Feature Article

Heat stress amelioration for pasture-based dairy cattle: challenges and opportunities

Stacey J. Hendriks,[†] John Paul Edwards,[†] Alice K. Shirley,[‡] Cameron E. F. Clark,[‖] Karin E. Schütz,[$] Kirsty J. Verhoek,[¶] and Jenny G. Jago[¶]

[†]DairyNZ Ltd., PO Box 85066, Lincoln 7647, New Zealand

[‡]Livestock Production and Welfare Group, School of Life and Environmental Sciences, The University of Sydney, Camden, NSW 2570, Australia

[‖]Gulbali Institute, Charles Sturt University, Wagga Wagga, NSW 2650, Australia

[$]AgResearch Ltd., Ruakura Research Centre, 10 Bisley Road, Hamilton 3214, New Zealand

[¶]DairyNZ Ltd., Private Bag 3221, Hamilton 3240, New Zealand

Implications

- The mental effects of heat stress in dairy cattle are poorly understood.
- Providing effective heat abatement while allowing cows to engage in highly motivated behaviors is important to maintain good welfare.
- On-animal sensors will help understand, monitor, and predict individual cow heat load.
- Mitigation now and in future should use known strategies, while research into novel mitigations continues.
- Advancing adaptation using genetic selection requires novel phenotypes for heat tolerance to be identified.

Key words: climate change, cow welfare, pasture, temperature, thermal comfort

Introduction

Societal scrutiny of animal welfare in food production systems is intensifying. In the dairy sector, the impact of heat stress on cow productivity, health, and welfare is a growing global concern, particularly with increasing temperatures and weather variability predicted to become more extreme (Nguyen et al., 2016). Excessive heat can negatively impact biological functioning including milk production, health, and reproduction (Kadzere et al., 2002), and in severe circumstances, it can cause suffering, reduce quality of life, or even lead to death (Polsky and von Keyserlingk, 2017). The cost of unmitigated heat stress to the global dairy industry could reach $30 billion (USD) by 2050 (Allen, 2024). This global challenge requires locally tailored solutions due to variations in animal characteristics, farm systems, locations, and climatic drivers.

Dairy farming occurs across the Northern and Southern Hemispheres, encompassing temperate, cold, and hot climates. Temperate climates provide conditions that fall mostly within the thermoneutral zone for modern dairy cattle breeds, which is ideal for dairy farming since cows do not need to expend additional energy to regulate their core temperature (Figure 1: Kadzere et al., 2002). Temperate climates also support low-cost, seasonal-calving systems reliant on seasonal pasture growth, common in New Zealand and Australia (Figure 2).

According to the Köppen–Geiger climate classification, dairying areas in New Zealand and Australia are mostly temperate, with average ambient temperatures from 0 to 20 °C (min: –40 °C; max: 40 °C) (Figure 2: Peel et al., 2007). About 5% of Australia's and 5% of New Zealand's dairy production occurs outside this zone, mainly in subtropical regions (i.e., Queensland and Northern New South Wales, Australia and Northland, New Zealand; Figure 2). All dairying areas in New Zealand and Australia, however, experience days when ambient temperatures exceed the cows' thermoneutral range. Solar radiation, humidity, and wind speed also impact heat load by affecting radiative heat transfer and evaporative cooling (Blackshaw and Blackshaw, 1994). Indices for predicting conditions associated with increased heat stress risk have been developed using environmental factors as predictors (Ji et al., 2020). The commonly used Temperature Humidity Index (**THI**) combines air temperature and humidity but omits weather variables such as wind speed and solar radiation, critical for outdoor-grazing cows (Blackshaw and Blackshaw, 1994). Indices that include these factors better predict outdoor cattle thermal load. New Zealand's Grazing Heat Load Index (**GHLI**) uses such factors to predict dairy cattle respiration rates (Bryant et al., 2022). On the contrary, Australia's mixed systems, where cows are pasture-fed or

https://doi.org/10.1093/af/vfae043

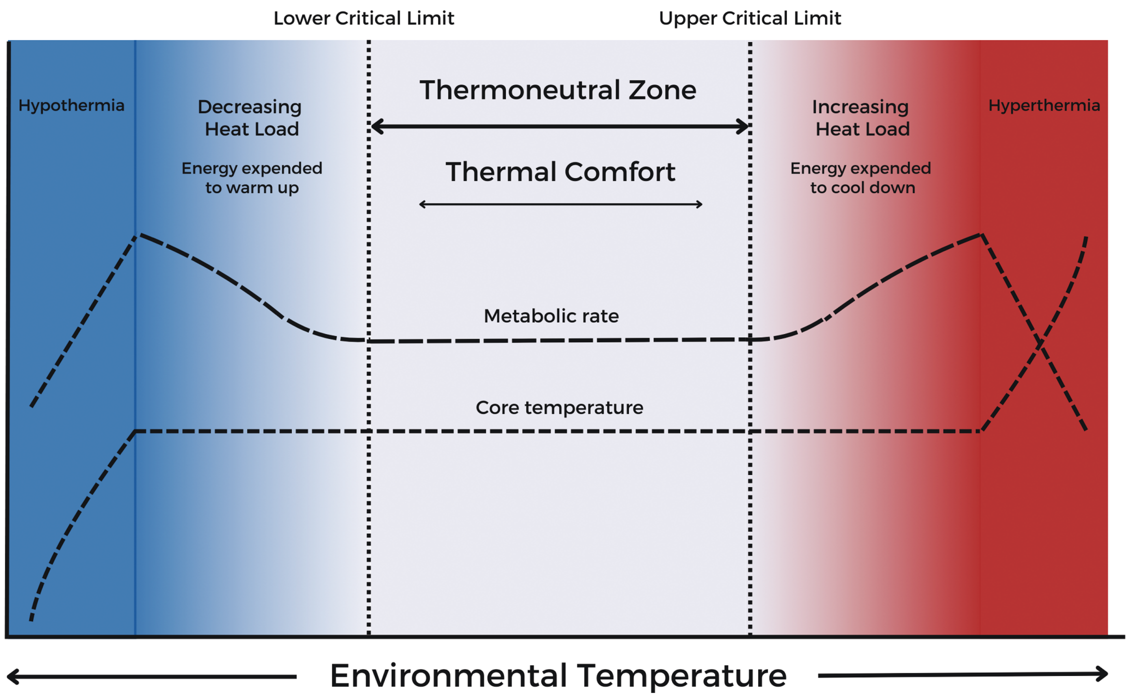

Figure 1. A schematic of the influence of environmental temperature on cattle metabolic rate (balance between heat loss and gain) and core temperature. According to the environmental temperature on the x-axis moving away from the center toward the left of the image indicates cooler temperatures and moving away from the center toward the right of the image indicates warmer temperatures. Adapted from Kadzere et al. (2002).

have pasture access with partial mixed rations, utilize both the THI and dairy heat load index (**DHLI**) (Lees et al., 2018). While there is a need for more accurate indices in both New Zealand and Australia, available indices have modeled scenarios to define current and predict future heat stress risk.

