Genetic variation in surface temperature measured using infrared thermography and genetic associations with production traits in grazing dairy cattle

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Abstract

Heat stress negatively impacts the production and reproduction of dairy cattle, and it is likely to worsen with increasing global temperatures due to climate change. Infrared thermography measured skin temperature could potentially be used as an indicator trait for heat stress in cows since it might correspond to the amount of heat dissipation. The aim of this research was to obtain infield skin temperature measurements for the eye, muzzle, and udder in dairy cows using infrared thermography in order to determine whether there is genetic variation in the skin temperature between cows in a dairy herd. Secondly, estimates of genetic correlations between skin temperature and economically important traits like milk yield were obtained.

Thermal images and herd test records were obtained for 225 cows belonging to a once-a-day, spring calving dairy herd at Massey University's dairy farm 1 in Palmerston North, New Zealand, during the 2022-23 production season. Breed, lactation number, and predicted milk yield were determined to significantly affect the average udder temperature. Holstein-Friesian× NZ Jersey crossbreds had the greatest average udder temperature as well as cows with higher lactation numbers and higher predicted milk yields. These results may be indicative of either higher producing cattle exhibiting greater udder temperatures and/or cows with greater udder temperatures exhibiting greater heat dissipation ability. The heritability estimates for infrared thermography measured eye, muzzle and udder temperature were low to moderate at 0.20, 0.24 and 0.39 respectively. The genetic correlations between the temperature and production traits were all positive and weak to moderately strong, with the exception of eye temperature with milk and protein yield. The estimates for the genetic parameters determined in this study indicate that increased skin surface temperature could be selected for without compromising production yield. These findings, if validated in a large-scale follow-up study would enable estimation of breeding values for udder temperature that could be incorporated into a selection index aimed at improving heat tolerance in dairy cattle.

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List of Abbreviations

BW	Breeding worth
DIM	Days in milk
DMCD	Deviation from median calving date
ECMY	Energy corrected milk yield
FY	Fat yield
LY	Lactose yield
MSY	Milk solids yield
MY	Milk yield
OAD	Once-a-day
PMY	Predicted milk yield
PW	Production worth
PY	Protein yield
r_G	Genetic correlation
r_P	Phenotypic correlation
SD	Standard deviation
SE	Standard error
TAD	Twice-a-day
THI	Temperature-humidity index

Chapter 1

General introduction

The pastoral farming system utilised by the dairy industry in New Zealand is oriented around the seasonal pattern of pasture growth. Most of the dairy farms in New Zealand (>90%) operate on a spring calving pattern in order to take advantage of the large peak in pasture growth in late spring and early autumn. This requires a tight calving interval of 365 days (Verkerk, 2003). The most commonly used dairy breeds in the New Zealand dairy industry are Holstein-Friesian, NZ Jersey, and Holstein-Friesian × Jersey crossbreds, with a trend of higher proportions of crossbred cattle used in the national herd (DairyNZ & LIC, 2022). Crossbred dairy cattle perform well under the payment system used in New Zealand, which emphasises milk solid yield by rewarding fat and protein content and penalising milk volume (Sneddon et al., 2016).

There are a number of drawbacks on using a pastoral system over a housing system which need to be considered when attempting to address welfare issues resulting from heat stress. These include, greater distances required for cattle to walk (between paddocks and the milking shed), greater exposure to parasites, pasture-based diets being harder to digest and generate more heat than concentrated diets, and constant exposure to the weather elements (Bryant et al., 2007; Van Iaer et al., 2014). Therefore, when there are adverse weather conditions such as extreme ambient temperatures and relative humidity, especially during the summer, the cattle are greatly affected (Van Iaer et al., 2014). Cattle experience heat stress when the heat generated through metabolism and gained from the environment is large enough that they are unable to dissipate enough heat to maintain their body temperature within healthy limits (Becker et al., 2020). Heat stress in dairy cattle has a deleterious effect on almost every system in their body, with the most well researched aspects being production and reproductive performance since these determine the potential economic output (Wankar et al., 2021). It also impacts the progeny of heat-stressed dams with late gestational heat stress resulting in calves with lower birth weights and a higher risk of failure of passive transfer (Cartwright et al., 2023). Lactation is energetically expensive and high producing dairy cattle experience negative energy balance in early lactation because energy intake is less than the energy produced in milk. In this period these high producing cows have to mobilise body reserves to meet energy requirements and have higher metabolic rates. This is part of the reason that high producing dairy cattle, especially Holstein-Friesians, are more sensitive to heat stress than lower producing dairy cattle or beef breeds (Wankar et al., 2021). Young cattle have a higher body surface to volume ratio therefore there is greater heat exchange between the animal and the environment, and they are more susceptible to both heat and cold stress (Wankar et al., 2021).

Climatic indices are commonly used to identify the climatic conditions for the onset and degree of heat stress in livestock animals (Van Iaer et al., 2014). One of the most commonly used climatic indices in the literature is the temperature-humidity index (THI), with reported THI thresholds for heat stress varying between 68 and 72 units (Galan et al., 2018).

There are physiological and behavioural changes in heat-stressed cattle that can be used as indicators; these include reduced feed intake, reduced rumination, less frequent urination and defecation, more time spent standing, shade seeking behaviour, increased drinking frequency, decline in milk production, increased core temperature, respiration, panting and sweating rates, and altered endocrine function. (Ratnakaran et al., 2017; Garner et al., 2016).

There is genetic variance, both within and between breeds of cattle, in the thermotolerance as well as variability in physiological variables including rectal, vaginal and body surface temperature (Cheruiyot et al., 2022; Correa-Calderon et al., 2022). Heat tolerance is a polygenic trait; therefore, its expression is controlled by many genes to varying degrees. For this reason, it is better to use a proxy for heat tolerance when incorporating heat tolerance in a breeding scheme. For example, the Australian breeding values for heat tolerance use the rate of decline in milk production with increasing THI values as a measure of heat tolerance or heat sensitivity. Alternatively, the magnitude of physiological indicators for heat stress such as rectal temperature, could be used as a proxy (Cartwright et al., 2023). When Jensen et al. (2022) compared heat tolerant Holsteins to heat sensitive Holsteins (determined using Australian breeding values for heat tolerance), heat tolerant individuals had a higher skin temperature. This suggests that selecting for greater body surface temperatures may convey greater heat dissipation ability, hence greater heat tolerance. Infrared thermography provides a non-invasive method of accurately measuring body surface temperatures and is promising tool for potentially identifying more heat tolerant or sensitive cattle based on variation in surface temperature (McManus et al., 2016; Santos Daltro et al., 2017). Traditional methods for measuring heat stress including body temperature (rectal and vaginal temperature) and physiological responses (respiratory, cardiac, and panting rate as well as blood cortisol concentration) are invasive and stressful for the subject which can influence the accuracy of the measurement. Additionally, such methods are more costly than infrared thermography in terms of labour, time, and money (McManus et al., 2016).

Many of the suggested mitigation strategies to alleviate heat stress involve modification of the cattle’s environment. These strategies reduce exposure or enhance heat dissipation. In the context of the NZ dairy industry, such strategies are of limited use (Jensen et al., 2022; Van Iaer et al., 2014). Genetic solutions to mitigate heat stress provide a promising option, as it would convey permanent and accumulative changes (Cartwright et al., 2023; Cheruiyot et al., 2022). Introgression of genes conveying superior heat tolerance, like the slick gene into Holstein-Friesians in New Zealand, has already begun (Davis et al., 2017). Crossbreeding *Bos taurus* breeds with the more heat tolerant *Bos indicus* breeds is not a financially viable option in the New Zealand context. Australia is the only country to develop breeding values related to heat tolerance where they used milk decline traits under increasing THI as a proxy for heat tolerance (Nguyen et al., 2016; Davis et al., 2017; Cartwright et al., 2023).

The determination of heritability of a reliable proxy for heat tolerance and its genetic correlation with economically important traits, like milk yield, provides the first step in generating a selection scheme to breed more heat tolerate dairy cattle. The objective of this thesis was to firstly determine if infrared thermography could be used to measure variation in skin temperature between members of a dairy herd, secondly to know if this variation is under genetic control, and finally to estimate genetic correlation of skin temperature with key production traits.

Chapter 2

Literature review: The effect of heat stress on the welfare and production of dairy cattle in New Zealand

2.1 New Zealand Dairy Industry

The New Zealand dairy industry has a seasonal calving and breeding system, operating on a 365-day calving interval. Pasture growth follows a characteristic seasonal pattern in which peak growth occurs in late spring to early summer, with a smaller peak in autumn. Productivity of dairy cows is typically timed to match this pattern so that the highest milk solids production occurs at the same time as there are larger quantities of high-quality pasture (a greater leaf to stem ratio and less dead matter) and less supplementary feed is necessary. For this reason, a tight calving interval is essential (Verkerk, 2003). Typically, as a result of this seasonal pasture growth and weather changes, dairy cows are dried off (not milked in order to stop lactation) in late summer or early autumn so that during winter, when there is much slower pasture growth and lower quality pasture, they do not go into a negative energy balance (Harris, 2005). There are generally three milking frequencies utilized in New Zealand herds: 55% of herds use twice a day (TAD) milking, 9% use once a day (OAD) and the remainder use variable milking frequencies during the production season (Jayawardana et al., 2023).

The export revenue for the dairy sector in New Zealand increased from approximately 19 billion NZD during the 2021 financial year to approximately 22 billion NZD in the 2022 financial year with the 2023 financial year ending on the 30th June 2024 predicting to approximately 26 billion NZD (Ministry for Primary Industries, 2023). The dairy industry accounted for 3.2% of New Zealand’s gross domestic product which can be subdivided into the dairy farming (approximately 2.2%) and dairy processing (approximately 0.9%) sectors (Partners, 2023). Of all the goods producing sectors in New Zealand dairy farming is the largest at $8 billion and dairy processing is the third largest at $3.4 billion. Therefore, any significant financial losses would have a major impact on the New Zealand economy. The breakdown of the relative contributions of dairy farming and processing to New Zealand’s total GDP by region is presented in Figure 2.1 (Partners, 2023).

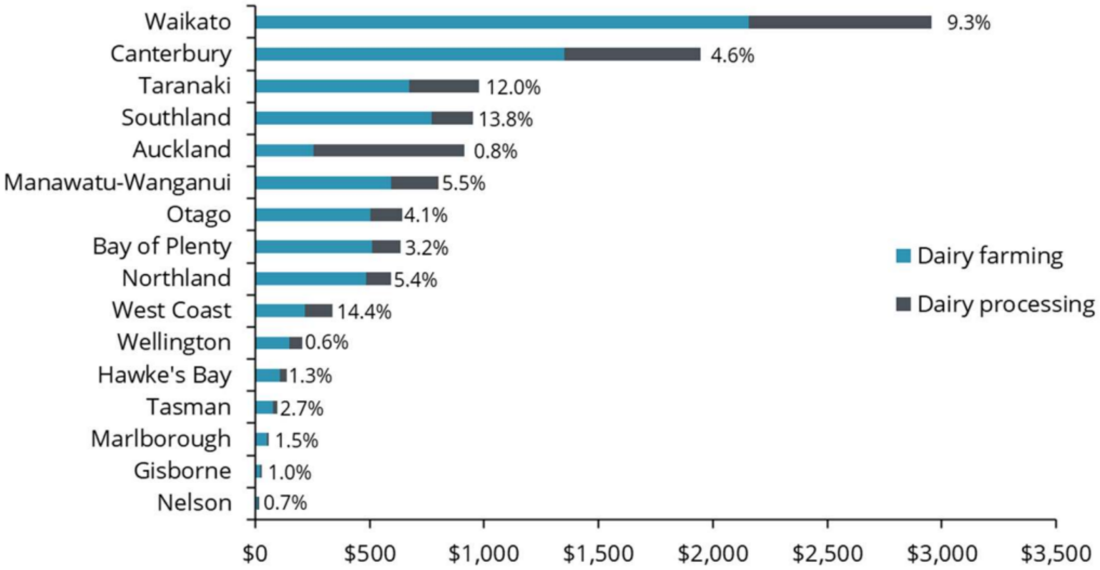

Figure 2. 1. The regional contribution to total gross domestic product in million NZD from year to March 2023 (Partners, 2023).

As shown in Figure 2.1 the dairy sector including both dairy farming and processing is conducted across the whole of NZ but there are regional differences in the amount of activity. Of the five largest contributing regions to the total GDP for the dairy sector, Waikato is the largest at over $2.9 billion, followed by Canterbury at approximately $2 billion, then Taranaki at over $1 billion, Southland at over $1 billion and Auckland at approximately $1 billion. If you consider only dairy farming, the Waikato, Canterbury, Southland, Taranaki, Manawatu, and Otago are the largest. The dairy industry is a huge source of employment across NZ with approximately 54,787 jobs in this sector in NZ during 2023.

In terms of New Zealand's export economy, dairy exports are the largest export earner by a large margin, with the exports for the twelve months up to April 2023 coming to $25.7 billion (35.3% of exported goods). If you look at the percentage of the production in both dairy farming and processing that is exported, very little is sold within NZ with 87% and 85.9 % of the output from dairy processing and dairy farming, respectively being exported.

