

Impact of hot weather on animal performance and genetic strategies to minimise the effect

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ABSTRACT

Dairy cows in Australia and New Zealand are generally kept outdoors, making them susceptible to weather variability and in particular heat stress. In this paper, we review (1) exploiting genetic variability to improve heat tolerance, (2) genotype by environment interactions, i.e. suitability of high merit cows to weather variability and (3) how novel phenotyping and genomics can help improve heat tolerance. Selection for heat tolerance is a permanent and cumulative strategy and especially useful in grazing situations where management practices, such as cooling mechanisms, are sometimes impractical. Australia was the first country in the world to release breeding values for heat tolerance in dairy cattle nationally in 2017. The breeding value captures genetic variation in the reduction of milk production traits with rising temperature and humidity. The breeding values have been validated in independent studies (in Victoria, Australia, and California, USA), showing that thermotolerant cows maintain a lower core body temperature under hot and humid conditions. Genotype by environment interactions for traits sensitive to heat is only a concern for farms in very extreme conditions and therefore affect only a small proportion of individuals (those in the extreme 5th percentile). Heat tolerance is a complex trait in that in addition to milk traits, health and fertility may also be affected. Next-generation heat tolerance breeding values may include sensor device information in addition to changes in milk composition, or other measurable biomarkers. This is especially useful when measured in genotyped female populations. Research into novel ways of measuring heat tolerance could transform the way we select for this trait and capture more of the complexity of this trait. To be successful in this area, multi-disciplinary collaboration among animal scientists is likely to facilitate this goal. Combining genomics, traditional and novel measures of heat tolerance with intermediate metabolic biomarkers and prioritised genetic variants could be a way to capture the complexity of thermotolerance in future heat tolerance breeding values. Finally, selecting cows that are resilient to variability in weather is feasible and heat tolerance is a good example of this.

Keywords: complex traits, environmental impact, genomics, genotype by environment interactions, heat tolerance, resilience, sensors, thermotolerance.

Introduction

Climate change due to global warming is likely to lead to more weather variability (CSIRO 2016). Weather variability affects animals directly by affecting their performance (production and reproduction) and indirectly by affecting the environment, including prevalence of disease and parasites, availability of quality and quantity of feed. Dairy cattle are likely to be especially sensitive because of the elevated metabolic load associated with lactation and high feed demand.

The impact of weather on animal performance is almost entirely due to warm and hot weather conditions, even in temperate regions that experience cold winters and springs. This is especially true for pasture-based systems (typical of Australia and New Zealand) where there is more opportunity for cows to be directly affected by ambient temperature and solar radiation.

Many indices have also been developed to account for the thermal flow mechanisms (ambient temperature, relative humidity, solar radiation, wind speed, precipitation) on the animal and then used to define thresholds beyond which heat stress begins. Due to limited publicly available data on solar radiation and wind speed, most studies have focused on ambient temperature and relative humidity to quantify environmental heat load. The most frequently used environmental heat load index in dairy cattle is the temperature–humidity index (THI), originally developed to measure discomfort in humans (Thom 1959). THI is a single value that combines ambient temperature and relative humidity.

The thermo-neutral range for dairy animals is from 16°C to 25°C; at this temperature a body temperature of 38.4–39.1°C can be maintained (Yousef 1985). In Australia, the proportion of days in a year when dairy cows are expected to experience conditions outside of this range which lead to reductions in performance as a result heat stress varies between ~300 days per year (Qld) to ~60 days (Tas.; Nguyen *et al.* 2016). Variability in weather is expected to continue and the intensity, frequency and duration of heat events are predicted to increase (CSIRO 2016).

Normally animals are well adapted to their production environment. However, genetic selection for increased productivity, particularly in dairy cattle over the past five decades, appears to have had an unintended negative effect on the ability of cows to withstand heat stress (Nguyen *et al.* 2016). In more recent times, there has been a greater focus on traits other than production, such as survival, fertility, longevity and feed efficiency in the breeding objective (Byrne *et al.* 2016; Cole and VanRaden 2018). This trend is likely to continue and is necessary to ensure that cattle are suited to the production environments most common in dairying worldwide.

Heat tolerance is defined as the ability to maintain thermal stability at high temperatures and humidity (Carabaño *et al.* 2019); this process is largely controlled by an animal's capacity to dissipate the heat generated by metabolic heat production. Heat stress decreases production, growth, sexual behaviour and fertility, with extreme heat stress sometimes resulting in death (Hansen 2020). In addition to reducing production losses, selecting for heat tolerance is likely to also have favourable effects on animal welfare, especially as heat stress is a growing welfare concern (Polsky and von Keyserlingk 2017).

One major concern for farmers is the reduction in productivity during hot weather. Dairy cows respond to heat stress through behavioural, physiological and cellular adaptations that are initiated to reduce the internal temperature of the animal when exposed to hot conditions (Dunshea *et al.* 2013). The main biological determinants of heat tolerance in animals include the relative body surface area (Berman 2003), sweating rate (determined by the morphology, density, and water transfer capacity of sweat glands), coat characteristics (length, thickness, colour,

weight per unit surface, etc.; Collier *et al.* 2008) as well as the rate of metabolic heat production and dissipation (Kadzere *et al.* 2002). These adaptations to heat stress may be responsive not only to immediate nutritional or management modification, but also to long-term targeted genomic selection of animals for improved heat tolerance (Nguyen *et al.* 2016).

The use of sprinklers and other cooling devices and the provision of shade have been shown to provide relief from hot weather (Dunshea *et al.* 2013). While there are significant benefits to these mitigation options for cow welfare and productivity, many are not practical in pasture-based, or extensively managed environments. Temperatures are projected to continue to rise and management solutions may not on their own be able to prevent heat stress in high-producing cows, even where mitigating infrastructure (e.g. cooling equipment) exists. The use of genetic selection is expected to provide an effective long-term solution since the effects of genetic improvement are permanent and cumulative over generations.

In this review we discuss (1) exploiting genetic variation to improve resilience to weather variability (restricted to heat tolerance), (2) genotype by environment interactions, i.e. suitability of high genetic merit cows to heat stress and (3) how novel phenotyping and genomics can help improve resilience to heat stress.