In New Zealand and Australia, where large populations of dairy cows are kept outdoors, it is recognized that heat stress is a significant and ongoing issue facing the dairy sector (Jago et al., 2023). Recent modeling indicates that dairy cows are at risk of heat stress annually for 40 to 85 days in New Zealand and 100 to 300 days in Australia, regardless of the indices or thresholds used in prediction (Nidumolu et al., 2010; Nguyen et al., 2016; Woodward et al., 2024a). By 2050, under low to high emission futures scenarios, the number of heat stress risk days is predicted to rise even in regions previously less prone to such conditions (Nidumolu et al., 2010; Woodward et al., 2024a).

This review highlights areas that require ongoing research to better understand the onset and effects of heat stress on dairy cows kept predominantly outdoors in New Zealand and Australia. We summarize the challenges and opportunities in developing fit-for-purpose tools to predict, monitor, and mitigate heat load, and strategies to adapt to heat load. Our goal is to support the development of sustainable and climate-resilient farm systems for outdoor dairy cows.

Defining Heat Stress and Heat Load

Heat load and heat stress are often used synonymously in the literature, with definitions differing among authors. Both terms relate to environmental conditions (temperature, humidity, solar radiation, and wind speed) and animal factors (genotype, coat color, breed, age, and stage of lactation) affecting cows' thermal balance and tolerance (Kadzere et al., 2002). Cattle maintain a stable core temperature within the range 38 to 39.3 °C for optimal functioning (Bewley et al., 2008). Heat exchange between an animal's body and its environment can lead to heat loss or gain through radiation, convection, conduction, and evaporation. Cattle respond to environmental conditions through hormonal, metabolic, behavioral, and physiological responses to balance heat loss with heat gain. An imbalance leads to hyperthermia (increased core temperature) or hypothermia (decreased core temperature) (Figure 1).

We define increased heat load as the thermal state where an animal must respond to environmental conditions physiologically (altered respiration, panting, and blood flow to the skin) or behaviorally (altered dry matter intake, activity, and lying time) to maintain thermal balance and normal functioning. We define heat stress as the physiological state where the animal's adaptive mechanisms to dissipate heat to maintain thermal balance have been overcome, which can lead to reduced biological functioning (Kadzere et al., 2002). Signs of heat stress may include hyperthermia (elevated core temperature beyond critical limits) (Bewley et al., 2008), reduced milk production (Chen et al., 2024), impaired fertility (Kadzere et al., 2002), drooling, and open-mouthed breathing, alongside behavioral changes that also occur during increasing heat load.

Predicting Heat Stress Risk

Developing tools to predict heat stress risk and monitor heat load and stress, while also exploring options to mitigate

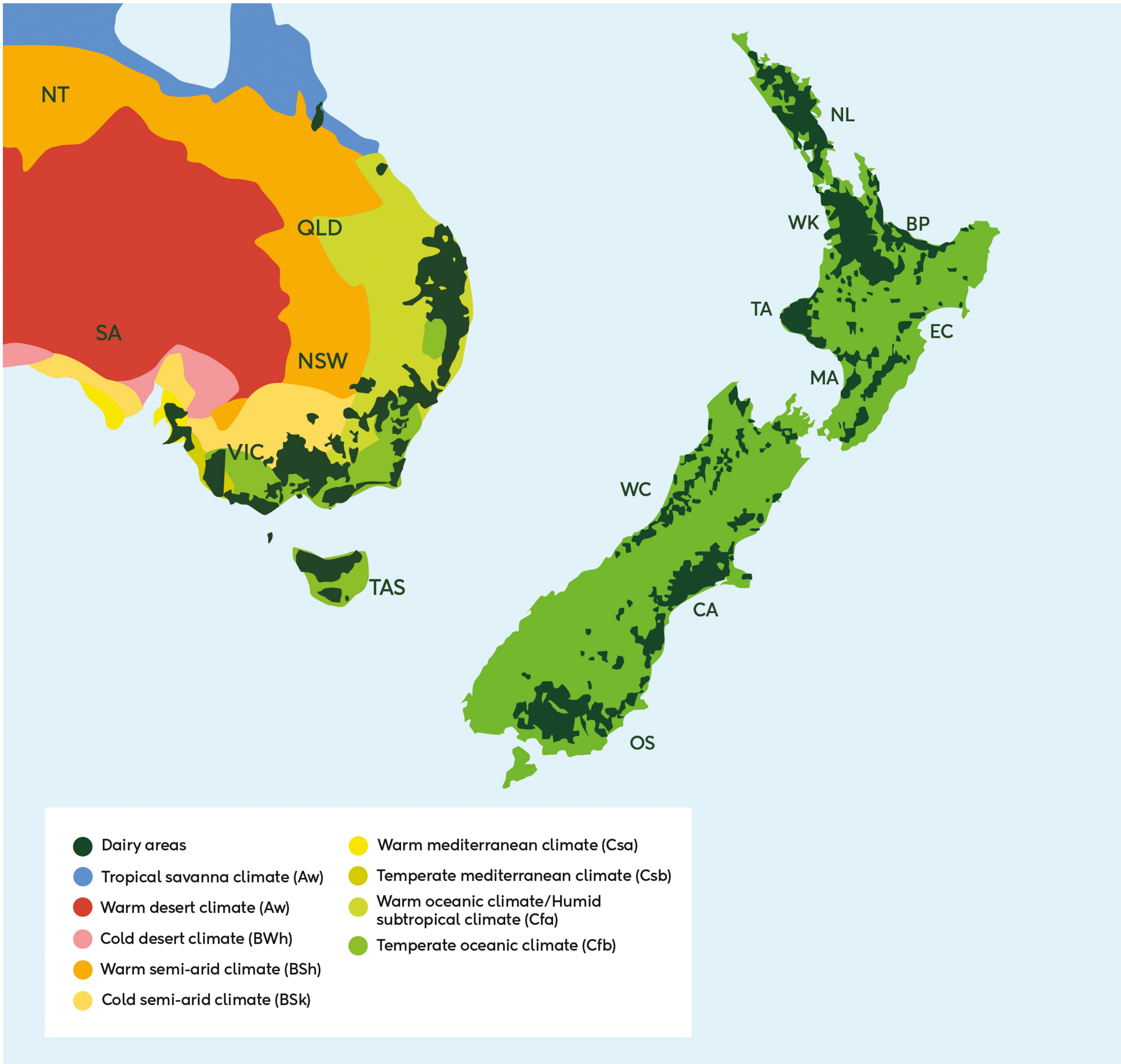

Figure 2. Key dairying areas in Australia (NT: Northern Territory; QLD: Queensland; SA: South Australia; NSW: New South Wales; VIC: Victoria; TAS: Tasmania) and New Zealand (NL: Northland; BP: Bay of Plenty; WK: Waikato; EC: East Coast; TA: Taranaki; MA: Manawatu; WC: West Coast; CA: Canterbury; OS: Otago-Southland) and climate classifications according to their location based on Köppen–Geiger classification between 1991 and 2020. Adapted from Woodward et al. (2024a), Dairy Australia (2023), and https://commons.wikimedia.org/w/index.php?curid=146726177, CC BY 4.0, via Wikimedia Commons.

elevated heat load in dairy cows, requires cow-level responses, and environmental and system-level drivers of heat load to be understood (Ji et al., 2020).