The export products from the dairy industry can be subdivided into whole milk powder (31.9%), butter and dairy spreads (17.7%), protein products (13.2%), cheese (11.1%), skim milk powder (9.6%), infant powder (7.7%), fluid milk and cream (5.6%), other 2.2%, and yogurt, buttermilk and kephir (0.9%) (Partners, 2023). During the 2021-22 production season 20.8 billion litres of milk was processed from which 1.87 billion kg of milk solids produced. The average milk solids yield was 386 kg per cow and the average production of milk solids per hectare was 1,098 kg. These quantities were produced by a total cow population of 4.84

million that made up 10, 796 herds. While there are three main breeds of dairy cattle utilised in NZ, the breed composition during the 2021-22 season can be subdivided into 59.2% Holstein-Friesian/Jersey crossbred, 25.2% Holstein-Friesian, 7.6% Jersey, 0.4% Ayrshire and 7.6% other breeds (DairyNZ & LIC, 2022). The reason that almost 60% of the cows in the total cow population were Holstein-Friesian/Jersey crossbreds (also marketed as the KiwiCross^{TM} by Livestock Improvement Corporation Ltd (LIC)) is that the offspring have the benefit of hybrid vigour providing higher productivity, better fertility and greater longevity as well as possessing the best traits from both parental breeds (DairyNZ & LIC, 2022; LIC, 2023). The mating season comprises of 6 to 8 weeks of artificial insemination and about 4 weeks of natural mating, aiming for 90% of the cows to become pregnant, any factors that could interfere with fertility, such as heat stress, would reduce reproductive performance of the herd (McDougall, 2006). Many characteristics of this system not only contribute towards heat stress but also make certain solutions for mitigating heat stress (currently used overseas) unsuitable for use in New Zealand. The diet for New Zealand cattle is primarily pasture based with some supplementary feed, when necessary, rather than concentrated diets seen in housing systems used overseas. This pasture-based diet takes longer to digest and generates more heat than concentrated diets (West, 2003.).

2.2 Effect of climate change

Climate change has resulted in rising global temperatures and increased incidence of heat waves. In New Zealand there has been a noticeable increase in the number of days, where the temperature has exceeded 25°C (Harrington, 2021). The effect of climate change on the dairy industry will be detrimental not only to the welfare of the animals themselves, but also on the pasture and supplemental crops that the industry relies on (Garcia et al., 2021). New Zealand has a lot of regional variability in climate across both islands, partially because of its position within the mid-latitude westerly wind belt and the rugged mountainous terrain in places. For this reason, the impact of global warming will not be homogenous across the whole of New Zealand. An international treaty on climate change, called the Paris agreement that was presented at the United Nations Climate change conference and adopted in 2015, specified global warming thresholds of 1.5 and 2°C. The current increases in the average global temperature are rapidly approaching these threshold values (Bodeker et al., 2022). There has been an observed trend of increasing mean temperatures that is likely to persist. The report by

Bodeker et al. (2022) interpreting the Intergovernmental Panel on Climate Change Working Group 1 assessment (IPCC WG1) reported that there is likely to be increased incidence and severity of extreme weather events such as droughts in the summer, extreme precipitation, flooding, and tropical cyclones. Additionally, there will likely be changes in the rainfall patterns across New Zealand with predicted increases during the winter and spring in the west and south and decreases in the east and north of the country. Also, less rainfall is predicted during the summer in the west and central North Island (Bodeker et al., 2022).

The pastoral based system used in New Zealand leaves the dairy industry particularly vulnerable to climatic fluctuations because of global warming than the housing dairy systems used overseas that are reliant on imported feed. With the profitability of dairy farms closely tied to the amount of dry matter per hectare per year available to the cows within the herd, any climatic fluctuations that interfere with pasture growth are concerning and will likely impact profit if feed is needed to be bought in (Kalaugher et al., 2017). With the summers becoming drier especially for the central and upper north island, it poses a challenge to the production and persistence of clover and perennial ryegrass swards that traditionally make up the pasture for dairy cattle (McCahon et al., 2021).

2.3 Heat stress

When an animal is unable to maintain their core body temperature within a normal healthy range, it experiences heat stress. When this happens the heat generated through the animal's metabolism and gained from the environment is greater than what they are able to dissipate (Becker et al., 2020). Heat stress becomes an issue when the ambient temperature exceeds what is known as the thermoneutral zone. The thermoneutral zone is a temperature range within which animals do not need to exert additional energy to maintain their core temperature within a healthy range and can do it using only passive mechanisms. The upper and lower thresholds for this range are called the upper and lower critical temperatures (Collier et al., 2019). The thermoneutral range in dairy cattle is between approximately -0.5 and 20.0 °C (Correa-Calderonet et al., 2022). However, there are differences between the upper and lower critical temperatures between individuals which means there are differences in the thermotolerance of individual dairy cattle (Collier et al., 2019). When the external temperature exceeds the upper critical temperature, an animal will experience heat stress and passive heat loss mechanisms are no longer effective. These heat loss mechanisms include conduction, convention, and radiation, however for these to be effective there needs to be a thermal gradient between the animal with the environment. When no such thermal gradient exists the next course of action is evaporative heat loss mechanisms such as panting and sweating. The relative humidity of the environment can influence the effectiveness of evaporative heat loss (Collier et al., 2019). Thermoregulatory responses are voluntary and involuntary and occur in an attempt to maintain their core body temperature within a healthy range; it is a complex process that is controlled by the endocrine system, the central nervous system, and the peripheral nervous system (Collier et al., 2019). The behavioural and physiological changes in dairy cattle in response to heat stress vary depending on the amount of previous exposure, how long they have been experiencing the heat stress, the intensity of the heat stress, the physiological state of the individual (such as pregnancy status, lactation status and body condition) as well the existing environmental factors. With exposure to heat stress there are corresponding changes to neuroendocrine function (the interaction between the nervous and endocrine systems) and metabolism of the individual because of the stress, as an attempt to address the heat stress. There are climatic factors other than ambient temperature that contribute towards heat stress including humidity, solar radiation and wind speed which is why heat stress may occur at lower ambient temperatures when there is higher humidity and more intense solar radiation. For this reason, climatic indices such as the temperature-humidity index (THI) are useful for identifying the climatic conditions within which livestock experience heat stress in order to make appropriate management decisions and for use in research. These climatic indices often have risk classes or thresholds used to assess the likely response by animals (Van Iaer et al., 2014). The temperature-humidity index is routinely used in studies investigating heat stress in livestock as this index accounts for temperature and relative humidity measurements. There is variation in reported temperature-humidity index for heat stress. The temperature-humidity index at which decline in milk production is reported to begin is lower in New Zealand than in other countries; this has been attributed to a number of factors including the higher solar radiation in New Zealand compared to countries like the USA, Canada, and Britain. The longer distances dairy cattle need to walk and the predominantly pasture-based diet which results in greater metabolic heat production during digestion (Bryant et al., 2007) contribute to a greater heat load leading to a decline in production beginning at a lower THI in New Zealand cows. However, as the temperature-humidity index does not include all of the environmental parameters that contribute to the thermal state of livestock, there are questions on its suitability to predict the biological responses of animals and define thresholds for heat stress. Other climatic indices such as the black globe-humidity index and the heat load index, which are also used to assess the thermal state of livestock have been suggested as better alternatives than the temperature-humidity index as they include the temperature, relative humidity as well as solar radiation and wind speed (Fournel et al., 2017). A study by Zimbelman et al. (2009) proposed the creation of a skin temperature-humidity index that incorporates the infrared measured skin temperature, and the dew point temperature in the calculation of the index in order for infrared thermography cameras or guns to be used to evaluate heat stress in cattle (Zimbelman et al., 2009).

Virtually all aspects of animal health, including feed intake, rumen function, immune function, production and reproduction, are impacted as a result of heat stress. Production and reproduction have been well studied in dairy cows as they contribute toward the greatest losses in profitability. International research and estimations by animal science experts suggest that heat stress is responsible for an enormous loss of revenue in the dairy industry globally (Wankar et al., 2021). In a New Zealand study, a THI of 68-75 units was identified as sufficiently high to result in a decrease of more than 10 g of milk solids per day per unit increase in the THI for the dairy breeds commonly used in NZ (Holstein Friesian, NZ Jersey, and Holstein-Friesian/Jersey crossbreds). THI values of 68-75 correspond to a temperature value of 21-25.5 °C at a 75% humidity (Bryant et al., 2007). In warmer climates the severity of the heat stress experienced by dairy cattle is greater; this can be illustrated by the losses observed in the study by Bouraoui et al. (2002), where they examined production losses in dairy cattle living in mediterranean climate. They reported for all ages and parities, an approximately 21% loss in milk production when the THI went from 68 to 78 or when the ambient temperature went above 27°C (Correa-Calderon et al., 2022; Bouraoui et al., 2002). Therefore, with the increase in heat stress days where this range is met or exceeded, there will likely to be significant losses (Harrington, 2021). The milk yield is not the only aspect of lactation that is affected by heat stress, the fat and protein concentration in the milk of Holstein-Friesians, New Zealand Jerseys as well as crossbreeds is also reduced (Bryant et al., 2007). A study conducted by Barash et al (2001) involving Israeli Holsteins examining the effect of calving month on milk and protein production reported that protein yield may be more sensitive to heat stress than milk production (Barash et al., 2001). Lactating cows are more susceptible than non-lactating cows, with 27-48% more metabolic heat generated by lactating Holstein-Friesians than their non-lactating counterparts. The reduction in feed intake and increase in maintenance requirements for heat-stressed cows can result in cows entering a negative energy balance and experiencing a depletion of reserves (Wankar et al., 2021). Heat stressed animals also experience changes in nutrient absorption and utilization such as the case for the glucose and lipid homeostasis which plays a key role in reduction of production in heat stressed cows. (Wankar et al., 2021; Wheelock et al., 2010). When feed intake is limited in the absence of heat stress, there is expected to be an increase in the non-esterified fatty acid (NEFA) concentration in blood plasma as well as a reduction in the action of systemic insulin which alters carbohydrate and lipid metabolism resulting in lipolysis and mobilisation of lipids from adipose tissue in order to maintain lactation. However, in the study by Wheelock et al. (2010), there was no increase in the concentration of NEFA and insulin in the blood plasma of heat-stressed cows, this may result in the preferential use of glucose over fatty acids in heat-stressed cows to support lactation (Wheelock et al., 2010). There are also changes in rumen function as a result of heat stress; this is supported by the increased plasma urea nitrogen (PUN) found in heat-stressed Holsteins by (Wankar et al., 2021; Wheelock et al., 2010). Higher producing dairy cattle are more sensitive to heat stress than lower producing cows due to higher metabolic rates. Of the three most common dairy cattle breeds in New Zealand , Holstein friesian, Jerseys and Holstein-friesian/Jersey crossbreds, Holstein-Friesians have been found to be the most sensitive to heat stress followed by crossbreds and Jerseys (Bryant et al., 2007). There is genetic variation in thermotolerance both between and within breeds of cattle (Hansen, 2020). *Bos taurus* breeds are more vulnerable to heat stress than *Bos indicus* breeds, which have adaptations allowing them to be better thermo-tolerant. Of the *Bos taurus* breeds used in dairy farming, Holstein-Friesians are the most sensitive (Correa-Calderon et al., 2022). There are also effects of heat stress observed in the offspring of heat stressed dams, for example there is an increased risk of failure of passive transfer in the calves of heat stressed dams. Dairy calves need to ingest and absorb enough immunoglobulin (Ig) through their gut from their dam's colostrum to provide immune support as their immune system develops. When they are unable to gain enough Ig through their gut failure of passive transfer occurs. This may occur due to decreased concentrations of Ig in the dam's colostrum and reduced absorption through the calf's gut. This second suggested reason is supported by dairy calves born from heat stressed dams still at higher risk of failure of passive transfer even when there is sufficient concentration of Ig in colostrum (Cartwright et al., 2023).

2.4 Methods for measuring heat stress

There are several ways to identify cows experiencing heat stress, including behavioural and physiological indicators such as panting, blood testing, milk cortisol levels and core body temperature (Neves et al., 2022). Behavioural indications of heat stress differ depending on factors including previous exposure, intensity of the heat stress and the physiological state of the cattle (such as pregnancy, lactation, and body condition score). Behavioural changes observed in heat stressed dairy cattle include reduced feed intake, increased consumption of water, reduced rumination, decline in the frequency of urination and defecation (evaporation of water through sweat, saliva, and respiratory secretions), more time spent standing, and shade seeking behaviour. The increased drinking frequency provides cooling of the reticulorumen which can aid in lowering core body temperature (Ratnakaran, et al., 2016). There are increases in respiration, panting, and heart rate in dairy cattle that are heat stressed which can be used to determine whether they are heat stressed (Garner, et al., 2016). Plasma urea nitrogen has been reported to be increased in heat stressed Holsteins which may be due to changes in rumen function during heat stress (Wheelock et al., 2010). Measuring cortisol metabolites in blood plasma, milk samples, faecal samples, and in hair samples can be used to measure heat stress as high cortisol metabolite concentrations are associated with heat stress. Blood plasma, milk and faecal cortisol metabolites measurements can provide an indication of acute heat stress. Using milk samples is efficient, non-invasive, and is less stressful for the animals but using blood plasma cortisol metabolite measurements requires expertise, requires manual handling and is stressful for the cattle. Hair cortisol metabolite measurements provide a longer-term measure of chronic stress (weeks to months depending on the cattle's coat), however like blood plasma sampling it can be stressful. Unfortunately, these samples require analysis in laboratories by trained personal and as large numbers of samples would need to be processed it is costly in both time and money (Idris et al., 2021).