Exploiting genetic variability to improve resilience to heat stress

One of the enabling technologies for improving novel traits, such as heat tolerance, has been the development of genomic selection, which has transformed livestock and plant breeding internationally (VanRaden 2020). Genomic selection uses a reference population that comprises genotyped individuals that also have phenotypes of interest (known as a genomic reference population) to develop genomic prediction equations. These predictions can then be applied to individuals that are genotyped but may not have phenotypic records. The dairy industry was an early adopter of genomic selection, with the first countries implementing it in 2009 (Hayes *et al.* 2009).

Australia introduced genomic breeding values for Holsteins and Jerseys in 2010, initially through male-only genomic reference populations. The inclusion of females to the Australian reference population was initiated in 2013, through ~100 herds recruited on the basis of excellent data recording, to participate in the Genomic Information Nucleus (Ginfo) research project and has been shown to increase the reliability of genomic breeding values (Pryce *et al.* 2018). Ginfo is now approaching 200 herds (~60 000 cows) and is now administered by DataGene Ltd (Bundoora, Australia), so that it is integrated into routine genetic evaluations of Australian dairy cattle. The reference population was

designed to improve the reliability of traditional breeding values such as production, conformation, fertility, etc. (Pryce *et al.* 2018), but also provides a dataset for genomic breeding values of new traits, such as heat tolerance, mastitis resistance, metabolic resilience, etc. Ginfo is designed to be used to also provide data on novel measures of heat tolerance, such as mid-infrared spectral data (from routine milk recording) and this can also be expanded to sensor body temperature measurements, or even inferred behaviours indicative of heat stress. When these phenotypes are matched to genotypes on the same cow, they could provide rich future opportunities for genomic prediction.

There are several strategies that should be considered for genetically altering heat tolerance; these include (1) choice of breed or cross, as some breeds are more heat tolerant than others, (2) introgression of genes that are associated with thermotolerance, and (3) selection criteria associated with heat tolerance, as follows:

- (1) *Choice of breed or use of crosses.* In tropical climates, *Bos indicus* breeds are frequently crossed with temperate dairy breeds so as to combine the heat resilience and parasite resistance of *Bos indicus* with the production qualities of temperate breeds (Davis *et al.* 2017; Burrow *et al.* 2019). For example, the Girolando breed in Brazil is a cross between Gir (more heat tolerant) and Holstein (higher production). Temperate breeds also exhibit a greater reduction in heat tolerance; for example, New Zealand Holsteins appear to exhibit greater reductions in milk yield (less tolerant) in hotter climates than do Jerseys or crossbreds (Bryant *et al.* 2007a).
- (2) *Introgression of useful locus that increase tolerance to heat.* Introgression involves introducing known alleles of favourable effect, usually from a completely different breed. Traditionally, introgression involves crossing back to the original breed to restore the favourable dairy characteristics from the base breed, this process takes several generations of crossing and is therefore time-consuming and inefficient. A mutation that confers heat tolerance and a smooth coat phenotype is a deletion in an exon of the prolactin receptor in Senepol cattle (Littlejohn *et al.* 2014; <http://omia.angis.org.au/OMIA001372/9913/>). The so-called slick mutation appears to be associated with the type of coat, being slick or smooth, with some possible alteration to sweating ability (Davis *et al.* 2017). The slick variant is generally fixed in most breeds, meaning that it needs to be introgressed to benefit from this variant. Breeding programs in some countries, including Puerto Rico and the USA, have already started incorporating the slick mutation in Holstein cattle (Carabaño *et al.* 2019; Hansen 2020).

The slick mutation is also a target for gene-editing, which will enable more rapid introgression of the desirable

mutation, with little to no background DNA from the donor breed. Other variants that could also be useful in introgression programs for heat tolerance have been identified, such as a deletion in the promoter regions of a heat shock protein gene (HSPA1) that confers cellular protection to high temperatures (Hansen 2020). Other genes associated with hair and skin colour (Collier *et al.* 2008) could also be candidate target genes.

Gene editing provides a faster alternative to introgression and is especially useful for precisely introducing single alleles and haplotypes from locally adapted breeds (Van Eenennaam 2019). Regardless of the technology used, the introgression of the slick locus from the Senepol breed, or other loci identified as conferring heat tolerance, could produce cattle that perform better in hot climates, without environmental modifications. This would be of great value to dairy farmers in many dairying regions around the world.

- (3) *Selection within breeds.* Although the slick variant confers an ability to regulate body temperature, heat tolerance is highly polygenic, meaning that a breeding value for heat tolerance (that includes many variants) could be an alternative, or even additional solution. The first step in developing a breeding value for any trait is to identify suitable selection criteria. To achieve improved heat tolerance, the selection criteria chosen could include one or several traits and where selection on these traits leads to a favourable outcome in the breeding objective. Methods to describe heat tolerance have been an active area of research for a considerable period. Measuring changes in core body temperature in addition to animal performance in relation to bioclimatic indices has commonly been used (Carabaño *et al.* 2019). Selection criteria for heat tolerance could include body temperature, respiration rate, heart rate, sweating rate, reduction in intake or milk yield and impacts on reproductive performance in relation to THI.

Rectal or vaginal temperature is a direct measure of body temperature regulation that is heritable (Dikmen *et al.* 2012), with evidence that cows selected to be heat tolerant have lower core body temperatures (Garner *et al.* 2016). A limitation of this approach is that it is often invasive and labour-intensive and, therefore, likely to be available only on a small number of selection candidates. Some devices such as vaginal probes that can measure intra-vaginal temperatures continuously over short periods can be useful for small-scale reference populations and especially in grazing systems (Garner *et al.* 2016; Koltes *et al.* 2018).

Changes in production and reproductive performance of cattle are associated with heat stress (West 2003; Das *et al.* 2016) and measurable on large numbers of cows, and, because of this, are likely to be the most convenient breeding targets (Carabaño *et al.* 2019). Since heat tolerance has an unfavourable genetic correlation with milk production

traits (Aguilar *et al.* 2009; Nguyen *et al.* 2017), it is likely that selection objectives focused on high yielding dairy cows will continue to be detrimental to heat tolerance. However, it is important to note that a reduction in yield to rising ambient temperatures is partially a consequence of a voluntary reduction in feed intake. The proportion of milk yield reduction directly attributed to the decline in feed intake during heat stress is between 30% and 50% (Rhoads *et al.* 2009; Wheelock *et al.* 2010). Therefore, identifying the genetics that confers an ability to maintain a high level of production, while minimising losses due to heat stress, is important.