Prediction using environmental drivers

Ambient temperature is the primary driver used to predict heat stress risk in housed (Ji et al., 2020) and grazing cows (Bryant et al., 2022; Hitchman et al., 2024). However, solar radiation, humidity, and wind speed also contribute to heat load by influencing radiative heat transfer and the efficiency of evaporative cooling (Blackshaw and Blackshaw, 1994). Previous research has focused on developing indices that capture the interaction of environmental conditions to predict heat stress risk for dairy cows housed indoors. The THI is one of the most widely used indices that was initially developed for humans and later modified by others (Ji et al., 2020) for use in housed cows. However, the THI is less applicable to cows outdoors (Nguyen et al., 2016; Bryant et al., 2022) due to solar radiation exposure, which can be the largest single contributor to heat load for these animals (Blackshaw and Blackshaw, 1994). Furthermore, grazing cows can also be exposed to wind, which can have a cooling effect (Hitchman et al., 2024).

Given the limitations of the THI for outdoor conditions, New Zealand and Australia have developed indices that are more accurate for their environments and systems. In Australia, Lees et al., (2018) developed the DHLI using panting score and environmental data in dairy cows with pasture and feedlot access. The DHLI incorporates ambient temperature, humidity, solar radiation, and wind speed. In New Zealand, Bryant et al. (2022) developed the GHLI using respiration and environmental data, and this index was recently updated using a more comprehensive dataset from grazing dairy cows across different locations in New Zealand (Hitchman et al., 2024). The GHLI combines ambient temperature, solar radiation, and wind speed (Bryant et al., 2022), with humidity being excluded due to providing inconsistent value in predicting GHLI. While humidity's impact on heat load is documented in hot climates, its exclusion from the New Zealand index supports the need for models developed using localized data to capture diverse combinations of environmental factors on heat stress risk. Despite several decades of research, highly accurate, predictive indices remain elusive in both housed and grazing cows, as evidenced by the continued development of existing indices and the reporting of more than 20 different indices in the literature (reviewed by Ji et al. (2020) and Wang et al. (2018) and reported elsewhere [Lees et al., 2018; Bryant et al., 2022; Hitchman et al., 2024]). Both New Zealand and Australia need to further refine and validate their indices before farmers can confidently rely on them for making management decisions.

Opportunities to improve predictive indices

Improving data collection can enhance the accuracy of predictive indices. Data should capture system-level factors unique to where the indices will be applied and represent local, temporal, cumulative, and real-time cow-level responses to environmental conditions (Gaughan et al., 2008).

System- and cow-level factors may partly explain the limitations when applying indices and thresholds developed for overseas systems to New Zealand and Australian grazing systems. System factors include but are not limited to, the distances that cows walk for milking and to acquire feed through grazing that increases metabolic heat production (Kendall et al., 2008), and increased metabolic heat production through digestion of feed with a higher amount of fiber (Conte et al., 2018). Cow factors may include differences in breed, production levels, and parity. These system and cow-level factors would not be fully captured in datasets used to develop predictive models for housed cows (Hitchman et al., 2024). Therefore, the intersection of environmental, system-, and cow-level differences between indoor and outdoor dairy systems further supports the need for indices developed using localized data.

Another limitation of current indices is their development from small, manually collected datasets (e.g., observations of respiration rate and drooling) (Ji et al., 2020). These datasets are limited in capturing complex biological associations between local environmental conditions and temporal cow-level responses such as cumulative effects of heat load across days (Gaughan et al., 2008). Cattle may carry an accumulated heat load into the next day due to insufficient night cooling, which may be a key factor for refining predictive indices (Chapman et al. 2023).

Automated monitoring of cow-level response using sensors generates large, highly granular temporal datasets and could aid in improving predictive indices (Woodward et al., 2024a). Such datasets provide the opportunity for advanced analytical methods that fully exploit the structure of the data to improve model predictions compared with linear approaches (Chapman et al., 2023; Woodward et al., 2024b). Biological systems are inherently complex and are not well accounted for linearly (Hitchman et al., 2024). Woodward et al. (2024b) used rumen boluses to capture temperature data at 10-min intervals from grazing dairy cows and weather data at 15-min intervals to predict heat stress events using both manual linear regression techniques and nonlinear machine learning (**ML**) approaches (cubist ML model). Compared with GHLI and linear models, the cubist ML model was better at discriminating heat stress determined by increased rumen temperature. Sensor technologies and novel analytical methods (e.g., ML and artificial intelligence) offer new opportunities to leverage rich datasets and advance predictive models for grazing dairy cows.

Responses to Increasing Heat Load and Monitoring Heat Stress

Cows respond to increased heat load through changes in biological functioning and the expression of heat-abating behaviors, with the success of these responses to manage heat load influencing the cows' mental affective state. A key gap in the literature is the threshold at which increasing heat load becomes stress based on a combination of biological and behavioral responses and their impact on affective state.

Cow-level responses to heat load (biological functioning)

Cow-level responses to increasing heat load that researchers have been able to manually measure or observe have received the most attention up to the early 2020s. Studies with housed dairy cows have used environmental indices (typically the THI; NRC, 1971) to determine heat load thresholds associated with physiological responses and used these thresholds to define when mitigation should occur (THI > 65 for respiration rate; >65 for rumen temperature; >70 for rectal temperature; and >72 for heart rate; Pinto et al., 2020; Shu et al., 2021). Such thresholds have not been defined for grazing dairy cows outdoors, with common thresholds in grazing dairy cows related to decreased milk production (THI > 60 to 74; Hitchman et al., 2024) or the onset of increased panting and drooling (GHLI > 55; Bryant et al., 2022). Other responses have been studied to improve our understanding of how animals cope with increasing heat load; however, these have also received less attention in grazing dairy cows. Cows increase their shade use and water intake and decrease feed intake and lying time (Schütz et al., 2008) as part of the process of regaining thermal balance, and these responses diminish once cows achieve homeothermy. Additionally, there are production, reproduction, health, and welfare responses to heat stress. Rather than replicating these well-known impacts of heat stress studied in housed cows and associated environmental thresholds at which cows respond, research in grazing dairy cows should be prioritized based on the relative importance of different cow-level responses within seasonal pasture-based dairy systems.

Within seasonal block calving systems, cows are outdoors for most of the year and calve within an annual cycle in a concentrated period driven by an intensive breeding period of 10 to 12 wk. Heat stress risk throughout the year varies by region, but generally, in New Zealand and Australia, the peak risk period for heat stress is in the summer months from December to February (Nguyen et al., 2016; Woodward et al., 2024b). The impact of heat stress events and how they intersect with the stage of lactation, breeding season, or gestation determined by the herd's planned start of calving needs to be considered as they will differ compared with housed cows. In housed systems where cows calve year-round, heat stress events can occur year-round within a herd as heat exposure can occur during all physiological stages. These system differences may result in lesser or more severe impacts within seasonal compared with year-round calving herds.

