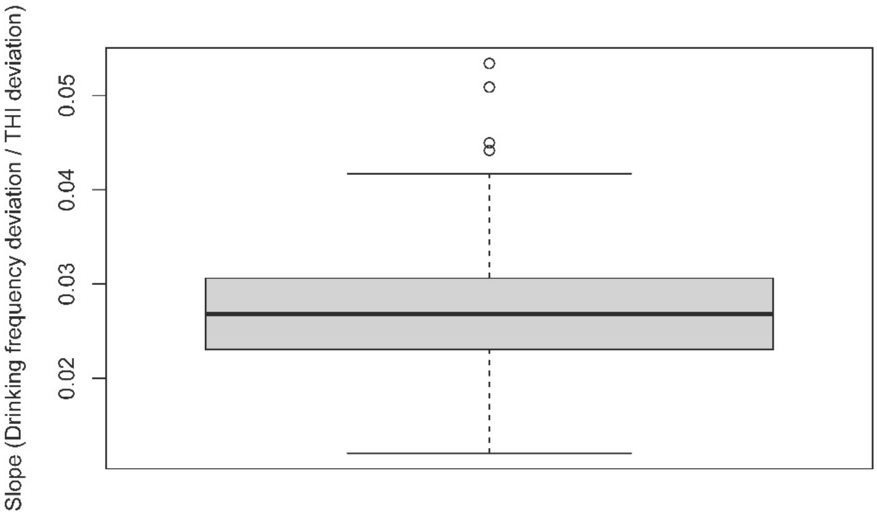

Figure 7. Sensitivity (slope) of $\mathrm{ndrink}_{\mathrm{dev}}$ per change in $\mathrm{THI}_{\mathrm{max\_dev}}$ for each individual.

Exploring the association between $\mathrm{THI}_{\mathrm{max\_smt}}$ and $\mathrm{ndrink}_{\mathrm{dev}}$, Wald test results revealed significant differences between $\mathrm{THI}_{\mathrm{max\_smt}}$ ($F_{1,\,36049} = 9.36$, $p = 0.0022$). This relationship is visualised in Supplementary Figure S3. Estimated variance components confirm insignificant variation for all ID interactions, with residuals capturing the largest amount of variation (Table 6).

Table 6. Estimated variance components for the association between THI_{max_smt} and $ndrink_{dev}$.

Source of variation	Variance estimate	Standard Error	*z*-ratio
$s(THI_{max\_smt})$	1.13×10^{-1}	6.64×10^{-2}	1.70
ID	1.13×10^{-7}	NA	NA
ID×THI_{max_smt}	4.50×10^{-10}	NA	NA
$s(THI_{max\_smt})$×ID	5.02×10^{-8}	NA	NA
Residual	1.11	2.94×10^{-3}	378.16

Reticulorumen temperature on milk yield

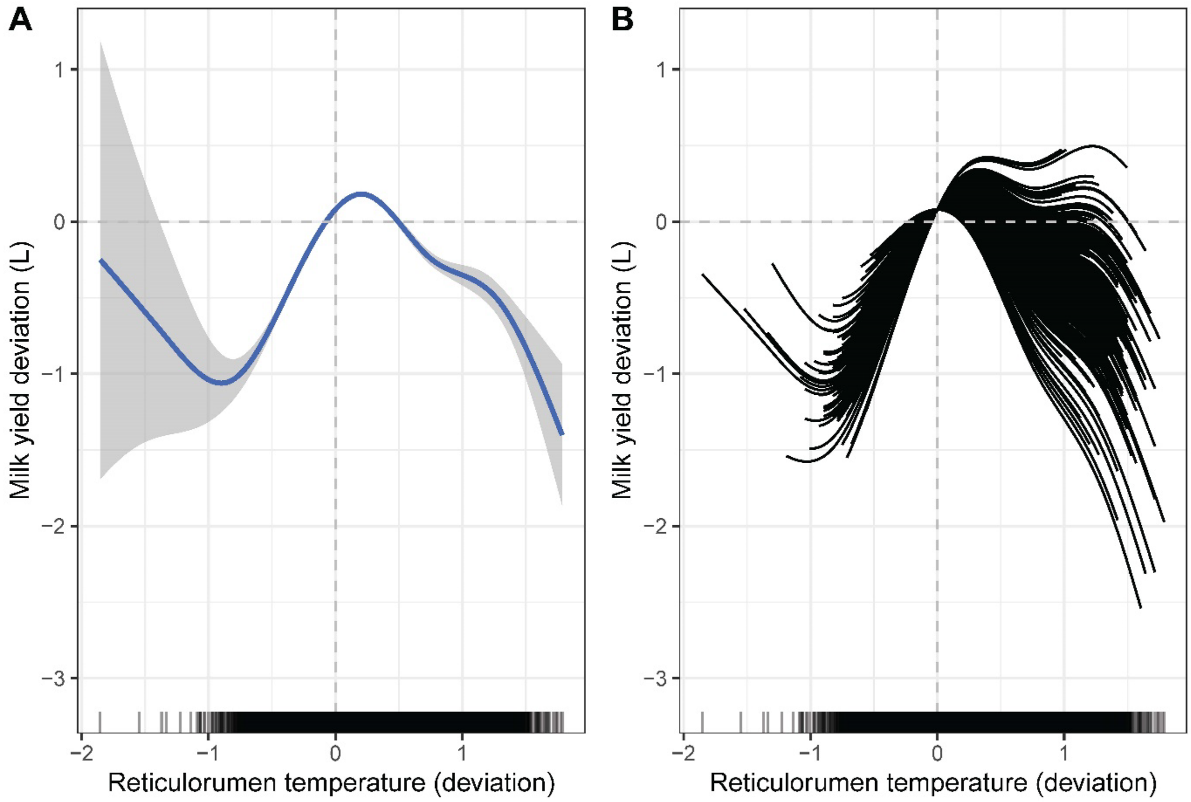

Figure 8. Association between $Temp_{dev}$ and $Yield_{dev}$ (L). Association depicted at both the farm (A) and individual (B) level. Truncation applied to display only THI ranges experienced by the farm and/or individual. The grey band in (A) represents ± 1 SE, a 'rug plot' is shown on the *x*-axis to indicate observed $Temp_{\_dev}$ values.

The association between $Temp_{dev}$ and $Yield_{dev}$ at both population and individual levels revealed overall positive associations at negative $Temp_{dev}$ and negative associations at positive Temp_{dev} (Figure 8). Low numbers of observed data points contributed to fanning of the SE at negative temperature deviations. A Wald test revealed the fixed effect of Temp_{dev} on $\text{Yield}_{\text{dev}}$ was not significant ($F_{1,25} = 0.08$, $p = 0.78$). Estimated variance components revealed significant variability in sensitivity to reticulorumen temperature change among individuals (Table 7). As estimated by the mixed model animal-specific slopes, individual variation (as changes to yield in response to reticulorumen temperature changes) were evident (Figure 9). All animals retained an average yield change between -1 and 1 L/°C change in reticulorumen temperature.

Table 7. Estimated variance components for the association between Temp_{dev} and $\text{Yield}_{\text{dev}}$.

Source of variation	Variance estimate	Standard Error	*z*-ratio
$s(\text{Temp}_{\text{dev}})$	9.30×10^{-1}	7.12×10^{-2}	1.31
ID	1.92×10^{-4}	NA	NA
ID× Temp_{dev}	2.09×10^{-1}	4.08×10^{-2}	5.12
$s(\text{Temp}_{\text{dev}})\times$ID	1.33×10^{-7}	NA	NA
Residual	8.35	2.65×10^{-2}	315.45

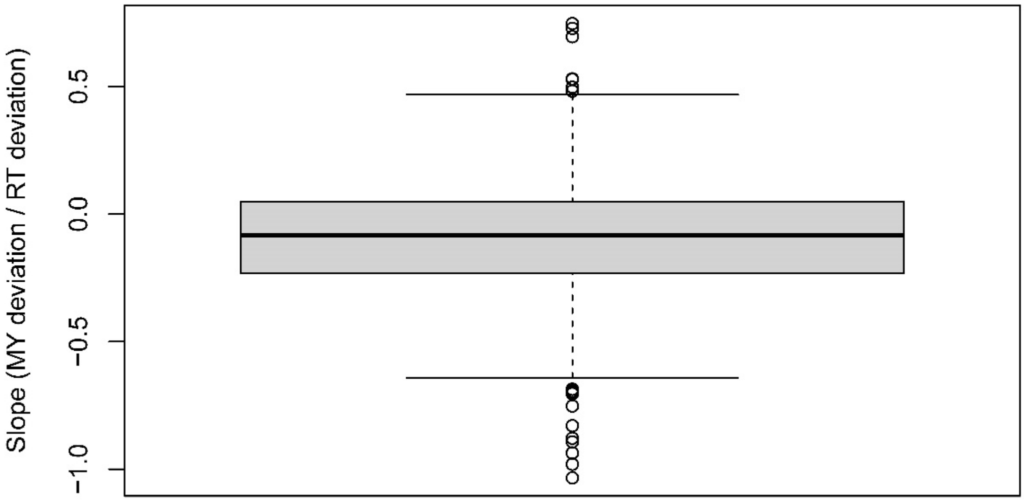

Figure 9. Sensitivity (slope) of $\text{Yield}_{\text{dev}}$ per change in Temp_{dev}, for each individual.