Ravagnolo *et al.* (2000) pioneered the use of dairy cow milk yield combined with temperature–humidity data from weather stations to measure variability in the rate of milk yield decline related to heat stress. Most dairy cow studies have used the so-called broken stick model to quantify the level of milk production traits under thermo-neutral conditions, which is the slope of decay (in milk production traits, for example) after passing a threshold associated with a transition to heat stress (Bernabucci *et al.* 2014). An alternative is to model using a reaction norm; this approach uses polynomials and, therefore, there is more flexibility than with the broken stick approach (Nguyen *et al.* 2016; Carabaño *et al.* 2019), such as, for example, if the slope gets steeper at higher THI values (non-linear relationship).

Case study: implementation of genetic evaluations for heat tolerance in Australia

Nguyen *et al.* (2016) found the the heritability of heat tolerance traits (i.e. slopes of milk, fat and protein) was

approximately 0.17–0.23. Using high-density single-nucleotide polymorphism (SNP) genotypes, heat tolerance modelled with a random regression models assuming the THI threshold of 60 (equivalent to a daily temperature of 20°C and 45% relative humidity) gives a genomic prediction accuracy of 0.42–0.61 (Nguyen *et al.* 2016). Heat tolerance breeding values were unfavourably correlated with milk production traits but were favourably associated with fertility (Nguyen *et al.* 2017), confirming the observations of Ravagnolo and Misztal (2000). Since these studies, additional animals have been added to the reference population (mainly genotyped females from Ginfo), enabling the release of the first genomic breeding values worldwide for dairy cow heat tolerance in 2017 (Nguyen *et al.* 2017). Reliabilities published by DataGene (the Australian national genetic evaluation unit for dairy) for bulls with no progeny are currently ~40%. Nguyen *et al.* (2017) found that the ability of dairy cattle in Australia to tolerate heat has been declining over the past years at a rate of 0.3%/year, in part, due to continued selection for milk production traits. This mirrors more recent data for heat tolerance from DataGene, the organisation responsible for routine genetic evaluation in Australia, with a steeper genetic decline of heat tolerance following the introduction of genomic selection in 2010 and approximating a 1 s.d. (five units of heat tolerance ABV) reduction over two decades (Fig. 1).

Animals identified to be divergent for heat susceptibility using the genomic breeding values for Australia developed by Nguyen *et al.* (2016) had significant differences in milk yield losses ($P < 0.023$, at Day 4), rectal ($P < 0.01$, Days 2–4) and vaginal ($P < 0.01$, on all 4 days) temperatures under a 4-day climate-controlled challenge designed to emulate a mild heatwave in south eastern Australia (Garner *et al.* 2016).

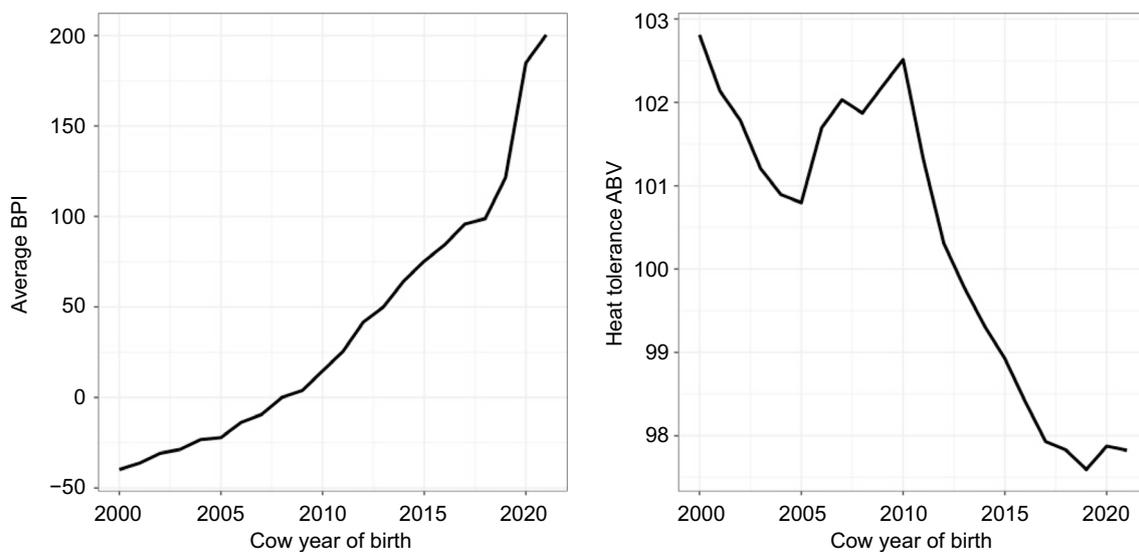


Fig. 1. Genetic trend of Australian average balanced performance index (BPI) and heat tolerance breeding values (ABVg) over the past years for Holstein cows (Date source; DataGene, <https://datagene.com.au/>; accessed September 2021).

More recently, heat tolerance genomic breeding values (developed using the same Australian reference population) were validated in a Californian dairy herd. Here, [Jensen *et al.* \(2021\)](#) found that for groups that were approximately 1 s.d. apart in heat tolerance ABVs, heat tolerant cows had significantly lower rectal and vaginal temperatures than did heat-sensitive cows ($P < 0.03$ and $P < 0.001$ respectively).

Genotype by environment interactions

Farmers operate very different farming systems; for example, while grazing dominates in Australia, some farmers have feeding systems that might be considered as more aligned to North American systems. Additionally, dairy farms in Australia are scattered over a wide range of climatic regions from Tasmania to Queensland. Therefore, producers are often interested in identifying sires that they believe will suit their production environment. Fortunately, this has been an area of extensive study for several decades, more specifically, quantifying the extent of genotype interactions with climatic and nutritional environments ([Veerkamp *et al.* 1994](#); [Ravagnolo and Misztal 2000](#); [Hayes *et al.* 2003](#); [Bryant *et al.* 2007b](#)).