Mid- to late-lactation coincides with heat stress risk in grazing dairy cows in New Zealand and Australia, therefore, impacts of heat stress on milk production are a concern. Studies undertaken in grazing dairy cows in Australia (Wildridge et al., 2018; Osei-Amponsah et al., 2020) and one study in heifers (Bryant et al., 2007) and two studies in adult cows in New Zealand (Kendall et al., 2006; Fisher et al., 2008) investigated the impacts of heat stress on milk yield and composition. Milk yield and milk protein concentration declined with increasing THI in grazing cows. Similarly, a meta-analysis of housed cows indicated that milk protein concentration declined by 3.9% and energy-corrected milk yield by 17.9% in heat-stressed compared with thermoneutral cows (Chen et al., 2024). Studies in a New Zealand and Australian context are sparse and more recent data from grazing dairy cows is needed to fully understand these effects. Furthermore, localized data on animal responses in addition to milk production (e.g., dry matter intake, body weight gain, and reproductive culls) under differing scenarios could allow economic modeling of heat stress implications. Such analyses are important for prioritizing mitigation options and funding future research areas, as well as being a key motivator for change.

The impact of intensity and duration of heat stress on other aspects of biological functioning such as reproduction, immune function, and offspring has also received less attention in grazing dairy cows compared with studies in housed cows (Dahl et al., 2020; Ouellet et al., 2021). The periconception, late gestation, and transition periods are key times when the impacts of heat stress may be significant. Nevertheless, their relative importance as future research priorities needs to be considered within a seasonal context. For spring-calving cows, the number of heat stress events occurring is negligible during the periconceptional period, and therefore, impacts of milk production are likely to be the main known biological factor impacting these herds. Downstream impacts of heat stress during mid-gestation have not been documented in housed or grazing dairy cows which may be important for spring-calving herds. On the contrary, for autumn-calving cows, the impacts of heat stress during late gestation on the cow's offspring and the cow's immune function during the transition period may be important (Dahl et al., 2020; Ouellet et al., 2021) but needs to be more clearly understood in these herds. In New Zealand, autumn-calving herds are a minority group (<3% of ~11,600 herds), and therefore, future research should prioritize areas relevant to spring-calving herds. Conversely, in Australia where autumn-calving herds are more common (40% of herds split or batch calving), this may be an important area for future research. Furthermore, future health-related impacts due to changes in climate should continue to be investigated within New Zealand and Australia (e.g., lameness, infectious and parasitic diseases; reviewed by Vallee et al., 2020).

Cow-level responses to heat load (natural behavior and affective state)

While cow-level responses to heat stress that impact biological functioning have important economic and health implications, they also contribute to an animal's mental experiences and overall quality of life (Polsky and von Keyserlingk, 2017). Negative affective experiences due to heat stress may occur due to impaired biological functioning leading to negative feelings such as hunger, thirst, malaise, and pain (reviewed by Polsky and von Keyserlingk, 2017 and Galán et al., 2018). Here, we focus on the expression of natural behaviors, particularly heat-abating behaviors and potential impacts on affective state.

Under increasing heat load, dairy cows respond by engaging in heat-abating behaviors such as shade-seeking, even at the expense of lying (Schütz et al., 2008), and increase water intake and decrease feed intake (Kadzere et al., 2002). The inability to engage in behaviors that animals are highly motivated to perform, or having to compete for access to resources, can lead to negative experiences manifesting as frustration, aggression, or even suffering (Polsky and von Keyserlingk, 2017). However, it is currently unclear when the progression of responses to increasing heat load becomes stress in dairy cows grazing outdoors, not just in terms of the cow's biological functioning but also regarding the animals' motivations to engage in heat-abating behaviors, and their combined impacts on affective state. Research on dairy cows outdoors should consider the environmental conditions that motivate heat-abating behaviors to better understand thermal comfort and heat stress.

Monitoring at herd-level

Environmental indices are commonly used to predict herd-level heat load. Changes in bulk milk yield, composition, and feed intake (Nguyen et al., 2016) allow farmers to assess the effectiveness of mitigation measures (Ji et al., 2020). Herd-level indicators lack specificity and would not allow for real-time decision-making in grazing cows. Furthermore, they do not represent an animal's experience of heat load due to different microclimates, animal factors, and individual variability that influence susceptibility and tolerance to heat stress (Ji et al., 2020; Islam et al., 2021). How an individual animal is coping (i.e., are they managing conditions of increasing heat load to maintain thermal balance) will require individual monitoring to capture the variable responses of cows to heat load not captured through herd-level data (Hitchman et al., 2024; Woodward et al., 2024b). However, herd-level monitoring will remain important for farmers who do not have access to cow-level monitoring.

Monitoring at cow-level

Our understanding of heat stress progression and intensity is limited due to variable responses to increasing ambient temperature (Shu et al., 2021), complicating the definition of early indicators for cow-level monitoring. Future work should focus on sensor technologies that allow animal-based measures to be collected automatically, in real-time, and with a level of granularity that enables the exploration of more nuanced questions regarding the manifestation and impacts of heat stress at cow-level (Pryce et al., 2022). This could provide practical information for farmers to identify cows at risk of heat stress or succumbing to the effects of heat stress, supporting targeted mitigation (i.e., on an individual needs basis) and monitoring the success of mitigation at cow-level. Due to the movement of grazing dairy cows around a large grazing area, off-animal sensors such as video surveillance and infrared thermography investigated for use in housed cows may have limitations (Islam et al., 2021). On-animal sensors may include sensors monitoring lying, eating, grazing, rumination, panting, and activity behaviors, rumen bolus monitoring rumen temperature, loggers monitoring ear, surface, and vaginal temperature, and GPS devices monitoring resource use (i.e., shade, water troughs) and other behaviors (i.e., bunching behaviors) (Islam et al., 2021; Pryce et al., 2022). These sensors may allow individual variability in heat stress susceptibility to be accounted for (Islam et al., 2021). Several factors including breed, coat color, genotype, stage of lactation, milk yield, system type, diet, and available mitigations and opportunities to access resources (i.e., social status and territoriality) impact a cow's susceptibility to heat stress which cannot be captured within herd-level monitoring (Galán et al., 2018). Therefore, cow-level monitoring is required to account for the susceptibility of individuals and the internal and external factors that drive susceptibility.

Short- and Long-Term Mitigation for Climate Resilient Farms

Outdoor access to pasture significantly benefits animal health and supports welfare by promoting natural behaviors (Mee and Boyle, 2020). However, at certain times of the year, it can also expose cows to thermal discomfort, and pasture alone can be nutritionally limiting, particularly under dry conditions, requiring the addition of alternative grown or bought-in feeds. Therefore, balancing the benefits and risks is crucial for advancing the welfare and productivity of dairy cows in these systems, without relying on routine use of controlled indoor environments. Meaningful mitigation will require accurate predictive indices embedded in tools that forecast heat stress risk which farmers can readily use to provide opportunities for cows to engage in heat-abating behaviors.

Australian and New Zealand dairy industries provide key messages regarding short- and long-term actions for their farmers to manage heat stress. Industries should continue to support farmers to adopt known heat stress mitigation practices now and in future based on their farms' unique environmental challenges while research investigating novel mitigation options continues. Some short-term actions include the provision of additional water points, access to shade or sprinklers in paddocks or in the holding yard before milking, altered milking frequency (e.g., once a day), or timing of milking or feeding to avoid the hottest time of the day.