The gold standard for measuring core temperature would be rectal or vaginal temperature measurements, however these are invasive and required manual handling. Other alternatives measurement practices for core temperature include ear (tympanic), reticulorumen, intraperitoneal cavity, and milk temperatures (Cartwright et al., 2023). Dairy cattle maintain their core temperature within a narrow range of approximately 37.9-39.5 °C under thermoneutral conditions (Wenz et al., 2011). Rumen boluses can be used to record core body temperatures over prolonged periods of time (Idris et al., 2021). The external body temperature can also be measured to determine core body temperature, which is less invasive (Neves et al., 2022). Skin surface temperatures can be measured using thermal data loggers glued to the skin, they can also be attached close to the tympanic membrane of the eardrum to measure core temperature. The issue with data loggers attached to the external body surface and internal temperature devices is that it requires restraining and manual handling of the cattle in order to attach or insert the devices which can be very stressful for the cattle (Idris et al., 2021).

Infrared thermography measures the emission of radiated heat from a surface such as the external body surface of cattle. It provides a non-invasive method to determine skin temperature while minimising stress for the subjects. Additionally, it can be automated and is efficient as it is able to measure large sample sizes in a relatively short time period and doesn't require restraining of the subjects (Idris et al., 2021). Infrared thermography has been shown to provide an accurate measure of body temperature by measuring the surface temperature of certain body surfaces like the eye as there is a positive correlation between eye temperature with vaginal and rectal temperature (Giro et al., 2019; Idris et al., 2021). The coronary band of the forelimb has also been suggested as an ideal target for infrared measurements of skin temperature as there is profuse blood circulation in this area and cows under stress have been shown to have a higher surface temperature in the coronary band of the forelimb relative to relaxed cows (Idris et al., 2021). Some studies have suggested that the lateral portion of the udder is an ideal target for measuring skin temperature using infrared thermography especially considering the high positive correlation with rectal temperature (dos Santos Daltro et al., 2017).

There are several factors that need to be considered when using infrared thermography for taking temperature measurements of livestock, including camera to object distance, camera angle, environmental factors (windspeed, humidity, and solar radiation) camera settings (e.g., emissivity factor setting on the camera, 0.95 used when subjects are cattle), and the amount of hair or dirt on the surface being measured (Cai et al., 2023; Church et al., 2014). It is difficult to account for the effect of environmental variables such as wind speed, solar radiation and humidity when taking infield measurements (Church et al., 2014). The presence of hair as well as the colour and density can also affect the accuracy of temperature measurements on thermograms as hair acts as an insulator decreasing the emission of radiated heat (Cai et al., 2023; Idris et al., 2021). With darker hair and skin having a greater absorption and emission of heat compared to lighter coat colours giving higher infrared thermography temperature measurements (Idris et al., 2021). In order to achieve accurate and consistent temperature measurements using infrared cameras confounding variable such as skin emissivity, health status, vigorous movement, as well as the variables discussed above need to be accounted for and minimised (Idris et al., 2021).

2.5 New Zealand breeding program

American Holstein-Friesians were imported into New Zealand in 1920 for dairy production, but these were kept in a closed population meaning that there were no new animals or semen brought in to inject new genetics into the herd. Instead, all the breeding occurred within the existing population. In 1960, the national dairy population within New Zealand was three quarters Jersey but that began to change between the early 1960s and 1980s through upgrading of the Jersey population through crossbreeding with Holstein-Friesians. Thus, the New Zealand Holstein-Friesian was developed. There was injection of new Holstein-Friesian genetics into New Zealand cattle from American population, beginning in the 1970s and this became more prevalent in the 1980s and 1990s. Studies conducted in the 1990s (Bryant et al.,1985; Ahlborn & Bryant, 1992) revealed breed differences between purebred Jersey and New Zealand Holstein-Friesian cows and provided greater understanding of beneficial heterosis effects (greater performance of particular traits in crossbreds relative to parental performance). These experiments also determined that despite breed differences Jerseys and New Zealand Holstein-Friesian cows had a very similar feed efficiency (the ability to convert feed into profit). This resulted in more widespread use of crossbreeding across New Zealand. The national breeding objective began with the inclusion of solely production traits such as fat and protein yield, but later included non-production traits (Harris, 2005). The national breeding objective in New Zealand is called Breeding Worth and it evaluates the genetic merit of dairy cattle in terms of their ability to produce the most efficient (converting feed into profit) progeny and therefore the most profitable progeny. The units for Breeding Worth are dollars of net farm income per 5 tonnes of Dry matter ($/5 t DM) (DairyNZ, 2023a). The genetic evaluation of cattle in the New Zealand dairy industry is provided by DairyNZ, through its subsidiary New Zealand Animal Evaluation Limited (NZAEL) which conduct the national evaluations, but the main artificial insemination companies (e.g. LIC and CRV) have their own genetic evaluations (Santos et al., 2023). The NZAEL genetic evaluation allows comparison of the genetic merit of all dairy cattle in New Zealand regardless of breed, sex, or age. The dairy industry in New Zealand is heavily reliant on artificial insemination in artificial breeding programs and for this reason much of the selection decisions are within the purview of the artificial insemination companies like LIC rather than the farmers themselves. However, farmers are able to decide what breeds of dairy cow that they include within their herd and the individual bull semen that they purchase from the artificial insemination companies (Montgomerie, 2005).

Currently, in New Zealand, the national breeding objective includes ten traits all with different economic values and effective emphases, as shown in Table 2.1 (DairyNZ, 2023b). Breeding

Worth is the sum of the multiplication of each of the ten traits multiplied by the corresponding economic value. The ten traits can be subdivided into two categories: production efficiency traits and robustness traits. The individual effective emphasis of the ten traits is included in Table 2.1 and they are split into 63% for the production efficiency traits and 37% for the robustness traits. The higher effective emphasis for production efficiency traits is due to such traits having a greater impact on profitability than robustness traits. Of the production efficiency traits, milk protein and fat and milk volume are important traits to be included in Breeding Worth as they directly relate to farm profits (DairyNZ, 2023a).

In New Zealand, the payment scheme is focused on milk solids due to the high proportion of dairy products (>85%) exported (Partners, 2023; Lembeye et al., 2016). The milk payment system in New Zealand for farmers by the dairy processing companies can be explained using the equation A+B-C, where A is the value per kg for fat, B the value per kg for protein and C the penalty per litre of milk volume. This is a simplified description of the New Zealand payment scheme as there are numerous other factors that contribute toward payment to farmers (Sneddon et al, 2013). However, from examination of this equation, you can see that fat and protein yield is rewarded as it has a positive economic value and milk volume is penalised. This makes sense when considering that very little of the exported dairy products are in the form of fluid milk and cream so a lot of the water that makes up milk volume is evaporated off during processing. The positive economic value for traits encourages the breeding values for those traits in dairy cattle to increase, and the negative economic values penalise certain traits such as milk volume and liveweight so that these traits aren’t increasing as the traits with positive economic values increase (Sneddon et al., 2013). Currently DairyNZ is advocating the inclusion of genomic data into the Breeding Worth calculations because of the faster rate of genetic gain that can be achieved than by using phenotype and pedigree information in the daughter proving scheme that has been used in New Zealand for a long time. The genomic breeding values are based on a combination of genotype and phenotypic data (DairyNZ, 2023c). In the daughter proving process a prospective bull would enter progeny testing and the genetic worth of the bull is proven through the performance of his daughters. After this process if the bull is deemed to be of sufficient worth their semen will be sold through artificial insemination companies like LIC (Harris, 2005; DairyNZ, 2023c). This daughter proving process from birth of the bull through their semen being used in artificial breeding programs takes approximately five years. The semen of genomically selected bulls however is available for use in artificial breeding programs much sooner at approximately three years of age as they could get their DNA tested as soon as they are born (DairyNZ, 2023c).

Table 2. 1. The ten traits included in the New Zealand Breeding Worth index and their economic values (EV) and effective emphasis (EE) in December 2023 (DairyNZ, 2023b).

Trait category	Trait (units)	EV[1] ($/unit change)	EE[2]
Production efficiency	Milk protein ($/kg)	6.83	19.1
Production efficiency	Milk fat ($/kg)	4.85	19.1
Production efficiency	Milk volume ($/L)	-0.01	9.4
Production efficiency	Liveweight ($/kg)	-1.59	15.1
Robustness	Somatic cell score ($/SCS)	-46.21	5.7
Robustness	Fertility ($/PR42[3])	5.77	12.4
Robustness	Gestation length ($/day)	-1.89	1.6
Robustness	Functional survival ($/%)	1.88	1.4
Robustness	Body condition score ($/unit)	164.09	7.9
Robustness	Udder overall (score)	0[4]	8.2

[1] EV= Economic value (dollar increase per one unit increase in the trait).

[2] EE= Effective Emphasis of each trait.

[3] PR42= Pregnancy rate after 42 days of mating.

[4] Udder Overall has a non-linear economic value, an udder overall BV of <0 has a negative value whereas an udder overall >0 results in a positive economic value. E.g. an udder overall BV >1.002 has a fixed economic value of $31.53.

2.6 Proposed methods for mitigation of heat stress

Alternative management practices, including cooling technologies in housing systems and milking sheds, generation of greater shade (planting trees), outdoor shelters and alternative feeds, require significant time and money to implement while some are not practical in New Zealand’s farming system (Jensen et al., 2022; Van Iaer et al., 2014). The provision of shelter and shade is one of the simplest and cost-effective ways to reduce solar radiation and is able to reduce the heat load experienced by the animal by up to 30% (Renaudeau et al., 2012). Cows that have been provided shade have lower rectal temperatures, lower respiration rates, lower panting rates, higher dry matter intake, lower corticosteroid concentration in blood plasma, lower concentration of cortisol metabolites in faecal samples and exhibit less decline in milk production(Osei-Amponsah et al., 2019; Van Iaer et al., 2014). There are a number of considerations that need to be made if artificial shelters are going to be erected for heat stress mitigation; the size of the shelter (3.5-6.5 m^2 of shade per cow), the amount of ventilation for the space (so that the floors are able to dry and for sufficient air convection) and the construction material. For instance, metal roofing provides the best protection from solar radiation while still being durable and cost-effective, but in a pastoral situation shade cloth is better as it is light and movable shelters can be constructed (Van Iaer et al., 2014). Trees and large shrubbery are a good option in pastoral farming systems, and it has the added benefit of the cooling effect that occurs when water evaporates from the leaves during transpiration (Renaudeau et al., 2012). The installation of cooling systems including sprinklers, cooling pads, fogging, and misting systems, fans and perforated air ducting systems are only useful when there is housing, and feedlots. They are of limited use in pastoral farming systems like New Zealand. They function by aiding in evaporative cooling and convective heat transfer from the cow to the environment and by decreasing air temperature and increasing humidity. Modifying feed and the use of supplements has been suggested to reduce the negative effects of heat stress. By using protein and/or energy rich concentrated feed with lower fibre content when there is a reduction in feed intake due to heat stress, cows are better able to meet their energy requirements and there is less heat generated during digestion of such feed (Osei-Amponsah et al., 2019). Additionally, genetic solutions have also been suggested as effective methods for mitigation of heat stress in dairy cattle.

2.6.1 Crossbreeding for heat tolerance

There are breed differences in economically important traits including production, reproduction and most importantly in this case heat tolerance between *Bos indicus* and *Bos taurus* cattle breeds. Crossbreeding has a long history of being used in order to convey the most desirable characteristics of the parental breeds to the progeny for the intended purpose of the cattle and environmental conditions that they will be living in (Hansen, 2004; Khatib, 2015). Crossbreeding the more heat tolerant *Bos indicus* cattle with *Bos taurus* in order to introduce breed characteristics that convey heat tolerance into *Bos taurus* cattle to breed more thermotolerant cattle is one possible solution to mitigating heat stress (McDowell et al., 1996). *Bos indicus* cattle, also known as Zebu cattle, originate from India and are used mostly in tropical and subtropical regions, they are well known to be better adapted to hot environments and irregular feed supply, compared to *Bos taurus* cattle which originate from Europe

(McDowell et al., 1996). Studies have proved that *Bos indicus* cattle are better able to modulate their body temperature, have lower metabolic heat production and are better able to dissipate excess heat than *Bos taurus* cattle (Cartwright et al., 2023). *Bos indicus* cattle have superior body temperature regulation under heat stress than *Bos taurus* cattle due to characteristics including lower metabolic rates, higher density of arteriovenous anastomoses (connections between small arteries and veins) allowing for faster blood flow to the skin surface. They generally have smooth shiny coats in a light colour which reflect more solar radiation, they experience less cellular damage caused by heat stress, and have a higher density of large sweat glands (Hansen, 2004). However, this is not a suitable option for dairy cattle in developed nations where resources are not limited and *Bos indicus*×*Bos taurus* crossbreds aren't as profitable as high producing dairy breeds and their crossbreds. *Bos indicus* cattle have some undesirable traits such as substantially lower production than *Bos taurus* breeds that impact the profitability of the *Bos indicus*×*Bos taurus* crossbreds (Cartwright et al., 2023). Such undesirable *Bos indicus* characteristics include lower milk yields and lactation persistency (the ability to maintain milk yields after peak lactation), shorter oestrus periods, and less docile temperaments than *Bos taurus* dairy breeds (Hansen, 2004). Additionally, the crossbred progeny would likely be less tolerant of cold temperatures, therefore in pastoral farming systems they would be at risk of cold stress during the winter (Cartwright et al., 2023). However, in hot tropical and subtropical climates *Bos indicus*×*Bos taurus* crossbreds have been used for dairy and meat when there has been limited resources and large declines in production when purebred *Bos taurus* breeds have been used. An alternative option to cross breeding *Bos indicus* and *Bos taurus* cattle breeds could be incorporation of beneficial *Bos indicus* genes that convey greater heat tolerance using gene editing (Hansen, 2004).