Generally, genetic variation in environmental sensitivity manifests itself as a scaling effect, where there are phenotypic differences in daughter performance on the basis of the environment they are in, i.e. greater levels of production for example in more favourable environments. Of greater importance from a breeding perspective is whether sires re-rank across environments. This can be investigated by looking at genetic correlations of the same trait evaluated in different environments. For example, while genetic correlations between countries often imply significant re-rankings between sires, most studies within countries have concluded that re-ranking is expected at only extreme environments ([Hayes *et al.* 2003](#); [Bryant *et al.* 2007b](#); [Haile-Mariam *et al.* 2008](#); [Cheruiyot *et al.* 2020](#)).

While estimated breeding values (EBVs) for milk production traits already to some extent include heat stress effects, this is true only when all cows are evaluated under heat stress conditions. Quite often this is not the case and could become more of an issue in the genomic era where this information is unlikely to be captured in conventional production EBVs. [Zwald *et al.* \(2003\)](#) found that the heritabilities of production traits in colder climates in the USA were lower than in hot environments (0.26 and 0.39 respectively), and the genetic correlation between these two groups was 0.66. This implies that heat stress may play a role in genotype and environment interactions ($G \times E$). However, [Bohmanova *et al.* \(2008\)](#) found that considering heat stress as part of EBVs estimated using northeastern and southeastern data increased the correlation between the two regions by 0.01 and that heat stress explains only a

small amount of regional differences. One of the reasons for this is that test-day records capture only a snap-shot of heat stress. [Bryant *et al.* \(2006\)](#) found that Holstein-Friesian genotypes originating from North America are environmentally more sensitive than are New Zealand Friesian and Jersey genotypes to variation in the feeding level.

One option for sire selection decisions is selecting for robustness, i.e. similar EBVs across environments could be an option for ensuring stable performance ([König and May 2019](#)). For example, using Australian Holstein data, [Cheruiyot *et al.* \(2020\)](#) found variation in EBVs estimated as the slope of reaction norms for milk production traits against THI, indicating that there are some sires that could be considered to have 'robust' performance, i.e. whose daughters had stable levels of production regardless of THI. Robustness is often considered to be the capacity to perform in a wide range of current environments ([Colditz and Hine 2016](#)). Similarly, [Bryant *et al.* \(2007b\)](#) classified bulls into generalist and specialist bulls and most bulls that originate in the New Zealand production system were generalist and are capable of coping with changing production environment better than are specialist bulls. Improving the robustness of animals does not necessarily improve their resilience, as future environments may not be represented adequately by current environments.

There is a need to identify potential environmental stressors that dairy cattle may confront in the future. For example, [Berry \(2015\)](#) identified the following nine traits that are of likely future importance: (1) high production, (2) good reproductive performance, (3) good health status, (4) good longevity, (5) feed efficiency (6) easy to manage, (7) good conformation, (8) low environmental footprint, and (9) resilience to external disturbances. Generally, selection indices are used to appropriately weight multiple selection objectives and a single index value is presented for selection decisions. While indices have traditionally included traits that contribute to farmer profitability, there is a growing move towards including farmer preferences for selection pressure ([Martin-Collado *et al.* 2015](#)) and consumer preferences. This is a theme that is likely to continue and it may mean that traits associated with animal welfare and environmental impact have higher weights in selection indices than do those from solely from economic drivers. Most of the traits ([Berry 2015](#)) are already considered in most national dairy cattle selection indexes. Extensive work by [Berghof *et al.* \(2019\)](#) showed that if production and the most important health-related traits are already included in the selection index, the benefit of adding resilience indicator traits is expected to be small. Resilience, which is the capacity of an animal to be minimally affected by disturbances or to rapidly return to the status before exposure to disturbance, is suggested as additional trait to select for ([Berghof *et al.* 2019](#)). Most likely resilient animals, as well as animals considered to be generalists, are likely to be able to withstand weather

variability compared with specialist animals (e.g. Bryant *et al.* 2007a; Cheruiyot *et al.* 2020).

Currently, heat tolerance is not included in Australia's national selection index (balanced performance index; BPI), which means that farmers need to consider the heat tolerance ABV as a secondary selection criterion. One of the challenges with including heat tolerance in the BPI is that Australia is a large country with very diverse climates, so the economic value of selecting for heat tolerance may vary by region. For instance, where the environmental heat load is higher, there may be more justification in selecting for heat tolerance than in regions with a lower heat load. Using projected climate data from Commonwealth Scientific and Industrial Research Organisation (CSIRO; Canberra Australia) and The Bureau of Meteorology, Nguyen *et al.* (2016) determined levels of heat load for various dairying regions in Australia and used this information as weights for heat tolerance in an adapted version of the BPI. The Pearson correlation between the two indices, i.e. BPI and the BPI with heat tolerance (with weights appropriate for a high THI environment) was ~ 0.95 , which implied only a small amount of re-ranking of sires and there is currently no justification to have regionally specific BPI.

To summarise this section, a question that is often posed is whether it is better to select the cow to suit the system, or alter the system to suit the cow? Most short-term challenges from a changing environment are best addressed by using management strategies and long-term problems can be addressed using genetic selection. Sires described as generalists have daughters with comparable performance across systems/environments. In effect, the heat tolerance ABV should be helpful in identifying generalists, as animals with higher ABVs have less reduction in yield in hotter and more humid conditions. Furthermore, it is often impractical to implement cooling equipment in grazing situations, making genetic selection a very cost-effective approach.

Novel phenotypes for heat tolerance

Currently, the Australian breeding objective for heat tolerance includes three measurements (usually referred to as selection criteria in animal breeding); they are the decline in milk, fat and protein yields as THI rises. It is possible to increase the reliability of breeding values by incorporating other selection criteria. This is an approach that has been used effectively for other traits; for example, traits such as fertility are complex and multi-factorial and lend themselves well to multi-trait models that include different aspects of the biology of fertility (González-Recio *et al.* 2016). The same is likely to be true for heat tolerance, that there are different heritable aspects of heat tolerance that can potentially be used to improve heat tolerance EBVs, such as sweat gland density, body temperature,

respiration rate etc. Understanding of genetic (co)variance components, for example, with other heat tolerance traits in addition to other traits under selection is important to quantify the possible impact of additional selection criteria. As mentioned earlier, the pre-requisite is that these traits need to be measurable in a genomic reference population, such as Australia's Ginfo (females) and obviously heritable. It should be noted that even lowly heritable traits, such as fertility, often have considerable genetic variation and even larger variation affected by management, environment, chance etc. (Berry *et al.* 2014). Here, we discuss the potential role of wearable sensor devices, either for continuously measuring internal body temperature or wearable devices that can provide behavioural data associated with heat tolerance in addition to promising molecular phenotypes.