Attempts to fit a model for Temp_{smt} on $\text{Yield}_{\text{dev}}$ were unsuccessful, due to model estimation instability.

Reticulorumen temperature on drinking frequency

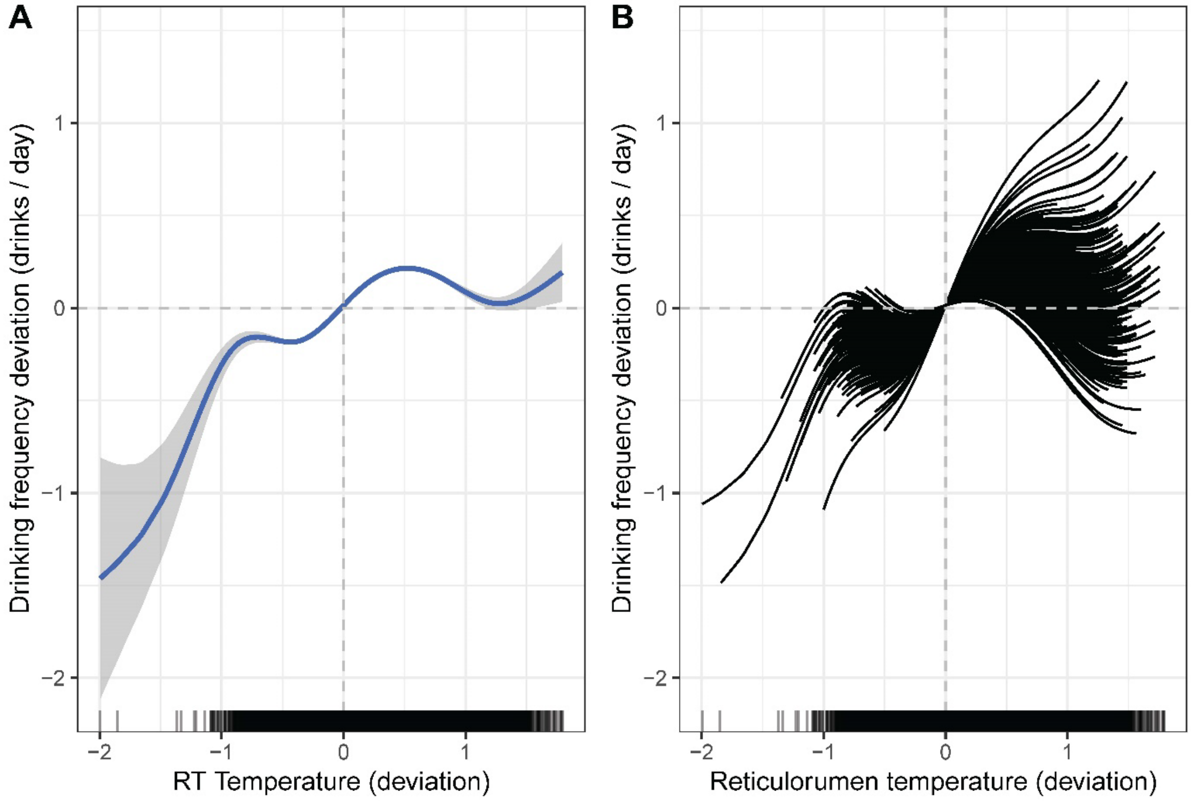

Figure 10. Association between Temp_{dev} and $\text{ndrink}_{\text{dev}}$ (drinks/day). Association depicted at both the farm (A) and individual (B) level. Truncation applied to display only THI ranges experienced by the farm and/or individual. The grey band in (A) represents ± 1 SE, a 'rug plot' is shown on the *x*-axis to indicate observed Temp_{dev} values.

The evaluation of Temp_{dev} and $\text{ndrink}_{\text{dev}}$ revealed positive associations (Figure 10). Wald test results confirmed significant differences between Temp_{dev} ($F_{1,\,104} = 9.48$, $p = 0.0027$). Intercept variability, based on its estimated variance component, was negligible though the between-animal slope variability was significant (Table 8). All animals maintained an average drinking frequency change between 0 – 1.5 events/Temp unit (Figure 11).

Table 8. Estimated variance components for the association between $\mathrm{Temp}_{\mathrm{dev}}$ and $\mathrm{ndrink}_{\mathrm{dev}}$.

Source of variation	Variance estimate	Standard Error	*z*-ratio
$s(\mathrm{Temp}_{\mathrm{dev}})$	4.11×10^{-1}	3.00×10^{-1}	1.37
ID	2.52×10^{-5}	NA	NA
ID× $\mathrm{Temp}_{\mathrm{dev}}$	6.45×10^{-2}	7.00×10^{-3}	9.23
$s(\mathrm{Temp}_{\mathrm{dev}})\times$ID	1.75×10^{-8}	NA	NA
Residual	1.10	2.95×10^{-3}	372.86

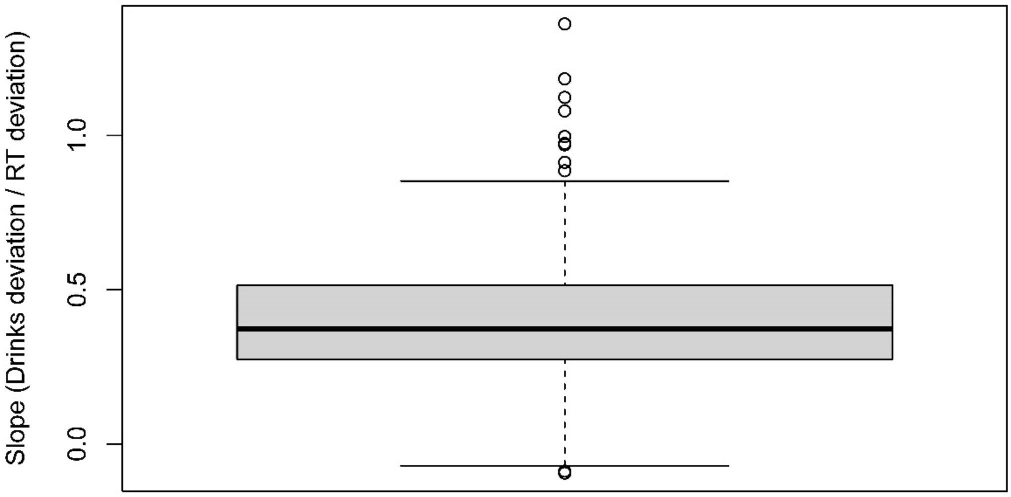

Figure 11. Sensitivity (slope) of $\mathrm{ndrink}_{\mathrm{dev}}$ per change in $\mathrm{Temp}_{\mathrm{dev}}$ for each individual.

Wald test results from the model of $\mathrm{Temp}_{\mathrm{smt}}$ and $\mathrm{ndrink}_{\mathrm{dev}}$ revealed no significant differences between $\mathrm{Temp}_{\mathrm{smt}}$ deviations ($F_{1,12} = 1.05$, $p = 0.33$). Visualisation of this model is available in Supplementary Figure S4. As for the above smoothed models, minimal individual variation was evident with residual error capturing the majority (Table 9).

Table 9. Estimated variance components for the association between Temp_{smt} and $\text{ndrink}_{\text{dev}}$.

Source of variation	Variance estimate	Standard Error	*z*-ratio
$s(\text{Temp}_{\text{smt}})$	1.48×10^{-3}	1.39×10^{-3}	1.07
ID	1.12×10^{-7}	NA	NA
ID× Temp_{smt}	4.50×10^{-10}	NA	NA
$s(\text{Temp}_{\text{smt}})$×ID	6.41×10^{-8}	NA	NA
Residual	1.11	2.98×10^{-3}	373.21

Association of slopes

As depicted above, we estimated the sensitivity of various traits to changes in either $\text{THI}_{\text{max\_dev}}$ or Temp_{dev}. These slopes reflect the degree of change in the respective traits per unit change in THI or reticulorumen temperature. To reveal the relationship between these slopes, a generalised pairs plot was developed (Figure 12). Naming conventions reflect the compared traits, for example Yield.THI represents how changes in milk yield (‘*y*’) occur in response to deviations in THI (‘*x*’). A very highly significant but weak negative relationship was evident between Drinks.THI and Temp.THI slopes. A very highly significant, weak positive relationship between Drinks.Temp and Drink.THI slopes was revealed. Highly significant, positive associations were evident between Yield.THI and Temp.THI, as well as Drinks.Temp and Yield.Temp. A significant, positive correlation was evident between Yield.Temp and Temp.THI slopes.