2.6.2 Selection for heat tolerance

Selective breeding has been proposed by many sources as a promising strategy for addressing production losses and welfare concerns arising from heat stress. Put simply, an index would be developed and used in order to rank animals for well-defined traits and from this ranking, the best performing individuals would be chosen as parents for the next generation of animals (Cheruiyot et al., 2022). The index would need to include estimates of the individual animal's genetic merit (breeding values) for the trait(s) of interest in order to rank the animals effectively. The breeding values can be estimated based on pedigree and phenotype data and/or genomic breeding values can be estimated based off genetic markers identified in reference populations where the phenotype and genotype are known. The use of genomic selection has become more popular as genetic technology has become more advanced and it can increase the rate of genetic improvement since individuals can be genotyped at a young age and there is no need to wait for progeny to be produced and tested before breeding values can be estimated (Pryce et al., 2018). Research into the genes responsible for conveying thermotolerance so that genetic markers can be utilised in breeding programs are still in the early stages but there have been some promising studies such as the case of the genetic markers used in the Australian breeding values for heat tolerance which utilise genomic breeding values using SNP markers (Correa-Calderon et al., 2022; Nguyen et al., 2016). Breeding objectives are tailored country-specific due to differences like the farm systems utilised, the breeds utilised and climatic differences (Harris, 2005). There are a few things that need to be known prior to the inclusion of a new trait into a national breeding objective like breeding worth in New Zealand. In terms of addressing heat stress breeding values for traits associated with higher thermotolerance could be estimated and incorporated into an existing selection index; so, over the course of generations the thermotolerance of the national herd may be improved (Luo et al., 2020; Nguyen et al., 2016). There needs to be sufficient phenotypic data as well as a heritability estimate for that phenotype, and a method of genetic evaluation in order to estimate breeding values for the trait, genotypic and phenotypic correlations between the trait with other economically important traits, and an economic value for that trait in order to determine breeding worth (Harris, 2005). There are a number of proposed approaches for selection for thermotolerance including selection for reduced milk production in heat stressed animals, selection based on physiological traits used in the identification of heat stress such as rectal or vaginal temperature, selection for physiological traits involved in dissipating excess heat, selection of cellular traits related to thermotolerance and selection for immune response (Cartwright et al., 2023). Genetic variation in the decrease in milk production has been documented between dairy cows when the ambient temperature exceeds heat stress thresholds. This genetic variation can be exploited in selection schemes using genomic breeding values or by estimating breeding values (using either genotype or pedigree and phenotype data) for the rate of decline in milk production as the ambient temperature and relative humidity increase beyond heat stress thresholds (Nguyen et al., 2016). Nguyen et al. (2016) developed genomic breeding values for heat tolerance where heat tolerance was defined according to milk decline over increasing THI using phenotype and high-density single nucleotide polymorphism genotypes. These genomic breeding values for heat tolerance were released in Australia in 2017. They were determined to be negatively correlated with production traits and positively correlated with fertility traits. The validity of these genomic breeding values for heat tolerance were confirmed by a study by Jensen et al. (2022), where the performance of heat tolerant and heat sensitive cows under heat stress identified by the Australian breeding values for heat tolerance (ABVHT) were compared. Cows identified as heat tolerant (ABVHT≥102 is considered heat tolerant) had lower rectal and vaginal temperatures, greater skin temperatures, slower decline in milk production, and less reduction in dry matter intake than heat sensitive cows (ABVHT<108 is considered heat sensitive) (Jensen et al., 2022). This was also evident in a study by Garner et al. (2016) which also examined the performance of so-called heat tolerant and heat sensitive lactating Holsteins experiencing heat stress; in this case, a four-day heat wave was simulated using controlled climate chambers. The Holsteins from this study exhibited the same differences in rectal, vaginal, and skin temperatures and differences in the rate of milk decline but they also reported lower respiration rates and panting scores (respiration rate and panting score are used as indicators of heat stress) in heat tolerant cows (Garner et al., 2016). The Australian genomic breeding values for heat stress have a low to moderate positive genetic correlation with fertility and a strong negative genetic correlation with production traits. Therefore, by selecting for thermotolerance using these breeding values, the rate of decline in milk yield under heat stress will be lower in heat tolerant cows, the 305-day milk yield will also probably be lower in heat tolerant cows than heat sensitive cows (Cartwright et al., 2023).

Selection for reduced rectal temperature is a possible target for selection and the genetic parameters for rectal temperature have been estimated in several studies for a number of different breeds (Table 2.1). Rectal temperature has been shown to be heritable with heritability estimates ranging from low to moderately heritable. There has reported to be a weak positive genetic correlation between rectal temperature and milk production traits (Table 2.2) and a strong negative correlation between rectal temperature and some reproduction traits (Dikmen et al., 2012; Luo et al., 2020). Studies comparing the rectal temperature in Holsteins identified to be thermotolerant and thermosensitive, based on the Australian genomic breeding values, have reported thermotolerant cows to have lower rectal temperatures (Garner et al., 2016). Therefore, it is possible to select for a lower rectal temperature in order to achieve genetic improvement in the thermotolerance of dairy cattle, but the positive correlation with milk production means that selection of lower rectal temperature may result in lower milk production (Hansen, 2020). Alternatively, respiration rate which is used to identify heat-stressed animals and increased respiration rate is known to be a mechanism for getting rid of excess heat is also a possible target for selection for increased heat tolerance. However, respiration rate has a reported heritability of 0.04 which is extremely low meaning that selection for this trait would be slow to make genetic gain (Cartwright et al., 2023). It has been suggested that selecting for enhanced nitric oxide production, known to be involved in vasodilation of the skin during heat stress, may convey greater vasodilation of the skin surface during heat stress thereby allowing greater heat dissipation. Therefore, individuals with a greater ability to dissipate excess heat will be more heat tolerant and suffer fewer negative effects of heat stress. Another possible target for selection is heat shock proteins as they are involved in cellular repair and protection during heat stress and are involved in immune responses. In particular, the expression of the HSP70 family of heat shock proteins has been identified as a potential biomarker for heat stress in dairy cattle (Osei-Amponsah et al., 2019; Cartwright et al., 2023). While there are currently no reported heritability estimates for heat shock proteins in dairy cattle, there have been studies reporting increased expression of heat shock proteins during heat stress (Abdelnour et al., 2019; Cartwright et al., 2023). Chinese Holstein cattle determined to be heat tolerant (determined using indices measuring physiological symptoms of heat stress including rectal temperature and respiration rate and response in milk yield to high temperatures) had higher blood plasma concentrations of the heat shock proteins HSP70 and HSP90 as well as cortisol when exposed to heat stress compared to Holsteins determined to be non-heat tolerant (Lui et al., 2020). One issue with selection using cellular traits like increased expression of heat shock proteins and enhanced nitric oxide production is that they are expensive and time consuming to measure, requiring trained personnel and it would be difficult to assemble a large reference population with data on these traits (Cartwright et al., 2023).

Skin surface temperature as well as other physiological variables (rectal temperature and respiration rate) have been shown to exhibit variability between cows. It may be possible to use skin surface temperature to select for cattle that have a greater heat tolerance as there is known to be genetic variation in heat tolerance within breeds of cattle (Cheruiyot et al., 2022). There is some evidence to suggest that there is a linkage between higher skin surface temperature and greater heat tolerance. In Holsteins, cows that are more heat tolerant based on Australian genomic breeding values for heat tolerance have been associated with higher skin temperatures than their less heat tolerant counterparts (Garner et al., 2016).This suggests that it may be possible for skin temperature to be used to select for cattle that have a greater heat tolerance as individuals that have a higher skin temperature may be better at getting rid of excess heat (Cheruiyot et al., 2022). Currently there are no published genetic parameters for skin surface temperature in dairy cattle. In order for genetic selection based on skin temperature to occur, estimates of heritability, as well as genetic and phenotypic correlations between skin temperature and economically important production traits are necessary. Eventually, if proven to be a viable target for selection, a large reference population of known pedigree and phenotype would need to be assembled and definition of selection index that includes not only this trait but also production, reproduction, health, and survival traits would need to occur for genetic improvement for heat tolerance to be made in New Zealand dairy cows. Ideal method for skin surface temperature recording, to be able to identify heat tolerant and heat sensitive phenotypes, will need to be determined before the phenotypes of the reference population can be determined. Consideration for monetary and time cost should be considered when deciding appropriate methods to assess skin temperature across very large number of dairy cows. Infrared thermography has been shown to provide an accurate surface temperature measurement for the eye, muzzle, and udder (dos Santos Daltro et al., 2017; George et al., 2014; Giro et al., 2019).

Table 2.2. Published estimates of the heritability (h^2) and repeatability (t) estimates for rectal temperature (RT) in cattle.

Study	Country	Breed	Temperature °C	RT °C	h^2	t
Seath et al. (1947)	USA	Holstein, Jersey	31.7	39.83	0.15	0.15
		Holstein, Jersey		39.91	0.31	0.38
Turner (1982)	Australia	Hereford × Shorthorn	22-32	39.8	0.25	0.34
		Bos indicus × Bos taurus				
McMillan and van der Werf (2007)	Australia	Holstein	-	36.5-41.8	0.11	0.28
Dikman et al. (2012)	USA (Florida)	Holstein	30.6	37.2-41.7	0.17	-
Otto et al. (2019)	Netherlands	Gir × Holstein	42	-	0.13	0.29
Luo et al. (2021)	China (Beijing)	Holstein	-	37.2-40.8	0.06	0.19

[1] Ambient temperature when the RT was measured.

Table 2.3. Reported estimates of the phenotypic (r_P) and genetic (r_G) correlations between rectal temperature and milk production traits[1] in dairy cows.

	Milk yield	Fat yield	Protein yield
r_P	-0.016[a]	0.067[a]	0.09[a]
r_G	0.09[a]	0.096[a]	0.102[a]
	0.34-0.41[b]	0.50-0.62[b]	0.45-0.51[b]

[a] Dikmen et al. (2012).

[b] Luo et al. (2021).

[1] Milk, fat and protein yields.

2.6.3 Gene introgression

Introgression in terms of animal breeding involves the transfer of desirable genetic variant(s) between separate populations often between different breeds. This can be achieved through traditional genetic introgression mating schemes involving repeated backcrossing or through gene editing (Hansen, 2020; Bourdon, 2014). If introduction of a desirable trait is achieved through repeated back crossing the first population is crossed with individuals from a separate population or breed with the desirable trait, then subsequently back crossed with the first population in order to retain the desirable trait but minimising undesirable genes from the second population (Bourdon, 2014). There are a number of target traits that would potentially convey superior heat tolerance into high producing dairy cattle including the SLICK1 mutation from Senepol cattle that causes a short, sleek coat with lower follicle densities, a mutation in the pre-melanosomal protein 17 (PMEL) which causes a coat colour dilution in Galloway and Highland cattle, and a mutation in the promotor region of the heat shock protein A1 (HSPA1) gene which gives greater protection from cellular damage by heat stress (Worku et al., 2023; Cartwright et al., 2023).

There are a series of mutations in the prolactin receptor gene (PRLR) on chromosome 20 that cause the “slick” phenotype, the most well documented being the SLICK1 mutation which occurs due to a SNP (single nucleotide polymorphism) which results in a premature stop codon and cuts off the c-terminus end of the prolactin receptor protein (Hansen, 2020). Holsteins with the Slick mutation have been shown to have a greater heat tolerance than their non-SLICK counterparts as shown by the lower rectal and vaginal temperatures as well as higher sweating rates in slick Holsteins compared to non-slick Holsteins. The greater thermotolerance has been largely attributed to the difference in coat characteristics of the SLICK phenotype but there is some evidence to suggest that there is superior sweating ability (Davis et al., 2017).

Puerto Rico, the United States and New Zealand have already begun introgression of the SLICK mutation into Holstein cattle (Worku et al., 2023). In 2014, introgression of the slick genetic variant from Senepol cattle into Holstein Friesians began with the aim of producing homozygous slick bulls with 75% New Zealand Holstein genetics. This was achieved through an initial cross using Senepol bulls with New Zealand Holstein Friesians, juvenile *in vitro* embryo transfer was then conducted using eggs from the F1 crosses when they were two years old to produce an F2 generation with 75% Holstein genetics, and then crossbreeding the F2 lines to produce bulls that were homozygous for the slick gene (Davis et al., 2017). Introgression of the slick gene and generating bulls that were homozygous for the slick gene with 75% Holstein genetics was a slow process over the course of several years (Davis et al., 2017).