Nutritional management (short- and long-term)

Effective mitigation options are more clearly understood in housed cows fed total mixed rations than in grazing cows, where key strategies involve nutritional management and modifying the physical environment. Nutritional management in housed cows has largely focused on reducing dietary fiber, increasing concentrate feed with more slow fermenting starch, fat supplementation, and using feed additives (Conte et al., 2018). While targeted use of feed additives could be a short-term option, whether this is viable in pasture-based systems requires consideration. Nutritional management through manipulating the homegrown feed base will require additional research if it involves species not routinely used by farmers, which may limit this as a short-term mitigation option. Nevertheless, future feed planning in pasture-based systems requires some consideration due to the changes in quantity and quality of feed that could arise from increased drought conditions (Jago et al., 2023) leading to increased use of fiber-rich supplements such as hay which could increase metabolic heat production (Conte et al., 2018). Future research could consider the role that alternative pasture species or crops play in managing heat stress while also addressing possible seasonal changes in pasture quantity and quality that may become more pronounced in future (Jago et al., 2023).

Modification of the physical environment (short-term)

Investment in infrastructure (i.e., sprinklers, fans, or man-made shelters) requires careful consideration due to cost (Islam et al., 2021); however, compared with other options such as planting trees, these are relatively accessible in the short term. While these options have practical limitations in pasture-based dairy systems, they could be provided through a centralized

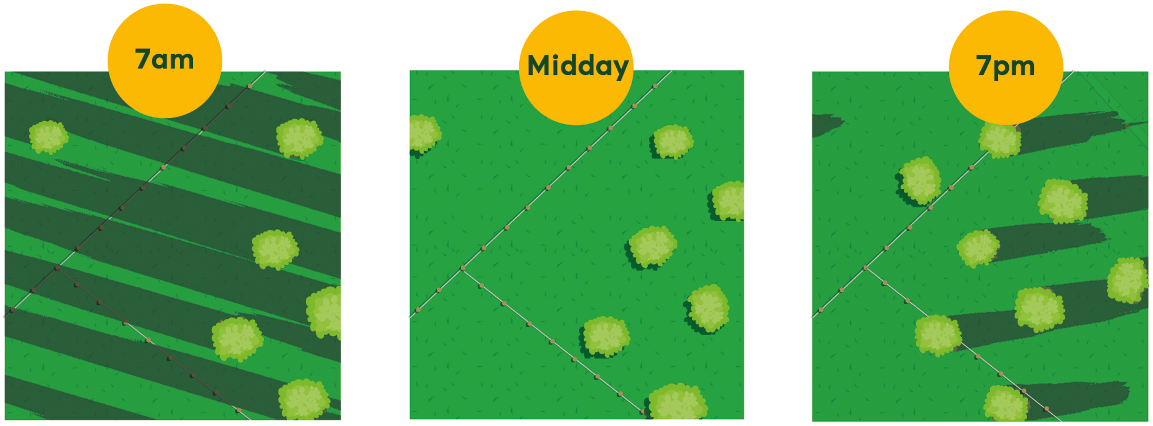

Figure 3. Schematic of the change in shade provided by single trees based on the position of the sun from satellite imagery captured at 7 am, midday, and 7 pm on February 8, 2024 near Wardville, New Zealand (Geographical location: 37°43'S 175°47'E).

location that cows can choose to access. In New Zealand and Australia, farms are providing sprinklers (34.7% and 54%, respectively) and shade over their holding yards (2.7% and 9%, respectively) (DairyNZ Ltd, 2023; Dairy Australia, 2024). However, this only provides temporary relief while waiting to be milked and sprinklers do not allow the expression of highly motivated behaviors such as seeking shade and could be aversive to some cows (Schütz et al., 2010). While a resource may be effective in cooling a cow down, there are many unknowns regarding the type, amount, and access to heat-abating resources that grazing dairy cows require to meet their behavioral and biological needs. Future research should consider the provision of heat-abating resources and impacts on a cows' time budget, particularly when grazing. Motivations to engage in certain behaviors may result in trade-offs with other important behaviors (Schütz et al., 2008); for example, when a cows' need to graze conflicts with her need to effectively cool down. Furthermore, if heat load is not successfully abated due to competition for resources (Polsky and von Keyserlingk, 2017) or cows choose not to utilize the provided resource (e.g., cattle prefer shade over other options for cooling such as wetting), this could lead to negative experiences, such as frustration. Future research investigating short-term mitigation options for grazing dairy cows should carefully consider these knowledge gaps to ensure farmers receive advice that supports effective mitigation while meeting the cows' biological, behavioral, and mental needs.

Modification of the physical environment (long-term)

Planting trees can provide a heat-abating resource at the paddock level (Schütz et al., 2008), but it is a long-term commitment due to growing time and has received little attention in intensive dairy systems. While 56% and 81% of farms have shade from trees in their paddocks in New Zealand and Australia (DairyNZ, 2023; Dairy Australia, 2024), respectively, little is known about the effectiveness of these trees as these values are from farmer-reported data. Trees can provide a source of shade for dairy cattle under certain conditions by blocking solar radiation (Schütz et al., 2009) but can also reduce wind speed which has a mitigating effect. The research lacks nuance regarding trees suited to optimize shade availability and area shaded based on preferred foliage, amount, type, and tree height. Furthermore, shade from trees varies considerably throughout the day due to the position of the sun, whereby in the middle of the day when the sun's position and solar radiation are greatest, a singular tree provides little shade (Figure 3), hence the placement of trees will be critical for optimal cooling.

Long-Term Adaptation for Climate Resilient Farms

Genetic strategies will be an important component of long-term adaptation to heat stress. A range of strategies were summarized and discussed in an Australian context by Cheruiyot et al. (2022), Pryce et al. (2022), and Scerri et al. (2023). We provide additional perspectives from the New Zealand context based on options that are currently available or likely to be available in future but recommend referring to these reviews for an in-depth discussion of genetics strategies. Exploiting genetic variability to improve resilience to heat stress will be an important component of long-term adaptation. Introgression of genes and selection for heat tolerance within breeds are areas currently being prioritized in New Zealand and Australia.

Introgression of genes

Introgression involves introducing known single genes associated with increased heat tolerance from a different breed. Traditional methods of introgression through crossbreeding are time-consuming and inefficient. Although novel methods using gene editing are a faster alternative (Pryce et al., 2022), this is a technology currently unavailable for commercial use in New Zealand and Australia and has limited application. However, since 2014, a breeding company from New Zealand, and more recently, in the United States and Puerto Rico, have advanced this space using traditional methods to introgress the "slick" gene (influences hair length and density) demonstrating the benefits of heat tolerance in dairy cattle (Donkersloot et al., 2021; Pryce et al., 2022). Further research is needed to understand the involvement of the "slick" gene and others being investigated in biological pathways and processes both related and unrelated to heat tolerance to ensure the production and welfare benefit of these traits are net positive.