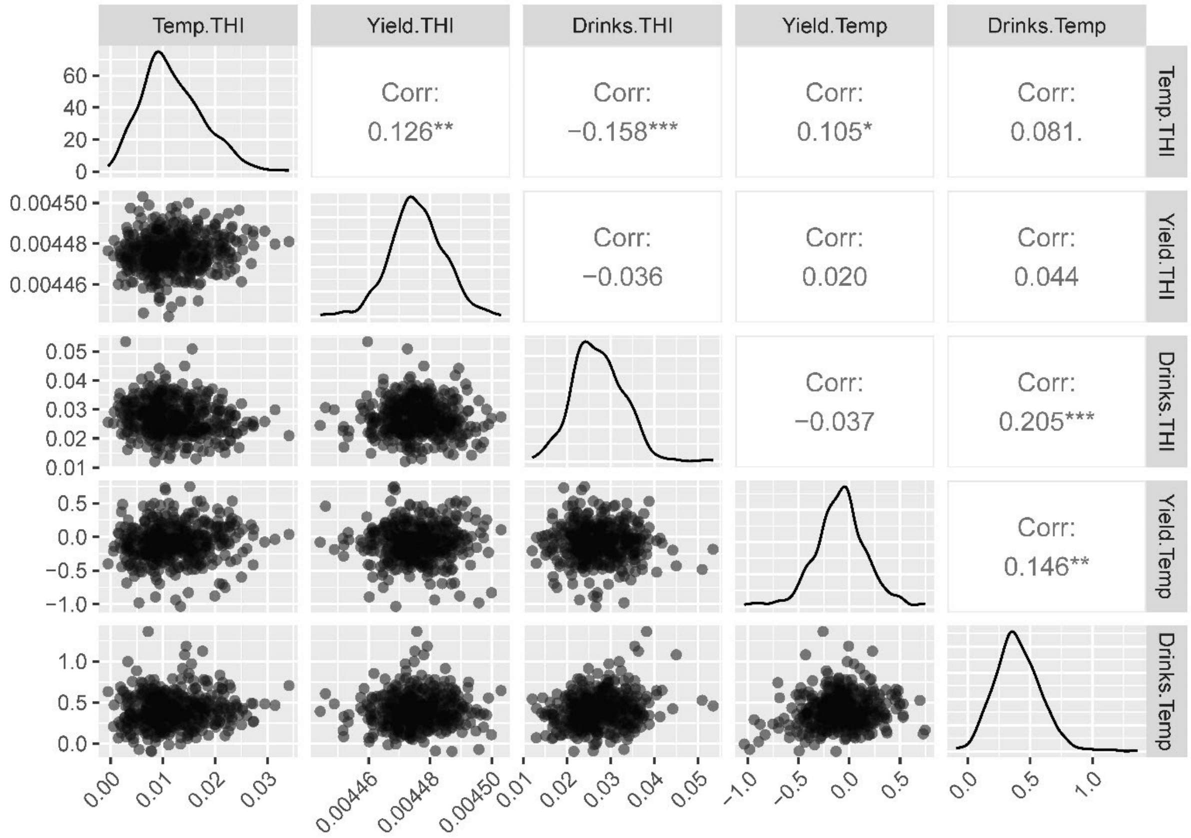

Figure 12. Generalised pairs plot revealing the association between slopes of Temp_{dev} per change in $\text{THI}_{\text{max\_dev}}$ (Temp.THI), $\text{Yield}_{\text{dev}}$ per change in $\text{THI}_{\text{max\_dev}}$ (Yield.THI), $\text{ndrink}_{\text{dev}}$ per change in $\text{THI}_{\text{max\_dev}}$ (Drinks.THI), $\text{Yield}_{\text{dev}}$ per change in Temp_{dev} (Yield.Temp), and $\text{ndrink}_{\text{dev}}$ per change in Temp_{dev} (Drinks.Temp) for each individual.

DISCUSSION

This research explored the impact of HS on dairy cattle, through an analysis of the temporal relationship between deviations in THI and reticulorumen temperature on resultant behavioural and physiological animal responses. Linear mixed models were fitted to determine how traits changed across environmental gradients over an 18-month period. Regression coefficients were extracted to compare individual animal sensitivity to heat, revealing selection strategies for heat tolerant animals.

Effects of thermal stress on dairy cattle systems were assessed through decomposition of all datasets. Cross-correlation analysis highlighted lag effects of $\text{THI}_{\text{max\_dev}}$ on $\text{Yield}_{\text{dev}}$, $\text{THI}_{\text{max\_dev}}$ on $\text{ndrink}_{\text{dev}}$ and Temp_{dev} on $\text{ndrink}_{\text{dev}}$. Many studies have demonstrated a large lag period of THI on milk yield (Polsky & von Keyserlingk, 2017; West, 2003); however, due to the nature of time series analysis, autocorrelation might impact the apparent association. Li et al. (2021) excluded autocorrelations using transfer function modelling and confirmed, as we did here, a one-day lag effect of maximum ambient temperature on milk yield. Although literature specific to the lagged effect of THI or reticulorumen temperature on drinking responses was not identified, the observed delay is not unprecedented. Limitations of daily milk yield measurements resulted in all data being levelled on a daily basis. As such, more regular analysis (e.g., hourly) might reveal different relationships and impact resultant analysis.

Significant effects of THI deviations were consistently evident for all physiological and behavioural responses. The high fixed effect significance confirms a strong population level effect was maintained for all traits in response to changes in THI. Smooth models generally provided no additional significance, suggesting that gradual changes in THI thresholds do not meaningfully differentiate animal responses; rather, sudden departures from the norm are most impactful. Climate projections have confirmed livestock will experience a higher HS this century (Thornton et al., 2021) and these results support others that advocate for the development of a robust HS alert system for Australian cattle (Cowan et al., 2024).

Positive associations of THI deviations on reticulorumen temperature, drinking frequency, and, unexpectedly, milk yield were revealed. Similarly, positive associations were seen for reticulorumen temperature deviations on drinking frequency. The exception to this was reticulorumen temperature on milk yield, which did not retain a positive relationship across all deviations. Instead, there was a positive relationship at low reticulorumen temperature deviations and negative at high reticulorumen deviations, aligning with biological expectations. Numerous studies have shown strong negative impacts of THI on milk yield, with Bouraoui et al. (2002) reporting a 32% decrease in milk production from THI 68 to 78, Spiers et al. (2004) a production decrease of 0.41 kg/cow/day for each THI unit increase above 69, and Hossain et al. (2023) reporting a yield decrease of 24.4% with a THI increase of 17%. Perhaps, our opposing result is reflective of the evaluation of THI as a deviation across a seasonal time frame rather than isolation into high THI thresholds. Alternatively, the positive association between THI and milk yield might reflect study-specific conditions, management strategies, and/or breed resilience but warrants further investigation to confirm this relationship. We do acknowledge this relationship was only obtained within certain limitations, with milk yield declining above a positive THI deviation of seven. Future work should consider repetition of this analysis at high range THI thresholds and optimally, include animal factors with the mixed model structure.

Slope coefficients were estimated to quantify individual animal responses to changing environmental stress. All traits revealed individual animal sensitivity in response to both THI and reticulorumen temperature variations. Individual diversity of internal body temperature and panting for feedlot cattle had been identified previously by Islam et al. (2023). A small amount of absolute variability was evident for milk yield responses here, compared to other traits, suggesting a more uniform effect of HS on production traits. Similarly, evaluating the effects of THI on physiological and production traits of dairy cattle, Amamou et al. (2019) found a 0.04 ˚C increase in rectal temperature per one THI unit increase, directly in line with our increase of 0.035 ˚C in reticulorumen temperature per THI unit. Milk yield appeared to retain consistency between their identified ‘tolerant’ and ‘sensitive’ groups (Amamou et al., 2019). Identifying a similar pattern, Levit et al. (2021) suggests exploration of milk composition rather than yield alone to enable distinction. Analysis of these slopes offers a potential selection tool for heat tolerant animals. Potential to transition these slopes into a genotype by environment evaluation should be considered.

As this analysis was conducted over an extended timeframe without isolation of HS events, the results will differ from similar datasets. Regardless, this analysis remains highly relevant due to the new insights provided from the exploration of these traits, contributing to a broader understanding of individual animal response to climate. The interpretation of these slopes is trait specific. To select for an animal demonstrating greater heat tolerance, preference would be for milk yield responses to remain positive or close to zero, indicative of stable or increasing production despite rising thermal challenge. A smaller increase in reticulorumen temperature with rising THI (i.e. a lower slope) would be selected for. Regarding drinking events, the behavioural response might be secondary to changes in internal temperature; therefore, while lower slopes are preferable, this should be interpreted with caution as it might not reflect a direct response to THI. Animals exhibiting response slopes indicative of heat tolerance should be further investigated to evaluate their comprehensive phenotypic response across all traits.

Slopes analysis revealed important inter-trait relationships for HS response. While correlations remained moderate, statistical significance was apparent. Drinking was a consistent behavioural response to cope with both internal and external heat stimuli, with animals increasing drinking frequency concurrent to both rising reticulorumen temperature and THI. Interrelated with this, animals that drank more during rising THI displayed a declining reticulorumen temperature under similar conditions, reinforcing the use of water consumption to reduce their own internal temperature, effectually buffering warm environmental conditions. Drinking behaviour of dairy cattle is linked closely with their ability to cope under high environmental stress (Hanušovský et al., 2017). An increase in drinking frequency is typically seen under HS, aligning with our findings, however lower quantities of water are consumed per visit (Tsai et al., 2020). Future studies should prioritise monitoring of frequency, water temperature, and consumption volume. Animals that drink more frequently due to increased reticulorumen temperature, can maintain milk production during that period of heightened internal temperature. This reinforces the ability of drinking behaviour to buffer production.