The 3 base pair mutation in the PMEL gene has a semi-dominant inheritance pattern with heterozygous individuals experiencing some dilution in coat colour and homozygous individuals experiencing a more extreme dilution effect. Darker coat colour absorbs more solar radiation than lighter colours and so experience greater heat loads. Therefore, having diluted coat colours in dairy cows may provide some improvement in heat tolerance compared to their counterparts with darker coats. While it is possible to introduce this mutation into dairy cows using repeated back crossing the early crossbreds would have a much lower genetic merit for production traits and it would take a relatively long time with many backcrossing to achieve a high genetic merit of the progeny (Laible et al., 2021).

Gene editing would allow for the introgression of beneficial genetic variants relatively quickly, without the need for the genetic variant to be present within the breed or population being selected and would prevent the inheritance of background or undesirable traits from other populations or breeds. Advances in gene editing tools such as CRISPR-Cas9-based nucleases make transfer of genetic variants that convey superior heat tolerance through gene editing a feasible option to aid in the mitigation of heat stress (Worku et al., 2023). Laibe et al. (2021) introduced the PMEL mutation into high producing Holstein Friesian cattle using gRNA/Cas9-mediated editing. The gene edited calves homozygous for the PMEL mutation had a characteristic silvery grey colouration of the coat, where calves without the PMEL mutation had black markings (Laible et al., 2021).

2.7 Summary and research objectives

Rising global temperatures and increased incidence of extreme weather conditions as a result of climate change has resulted in huge negative impacts of the production, reproduction, and profitability of dairy cattle. In terms of the New Zealand dairy industry they are particularly susceptible to heat stress due to the higher solar radiation in New Zealand relative to countries like the USA, Canada and Britain, as well as the pastoral farming system utilised in New Zealand which leaves cattle constantly exposed to the elements, the longer distances required for cows to travel relative to housing based systems, and the pasture based diet which generates more heat during digestion than concentrated diets. With no single solution able to sufficiently mitigate heat stress a combination of strategies is required. Genetic solutions including selection and breeding has promise in providing a sustainable way to make the national herd in New Zealand more thermotolerant.

Previous studies have established that there is genetic variation in the thermotolerance between dairy cattle which is supported by the development of the Australian breeding values for heat tolerance in 2016 which is based on the decline of milk production over increasing THI. Cows identified as heat tolerant and heat sensitive according to these breeding values have shown that heat tolerant cows have lower rectal and vaginal temperatures, greater skin temperatures, less reduction in milk production and dry matter intake than their heat sensitive counterparts. This suggests that selection for higher skin temperature could be used as a target for selection to improve the heat tolerance of dairy cows.

The objectives of this study were to determine whether infrared thermography can be used to measure variation in skin temperature between members of a dairy herd, whether this variation is genetic and to establish the genetic correlation between skin temperature and economically important production traits.

Chapter 3

Materials and methods

3.1 Animals

Thermal images were obtained from 225 dairy cows from Massey University's Dairy 1 farm located in Palmerston North, New Zealand. Dairy 1 farm has a low input farming practice with once-a-day milking and operates on a spring calving pattern. The farm has an effective farm area of 119.7 hectares and the pasture is composed of primarily perennial ryegrass and clover with the exceptions of supplemental crops including lucerne (10 hectares), and a mixture of chicory, plantain, and clover (10 hectares). There are also paddocks seeded with alternative feeds used for other post-graduate research conducted at Dairy farm 1.

The herd can be divided into three different genetic groups: Holstein-Friesian (49), NZ Jersey (77) and Friesian-Jersey hybrids (99).

3.2 Thermogram recordings

Two thermograms, one covering the eyes and, muzzle and another covering the hind quarters of the udder of each cow were taken on 20th February 2023 using an infrared camera (FLIR T650sc; Teledyne FLIR, Wilsonville, OR, USA) while the cows were in the paddock. Two people were involved in recording the thermal images; one person took the thermal images with the camera, while another recorded ear tag numbers for animal identification. The camera was handheld and kept as level as possible at approximately 1.2 m above the ground and within 1 m from the animals when the thermograms were taken.

Thermograms were processed using the FLIR Research IR Max software (version 4.40 12.38; Teledyne FLIR, Wilsonville, OR, USA). Using the FLIR software three points across the orbit of one of the eye's, the surface of the muzzle and the surface of the udder were obtained. The temperature of the three points within each of the target areas were averaged to determine the final temperature measurement for the eye, muzzle and udder that were used in the analysis. Care was taken to select areas with the least amount of hair in the surfaces.

3.3 Pedigree and herd testing data

Pedigree and herd testing records pertaining to the cows were extracted from MINDA® (https://www.lic.co.nz/products-and-services/minda/), database of the Livestock Improvement Corporation (LIC), New Zealand. The obtained records included breeding worth (BW), production worth (PW), age, breed composition, pedigree information, calving dates, and seasonal milk yield (MY), fat yield (FY), protein yield (PY), and milk solids (fat plus protein) yield (MSY). From these, lactation number, energy corrected milk yield (ECMY), days in milk

(DIM), median calving date, predicted milk yield on the day of temperature measurement (PMY), and deviation from the herd median calving date were determined for all the temperature-recorded cows.

The lactation number was grouped into four categories (one to four), with cows in their fourth lactation and higher being grouped under lactation number four.

The deviation from the herd median calving date was determined as deviation of each cow's calving date from the median calving date (08/10/22).

The ECMY was calculated using the equation below (Sjaunja et al., 1991):

$$\mathrm{ECMY(kg)} = 0.25\mathrm{MY} + 12.2\mathrm{FY} + 7.7\mathrm{PY}$$

Hourly ambient temperature and relative humidity data was obtained from CliFlo (NIWA, 2023) which provides access to data from New Zealand's National Climate Database.

The temperature humidity index (THI) was calculated using the equation below (Kibler, 1964):

$$\mathrm{THI}=1.8\mathrm{T}-(1-\mathrm{RH})(\mathrm{T}-14.3)+32$$

where T is the ambient temperature (°C) and RH is the relative humidity.

Herd-test records for daily yields of milk, fat and protein for each cow for the whole production season (July 2022 to May 2023) were obtained from MINDA® (https://www.lic.co.nz/products-and-services/minda/) and used to model the lactation curves for daily yields of milk for each cow using random regression with 3rd order Legendre polynomials as described by Lembeye et al. (2016). Predicted daily yields of milk, fat, and protein for each cow at the day of temperature recording were obtained for the corresponding day in milk.

3.4 Statistical analysis

The resulting data was analysed using SAS version 9.4 software (SAS Institute Inc, Cary NC, USA). The MEANS procedure in SAS was used to determine the descriptive statistics for all the relevant continuous variables.

The GLM procedure was used to conduct the analysis of variance for the eye, muzzle, and udder temperatures with the following linear model:

$$y_{ijk} = \mu + B_i + L_j + BL_{ij} + \beta_1 d_{ijk} + \beta_2 m_{ijk} + \beta_3 p_{ijk} + e_{ijk}$$

where,

y_{ijk} is the temperature observation measured on cow *k* with lactation number *j* and belonging to breed i,

μ is the population mean,

B_i is the fixed effect of breed i (where i is either F, F×J or J), L_j is the fixed effect of the lactation number j (where j is either 1, 2, 3, or 4),

BL_{ij} is the fixed effect of the interaction between the breed i and lactation number j,

β_1 is the linear regression coefficient of the dependent variable on deviation from herd median day (d_{ijk}) of cow with observation y_{ijk},

β_2 is the linear regression coefficient of dependent variable on THI (m_{ijk}) of the cow with observation y_{ijk},

β_3 is the linear regression coefficient of dependent variable on predicted milk yield (p_{ijk}) of the cow with observation y_{ijk},

e_{ijk} is the random residual error assumed with mean zero and variance σ^2_e.

The GLM procedure was used in the analysis of variance of the production traits (BW, PW, MY, FY, PY, MSY, ECMY and PMY) using the same linear model stated above but without predicted milk yield as a covariate.

For both these models the *F*-values were used to assess the significance of the influence of the fixed effect on the dependent variables. In the analysis, the least-squared means (LSM) and the standard errors (SE) for all the fixed effects levels were obtained and used in multiple mean comparisons using Fisher's least significant difference test. Significant differences were declared at P<0.05.

3.5 Estimation of variance components and genetic parameters

Estimates of (co)variance components for animal additive genetic (σ^2_a) and residual (σ^2_e) variances were obtained by fitting a univariate and bivariate animal models as implemented in the JWAS package (Cheng et al., 2018) of Julia version 1.7.3, using Bayesian estimation method and Markov chain Monte Carlo (MCMC) procedures.

The animal model was represented as follows:

$$\mathbf{y} = \mathbf{Xb} + \mathbf{Za} + \mathbf{e}$$

where **y** is the vector of records for traits 1 and 2; **b** is the vector of the fixed effects of the breed and, lactation number and the linear effects of deviation from herd median calving date, **a** is the vector of animal genetic effects; **e** is the vector of random residual effects; **X** and **Z** are the design matrices relating to the records of fixed and animal additive genetic, respectively.

Heritability (h^2) for each trait was calculated as the proportion between the genetic variance and the phenotypic variance.

$$h^2 = \frac{\sigma_a^2}{\sigma_a^2 + \sigma_e^2}$$

With phenotypic variance $\sigma_p^2 = \sigma_a^2 + \sigma_e^2$.

The pedigree file containing all breeds had 428 individuals, 64 sires, 189 dams, and 203 founders.

Genetic (r_G) and phenotypic (r_p) correlations were calculated as:

$$r_G = \frac{\sigma_{a1a2}}{\sigma_{a1} \times \sigma_{a2}}$$

and

$$r_p = \frac{\sigma_{p1p2}}{\sigma_{p1} \times \sigma_{p2}}$$

where σ_{p1p2} is the phenotypic covariance between trait 1 and 2, which is equivalent to σ_{a1a2} + σ_{e1e2}; σ_{p1} is the phenotypic standard deviation for trait 1, equivalent to $\sqrt{\sigma_{a1}^2 + \sigma_{e1}^2}$, and σ_{p2} is the phenotypic standard deviation for trait 2, equivalent to $\sqrt{\sigma_{a2}^2 + \sigma_{e2}^2}$.

Marginal posterior distributions of all unknowns were estimated using the Gibbs sampling algorithm using samples obtained every 100 successive sampling.

Chapter 4

Results

Descriptive statistics for age, breeding worth (BW), production worth (PW), days in milk (DIM), production and temperature traits for cows at Dairy 1 farm are presented in Table 4.1. The 225 cows that were recorded ranged from two to ten years of age. The mean udder temperature (38.2 °C) was higher than the mean muzzle (37.7 °C) and eye (37.9 °C) temperature which were very similar in magnitude. As shown in the standard deviations for the temperature traits there was the most variation in the muzzle temperature and the least in the eye temperature. Eye temperature had the greatest range (9.41 °C), and the highest maximum temperature. Udder temperature had the smallest range (6.5 °C), and muzzle temperature had the lowest minimum temperature.

The F-values and associated significance level for the fixed effects and covariates for the profitability, production, and temperature traits for the herd at dairy farm 1 are presented in Table 4.2. Breed effects were significant ($P <0.05$) for Breeding Worth (BW), lactation yields of milk (MY), fat (FY), and milk solids (MSY), energy corrected milk yield (ECMY) and udder temperature. Effect of lactation number was significant ($P < 0.05$) for BW, MY, FY, MSY, ECMY, and predicted milk yield on the day temperature measurements were taken (PMY), and for muzzle and udder temperatures. The effect of interaction between breed and lactation number was not significant for any of the dependent traits.

The linear effect of deviation from herd median calving date was significant for MY, FY, PY, MSY and ECMY, and predicted milk yield of the predicted milk yield at day in milk of recorded temperature. The linear effect of THI was not significant for any of the dependent variables. The linear effect of predicted milk yield at day in milk of recorded temperature was significant ($P < 0.05$) for udder temperature.

Holstein-Friesians had the highest MY (4,366 kg) followed by crossbreds (3,978 kg) and Jerseys (3,458 kg). There was no significant difference in the FY, PY, MSY and ECMY between Holstein-Friesians (216.4, 176.3, 394.7 and 5,090 kg, respectively) and crossbreds (216.1, 168.6, 384.7 and 4,930 kg, respectively). Holstein-Friesians and crossbreds had a greater FY, PY, MSY and ECMY than Jerseys (202.3, 152.4, 354.7 and 4,506 kgs, respectively).

Table 4. 1. Descriptive statistics for age, body temperature measurements and milk production traits for dairy cows from Massey University Dairy 1 farm in the production season 2022–23.