Sensor devices

Many modern internal (adapted intra-vaginal or rectal) devices are capable of continuously logging body temperature data; however, the limitation is that these can be used only for short periods (currently up to ~ 14 days) and are comparatively expensive, making them unsuitable for large-scale measurement. Nevertheless, Dikmen *et al.* (2012) generated a large enough dataset to determine the heritability of rectal temperatures under heat stress conditions of 0.17. More expensive and longer-term alternatives include surgically implantable temperature measurement devices, including loggers that require subsequent removal from the animal and, more attractively, those that transmit data via telemetry. Ruminant temperature boli with telemetry capability also show promise and are less invasive but may be influenced by water intake (Bewley *et al.* 2008; Cantor *et al.* 2018) and, unless the animal is fistulated, remain in the animal forever, rendering them single use and reliant on adequate battery life. Ruminant temperature is approximately $0.5\text{--}0.6^\circ\text{C}$ greater than is rectal temperature (AlZahal *et al.* 2011; Timsit *et al.* 2011).

Recent advances in sensor device technology might make devices that are wearable on the outside of an animal a viable alternative, such as panting scores (Gaughan *et al.* 2008) and tympanic temperature measurement devices. Many wearable sensor devices are now capable of measuring heavy breathing on an almost continuous basis. Bar *et al.* (2019) found good concordance between accelerometer measures of lactating cows breathing heavily and vaginal temperatures.

As wearable devices are becoming more popular, this could be an excellent opportunity for developing large datasets for estimating breeding values on the ability of animals to tolerate heat. However, simply relying on these sorts of behavioural measures without validation can be risky. For example, Garner *et al.* (2016) observed that cows with the greatest respiration rate/panting score did not always have the greatest core body temperature or the level of heat

stress. This is probably due to cows dissipating more heat through respiratory evaporative cooling. [Garner *et al.* \(2016\)](#) found that cows can have only slightly elevated respiratory rates, but very high core body temperatures, which was the case for most of the heat susceptible cows since they have less efficient evaporative cooling systems. One of the significant gaps in current knowledge is how to use sensor data to develop phenotypes for heat tolerance that could be used for animal breeding purposes. However, at the very least, breeding values developed using solely panting scores need to be carefully validated, ideally with internal body temperatures.

Metabolites and biomarkers

Other selection criteria that could be worth considering include metabolites that change under heat stress. Initial work by Agriculture Victoria colleagues ([Liu *et al.* 2017](#)) has shown that heat alters the lipid composition of milk. The review by [Ríus \(2019\)](#) describes how the breakdown of whole-body protein and synthesis of urea increases under heat stress, suggesting that amino acids are mobilised to meet the animal requirements. The limitation with this type of approach has been to obtain phenotypes on a sufficiently large population for genetic evaluation purposes. One option is to use MIR, as this should detect the biomarkers associated with variation in heat tolerance present in milk ([König and May 2019](#)). [Hammami *et al.* \(2015\)](#) found that several milk fatty acids predicted using MIR were sensitive to heat stress, most notably C18:1 *cis*-9, which is known to reflect body tissue mobilisation and could indicate cows with depressed appetites and yields.

A rise in body temperature modifies cellular function ([Hansen 2020](#)). In this regard, biomarkers of oxidative stress could also be useful, especially if these underpin pathways that are associated with genetic variation, which seems plausible. Specific heat shock protein genes have been proposed as promising biomarkers for heat stress and thermotolerance in dairy cattle ([Zachut *et al.* 2017](#); [Garner *et al.* 2020](#)). A potential biomarker of oxidative stress is heat shock protein 70 ([Basiricò *et al.* 2011](#)) which has been found to be upregulated in the mammary epithelial cells of dairy cows during heat stress to improve the thermotolerance of the mammary gland ([Garner *et al.* 2020](#)). In addition, how the immune system responds to an environmental stressor, such as heat, could also be useful to know. [Garner *et al.* \(2020\)](#) found that genes highly upregulated during heat stress were involved in increasing the rate of inflammation and the function of the innate immune system via the action of cytokines. Additionally, it appears that there may be endocrine and paracrine signals to heat stress that modify intracellular responses to heat stress ([Collier *et al.* 2008](#)). These systems can also lead to an altered physiological state (acclimation).

On the basis of our recent work of genomic selection applied to serum biomarkers of animal health ([Luke *et al.* 2019](#)), it appears that developing genomic predictions using female reference populations where biomarkers are measured in serum is promising. Furthermore, research in phenotypes predicted using mid-infrared spectroscopy, where a spectrum is obtained from a routine herd-testing of milk sample, could pave the way for expanding the genomic reference population at a minimal extra cost ([van den Berg *et al.* 2021](#)). Elucidating the physiological systems controlled by genes involved in thermoregulation is an area worthy of further research, as understanding the biological control will help prioritise variants in genomic selection strategies in addition to understanding how $G \times E$ is modulated.

Physiological and immune responses

There are other ways that heat affects dairy cows. For example, [Dahl *et al.* \(2016\)](#) stated that heat stress reduces dry-matter intake, which in turn reduces yield and compromises immune function. Alternatively, indicators of recovery after a heat event could also be a useful selection criteria, such as an analysis of the slope of the return to baseline milk yield following heat stress, sensors may improve our understanding of the recovery period. There is evidence that dairy cows varying in genomic heat tolerance recover their feed intake and milk production differently following periods of heat stress ([Garner *et al.* 2016](#)). Many of these traits are correlated. For example, there is evidence that traits associated with disease or parasite resistance are favourably correlated with heat tolerance ([Mackinnon *et al.* 1991](#); [Burrow *et al.* 2019](#)). This is an important concept in defining new breeding objectives and corresponding selection criteria for traits associated with adaptation and robustness across a broad range of environments. Opportunities to extend selection criteria to include the impact of heat stress on health and fertility will help capture the complexity of heat stress and, potentially, lead to the selection of better adapted dairy cattle.