Selection for heat tolerance within breeds

Genetic selection for heat-tolerant cattle is a permanent, cumulative management strategy that provides a long-term solution to heat stress at a relatively low cost, particularly in outdoor systems where the provision of heat abatement resources may be challenging (Pryce et al., 2022). Currently, Australia is significantly ahead of New Zealand and other countries in the inclusion of heat tolerance genotypes in their national dairy industry breeding programs, where Australia was the first country in the world to release genomic breeding values (**BV**) for heat tolerance in 2017 (Nguyen et al., 2016; Pryce et al., 2022). This BV captures individual genetic variability in milk production responses to increasing temperature and humidity (Osei-Amponsah et al., 2023); however, milk production is just one indicator of thermal balance and is a lag response to heat stress. Furthermore, milk production is already captured through other economic traits (Cheruiyot et al., 2022). Therefore, a BV for heat tolerance could be improved by incorporating other sensitive phenotypic responses to heat stress, particularly if measured in genotyped dairy cows to identify thermotolerant individuals (Pryce et al., 2022). To the best of our knowledge, no heat tolerance BV has been developed for cows outdoors using phenotypes other than milk production (Nguyen et al., 2016).

Novel phenotypes for heat tolerance selection

Milk production was a preferred phenotype for developing the first heat tolerance BV due to the availability of large herd test and combined weather station datasets (Nguyen et al., 2016). However, as captured within this review, heat stress is complex, and therefore, heat tolerance is likely to be affected by a multitude of factors (Pryce et al., 2022). Possible phenotypes that could be utilized in developing breeding objectives for heat tolerance include physiological indicators such as respiration rate and core temperature or behaviors associated with heat tolerance. If these phenotypes are heritable, this may provide additional selection criteria for heat-tolerant cows. Due to the large datasets required for estimating BV, cow-level responses captured automatically using sensors are promising (Pryce et al., 2022). For example, The University of Sydney is leading research in this space through the Dairy–UP program, collecting phenotypic rumen temperature data to reveal individual variability in dairy cows in response to heat as demonstrated in beef cattle (Islam et al., 2023). These data could be utilized to rapidly advance the selection criteria for heat-tolerant cattle (A.K. Shirley, *Pers. Comms*.). With the increasing uptake of sensors on commercial farms, there are significant opportunities in this space to support the selection of heat-tolerant cows.

Conclusion

The increasing focus on animal welfare and climate change challenges highlights the need for proactively managing heat stress in dairy cows managed outdoors. The complexity of environmental, system- and cow-level factors and their interactions presents a challenge in understanding and predicting heat stress. However, advancements in sensor technologies, data collection, and predictive modeling offer opportunities to address these challenges. By integrating artificial intelligence and ML, we can develop more accurate and real-time monitoring tools that inform targeted mitigation strategies. Ensuring that cows can engage in highly motivated behaviors while providing effective heat abatement resources is important for maintaining animal welfare and productivity. Continued research focusing on localized conditions and cow-level responses is important to advance our understanding and management of heat stress in outdoor grazing systems. Mitigation now and in the future should be prioritized in New Zealand and Australia using known strategies to support thermal comfort in dairy cows outdoors, while research into mitigation and adaptation continues. These efforts will support sustainable and resilient dairy farming practices that demonstrate high standards of animal welfare, retaining market competitiveness, and consumer trust.

Acknowledgments

This feature article was funded by the dairy farmers of New Zealand through DairyNZ Inc. and the Enhanced Animal Care program (Project Code 6185: Climate Stress Solutions for Cows). This article was invited for submission by the European Association for Animal Science (EAAP). The views expressed in this publication are those of the authors and do not necessarily reflect the views or policies of the European Association for Animal Science, the journal, or the publisher. S.J.H. is a guest editor for this issue. This had no impact on the peer review process or final decision.

Author Contributions

Conceptualization: S.J.H., J.P.E., A.K.S., C.E.F.C., K.E.S., K.J.V., J.G.J.; investigation: S.J.H.; writing—original draft: S.J.H.; writing—review & editing: S.J.H., J.P.E., A.K.S., C.E.F.C., K.E.S., K.J.V., J.G.J.; supervision: K.J.V., J.G.J.; project administration: K.J.V., J.G.J.; funding acquisition: J.G.J.

Conflict of interest statement

The authors declare no conflicts of interest relevant to this work. S.J.H. holds the position of guest editor for this special issue in Animal Frontiers and has not peer-reviewed or made any editorial decisions for this paper.

Literature Cited

Allen, K. 2024. Heat stress is a worldwide concern. Hoards Dairyman. [accessed June 04, 2024]. https://hoards.com/article-34396-heat-stress-is-a-worldwide-concern.html.

Bewley, J.M., M.E. Einstein, M.W. Grott, and M.M. Schutz. 2008. Comparison of reticular and rectal core body temperatures in lactating dairy cows. J. Dairy Sci. 91(12):4661–4672. doi:10.3168/jds.2007-0835

Blackshaw, J.K., and A.W. Blackshaw. 1994. Heat stress in cattle and the effect of shade on production and behaviour: a review. Aust. J. Exp. Agric. 34(2):285–295. doi:10.1071/ea9940285

Bryant, J.R., F. Huddart, and K.E. Schütz. 2022. Development of a heat load index for grazing dairy cattle. N. Z. J. Agric. Res. 66:1–15. doi:10.1080/00288233.2022.2114504

Bryant, J.R., N. López-Villalobos, J.E. Pryce, C.W. Holmes, and D.L. Johnson. 2007. Quantifying the effect of thermal environment on production traits in three breeds of dairy cattle in New Zealand. N. Z. J. Agric. Res. 50:327–338. doi:10.1080/00288230709510301

Chapman, N.H., A. Chlingaryan, P.C. Thomson, S. Lomax, M.A. Islam, A.K. Doughty, and C.E.F. Clark. 2023. A deep learning model to forecast cattle heat stress. Comput. Electron. Agric. 211:107932. doi:10.1016/j.compag.2023.107932

Chen, L., V.M. Thorup, A.B. Kudahl, and S. Østergaard. 2024. Effects of heat stress on feed intake, milk yield, milk composition, and feed efficiency in dairy cows: a meta-analysis. J. Dairy Sci. 107(5):3207–3218. doi:10.3168/jds.2023-24059

Cheruiyot, E.K., M. Haile-Mariam, B.G. Cocks, and J.E. Pryce. 2022. Improving genomic selection for heat tolerance in dairy cattle: current opportunities and future directions. Front. Genet. 13:894067. doi:10.3389/fgene.2022.894067

Conte, G., R. Ciampolini, M. Cassandro, E. Lasagna, L. Calamari, U. Bernabucci, and F. Abeni. 2018. Feeding and nutrition management of heat-stressed dairy ruminants. Ital. J. Anim. Sci. 17(3):604–620. doi:10.1080/1828051x.2017.1404944

Dahl, G.E., S. Tao, and J. Laporta. 2020. Heat stress impacts immune status in cows across the life cycle. Front. Vet. Sci. 7:116. doi:10.3389/fvets.2020.00116

Dairy Australia. 2023. In Focus 2023: The Australian Dairy industry. [accessed June 07, 2024]. https://cdn-prod.dairyaustralia.com.au/-/media/project/dairy-australia-sites/national-home/resources/industry-reports/in-focus/in-focus-report-2023.pdf?rev=4e1d1ac7ebe5499b9aca1fedf20f5f59.