Animals that experienced increased milk yield with rising THI also experienced increasing reticulorumen temperature in the same conditions. This reinforces the notion that high producing animals experience an elevated internal heat load, likely reflective of metabolic rate from high milk yields and dry matter intake (Bernabucci et al., 2015; Pryce et al., 2022; West, 2003). Predictably, slope analysis showed that cows with a stronger increase in milk yield with rising internal temperature tended to have a greater rise in reticulorumen temperature with rising THI. This linked pattern of production and internal body temperature response to environmental heat is likely reflective of management conditions, providing cows the ability to cope with internal heat and maintain production.

The investigation of slopes analysis has highlighted the opportunity to consider multi-trait heat responses – using one trait to indicate another. Understanding these sensitivities within a herd is crucial to optimise production whilst maintaining welfare in a potentially challenging environment. Emphasised in the above results are the benefits of increased drinking frequency for minimising HS impact, alongside the consistent correlation of drink related traits to other indicators. Drinking behaviour is known to be an early indicator of HS (Idris et al., 2021) and the most important resource for a dairy cow experiencing HS (Polsky & von Keyserlingk, 2017). Therefore, monitoring of such behaviour might enable identification of animals affected by heat, prior to production losses occurring. This could be enabled through integration of automated water sensors and/or utilisation of artificial intelligence and large language models from video recordings near a water source, each offering non-invasive measurement possibilities. A proposed embedding imaging system by Tsai et al. (2020) offers novel approaches to the automatic and quantitative assessment of dairy cow drinking behaviour, with factors such as hierarchy within the herd, as explored by Foris et al. (2024), important considerations. Integration of drinking behaviour measurements into current technologies implemented on farm can provide deeper insights into health and productivity across a herd and should be considered.

CONCLUSION

This study investigated associations between reticulorumen temperature, milk yield, and drinking frequency as indicators of heat tolerance in dairy cattle. Findings confirmed significant effects of thermal stress on all three traits, with notable variability in individual animal responses. Slopes analysis revealed key inter-trait correlations, underscoring their interconnected role in the physiological and behavioural response to thermal change. Drinking behaviour emerged as a correlated, easily measurable proxy for HS. Integration of behavioural monitoring, especially for drinking activity, offers a practical, low-cost approach for the identification and support of individuals with less tolerance. These outcomes support the sustainability of dairy systems moving forward.

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CHAPTER 7

General Discussion and Conclusion

INTRODUCTION

The requirement for heat stress (**HS**) research has become increasingly necessary within the dairy industry and agriculture more broadly. Projected climate outlooks forecast significant negative implications on ruminant productivity (Blunden & Boyer, 2022), with high-producing dairy cattle greatly susceptible to HS (Tao et al., 2020; West, 2003). Industry restructuring has forced efficiency improvements, largely made possible through technological adoption. The era of precision livestock farming has contributed to on-farm management optimisation, offering new opportunities for production gains and welfare improvements, while maintaining social licence to operate (Hendriks et al., 2025; Rose & Chilvers, 2018). Yet, the full use of generated data for health and welfare improvements, specifically within the realm of ruminant HS, remains untapped.

The overarching aim of this thesis was to reveal and exploit the diversity in dairy cattle reticulorumen temperature data for HS amelioration, motivated by potential benefits to cattle welfare in changing climatic conditions. Progression was evident from a conceptual and definitional foundation (Chapters 2 and 3), through technical development and modelling (Chapter 4), to applied analyses of environmental and individual-level variation (Chapters 5 and 6). This final chapter brings these components together, offering a synthesis of key findings and discussion of broader implications and future directions.

KEY FINDINGS

In Chapter 2, existing dairy cattle HS literature was explored, with a sequential focus on thermal indices, physiological and behavioural responses, monitoring methods, and heat amelioration techniques. While their use is not new, the benefits of a reticulorumen bolus for monitoring at the individual animal level as a proxy for core body temperature warranted further investigation. Exploration of such technology that can improve on-farm decision making was aligned with the evolution of precision livestock farming (Aquilani et al., 2022). As such, an improved understanding of the current state and gaps in knowledge regarding dairy cattle HS was achieved (Objective 1). While highlighting areas for ongoing research, Chapter 2 also called attention to inconsistencies in the definitions of terms used within the field. In the provision of definition clarity for common heat abatement terminology

(Objective 2), namely 'resistance', 'tolerance', 'resilience', and 'susceptibility', Chapter 3 set a strong foundation for conducting HS research and its practical application moving forward. Demonstrating the value of reticulorumen bolus technology for continuous monitoring at the individual level, Chapter 4 confirmed the use of internal body temperature and water consumption as key physiological indicators of HS. Development of a novel drinking event detection model (Objective 3) provided algorithm transparency that commercial bolus companies do not typically provide. This work showcased the dynamics of animal temperature responses to climate conditions across seasons, improving our understanding of core body temperature diversity (Objective 3). Extending this research, Chapter 5 retained a specific focus on the influence of environmental conditions, specifically temperature humidity index (**THI**), on changes in reticulorumen temperature across three farm contexts. Significant variability in sensitivity to thermal change between individuals was confirmed, reinforcing the requirement for individualised, animal-level monitoring (Objective 4). The requirement to review industry-established THI thresholds to better reflect responses of the high-producing dairy cow seen today was recognised, in agreement with other research (Moore et al., 2024; Pinto et al., 2020). Chapter 6 prioritised the investigation of 'easy to monitor' phenotypic indicators, revealing associations between key heat tolerance traits. Associations between relevant trait slopes revealed an opportunity for genotype by environment evaluations to transition these phenotypes into a genetic selection tool for heat tolerant animals (Objective 5). Together, these chapters form a cohesive body of work that supports the implementation of precision livestock farming practices and their role in using physiological differences for early identification of HS to enable targeted intervention and/or selective breeding.

INDUSTRY CONTRIBUTIONS

Contextually, this research contributes to knowledge development regarding climate resilience and technology integration across the dairy sector. The review of HS terminology yields a robust framework for both scientific inquiry and industry communication. Critically, clarification on what each heat abatement term constitutes, reduces ambiguity of future work and ensures that research and industry output can be analogous (Chapter 3). The potential for boluses as a foundational tool to aid primary decision making at a farm level has been showcased (Chapters 5 and 6), supporting the integration of this and similar tools into commercial production across the broader industry. The practicality of bolus technology for both research and commercial practice has been highlighted. A high percentage of data examined throughout this work was historical, demonstrating the potential output when using sophisticated data analysis to best leverage existing data collection efforts (Chapters 4, 5 and 6). Through the incorporation of physiological data with environmental metrics, greater profundity has been brought to the data analysis, uncovering novel insights (Chapter 5). Recognition of the cow as an individual, rather than collective grouping within the larger herd, reinforces the need for tailored management in the short-term and selective breeding in the long-term (Chapters 5 and 6). Identification of correlations between phenotypic traits for heat tolerance offers the potential for ongoing genotypic investigation (Chapter 6). Overall, this research provides opportunities for climate-smart breeding at the animal level that will contribute to the preparation of a future-proof industry.

RESEARCH GAPS AND FUTURE WORK

Industry contributions have been numerous, but this research is not without its limitations. As discussed in the Chapter 2 literature review, there are several thermal indices used across the livestock industry, each investigated across various environmental conditions and production systems (Wang et al., 2018). Limitations due to restricted data availability from the weather stations of closest proximity to our study locations, enabled only THI to be examined across all research chapters (Chapters 4, 5, and 6). Further work should prioritise investigation of individual animal response to thermal changes, not just with THI, but across indices developed for dairy cattle that account for additional environmental factors such as the dairy heat load index (Lees et al., 2018) and the grazing heat load index (Bryant et al., 2023). Chapters 4 and 5 presented findings from three different herds, under different management conditions across an up to four-year period. While considerable animal numbers were included (n = 1,429), broader representation of diversity across the national dairy herd might be beneficial. This was particularly evident in Chapter 6 where a single farm was investigated (n = 498). Additionally, complementary animal factor information was not available, restricting comparison to more recent research developments. As such, replicated studies should not only be conducted across a broader range of farms and locations but prioritise the inclusion of animal-level factors for model development such as age, parity, and specific breed composition, as they have been shown to influence HS response (Gantner et al., 2020;

Osei-Amponsah et al., 2023). As the current heat tolerance Australian breeding value (ABV) accounts not only for total milk yield, but for fat and protein components (Nguyen et al., 2016), their collection should also be prioritised in future work.

Moving forward, the work presented here has highlighted numerous opportunities for HS research. The identification of a potential core body temperature phenotype, alongside investigation into the association between phenotypic indicators of heat tolerance, is well-positioned to be extended into genetic evaluation. The benefits of a data-driven approach through hybrid modelling (Chapter 2) must be capitalised on. The optimisation of systems to analyse animal data collected in real-time to trigger targeted, on-farm heat amelioration could reform how we perceive the impacts of HS. Further, the expansion of monitoring frameworks across the industry will enable a more holistic understanding of HS impact and drive ongoing research outputs to optimise productivity, profitability, and welfare across the industry.