Improving weather measurements

The more accurate the measure of microenvironment surrounding animals is, the more reliable is the breeding value estimated. Most studies have relied on public weather stations for temperature and humidity data, which can be scarce in some areas or located in uneven terrain and are unlikely to represent microclimate at a farm level. That makes matching the environmental with phenotypic records less than ideal. One option is to have mini-weather stations installed on farms, such as locations of Ginfo herds. Another option is to obtain higher resolution/downscale weather data from meteorological agencies. The above will bring about better representation of farm microclimates and more variance on heat tolerance could be captured.

Conclusions

An approach of combining genomics, and traditional and novel measures of heat tolerance with intermediate metabolic biomarkers and prioritised genetic variants is likely to be an effective strategy to capture the complexity of thermotolerance in next-generation heat-tolerance breeding values. Reducing the impact of heat stress on animal performance can be achieved by using both genetic selection as well as improving herd management; in this regard, selection and modifying the conditions we keep cows are complementary strategies.

References

- Aguilar I, Misztal I, Tsuruta S (2009) Genetic components of heat stress for dairy cattle with multiple lactations. *Journal of Dairy Science* **92**, 5702–5711. doi:10.3168/jds.2008-1928
- AlZahal O, AlZahal H, Steele MA, Van Schaik M, Kyriazakis I, Duffield TF, McBride BW (2011) The use of a radiotelemetric ruminal bolus to detect body temperature changes in lactating dairy cattle. *Journal of Dairy Science* **94**, 3568–3574. doi:10.3168/jds.2010-3944
- Bar D, Kaim M, Flamenbaum I, Hanochi B, Toaff-Rosenstein RL (2019) Technical note: Accelerometer-based recording of heavy breathing in lactating and dry cows as an automated measure of heat load. *Journal of Dairy Science* **102**, 3480–3486. doi:10.3168/jds.2018-15186
- Basiricò L, Morera P, Primi V, Lacetera N, Nardone A, Bernabucci U (2011) Cellular thermotolerance is associated with heat shock protein 70.1 genetic polymorphisms in Holstein lactating cows. *Cell Stress and Chaperones* **16**, 441–448. doi:10.1007/s12192-011-0257-7
- Berghof TVL, Poppe M, Mulder HA (2019) Opportunities to Improve Resilience in Animal Breeding Programs. *Frontiers in Genetics* **9**, 692. doi:10.3389/fgene.2018.00692
- Berman A (2003) Effects of body surface area estimates on predicted energy requirements and heat stress. *Journal of Dairy Science* **86**, 3605–3610. doi:10.3168/jds.S0022-0302(03)73966-6
- Bernabucci U, Biffani S, Buggiotti L, Vitali A, Lacetera N, Nardone A (2014) The effects of heat stress in Italian Holstein dairy cattle. *Journal of Dairy Science* **97**, 471–486. doi:10.3168/jds.2013-6611
- Berry DP (2015) Breeding the dairy cow of the future: what do we need? *Animal Production Science* **55**, 823–837. doi:10.1071/AN14835
- Berry DP, Wall E, Pryce JE (2014) Genetics and genomics of reproductive performance in dairy and beef cattle. *Animal* **8**, 105–121. doi:10.1017/S1751731114000743
- Bewley JM, Grott MW, Einstein ME, Schutz MM (2008) Impact of intake water temperatures on reticular temperatures of lactating dairy cows. *Journal of Dairy Science* **91**, 3880–3887. doi:10.3168/jds.2008-1159
- Bohmanova J, Misztal I, Tsuruta S, Norman HD, Lawlor TJ (2008) Short communication: Genotype by environment interaction due to heat stress. *Journal of Dairy Science* **91**, 840–846. doi:10.3168/jds.2006-142
- Bryant JR, López-Villalobos N, Pryce JE, Holmes CW, Johnson DL (2006) Reaction norms used to quantify the responses of New Zealand dairy cattle of mixed breeds to nutritional environment. *New Zealand Journal of Agricultural Research* **49**, 371–381. doi:10.1080/00288233.2006.9513727
- Bryant JR, López-Villalobos N, Pryce JE, Holmes CW, Johnson DL (2007a) Quantifying the effect of thermal environment on production traits in three breeds of dairy cattle in New Zealand. *New Zealand Journal of Agricultural Research* **50**, 327–338. doi:10.1080/00288230709510301
- Bryant JR, López-Villalobos N, Pryce JE, Holmes CW, Johnson DL, Garrick DJ (2007b) Environmental sensitivity in New Zealand dairy cattle. *Journal of Dairy Science* **90**, 1538–1547. doi:10.3168/jds.S0022-0302(07)71639-9