Dairy Australia. 2024. Animal care on Australian dairy farms. [accessed June 26, 2024]. https://cdn-prod.dairyaustralia.com.au/-/media/project/dairy-australia-sites/national-home/resources/2020/08/09/dairy-welfare-we-care-animal-husbandry-survey-2019/animal-husbandry-survey-2019.pdf?rev=4e9c5f20af8e45db867c175533976d50.

DairyNZ Ltd. 2023. Animal care consult detailed analysis 2022/23 [Internal Report].

Donkersloot, E.G., G.M. Worth, A.F. Yeates, M.D. Littlejohn, L.R. McNaughton, and S.R. Davis. 2021. The benefit of a slick hair coat for heat tolerance in New Zealand dairy cattle. Proc. Assoc. Adv. Anim. Breed. Genet. Conf. 24:94–97. Available from https://www.cabidigitallibrary.org/doi/pdf/10.5555/20220454602

Fisher, A.D., N. Roberts, S.J. Bluett, G.A. Verkerk, and L.R. Matthews. 2008. Effects of shade provision on the behaviour, body temperature and milk production of grazing dairy cows during a New Zealand summer. N. Z. J. Agric. Res. 51(2):99–105. doi:10.1080/00288230809510439

Galán, E., P. Llonch, A. Villagrá, H. Levit, S. Pinto, and A. del Prado. 2018. A systematic review of non-productivity-related animal-based indicators of heat stress resilience in dairy cattle. PLoS One 13:e0206520. doi:10.1371/journal.pone.0206520

Gaughan, J.B., T.L. Mader, S.M. Holt, and A. Lisle. 2008. A new heat load index for feedlot cattle. J. Anim. Sci. 86(1):226–234. doi:10.2527/jas.2007-0305

Hitchman, S., G. Zobel, K. Schütz, J. Jago, C. Reed, E. Hay, C. Thomas, J.P. Edwards, and K. Verhoek. 2024. Updated method of estimating heat load for grazing dairy cattle. N. Z. J. Agric. Res. 1–21. doi:10.1080/00288233.2024.2396970

Islam, M.A., S. Lomax, A. Doughty, M.R. Islam, O. Jay, P. Thomson, and C. Clark. 2021. Automated monitoring of cattle heat stress and its mitigation. Front. Anim. Sci. 2:1–20. doi:10.3389/fanim.2021.737213

Islam, M.A., S. Lomax, A.K. Doughty, M.R. Islam, P.C. Thomson, and C.E.F. Clark. 2023. Revealing the diversity of internal body temperature and panting response for feedlot cattle under environmental thermal stress. Sci. Rep. 13(1):4879. doi:10.1038/s41598-023-31801-7

Jago, J., P. Beukes, E. Cuttance, D. Dalley, J.P. Edwards, W. Griffiths, K. Saunders, L. Shackleton, and K. Schütz. 2023. Strategies to minimise the impact of climate change and weather variability on the welfare of dairy cattle in New Zealand and Australia. Anim. Prod. Sci. 64(1):AN22359. doi:10.1071/AN22359

Ji, B., T. Banhazi, K. Perano, A. Ghahramani, L. Bowtell, C. Wang, and B. Li. 2020. A review of measuring, assessing and mitigating heat stress in dairy cattle. Biosyst. Eng. 199:4–26. doi:10.1016/j.biosystemseng.2020.07.009

Kadzere, C.T., M.R. Murphy, N. Silanikove, and E. Maltz. 2002. Heat stress in lactating dairy cows: a review. Livest. Prod. Sci. 77(1):59–91. doi:10.1016/s0301-6226(01)00330-x

Kendall, P., P. Nielsen, J. Webster, G.A. Verkerk, R. Littlejohn, and L. Matthews. 2006. The effects of providing shade to lactating dairy cows in a temperate climate. Livestock Sci. 103(1-2):148–157. doi:10.1016/j.livsci.2006.02.004

Kendall, P.E., C.B. Tucker, D.E. Dalley, D.A. Clark, and J.R. Webster. 2008. Milking frequency affects the circadian body temperature rhythm in dairy cows. Livestock Sci. 117(2-3):130–138. doi:10.1016/j.livsci.2007.12.009

Lees, J.C., A.M. Lees, and J.B. Gaughan. 2018. Developing a heat load index for lactating dairy cows. Anim. Prod. Sci. 58(8):1387. doi:10.1071/AN17776

Mee, J., and L.A. Boyle. 2020. Assessing whether dairy cow welfare is “better” in pasture-based than in confinement-based management systems. N Z Vet. J. 68(3):168–177. doi:10.1080/00480169.2020.1721034

Nguyen, T.T.T., P.J. Bowman, M. Haile-Mariam, J.E. Pryce, and B.J. Hayes. 2016. Genomic selection for tolerance to heat stress in Australian dairy cattle. J. Dairy Sci. 99(4):2849–2862. doi:10.3168/jds.2015-9685

Nidumolu, U., S. Crimp, D. Gobbett, A. Laing, M. Howden, and S. Little. 2010. Heat stress in dairy cattle in northern Victoria: responses to a changing climate. CSIRO Climate Adaptation Flagship Working paper No. 10. Available from https://research.csiro.au/climate/wp-content/uploads/sites/54/2016/03/10_CAF_WorkingPaper10_pdf.pdf

NRC. 1971. A guide to environmental research on animals. Washington (DC): National Academies Press.

Osei-Amponsah, R., F.R. Dunshea, B.J. Leury, A. Abhijith, and S.S. Chauhan. 2023. Association of phenotypic markers of heat tolerance with Australian genomic estimated breeding values and dairy cattle selection indices. Animals. 13(14):2259. doi:10.3390/ani13142259

Osei-Amponsah, R., F.R. Dunshea, B.J. Leury, L. Cheng, B. Cullen, A. Joy, A. Abhijith, M.H. Zhang, and S.S. Chauhan. 2020. Heat stress impacts on lactating cows grazing Australian summer pastures on an automatic robotic dairy. Animals. 10(5):869. doi:10.3390/ani10050869

Ouellet, V., A. Boucher, G.E. Dahl, and J. Laporta. 2021. Consequences of maternal heat stress at different stages of embryonic and fetal development on dairy cows’ progeny. Anim. Front. 11(6):48–56. doi:10.1093/af/vfab059

Peel, M.C., B.L. Finlayson, and T.A. McMahon. 2007. Updated world map of the Köppen-Geiger climate classification. Hydrol. Earth Syst. Sci. 11(5):1633–1644. doi:10.5194/hess-11-1633-2007

Pinto, S., G. Hoffmann, C. Ammon, and T. Amon. 2020. Critical THI thresholds based on the physiological parameters of lactating dairy cows. J. Therm. Biol. 88:102523. doi:10.1016/j.jtherbio.2020.102523

Polsky, L., and M.A.G. von Keyserlingk. 2017. Invited review: effects of heat stress on dairy cattle welfare. J. Dairy Sci. 100(11):8645–8657. doi:10.3168/jds.2017-12651