CONCLUSION

This thesis explored the diversity in dairy cattle reticulorumen temperature data for HS amelioration. The current state of knowledge regarding HS research was identified. Precise definitions for terms relevant to ruminant HS were established, ensuring alignment of research and industry implementation. A novel drinking event detection algorithm was developed and used to explore the temporal variability in drinking behaviour of pasture-based dairy cattle. Using time series and mixed model analysis, the impact of reticulorumen temperature in response to THI was established, revealing significant variability in sensitivity to thermal change among individuals. Finally, the association between reticulorumen temperature, milk yield, and drinking frequency in response to THI was determined, discovering innovative selection strategies for heat tolerant animals. From the confirmation of individual animal reticulorumen temperature diversity, future work can target transition from phenotypic identification to genetic selection for heat tolerance. This work has contributed to growing evidence that recognition of diversity among individual cattle within a herd is critical for both scientific understanding and practical management. Under progressive effects of climate change, this research supports a shift in position from reactive, group-level monitoring to proactive, data-driven care. While the impacts of HS cannot be entirely removed on-farm, outputs from this work will contribute to improvements in welfare and productivity across the system, supporting preparation for a sustainable future.

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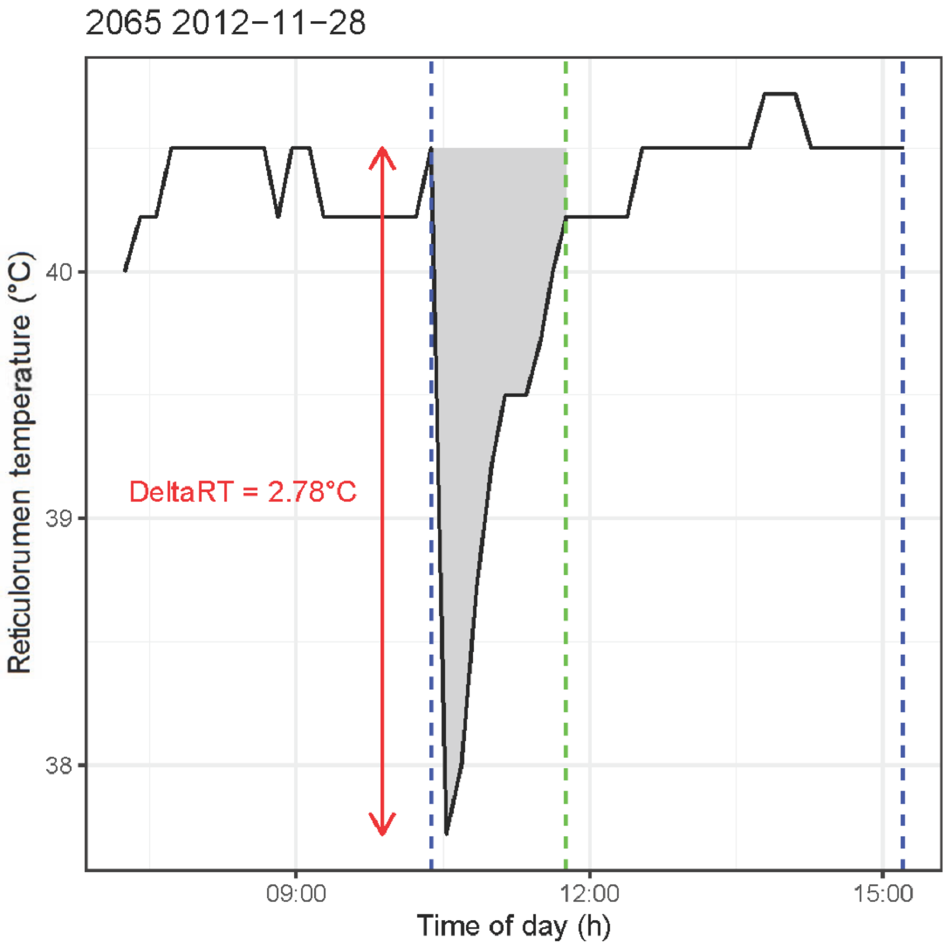
APPENDIX

Supplementary Material

SUPPLEMENTARY MATERIAL: CHAPTER 4

Cumulative temperature loss during drinking event

As a measure of overall heat loss during a drinking event, the ‘area under the curve’ between times t and $t_i^{(k)}$ using reticulorumen values over this interval is calculated using a simple trapezoidal method. These areas will also be censored if $t_i^{(k)}$ is censored.



Blue dashed lines: start of temperature drop.

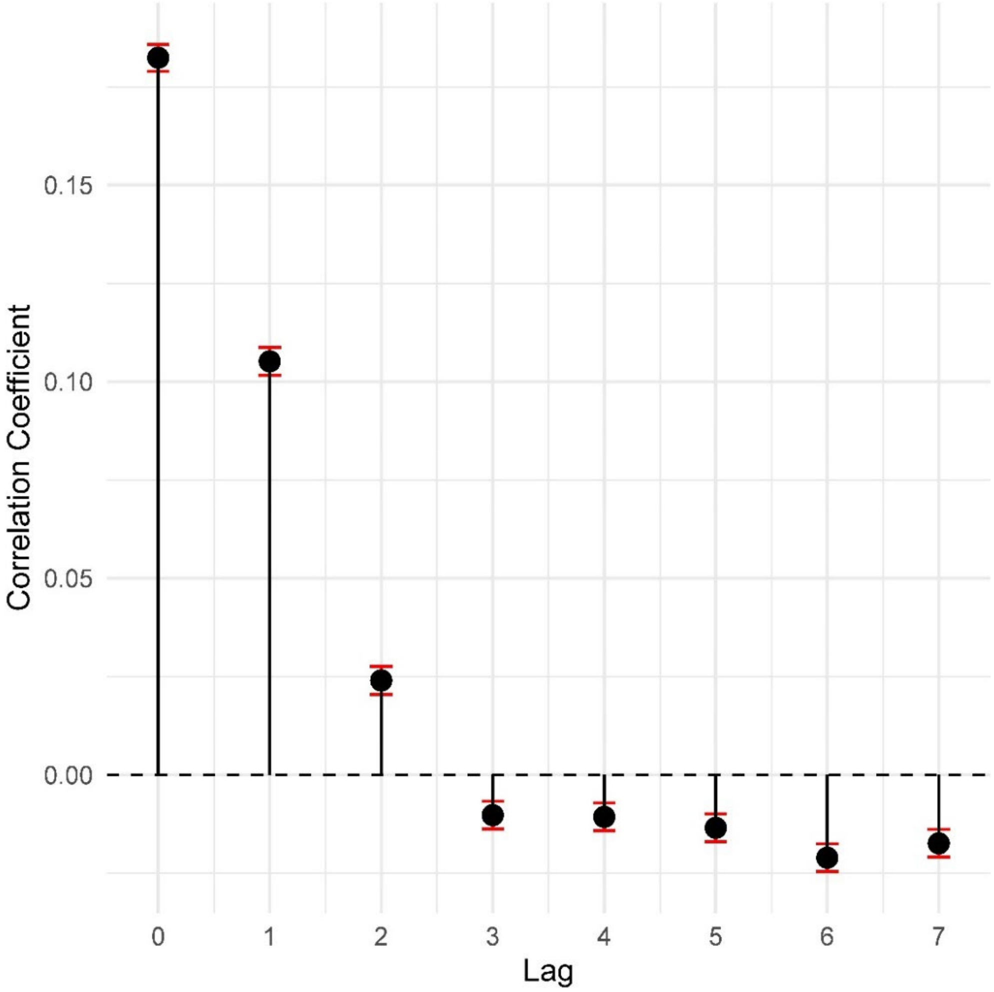
Green dashed line: end of temperature drop (90% recovery).

Red line: magnitude of temperature drop (ΔRT).