- Burrow HM, Mans BJ, Cardoso FF, Birkett MA, Kotze AC, Hayes BJ, Mapholi N, Dzama K, Marufu MC, Githaka NW, Djikeng A (2019) Towards a new phenotype for tick resistance in beef and dairy cattle: a review. *Animal Production Science* **59**, 1401–1427. doi:10.1071/AN18487
- Byrne TJ, Santos BFS, Amer PR, Martin-Collado D, Pryce JE, Axford M (2016) New breeding objectives and selection indices for the Australian dairy industry. *Journal of Dairy Science* **99**, 8146–8167. doi:10.3168/jds.2015-10747
- Cantor MC, Costa JHC, Bewley JM (2018) Impact of observed and controlled water intake on reticulorumen temperature in lactating dairy cattle. *Animals* **8**, 194. doi:10.3390/ani8110194
- Carabaño MJ, Ramón M, Menéndez-Buxadera A, Molina A, Díaz C (2019) Selecting for heat tolerance. *Animal Frontiers* **9**, 62–68. doi:10.1093/af/vfy033
- Cheruiyot EK, Nguyen TTT, Haile-Mariam M, Cocks BG, Abdelsayed M, Pryce JE (2020) Genotype-by-environment (temperature–humidity) interaction of milk production traits in Australian Holstein cattle. *Journal of Dairy Science* **103**, 2460–2476. doi:10.3168/jds.2019-17609
- Colditz IG, Hine BC (2016) Resilience in farm animals: biology, management, breeding and implications for animal welfare. *Animal Production Science* **56**, 1961–1983. doi:10.1071/AN15297
- Cole JB, VanRaden PM (2018) Symposium review: possibilities in an age of genomics: the future of selection indices. *Journal of Dairy Science* **101**, 3686–3701. doi:10.3168/jds.2017-13335
- Collier RJ, Collier JL, Rhoads RP, Baumgard LH (2008) Invited review: genes involved in the bovine heat stress response. *Journal of Dairy Science* **91**, 445–454. doi:10.3168/jds.2007-0540
- CSIRO (2016) 'State of the climate 2016, Commonwealth of Australia, Canberra, Australia.' (CSIRO and Bureau of Meteorology: Melbourne, Vic., Australia)
- Dahl GE, Tao S, Monteiro APA (2016) Effects of late-gestation heat stress on immunity and performance of calves. *Journal of Dairy Science* **99**, 3193–3198. doi:10.3168/jds.2015-9990
- Das R, Sailo L, Verma N, Bharti P, Saikia J, Imtiwati, Kumar R (2016) Impact of heat stress on health and performance of dairy animals: a review. *Veterinary World* **9**, 260–268. doi:10.14202/vetworld.2016.260-268
- Davis SR, Spelman RJ, Littlejohn MD (2017) Breeding and genetics symposium: Breeding heat tolerant dairy cattle: the case for introgression of the 'slick' prolactin receptor variant into *Bos taurus* dairy breeds. *Journal of Animal Science* **95**, 1788–1800. doi:10.2527/jas.2016.9596
- Dikmen S, Cole JB, Null DJ, Hansen PJ (2012) Heritability of rectal temperature and genetic correlations with production and reproduction traits in dairy cattle. *Journal of Dairy Science* **95**, 3401–3405. doi:10.3168/jds.2011-4306
- Dunshea FR, Leury BJ, Fahri F, DiGiacomo K, Hung A, Chauhan S, Clarke IJ, Collier R, Little S, Baumgard L, Gaughan JB (2013) Amelioration of thermal stress impacts in dairy cows. *Animal Production Science* **53**, 965–975. doi:10.1071/AN12384
- Garner JB, Douglas ML, Williams SRO, Wales WJ, Marett LC, Nguyen TTT, Reich CM, Hayes BJ (2016) Genomic selection improves heat tolerance in dairy cattle. *Scientific Reports* **6**, 34114. doi:10.1038/srep34114
- Garner JB, Chamberlain AJ, Vander Jagt C, Nguyen TTT, Mason BA, Marett LC, Leury BJ, Wales WJ, Hayes BJ (2020) Gene expression of the heat stress response in bovine peripheral white blood cells and milk somatic cells in vivo. *Scientific Reports* **10**, 19181. doi:10.1038/s41598-020-75438-2
- Gaughan JB, Mader TL, Holt SM, Lisle A (2008) A new heat load index for feedlot cattle. *Journal of Animal Science* **86**, 226–234. doi:10.2527/jas.2007-0305
- González-Recio O, Haile-Mariam M, Pryce JE (2016) Improving the reliability of female fertility breeding values using type and milk yield traits that predict energy status in Australian Holstein cattle. *Journal of Dairy Science* **99**, 493–504. doi:10.3168/jds.2015-10001
- Haile-Mariam M, Carrick MJ, Goddard ME (2008) Genotype by environment interaction for fertility, survival, and milk production traits in Australian dairy cattle. *Journal of Dairy Science* **91**, 4840–4853. doi:10.3168/jds.2008-1084