Variable	N	Mean	SD[1]	Min[1]	Max[1]
Age, years	225	4.28	1.99	2.00	10.00
Breeding Worth, $/5 t DM	185	246.3	79.1	13.0	394.0
Production Worth, $/5 t DM	185	271.4	189.9	-330.0	728.0
Days in milk	225	271.7	22.1	212.0	305.0
Milk yield, kg	225	4,000	898	1,053	6,858
Fat yield, kg	225	216.8	40.3	62.0	336.0
Protein yield, kg	225	169.0	34.4	46.0	258.0
Milk solids yield, kg	225	385.8	72.9	108.0	587.0
ECMY[2], kg	225	4,946	946	1,374	7,739
PMY[3], kg	225	8.03	2.12	2.63	13.7
Eye temperature, °C	225	37.8	1.16	33.9	43.3
Muzzle temperature, °C	221	37.7	1.51	32.9	42.5
Udder temperature, °C	225	38.2	1.19	34.5	41.0

[1] SD = standard deviation, Min = minimum value, Max = maximum value.

[2] ECMY = energy corrected milk yield.

[3] PMY=predicted daily milk yield on the day of temperature recording.

Table 4.2. F-values and significant levels for factors affecting profitability, production, and body temperature traits for grazing dairy cows at Massey University Dairy 1 farm in the production season 2022-23.

Trait	Breed	Lactation number	B×L[1]	β_{DMCD}[2]	β_{THI}[3]	β_{PMY}[4]
Breeding Worth, \$/5 t DM	18.19***	9.61***	1.43	0.77	1.66	
Production Worth, \$/5 t DM	1.71	1.42	1.2	0.22	0.06	
Milk yield, kg	28.86***	37.86***	1.10	8.70**	0.71	
Fat yield, kg	4.31*	32.86***	0.27	15.65**	0.49	
Protein yield, kg	12.96***	35.16***	0.84	23.75***	1.61	
Milk solids yield, kg	8.05**	36.54***	0.48	20.71***	0.97	
Energy corrected milk yield, kg	10.86***	38.08***	0.46	17.59***	0.86	
Predicted milk yield, kg	0.59	3.30*	1.01	9.68**	2.78	
Eye temperature, °C	0.11	1.61	0.40	0.96	0.12	0.84
Muzzle temperature, °C	2.17	3.13*	0.61	2.48	1.90	1.55
Udder temperature, °C	9.61**	7.63***	1.44	0.00	0.16	9.95**

* $P<0.05$, ** $P<0.01$, *** $P<0.001$.

[1] B×L=fixed effect of the interaction between breed and lactation number, lactation = lactation number.

[2] Regression coefficient for DMCD (deviation from the median calving date) covariate.

[3] Regression coefficient for THI (temperature-humidity index).

[4] Regression coefficient for PMY (predicted milk yield) covariate.

The least squares means (LSM), standard errors (SE) and the corresponding p-values for the profitability (BW and PW), production (MY, FY, PY, MSY and ECMY), and temperature traits for the three different breeds of cow are presented in Table 4.3.

All of the LSM for breeding worth were significantly different between the three breeds of cattle in the herd (Holstein-Friesians, crossbreds, and NZ jerseys). Jersey cows had the highest mean BW (291.9 \$/5 t DM), followed by crossbreds (244.8 \$/5 t DM), then the Holstein-Friesians (209.3 \$/5 t DM).

The LSM for udder temperature were significantly different between crossbreds (38.42 °C) and both Holstein-Friesians (37.91 °C) and NZ Jerseys (37.69 °C) with the crossbreds having the highest udder temperature. There was no significant difference in the LSM for Holstein-Friesians and NZ Jerseys.

Table 4.3. Least squares means and standard errors (within brackets) for profitability, production, and temperature traits for the different cow breeds at Massey University Dairy farm 1 during the 2022-23 production season.

	Breed[1]			
Traits	F	F×J	J	P-value
Breeding Worth, \$/5 t DM	209.3^c (10.7)	244.8^b (7.6)	291.9^a (9.3)	<0.0001
Production Worth, \$/5 t DM	230.6 (29.2)	289.4 (21.1)	300.4 (25.7)	0.2385
Milk yield, kg	$4{,}366^a$ (97)	$3{,}978^b$ (66)	$3{,}458^c$ (79)	<0.0001
Fat yield, kg	216.4^a (4.82)	216.1^a (3.29)	202.3^b (3.94)	0.0146
Protein yield, kg	176.3^a (3.95)	168.6^a (2.70)	152.4^b (3.23)	<0.0001
Milk solids yield, kg	394.7^a (8.44)	384.7^a (5.76)	354.7^b (6.90)	0.0004
ECMY[2], kg	$5{,}090^a$ (108)	$4{,}930^a$ (74)	$4{,}506^b$ (88)	<0.0001
Predicted milk yield, kg	8.03 (0.30)	8.09 (0.21)	7.75 (0.25)	0.5565
Eye temperature, °C	37.8 (0.18)	37.7 (0.12)	37.8 (0.14)	0.8955
Muzzle temperature, °C	37.9 (0.22)	37.7 (0.15)	37.3 (0.18)	0.1168
Udder temperature, °C	37.9^a (0.16)	38.4^b (0.11)	37.7^a (0.13)	0.0001

$^{a, b \text{ and } c}$Means with different superscripts within the row are significantly different ($P \leq 0.05$).

[1] F=Holstein-Friesian, F×J=crossbred, J= Jersey.

[2] ECMY= energy corrected milk yield.

The least squares means, standard errors and the corresponding p-values for the profitability, production, and temperature traits for cows in the four different lactation groups are presented in Table 4.4. There was no difference in the BW between first (283.5 \$/5 t DM) and second lactation (276.2 \$/5 t DM) cows. The BW was highest in cows in their first and second lactations, followed by cows in their third (234.6 $/5 t DM) and fourth lactations (200.4 $/5 t DM).

There was no difference in the MY, FY, PY, MSY and ECMY between cows in their second (3,910, 212.8, 166.6, 379.4, 4,857 kg, respectively) and third lactation (4,158, 223.3, 178.1, 401.4 and 5,135 kg, respectively). The MY, FY, PY, MSY, and ECMY was highest in cows in their fourth lactation (4,629, 242.0, 190.3, 432.2, and 5,574.1 kg, respectively), followed by cows in their second and third lactation and cows in their first lactation (3,039, 168.4, 128.2, 296.5 and 3,801 kg, respectively). The MY in first lactation cows is approximately 66% of the MY in fourth lactation cows. There was no difference in the predicted milk yield between cows in their first (7.22 kg) and third (7.85 kg) lactation and between cows in their second (8.25 kg), third and fourth lactation (8.51 kg). The predicted milk yield was lowest in cows in their first and third lactation and highest in cows in their second, third and fourth lactation.

There was no difference in the muzzle temperature of cows in their first (37.4 °C), second (37.3 °C) and third lactation (37.6 °C). Cows in their fourth lactation (38.2 °C) had the highest muzzle temperature. There was no difference in the udder temperature of cows in their second (37.9 °C) and third lactation (38.2 °C) or between cows in their third and fourth lactation (38.6 °C). The udder temperature was highest in fourth and third lactation cows, followed by cows in their second and third lactation, then cows in their first lactation (37.4 °C).

Table 4.4. Least squares means and standard errors (within brackets) for profitability, production, and temperature traits for the cows in the four lactation groups at Massey University Dairy farm 1 during the 2022-23 production season.

	Lactation number				
Traits	1	2	3	4	P-Value
Profitability, \$/5 t DM					
Breeding Worth	283.5^{a} (12.80)	276.2^{a} (12.73)	234.6^{b} (11.60)	200.4^{c} (9.36)	<0.0001
Production Worth	302.9 (35.97)	298.5 (35.65)	274.4 (32.62)	220.5 (26.23)	0.2385
Production, kg					
Milk yield	3,039^{c} (114)	3,910^{b} (110)	4,158^{b} (108)	4,629^{a} (78)	<0.0001
Fat yield	168.4^{a} (5.70)	212.8^{b} (5.48)	223.3^{b} (5.39)	242.0^{c} (3.91)	<0.0001
Protein yield	128.2^{a} (4.66)	166.6^{b} (4.49)	178.1^{b} (4.42)	190.3^{c} (3.20)	<0.0001
Milk solids yield	296.5^{a} (9.97)	379.4^{b} (9.59)	401.4^{b} (9.44)	432.2^{c} (6.85)	<0.0001
ECMY[1]	3,801^{a} (127.32)	4,857^{b} (122.48)	5,135^{b} (120.59)	5,574^{c} (87.48)	<0.0001
Predicted milk yield	7.22^{a} (0.36)	8.25^{b} (0.34)	7.85^{ab} (0.34)	8.51^{b} (0.24)	0.0212
Temperature, °C					
Eye temperature	37.6 (0.21)	37.6 (0.20)	37.9 (0.20)	38.1 (0.14)	0.189
Muzzle temperature	37.4^{a} (0.26)	37.3^{a} (0.25)	37.6^{a} (0.25)	38.2^{b} (0.18)	0.0268
Udder temperature	37.4^{a} (0.19)	37.9^{b} (0.18)	38.2^{bc} (0.18)	38.6^{c} (0.13)	<0.0001

$^{a,\ b\ \text{and}\ c}$ Means with different superscripts within the row are significantly different ($P \leq 0.05$).

[1] ECMY= energy corrected milk yield.

The estimates and SE of the regression coefficients of temperature traits on each of the three covariates in the model (deviation from median calving date, temperature-humidity index, and predicted milk yield) are presented in Table 4.5.

None of the regression coefficients were significantly different from zero, except the regression coefficient of udder temperature on predicted milk yield at the day in milk of recorded temperature; udder temperature increases by 0.11 °C per 1 kg of milk daily yield.

Table 4.5. Regression coefficients, standard errors (within brackets) and the level of significance for the deviation from median calving date (DMCD), temperature-humidity index (THI) and predicted milk yield (PMY) for the temperature traits in cows at Massey University Dairy 1 farm during the 2022-23 production season.

	Estimate (SE)		
Traits	β_{DMCD}[2]	β_{THI}[3]	β_{PMY}[4]
Eye temperature, °C	-0.005 (0.005)	0.053 (0.15)	0.037 (0.04)
Muzzle temperature, °C	-0.011 (0.006)	0.26 (0.19)	0.062 (0.05)
Udder temperature, °C	-0.000 (0.005)	0.055 (0.14)	0.11 (0.04)**

* P<0.05, ** P<0.01, *** P<0.001.

[2] Regression coefficient for DMCD covariate.

[3] Regression coefficient for THI covariate.

[4] Regression coefficient for PMY covariate.

The estimation of the genetic parameters including heritability (h^2), residual error variance (σ^2_e), genetic variance (σ^2_a) and the total variance (σ^2_{Total}) along with their corresponding standard deviation's (SD) for each variable considered in this study are presented in Table 4.6.

The h^2 estimates for MY, FY, PY MSY, ECMY and predicted milk yield were 0.40, 0.38, 0.36, 0.33, 0.48, and 0.27 respectively. These estimates were very similar except for PMY.
The h^2 estimates for the eye temperature, muzzle temperature and udder temperature were slightly lower than the estimates for production traits except for udder temperature which had an estimate of 0.39.

Table 4.6. Estimates of the heritability (h^2) and variance components with their associated standard deviations (SD) for the production and temperature traits in cows at Massey University Dairy 1 farm during the 2022-23 production season.

	Variance components[2]							
Trait[1]	σ^2_e	SD	σ^2_a	SD	σ^2_{Total}	SD	h^2	SD
MY	245,913	34,565	164,278	26,056	410,191	60,622	0.40	0.05
FY	635.5	109.6	394.7	132.2	1,030	241.8	0.38	0.11
PY	447.6	56.6	251.8	67.6	699.4	124.3	0.36	0.08
MSY	2,156	336.4	1,052	280.2	3,208	616.6	0.33	0.08
ECMY	267,658	48,412	248,898	46,091	516,556	94,503	0.48	0.08
PMY	3.01	0.47	1.12	0.33	4.12	0.80	0.27	0.08
ET	1.06	0.15	0.27	0.10	1.33	0.25	0.20	0.08
MT	1.64	0.20	0.51	0.14	2.15	0.34	0.24	0.06
UT	0.69	0.11	0.44	0.07	1.13	0.17	0.39	0.06

[1] MY=milk yield (kg), FY=fat yield (kg), PY=protein yield (kg), MSY=milk solids yield (kg), ECMY=energy corrected milk yield (kg), PMY=predicted milk yield on day of temperature measurement (kg/day), ET=eye temperature (°C), MT=muzzle temperature (°C), UT=udder temperature (°C).

[2] σ^2_e=residual error variance, σ^2_a=genetic variance, σ^2_{TOTAL}=total variance.

The estimates of genetic (r_G) and phenotypic (r_P) correlations for the production and temperature traits are presented in Table 4.7. The genetic correlations between MY and PY, MSY, and ECMY were positive and high ($r_G>0.60$). The genetic correlations between FY and PY, MSY, and ECMY were positive and high. The genetic correlations between PY and MSY, PY and ECMY as well as between MSY and ECMY were positive and high. The genetic correlations between FY and MY as well as PMY with MY, FY, PY, MSY and ECMY were positive and moderate ($0.60>r_G<0.20$). The phenotypic correlations between production traits were positive and ranged from moderate to high. The phenotypic correlations of MY with FY, PY, MSY, and ECMY were positive and high as was the phenotypic correlations of FY with MSY and ECMY. The phenotypic correlations PY with MSY and ECMY were positive and high. The phenotypic correlation between MSY and ECMY was positive and high. The phenotypic correlations of PMY with MY, FY, PY, MSY and ECMY were positive and moderate.