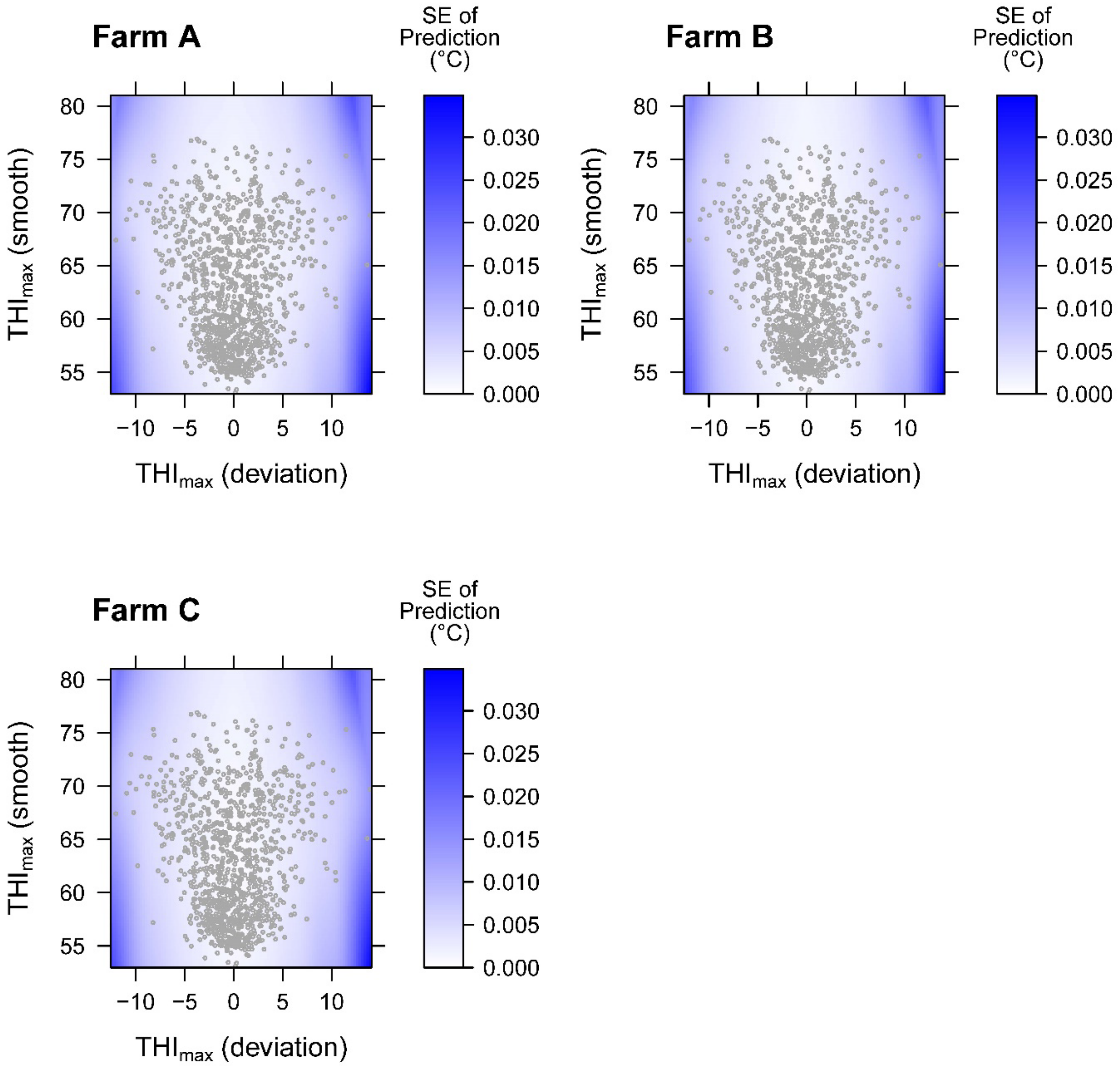
Grey shaded area: cumulative temperature loss.

SUPPLEMENTARY MATERIAL: CHAPTER 5

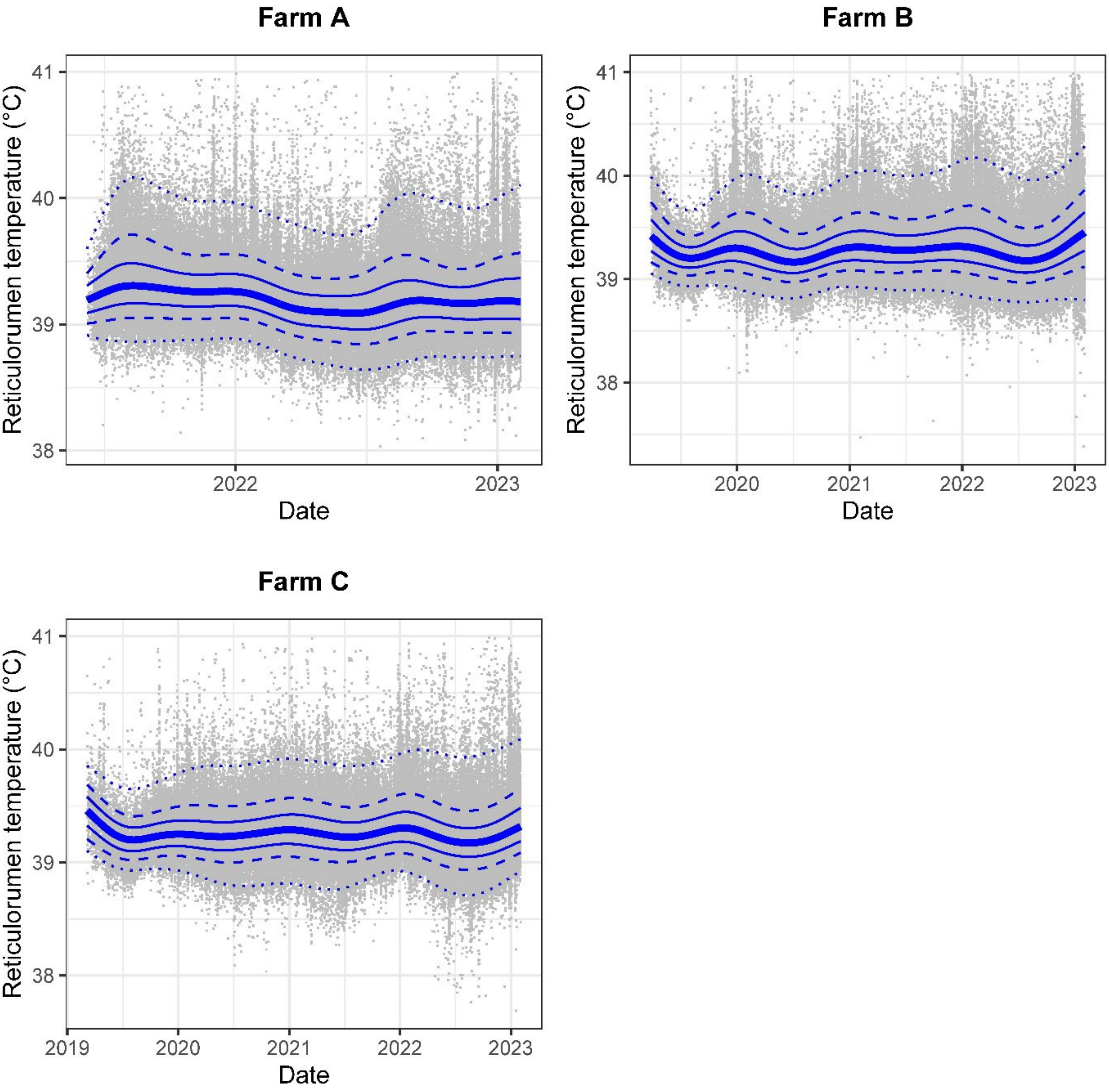
Supplementary Figures



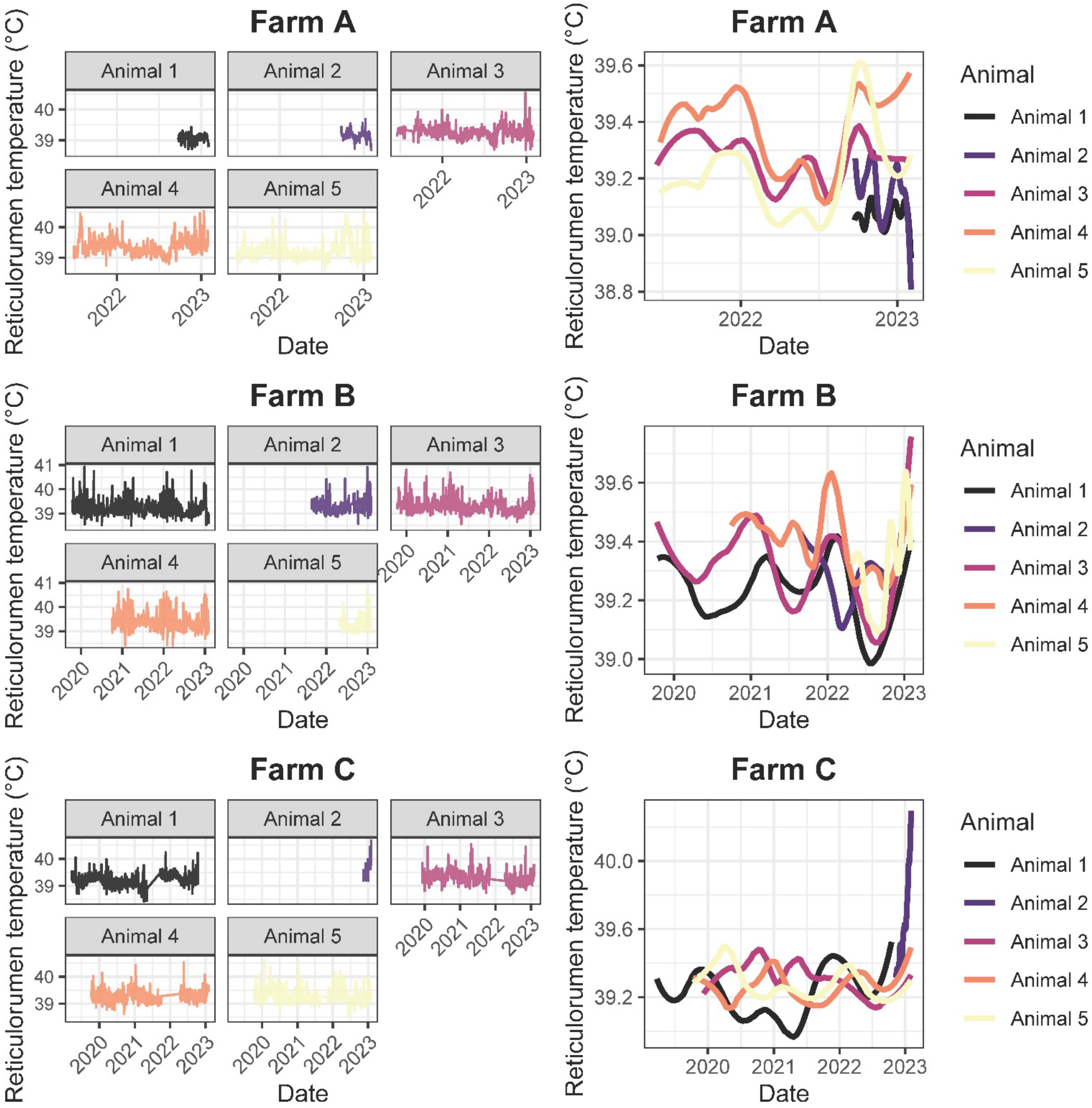
Supplementary Figure S1. Cross-correlation plot between reticulorumen temperature and temperature humidity index (decomposed residual deviations of THI_{max}) for lags up to seven days. Bars represent 95% confidence intervals.