Pryce, J.E., T.T.T. Nguyen, E.K. Cheruiyot, L. Marett, J.B. Garner, and M. Haile-Mariam. 2022. Impact of hot weather on animal performance and genetic strategies to minimise the effect. Anim. Prod. Sci. 62(8):726–735. doi:10.1071/an21259

Scerri, T.M., S. Lomax, and C.E.F. Clark. 2023. Bovine heat stress management: current amelioration approaches and the case for a novel mitogenomic strategy. Front. Anim. Sci. 4:1169743. doi:10.3389/fanim.2023.1169743

Schütz, K.E., N.R. Cox, and L.R. Matthews. 2008. How important is shade to dairy cattle? Choice between shade or lying following different levels of lying deprivation. Appl. Anim. Behav. Sci. 114(3-4):307–318. doi:10.1016/j.applanim.2008.04.001

Schütz, K.E., A.R. Rogers, N.R. Cox, and C.B. Tucker. 2009. Dairy cows prefer shade that offers greater protection against solar radiation in summer: shade use, behaviour, and body temperature. Appl. Anim. Behav. Sci. 116(1):28–34. doi:10.1016/j.applanim.2008.07.005

Schütz, K.E., A.R. Rogers, N.R. Cox, J.R. Webster, and C.B. Tucker. 2010. Dairy cattle prefer shade over sprinklers: effects on behavior and physiology. J. Dairy Sci. 94(1):273–283. doi:10.3168/jds.2010-3608

Shu, H., W. Wang, L. Guo, and J. Bindelle. 2021. Recent advances on early detection of heat strain in dairy cows using animal-based indicators: a review. Animals. 11(4):980. doi:10.3390/ani11040980

Vallee, E., M. Wada, N. Cogger, V. Kelly, J. Marshall, J. Benschop, G. Macara, and A. Tait. 2020. Effects of climate change on grazing livestock health in New Zealand. Wellington (NZ): Ministry for Primary Industries.

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

Wildridge, A.M., P.C. Thomson, S.C. Garcia, A.J. John, E.C. Jongman, C.E.F. Clark, and K.L. Kerrisk. 2018. Short communication: the effect of temperature-humidity index on milk yield and milking frequency of dairy cows in pasture-based automatic milking systems. J. Dairy Sci. 101(5):4479–4482. doi:10.3168/jds.2017-13867

Woodward, S.J.R., P.C. Beukes, J.P. Edwards, K. Verhoek, J.G. Jago, and C. Zammit. 2024a. Prediction of regional heat stress risk for grazing dairy cows in a changing climate. agriRxiv [Preprint] 20240429911:1. doi:10.31220/agriRxiv.2024.00280

Woodward, S.J.R., J.P. Edwards, K. Verhoek, and J.G. Jago. 2024b. Identifying and predicting heat stress events for grazing dairy cows using rumen temperature. J. Dairy Sci. Commun. 5:431–435. doi:10.3168/jdsc.2023-0482

Author Biographies:

Stacey J. Hendriks is a Scientist with DairyNZ (Lincoln, New Zealand) with a background in transition cow health, and cow behavior and welfare. Stacey is an early career researcher working on projects to enhance animal care on New Zealand dairy farms. She is interested in research with practical applications that can improve animal health and welfare, and providing farmers with tools to improve animal care on farms. Stacey completed her PhD in Animal Science from Massey University, New Zealand, and was a postdoctoral researcher at Massey University, New Zealand, and Teagasc, Ireland. **Corresponding author:** Stacey.Hendriks@dairynz.co.nz

John Paul Edwards is a Senior Scientist at DairyNZ (Lincoln, New Zealand) specializing in Farm Systems. His family are dairy farming in the Northland region of New Zealand. His career goal is to utilize his scientific and critical thinking skills and background in dairy farming to integrate new knowledge and technologies into parts of the wider farm system, to improve the profitability and sustainability of New Zealand dairy farms. Over the past 15 years, his research has spanned several topics relating to milking management to improve labor efficiency and nutrient management, strategic and operational farm management, and animal welfare.

Alice K. Shirley is a PhD candidate at the University of Sydney, supported by Dairy–UP, a collaborative RD&E program for New South Wales, Australia. She completed a Bachelor of Science/Bachelor of Advanced Studies (Animal and Veterinary Bioscience) with a major in animal health, disease, and welfare at The University of Sydney. Graduating with first-class honors, her project focused on on-animal sensor technology to monitor animal behavior in beef cattle. Alice's current research explores the diversity in dairy cattle reticulorumen temperature data for heat stress amelioration, looking to determine individual animal variability in response to heat to provide new phenotypes for genetic selection.

Cameron E. F. Clark is an applied research leader and academic with a love of agriculture and passion for precision livestock farming. Within this broad, applied research field, he focuses on precision cattle production and welfare. Cameron's collaborative, high impact research is transforming production systems by revealing and exploiting diversity through the application of agricultural technologies and most importantly, the extraction of (industry) value from the data generated. His current effort in this field has a focus on heat tolerance and water intake with collaborative work in synthetic biology, livestock feed base, and livestock pain and wound management. His vision is to bring scientific expertise together to co-develop and demonstrate robust low-carbon, biodiverse, productive, and profitable livestock systems. In parallel with this effort in Australia, he works to improve the sustainability and security of global food production by applying farm systems knowledge, with a specific focus on animal-sourced protein production. Current work in this field focuses on the management of Napier Grass, the surrounding feed base, and system circularity to double levels of milk and meat production in Bangladesh.

Karin E. Schütz is a Senior Scientist in animal behavior and welfare with over 25 years' of experience in animal welfare research. She completed her Master of Science in Biology at Linköping University followed by a PhD in Ethology at the Swedish University of Agricultural Sciences where she studied behavioral and genetic changes associated with selection for production traits in chickens. In 2004, she moved to New Zealand to take up a scientist role in the Animal Behaviour and Welfare Team at AgResearch Ltd. Most of her research in New Zealand has been aimed at improving the welfare of dairy cows managed on pasture, with a focus on the impacts of different management practices and environmental conditions on cow welfare.

Kirsty J. Verhoek (nee Hammond) is a Senior Scientist at DairyNZ (Hamilton, New Zealand). Kirsty holds a PhD in ruminant nutrition and methane emissions and over the past 15 years has contributed to projects both nationally and internationally aimed at enhancing ruminant production efficiency and sustainability. Alongside her academic and research roles, Kirsty operates a 750-cow sharemilking operation in Waikato with her husband, Nic. Her research interests include enhancing the integrity and reputation of the New Zealand dairy sector, focusing on sustainable practices (reducing methane emissions) and animal welfare (mitigating thermal stress). Kirsty's approach involves co-designing solutions with farmers, community, industry, and researchers, ensuring practical and impactful implementation that maintains or improves productivity.

Jenny G. Jago is a Principal Scientist at DairyNZ (Hamilton, New Zealand) leading the enhanced animal care research, development, and extension program. Her research interests cover farm systems, workplace productivity, milking efficiency, and the incorporation of precision technologies to improve decision-making, reduce labor demand, and improve farm working conditions. Jenny has a passion for creating opportunities for young researchers to grow their skills and networks through the programs she leads.