The genetic correlations between eye temperature and muzzle temperature, eye temperature and udder temperature, and muzzle temperature and udder temperature were positive and moderate. The phenotypic correlations of udder temperature with eye and muzzle temperatures were positive and moderate. The phenotypic correlation between eye and muzzle temperature was positive and high. The genotypic and phenotypic correlations were lower between the temperature traits than between the production traits.

The genetic correlations between eye temperature and MY and eye temperature and PY were negative and weak (r_G<0.20), while the genetic correlation between MY and eye temperature was close to zero. The genetic correlations of muzzle temperature with MY and ECMY were positive and close to zero. The genetic correlations of eye temperature with MSY, muzzle temperature and that between MSY and PMY were positive and weak. The genetic correlations of udder temperature with PY and MSY were positive and weak. The genetic correlations of eye temperature with FY, ECMY and PMY were positive and moderately strong. The genetic correlations of muzzle temperature with FY and PY were positive and moderate. The genetic correlations of udder temperature with MY, FY, ECMY and PMY were positive and moderately strong. The phenotypic correlations of eye temperature with MY, FY, PY, MSY, ECMY and PMY were positive and weak and the genetic correlations of eye temperature with both FY and PY were close to zero. The phenotypic correlations of muzzle temperature with MY, FY, PY, MSY, ECMY and PMY were positive and weak with the correlations between MY and PMY was close to zero. The phenotypic correlations of udder temperature with MY, FY, PY, MSY, ECMY and PMY were positive and weak.

Table 4.7. Estimates of the genetic (below diagonal) and phenotypic (above diagonal) correlations with their associated standard deviations (SD) for production and temperature traits in grazing dairy cows at Massey University Dairy 1 farm during the 2022-23 production season.

Trait[1]	MY	FY	PY	MSY	ECMY	PMY	ET	MT	UT
MY		0.74 (0.07)	0.87 (0.07)	0.83 (0.08)	0.86 (0.08)	0.58 (0.06)	0.04 (0.06)	0.03 (0.06)	0.20 (0.06)
FY	0.57 (0.13)		0.81 (0.06)	0.91 (0.09)	0.91 (0.07)	0.54 (0.05)	0.03 (0.06)	0.07 (0.06)	0.22 (0.07)
PY	0.86 (0.11)	0.78 (0.11)		0.91 (0.07)	0.90 (0.07)	0.58 (0.05)	0.03 (0.06)	0.08 (0.06)	0.18 (0.05)
MSY	0.77 (0.10)	0.90 (0.13)	0.87 (0.11)		0.94 (0.07)	0.56 (0.06)	0.05 (0.06)	0.05 (0.07)	0.19 (0.23)
ECMY	0.77 (0.11)	0.88 (0.13)	0.86 (0.09)	0.90 (0.12)		0.57 (0.06)	0.06 (0.07)	0.07 (0.07)	0.23 (0.05)
PMY	0.50 (0.11)	0.42 (0.14)	0.49 (0.09)	0.43 (0.09)	0.39 (0.10)		0.08 (0.06)	0.04 (0.05)	0.17 (0.07)
ET	-0.04 (0.18)	0.25 (0.17)	-0.18 (0.17)	0.10 (0.08)	0.32 (0.21)	0.34 (0.20)		0.71 (0.06)	0.34 (0.06)
MT	0.03 (0.24)	0.31 (0.10)	0.23 (0.10)	0.07 (0.12)	0.02 (0.12)	0.14 (0.20)	0.47 (0.12)		0.33 (0.06)
UT	0.20 (0.12)	0.48 (0.18)	0.15 (0.14)	0.15 (0.08)	0.36 (0.13)	0.27 (0.19)	0.32 (0.19)	0.39 (0.09)	

[1] MY=milk yield (kg), FY=fat yield (kg), PY=protein yield (kg), MSY=milk solids yield (kg), ECMY=energy corrected milk yield (kg), PMY=predicted milk yield on day of temperature measurement (kg/day), ET=eye temperature (°C), MT=muzzle temperature (°C), UT=udder temperature (°C).

Chapter 5

Discussion

Means of eye and muzzle temperature were very similar in magnitude, with the minimum and maximum temperatures being lower and higher than that for udder temperature. However, the udder temperature had a higher mean and smaller range than the eye and muzzle. The larger range in the muzzle and eye may be due to both the eye and muzzle being in close proximity and therefore exposed to very similar amounts of shade, sunlight, and wind. Additionally, moisture on the muzzle transferred from the grass when grazing or from the water trough while drinking may be a contributing factor. The udder has some protection from direct sun due to its location in the hind quarters of the animal and experiencing shading by the tail therefore the eye and muzzle temperature measurements fluctuated more with hourly temperature and humidity, whereas the udder temperature remained more constant. The higher mean temperature in the udder is likely due to the heat generated through milk production.

The ECMY calculated in this study was significantly larger than the seasonal MY; this is due to the high FY and PY compared to the MY taken from the herd test results from MINDA. During the 2019-20 production season, the average cow produced 4,371 L of milk with a fat and protein percentages of 4.74% and 3.87%, respectively (DairyNZ & LIC, 2022). The cows from Massey University's Dairy farm 1 as shown in Figure 4.1 had an average MY, FY and PY of 4,000 kg, 217 kg, and 169 kg, respectively. This comes to a fat and protein percentage of approximately 5.4 % and 4.2 %, respectively. The fat and protein percentages from this study are much higher than values reported by LIC and DairyNZ (2022). The higher fat and protein yields and lower MY have resulted in ECMY values to be greater than the seasonal MY. The higher fat and protein yield relative to overall milk yield is likely due to the OAD milking utilised at Massey University's Dairy Farm 1.

For all the production traits (MY, FY, PY, MSY and PMY) barring PMY the fixed effects of breed and lactation number were found to be significant as well as the covariate DMCD. In the case of PMY there was no breed effect.

A study by Liang et al. (2013) explored the effects of breed, production, and ambient temperature on the daily reticulorumen temperature as a measure of core temperature in Holsteins, Jerseys and crossbred (Holstein×Jersey, Brown Swiss×Holstein×Jersey and Scandinavian×Holstein×Jersey) cows; breed, production, and ambient temperature have all been found to significantly influence the daily reticulorumen temperature. Additionally, it has been shown in previous studies that there are differences in the genetic variance between dairy cows in different parities and that multiple parity cows were more sensitive to heat stress than single parity cows (Aguilar et al., 2009; Armstrong, 1994). Based on the results determined in these studies, it was expected that the fixed effects of breed and lactation number and the covariate for THI would be significant for the surface temperature of the eye and muzzle in this project. However, none of the fixed effects or covariates included in the final models were found to be significant in the case of eye temperature and only lactation number was found to be significant in the case of muzzle temperature.

The fixed effects of breed and lactation number as well as the covariate PMY were found to significantly affect the udder temperature in this study which was more in keeping with what was expected based on past studies conducted on daily reticulorumen, skin, and rectal temperatures (Amamou et al., 2019; Luo et al., 2020; Cheruiyot et al., 2022).

5.1 Breed effects

There are known differences in the BW between the three common dairy breeds used in New Zealand (LIC and DairyNZ, 2022), which supports the results of this study; Jerseys have higher average BW, followed by F×J crossbred and then Holstein-Friesian cows.

There was a trend in BW across lactation number; average of BW decreased as the cows become older. This pattern in which older cows in later lactation numbers had lower BWs than their younger counterparts in earlier lactation numbers may be because with each subsequent generation in a herd the aim is to have an animal that better fits the national breeding objective. This is achieved by choosing bulls with high BWs to inseminate the mothers of the next generation of daughters so that the progeny will have a BW comparable or greater than that of the dam and the sire.

Of the three breeds involved in this study Holstein-Friesians had a greater MY than both crossbreds and Jerseys, and crossbreds had a greater MY than Jerseys. This fits well with the findings of Lopez-Villalobos et al. (2018) where Holstein-Friesians had a higher MY and PY than Jerseys. For FY, PY, and MSY the same breed differences were observed with no significant difference between Holstein-Friesians and crossbreds but both having greater yields than Jerseys. This is supported by the results reported by a study conducted in New Zealand in the 2015-16 and 2017-18 production seasons investigating the fertility and production of Holstein-Friesian, Jersey and crossbreds between once a day (OAD) and twice a day (TAD) milking frequency, the following breed differences were observed. Holstein-Friesians were found to have a higher milk yield (MY), protein yield (PY), and lactose yield (LY) than the Jersey and crossbred animals involved in the studies (Grosshans et al., 1997; Jayawardana et al., 2023).

The average udder temperature was greatest in crossbred cows and no significant difference in the average udder temperature between Holstein-Friesians and Jerseys. Greater average udder temperature of crossbreds as well as the moderate genetic correlation between udder temperature and production traits may be indicative of both higher producing cows with greater activity in the udder exhibiting a higher udder temperature, as well as an indication of more radiation of heat through the skin surface of the udder. A study by Liang et al. (2013) used a SmartBolus system to record reticulorumen temperature over 615 days in Holsteins, Jerseys and crossbred (Holstein×Jersey, Brown Swiss×Holstein×Jersey and Scandinavian×Holstein×Jersey) cows. They reported that the daily reticulorumen temperature of the crossbred cows in the study increased more slowly than Holsteins as the atmospheric temperature increased and overall, above the threshold temperature for heat stress (upper critical temperature of 23.9 °C) Holsteins in the herd had the greatest daily reticulorumen temperature followed by crossbreds than Jerseys. Liang et al. (2013) suggested that these results indicate that crossbreds may be more thermotolerant than Holsteins, possibly as a result of hybrid vigour (Liang et al., 2013). Garner et al. (2016) compared the performance of Holstein cows that had been identified as heat tolerant against cows that had been identified as heat sensitive after exposure to a four-day simulated heat wave in a controlled-climate chamber. Heat tolerant and heat sensitive cows were identified based on genomic breeding values calculated based on the rate of decline in production as the THI increased and genotyping using SNP chips using 632,003 SNPs. During the four days of exposure in the controlled-climate chamber, the heat-tolerant cows on the second, third and fourth day had a lower vaginal and rectal temperature (measured using digital thermometers), and higher flank and neck skin temperatures (measured using non-contact infrared thermometers) than their heat-sensitive counterparts. Garner et al. (2016) speculated that the higher skin surface temperature reported for the heat-tolerant cows compared to the heat-sensitive Holsteins may be because of the greater thermotolerance and vasodilation of the skin surface in the heat-tolerant Holsteins (Garner et al., 2016). The studies by Liang et al. (2013) and Garner et al. (2016) support the hypothesis that part of the reason that there is a greater udder temperature in crossbreds is due to a more excess heat dissipated through the udder. However, the moderate genetic and phenotypic correlations between udder temperature and production traits contradict this hypothesis as higher producing animals have been reported as being more sensitive than lower producing dairy cows. Therefore, higher udder temperature is likely due to more than simply greater heat dissipation but is likely the result of multiple causes including production ability.

5.2 Effect of lactation number and calving date

There were slight differences in the pattern for all the production traits between the four lactation numbers. However, for all the traits, as the lactation number increased so did the MY, FY, PY, MSY and PMY. The proportion of milk production in first lactation cows relative to fourth lactation cows was approximately 0.66. The milk yield of the Holstein Friesians, Jerseys and Holstein Friesian Jersey crossbreds, in the study by Lopez-Villalobos et al. (2022) analysing maturity rate of New Zealand dairy cattle, became greater as the cows got closer to their fourth lactation. It is known that as dairy cows become more mature the milk production increases until the fourth or fifth lactation (Lopez-Villalobos et al., 2022; Ray et al., 1992; Eski & Kurt, 2021). Cows with a higher deviation from median calving date calved later in the season than cows with a lower deviation from median calving date. That the covariate deviation from median calving date was found to significantly affect all of the production traits is unsurprising considering that the season and pattern of calving is known to affect the lactation curve, the number of days in milk, the shape and size of lactation curve (height of the peak in lactation and the rate of decline in production), the magnitude of the total seasonal milk production, the milk composition, reproductive performance and animal health of dairy cattle (Garcia & Holmes, 1999). Cows with different deviation from median calving dates experienced peak lactation at different times during the season with cows calving earlier experiencing peak production at different environmental conditions including differences in temperature, feed availability and light levels. These factors will all affect daily and seasonal milk production and animal performance (Perera et al., 1985). Additionally, unless the herd is split up into smaller groups all the cows in the herd will be dried off at the same time. Therefore, the cows with lower deviation from median calving date will have calved earlier in the season and will be lactating longer than cows with a higher deviation from median calving date.

In terms of the effect of lactation number, the udder temperature was higher in cows with a higher lactation number. This fits well with the hypothesis that udder temperature is closely related to the level of production of the animal rather than solely to core body temperature.

Early lactating dairy cows have a higher body temperature measured by infrared thermography than late lactating cows due to early lactating cows having greater tissue metabolism and generating higher metabolic heat than late lactating cows (Idris et al., 2021). This is further supported by the small positive regression coefficient for the PMY, which indicates that for every unit increase in the udder temperature there is a 0.11 kg increase in the predicted milk yield.