Supplementary Figure S2. Surface plot of standard error of predictions, overlayed with points showing observed value of THI$_{max}$ (deviation) and THI$_{max}$ (smooth). An individual surface plot is displayed per farm alongside a colour legend.



Supplementary Figure S3. Scatter plot of raw reticulorumen temperature data for all animals over time, for each farm. The overlaid smoothed lines represent from bottom to top, the 1%, 10%, 25%, 50% (median), 75%, 90% and 99% quantiles.



Supplementary Figure S4. Illustrative plot of a random sample of five animals from each farm showing raw reticulorumen temperature data (LHS) and smoothed data (RHS) illustrating between-animal variation.

Supplementary Tables

Supplementary Table 1. Wald tests for fixed effects; response = reticulorumen temperature deviation ($\mathrm{THI}_{\mathrm{max}}$ (deviation)).

	Num. DF	Den. DF	*F*-statistic	*P*-value
Farm	2	303,988	3.12	0.0057
$\mathrm{THI}_{\mathrm{max\_dev}}$	1	2570	710.10	< 0.0001
Farm × $\mathrm{THI}_{\mathrm{max\_dev}}$	2	749	40.96	< 0.0001

Supplementary Table 2. Estimated variance components for the association between $\mathrm{THI}_{\mathrm{max}}$ (deviation) and reticulorumen temperature (˚C).

Source of variation	Variance estimate	Standard Error	*z*-ratio
$s(\mathrm{THI}_{\mathrm{max\_dev}})$	2.60×10^{-3}	1.59×10^{-3}	1.63
ID	2.19×10^{-10}	NA	NA
ID×$\mathrm{THI}_{\mathrm{max\_dev}}$	3.72×10^{-5}	2.29×10^{-6}	16.27
$s(\mathrm{THI}_{\mathrm{max\_dev}})$×ID	2.19×10^{-10}	NA	NA
Residual	3.42×10^{-2}	8.77×10^{-5}	389.85

Supplementary Table 3. Wald tests for fixed effects; response = reticulorumen temperature remainder ($\mathrm{THI}_{\mathrm{max}}$ (smooth)).

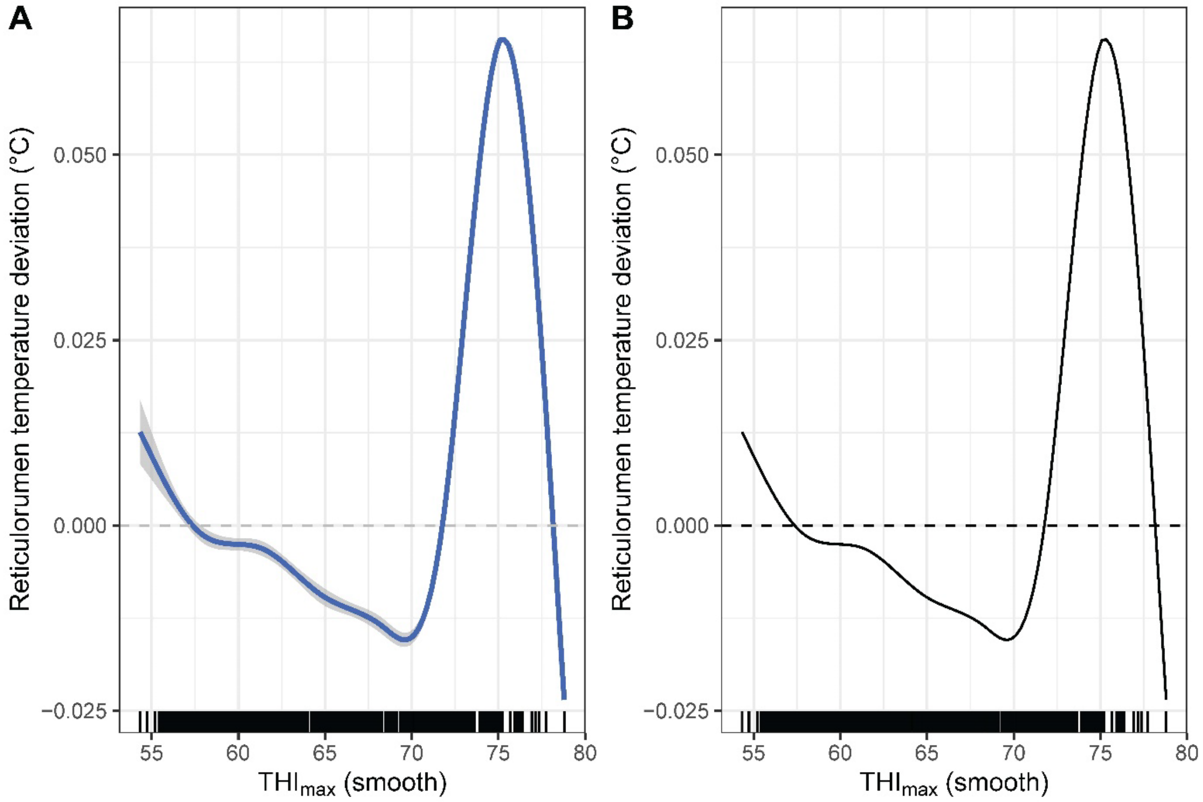
	Num. DF	Den. DF	*F*-statistic	*P*-value
Farm	2	304,752	36	< 0.0001
$\mathrm{THI}_{\mathrm{max\_smooth}}$	1	52,188	1458	< 0.0001
Farm × $\mathrm{THI}_{\mathrm{max\_smooth}}$	2	304,753	164.8	< 0.0001

Supplementary Table 4. Estimated variance components for the association between $\mathrm{THI}_{\max}$ (smooth) and reticulorumen temperature (˚C).

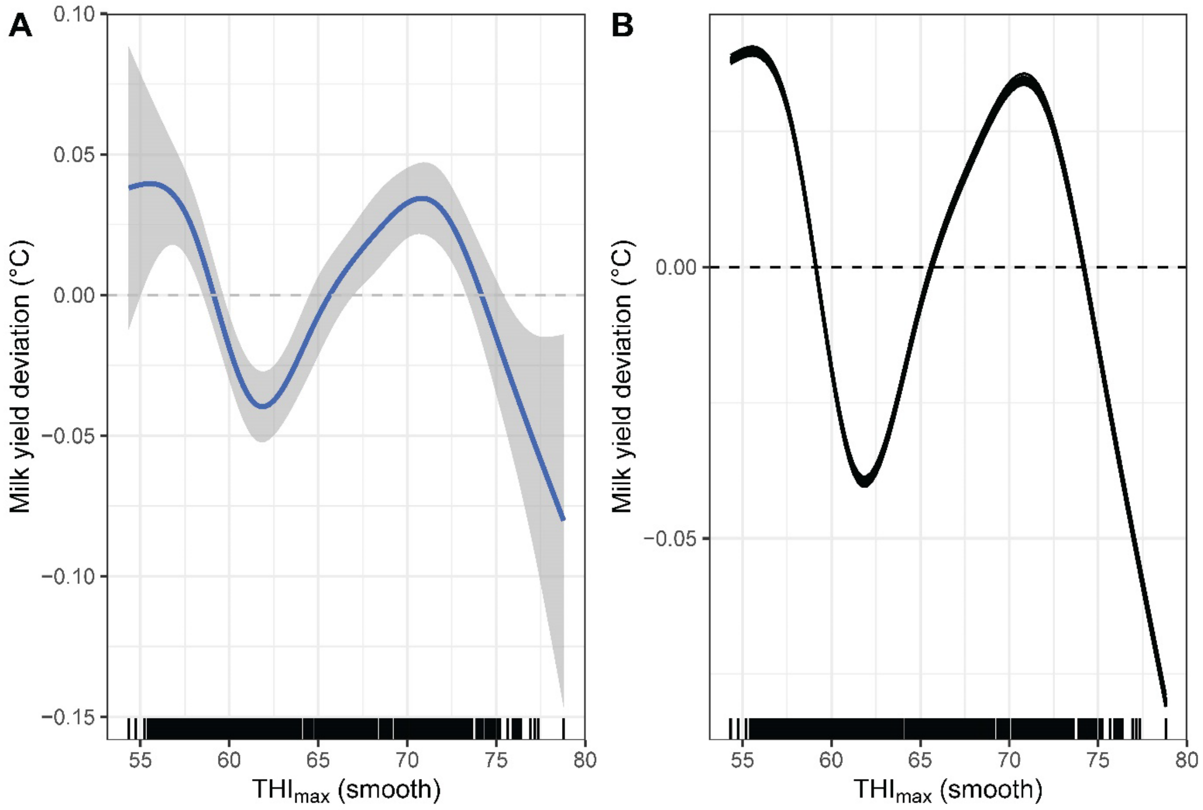
Source of variation	Variance estimate	Standard Error	*z*-ratio
$s(\mathrm{THI}_{\mathrm{max\_smooth}})$	7.06×10^{-3}	4.12×10^{-3}	1.72
ID	3.62×10^{-9}	NA	NA
$\mathrm{ID} \times \mathrm{THI}_{\mathrm{max\_smooth}}$	1.45×10^{-11}	NA	NA
$s(\mathrm{THI}_{\mathrm{max\_smooth}}) \times \mathrm{ID}$	9.78×10^{-10}	NA	NA
Residual	3.57×10^{-2}	9.15×10^{-5}	390.35