- Hammami H, Vandenplas J, Vanrobays M-L, Rezik B, Bastin C, Gengler N (2015) Genetic analysis of heat stress effects on yield traits, udder health, and fatty acids of Walloon Holstein cows. *Journal of Dairy Science* **98**, 4956–4968. doi:10.3168/jds.2014-9148
- Hansen PJ (2020) Prospects for gene introgression or gene editing as a strategy for reduction of the impact of heat stress on production and reproduction in cattle. *Theriogenology* **154**, 190–202. doi:10.1016/j.theriogenology.2020.05.010
- Hayes BJ, Carrick M, Bowman P, Goddard ME (2003) Genotype × environment interaction for milk production of daughters of Australian dairy sires from test-day records. *Journal of Dairy Science* **86**, 3736–3744. doi:10.3168/jds.S0022-0302(03)73980-0
- Hayes BJ, Bowman PJ, Chamberlain AJ, Goddard ME (2009) Invited review: genomic selection in dairy cattle: progress and challenges. *Journal of Dairy Science* **92**, 433–443. doi:10.3168/jds.2008-1646
- Jensen LM, Jannaman EA, Pryce JE, De Vries A, Hansen PJ (2021) Evaluation of Australian breeding values for heat tolerance under US conditions. *Proceedings of Association for the Advancement of Animal Breeding and Genetics* **24**, 179–182.
- Kadzere CT, Murphy MR, Silanikove N, Maltz E (2002) Heat stress in lactating dairy cows: a review. *Livestock Production Science* **77**, 59–91. doi:10.1016/S0301-6226(01)00330-X
- Koltes JE, Koltes DA, Mote BE, Tucker J, Hubbell III DS (2018) Automated collection of heat stress data in livestock: new technologies and opportunities. *Translational Animal Science* **2**, 319–323. doi:10.1093/tas/txy061
- König S, May K (2019) Invited review: Phenotyping strategies and quantitative-genetic background of resistance, tolerance and resilience associated traits in dairy cattle. *Animal* **13**, 897–908. doi:10.1017/S1751731118003208
- Littlejohn MD, Henty KM, Tiplady K, Johnson T, Harland C, Lopdell T, Sherlock RG, Li W, Lukefahr SD, Shanks BC, Garrick DJ, Snell RG, Spelman RJ, Davis SR (2014) Functionally reciprocal mutations of the prolactin signalling pathway define hairy and slick cattle. *Nature Communications* **5**, 5861. doi:10.1038/ncomms6861
- Liu Z, Logan A, Cocks BG, Rochfort S (2017) Seasonal variation of polar lipid content in bovine milk. *Food Chemistry* **237**, 865–869. doi:10.1016/j.foodchem.2017.06.038
- Luke TDW, Nguyen TTT, Rochfort S, Wales WJ, Richardson CM, Abdelsayed M, Pryce JE (2019) Genomic prediction of serum biomarkers of health in early lactation. *Journal of Dairy Science* **102**, 11142–11152. doi:10.3168/jds.2019-17127
- Mackinnon MJ, Meyer K, Hetzel DJS (1991) Genetic variation and covariation for growth, parasite resistance and heat tolerance in tropical cattle. *Livestock Production Science* **27**, 105–122. doi:10.1016/0301-6226(91)90090-D
- Martin-Collado D, Byrne TJ, Amer PR, Santos BFS, Axford M, Pryce JE (2015) Analyzing the heterogeneity of farmers' preferences for improvements in dairy cow traits using farmer typologies. *Journal of Dairy Science* **98**, 4148–4161. doi:10.3168/jds.2014-9194
- Nguyen TTT, Bowman PJ, Haile-Mariam M, Pryce JE, Hayes BJ (2016) Genomic selection for tolerance to heat stress in Australian dairy cattle. *Journal of Dairy Science* **99**, 2849–2862. doi:10.3168/jds.2015-9685
- Nguyen TTT, Bowman PJ, Haile-Mariam M, Nieuwhof GJ, Hayes BJ, Pryce JE (2017) Short communication: implementation of a breeding value for heat tolerance in Australian dairy cattle. *Journal of Dairy Science* **100**, 7362–7367. doi:10.3168/jds.2017-12898
- Polsky L, von Keyserlingk MAG (2017) Invited review: effects of heat stress on dairy cattle welfare. *Journal of Dairy Science* **100**, 8645–8657. doi:10.3168/jds.2017-12651
- Pryce JE, Nguyen TTT, Axford M, Nieuwhof G, Shaffer M (2018) Symposium review: Building a better cow: the Australian experience and future perspectives. *Journal of Dairy Science* **101**, 3702–3713. doi:10.3168/jds.2017-13377
- Ravagnolo O, Misztal I (2000) Genetic component of heat stress in dairy cattle, parameter estimation. *Journal of Dairy Science* **83**, 2126–2130. doi:10.3168/jds.S0022-0302(00)75095-8
- Ravagnolo O, Misztal I, Hoogenboom G (2000) Genetic component of heat stress in dairy cattle, development of heat index function. *Journal of Dairy Science* **83**, 2120–2125. doi:10.3168/jds.S0022-0302(00)75094-6
- Rhoads ML, Rhoads RP, VanBaale MJ, Collier RJ, Sanders SR, Weber WJ, Crooker BA, Baumgard LH (2009) Effects of heat stress and plane of nutrition on lactating Holstein cows: I. Production, metabolism, and aspects of circulating somatotropin. *Journal of Dairy Science* **92**, 1986–1997. doi:10.3168/jds.2008-1641
- Rius AG (2019) Invited review: Adaptations of protein and amino acid metabolism to heat stress in dairy cows and other livestock species. *Applied Animal Science* **35**, 39–48. doi:10.15232/aas.2018-01805
- Thom EC (1959) The discomfort index. *Weatherwise* **12**, 57–61. doi:10.1080/00431672.1959.9926960
- Timsit E, Assié S, Quiniou R, Seegers H, Bareille N (2011) Early detection of bovine respiratory disease in young bulls using reticulo-rumen temperature boluses. *The Veterinary Journal* **190**, 136–142. doi:10.1016/j.tvjl.2010.09.012
- van den Berg I, Ho PN, Luke TDW, Haile-Mariam M, Bolormaa S, Pryce JE (2021) The use of milk mid-infrared spectroscopy to improve genomic prediction accuracy of serum biomarkers. *Journal of Dairy Science* **104**, 2008–2017. doi:10.3168/jds.2020-19468
- Van Eenennaam AL (2019) Application of genome editing in farm animals: cattle. *Transgenic Research* **28**, 93–100. doi:10.1007/s11248-019-00141-6
- VanRaden PM (2020) Symposium review: how to implement genomic selection. *Journal of Dairy Science* **103**, 5291–5301. doi:10.3168/jds.2019-17684
- Veerkamp RF, Simm G, Oldham JD (1994) Effects of interaction between genotype and feeding system on milk production, feed intake, efficiency and body tissue mobilization in dairy cows. *Livestock Production Science* **39**, 229–241. doi:10.1016/0301-6226(94)90202-X
- West JW (2003) Effects of heat-stress on production in dairy cattle. *Journal of Dairy Science* **86**, 2131–2144. doi:10.3168/jds.S0022-0302(03)73803-X
- Wheelock JB, Rhoads RP, VanBaale MJ, Sanders SR, Baumgard LH (2010) Effects of heat stress on energetic metabolism in lactating Holstein cows. *Journal of Dairy Science* **93**, 644–655. doi:10.3168/jds.2009-2295
- Yousef MK (1985) 'Stress physiology in livestock: basic principles. Vol. 1.' (CRC Press: Boca Raton, FL, USA)
- Zachut M, Kra G, Livshitz L, Portnick Y, Yakoby S, Friedlander G, Levin Y (2017) Seasonal heat stress affects adipose tissue proteome toward enrichment of the Nrf2-mediated oxidative stress response in late-pregnant dairy cows. *Journal of Proteomics* **158**, 52–61. doi:10.1016/j.jprot.2017.02.011
- Zwald NR, Weigel KA, Fikse WF, Rekaya R (2003) Identification of factors that cause genotype by environment interaction between herds of Holstein cattle in seventeen countries. *Journal of Dairy Science* **86**, 1009–1018. doi:10.3168/jds.S0022-0302(03)73684-4

Data availability. Australian breeding values for heat tolerance are publicly available for active sires and can be accessed from the DataGene website (<https://datagene.com.au/BreedingValues>). Other requests should be directed to DataGene Ltd (Melbourne, Australia) as custodians of data on Australian dairy cows. Research-related requests for access to the data may be accommodated on a case-by-case basis.

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