It was surprising that the DMCD was not found to be significant in the case of udder temperature because in early data exploration where only DMCD was included as a covariate in the model for udder temperature there was a weak positive linear relationship in which the higher the deviation from median calving date the greater was the observed udder temperature. However, in the final model for udder temperature which included the fixed effect of breed, lactation number, interaction effect and corrected for the covariate's deviation from median calving date, temperature-humidity index and predicted milk yield, the effect of deviation from median calving date was not significant. The significance of the deviation of median calving date observed in the initial data exploration was attributed to later calving cows (greater deviation from median calving date) experiencing peak lactation during the production season when the ambient temperature was higher which in combination with the high metabolic heat production experienced in cows during peak lactation occurring in the higher udder temperature in cows with a higher deviation from median calving date. Barash et al. (2001) determined that cows in their second month of lactation (peak production) are more sensitive than cows in their ninth month of lactation to reductions in MY and PY caused by temperature (i.e., more sensitive to heat stress). In their ninth month, there is a decline in production relative to their second month meaning that less heat is generated (Barash et al., 2001).

5.3 Estimates of heritability

There are many reported heritability estimates for MY, FY and PY for New Zealand dairy cows in the literature. Many of the previously reported heritability estimates for New Zealand dairy cows were lower than those obtained in this study with Lopez-Villalobos et al. (2018), Sneddon et al. (2015), and Jayawardana et al. (2023) reporting heritability estimates between 0.12-0.35. The heritability estimates for milk production traits obtained in this study were similar to the heritability estimates reported by Lembeye et al. (2016) for New Zealand dairy cows and international heritability values reported by Berry et al. (2003) for Irish Holstein-Friesians and by Miglior et al. (2007) for Canadian Holsteins.

There are currently no published heritability estimates or genetic and phenotypic correlations for surface temperature in dairy cattle however, there have been numerous studies investigating the genetic parameters for rectal temperature as a proxy measure for thermotolerance in cattle (Seath & Miller, 1947; McMillan & van der Werf, 2007; Dikmen et al., 2012; Luo et al., 2021). Therefore, comparisons between heritability estimates and correlations between the temperature traits from this study with literature values will be conducted with rectal temperature. Reported heritability estimates for rectal temperature in dairy cattle breeds, presented in Table 2.2, range from 0.06 to 0.31, however most were higher than 0.11. Eye temperature, muzzle temperature and udder temperature had moderate heritability estimates (see Table 4.6) which fall on the higher end of the reported heritability range for rectal temperature with udder temperature having a slightly higher heritability estimate. These heritability estimates are sufficiently high to make genetic change in these traits if genetic selection were employed.

The standard deviations for the estimates of the heritability of the production and temperature traits are higher than reported standard errors for the heritability estimates in the literature possibly due to the small data set utilised in this experiment. Additionally, as only a single herd is used in this study much of the environmental variance cannot be identified and therefore minimised which may contribute to why the standard deviations for the heritability estimates are so large.

5.4 Estimates of genetic and phenotypic correlations

In regard to the genetic correlations between temperature traits and between temperature traits and production traits the magnitude of the genetic correlation values was lower than those between the production traits.

5.5 Correlations among production traits

The estimates of genetic correlations (r_G) between the production traits were all positive and high, for MY, FY, PY, MSY and ECMY with all the genetic correlations ≥ 0.57. This is in agreement with the genetic correlations reported in the literature. The estimated genetic correlations between MY, FY and PY estimated ($r_{G_{MY,\ FY}}$=0.57, $r_{G_{MY,\ PY}}$=0.86 and $r_{G_{FY,\ PY}}$=0.78) were higher than those reported by Lembeye et al. (2016), Sneddon et al. (2016) and Jayawardana et al. (2023) but very similar to the genetic correlations reported by Miglior et al. (2007) and Lopez-Villalobos et al. (2018).

The phenotypic correlations between the production traits were all positive and very strong with the exception of predicted milk yield, which was moderately strong, meaning that when the phenotype of one of these traits changes the others will also closely follow this change. The phenotypic correlations (r_P) between MY, FY and PY ($r_{P_{MY,\ FY}}$=0.74, $r_{P_{MY,\ PY}}$=0.87 and $r_{P_{FY,\ PY}}$=0.8) were similar to those reported by Sneddon et al. (2016), Lopez-Villalobos et al. (2018) and Jayawardana et al. (2023) but slightly lower than the reported correlations for these traits by Miglior et al. (2007).

5.6 Correlations among temperature traits

The genetic correlations between the temperature traits were all positive and moderately strong with the correlations between eye and muzzle temperature, eye and udder temperature, and muzzle and udder temperature falling between 0.2 and 0.6. This indicates that there are some genes controlling the expression of these traits in common and selection for one of these traits would result in a moderate increase in the other temperature traits in the same direction.

The phenotypic correlation between eye and muzzle temperature was positive and high (r_P<0.6). The phenotypic correlations between udder and eye temperature, and udder and muzzle temperature were moderately strong and positive. Therefore, there is a strong linkage between eye and muzzle temperature and a moderately strong linkage between udder temperature and both eye and muzzle temperature so when one of these traits increases so does the others.

5.7 Correlations among production and temperature traits

All of the genetic correlations among the production and temperature traits were positive with the exception of eye temperature and MY and PY which were negative and weak. The genetic correlations between muzzle temperature and MY, and between muzzle temperature and ECMY was very low and close to zero. Therefore, it is unlikely that there are many if any genes in common controlling the expression of these traits. The genetic correlations between eye temperature and MSY, muzzle temperature and MSY, muzzle temperature and PMY, udder temperature and PY, udder temperature and MSY were weak. The genetic correlations between eye temperature and FY, eye temperature and ECMY, eye temperature and PMY, muzzle temperature and FY, muzzle temperature and PY, udder temperature and MY, udder temperature and FY, udder temperature and ECMY, and udder temperature and PMY were moderately strong. Therefore, the expression of these traits may be controlled by some of the same genes.

The phenotypic correlations between eye temperature and MY, FY, and PY as well as between muzzle temperature and MY and PMY were positive and weak with a magnitude close to zero. An r_P close to zero means that the relationship between the phenotype of the two traits is negligible so the performance of the two traits is not linked. The phenotypic correlation between eye temperature and MSY, ECMY and predicted milk yield, muzzle temperature and MSY, FY, ECMY and PY were all positive and weak indicating that there may be a small linkage between the performance of these traits. The phenotypic correlations between udder temperature and the production traits (MY, FY, PY, MSY, ECMY and predicted milk yield) were all low to moderately positive and ranged from 0.17 to 0.23, indicating that there is a relationship between the performance of udder temperature and the production traits.

5.8 Response to selection

The genetic correlations between eye and muzzle temperature and the production traits were all positive and mostly weak apart from eye temperature and ECMY and PMY, which were on the low end of moderately strong. This indicates that it is likely that there is not much crossover in the genes affecting the expression of these genes and selection for one of these traits would result in only a small change in the other traits.

As the genetic correlations among udder temperature and the production traits are all positive and moderate, it is likely they have genes affecting their expression in common and selection toward a higher udder temperature would likely result in a moderate increase in the production traits. Due to the breed and lactation number effects, the moderate heritability, and the close relationship with profitability and production traits udder temperature provides the most promise out of all the temperature traits in this study, as a potential trait for inclusion in a selection index like breeding worth used in New Zealand. This decision is supported by other studies where higher body surface temperatures were reported in dairy cows deemed heat tolerant according to genomic breeding values based off milk decay with increasing THI compared to their heat sensitive counterparts (Garner et al., 2016). However, more research is necessary before inclusion of udder surface temperature or any other temperature traits.

5.9 Study limitations

The sample size used in this study was very small, one of the consequences was that it made it difficult to use the statistical package ASREML to estimate the genetic parameters for skin temperature. In response to this, the JWAS package for JULIA was used to estimate the genetic parameters. The months of January and February in 2023 when the thermograms were taken, the weather was unpredictable and unexpectedly cool compared to previous years. For this reason, it was difficult to predict the likely daily temperature and humidity ahead of time to arrange to take thermograms on days where the environmental conditions were sufficient to cause heat stress. Therefore, the temperature-humidity index on the day of measurement was below the thresholds reported for heat stress. The thermal state of the cattle was assessed only using the temperature-humidity index, there were no measurement of physiological indicators of heat stress such as rectal temperature or respiration rate in the animals which would have been useful during the analysis of this study. Additionally, the daily milk yields on the day of measurement or close to the day of measurement would have been useful in the analysis, none of the herd tests were conducted close to the measurement day. Ideally, repeated measurements would have been taken across several days when the daily ambient temperature was high in order to calculate repeatability estimates.

5.10 Future research

Now that heritability estimates of the surface temperature of the eye, muzzle and udder have been determined, it is likely that the surface temperature of other body surfaces is also heritable. Using alternate methods for measuring body surface temperature such as data loggers at key body surfaces when the THI is expected to exceed heat stress thresholds, in conjunction with physiological indicators of heat stress (respiration rate, rectal temperature, or reticulorumen temperature), would allow a more direct measure of body temperature to be achieved. The use of data loggers attached to the skin surface and reticulorumen boluses would allow temperature measurements to be taken at regular intervals over the course of several days while the cattle are in the paddocks expressing typical behaviour.

The temperature-humidity index is commonly used in studies assessing heat stress in cattle; however, as it only includes ambient temperature and relative humidity and does not include other environmental variables contributing to heat stress such as solar radiation and wind speed this index may underestimate the degree of heat stress experienced by the cattle. The use of alternate indices that do include these variables may be useful in experiments examining potential selection targets for breeding programs in establishing the relationship between the potential selection targets and such indices. An alternative climatic index called the Equivalent Temperature Index for Cattle (ETIC) which includes ambient temperature, relative humidity, wind speed and their interactions may be more effective at assessing the thermal state of animals (Cheruiyot et al., 2022). Additionally, Zimbelman et al. (2009) proposed the development of a skin temperature humidity index (STHI) which incorporates infrared measured body surface temperature and the dew point temperature. This index could be useful for evaluating heat stress in dairy cattle using infrared thermography guns or cameras especially if these tools became more common place in the assessment of the thermal state of dairy cattle (Zimbelman et al., 2009).

There are bulls in New Zealand that are homozygous for the slick mutation with 75% New Zealand Holstein-Friesian genetics with the “slick” phenotype conveying greater thermotolerance with lower rectal and vaginal temperatures (Davis et al., 2017). It could be helpful to conduct a study investigating the correlation between skin temperature especially udder temperature with milk production traits in dairy cattle known to be more thermotolerant such as the case in cows with the slick phenotype.

The genetic parameters estimated in this study for eye, muzzle and udder temperature indicate that these traits are heritable and have a positive genetic correlation with production traits therefore, it is possible to select for a greater eye, muzzle, and udder temperature without compromising the seasonal milk production. In order for these results to be useful for animal breeding schemes the heritability and correlations between eye, muzzle and udder temperature with production and reproduction traits would need to be validated on a large number of animals (1000s of animals). In this case from all the skin temperature traits investigated udder temperature was the most promising as it has a higher correlation with production traits. Prior to inclusion of temperature traits into a selection index, more research on using such traits alongside physiological indicators of heat stress needs to be conducted across different regions of New Zealand, in order to validate heritability and correlation data as well as provide support that greater skin temperature does in fact indicate greater heat dissipation ability.

Chapter 6

Conclusion

Infrared thermography was used successfully in field to measure the surface temperature of the eye, muzzle, and udder of cows in the herd at Massey University's Dairy Farm 1. The average eye, muzzle and udder temperatures were 38.2 °C, 37.7 °C, and 37.9 °C, respectively. The greatest variation in surface temperature was observed in the muzzle, while the variation in the eye and udder temperature was similar in magnitude.

Based on previous studies by Liang et al. (2013), Luo et al. (2020), and Aquilar et al. (2009) it was expected that breed, lactation number, and THI would impact eye, muzzle, and udder temperature in the final model. Breed, lactation number and the covariate predicted milk yield affected udder temperature in the final model but surprisingly the covariate THI did not. None of the fixed effects in the final model significantly affected the eye temperature and only lactation number affected the muzzle temperature. Cows in higher lactation numbers had higher average muzzle and udder temperatures. Additionally, the regression coefficient for the predicted milk yield in the case of udder temperature was 0.11, therefore animals with higher daily milk yields had higher udder temperatures. These results suggest that higher udder temperatures are related to greater production. Crossbreds had the highest average udder temperature even though they did not have the highest milk yield which supports the hypothesis that higher udder temperature does not occur solely due to greater levels to production, rather may partly be due to greater heat dissipation through the skin surface of the udder.

The heritability estimates for the eye, muzzle and udder temperature were moderate at 0.20, 0.24, and 0.39, respectively. The genetic correlations between the temperature and production traits were positive and weak to moderately strong except for eye temperature with milk and protein yield which were low and negative. The standard deviations for the estimates of the genetic parameters were large likely due to the small sample size used. The genetic parameters estimated for eye, muzzle, and udder temperature for the herd at Massey University's Dairy farm 1 suggest that it would be possible to select for higher skin surface temperatures. However, the results should be validated using a larger sample size.

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