SUPPLEMENTARY MATERIAL: CHAPTER 6

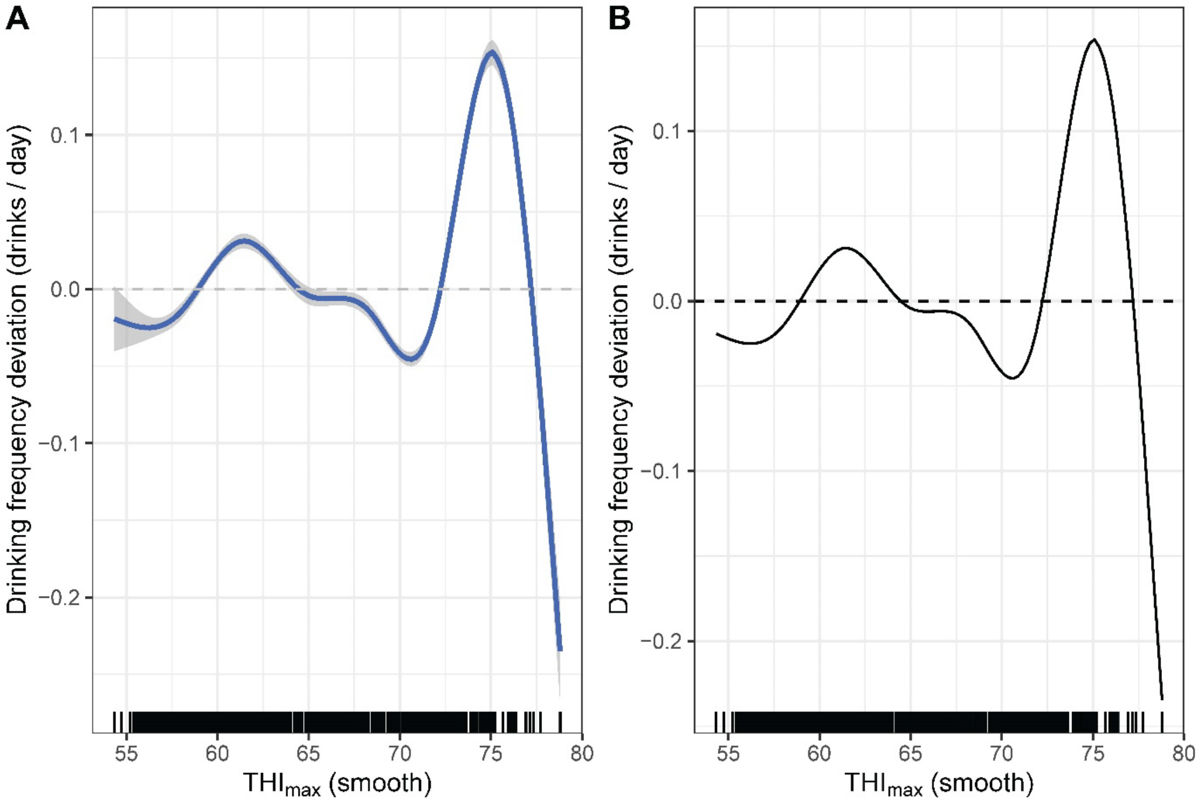
Supplementary Figures



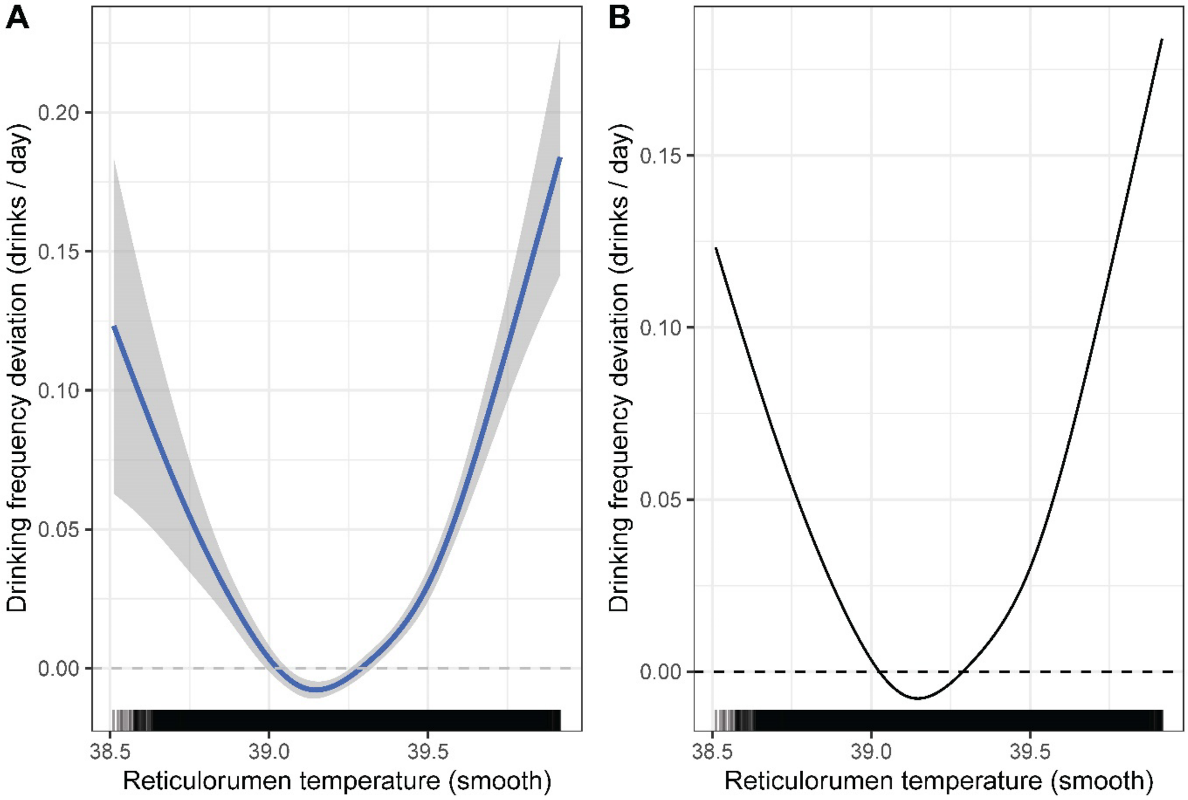
Supplementary Figure S1. Association between THI$_{max\_smt}$ and Temp$_{dev}$ (˚C). Association depicted at both the farm (A) and individual (B) level. Truncation applied to display only THI ranges experienced by the farm and/or individual. The grey band in (A) represents ± 1 SE, a ‘rug plot’ is shown on the *x*-axis to indicate observed THI$_{max\_smt}$ values.



Supplementary Figure S2. Association between $\text{THI}_{\text{max\_smt}}$ and $\text{Yield}_{\text{dev}}$ (L). Association depicted at both the farm (A) and individual (B) level. Truncation applied to display only THI ranges experienced by the farm and/or individual. The grey band in (A) represents ± 1 SE, a 'rug plot' is shown on the *x*-axis to indicate observed $\text{THI}_{\text{max\_smt}}$ values.



Supplementary Figure S3. Association between THI$_{max\_smt}$ and ndrink$_{dev}$ (drinks/day). Association depicted at both the farm (A) and individual (B) level. Truncation applied to display only THI ranges experienced by the farm and/or individual. The grey band in (A) represents ± 1 SE, a 'rug plot' is shown on the *x*-axis to indicate observed THI$_{max\_smt}$ values.



Supplementary Figure S4. Association between Temp_{smt} and $\text{ndrink}_{\text{dev}}$ (drinks/day). Association depicted at both the farm (A) and individual (B) level. Truncation applied to display only THI ranges experienced by the farm and/or individual. The grey band in (A) represents ± 1 SE, a 'rug plot' is shown on the *x*-axis to indicate observed Temp_{smt} values.