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Influence of acute mild winter conditions on the productivity of feedlot cattle: An Australian perspective

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ABSTRACT

The impact of cold stress on feedlot cattle has received limited investigation in temperate climates. However, cold stress has been found to impact cattle welfare and production in temperate climatic conditions, where ambient temperature (T_A), precipitation, relative humidity (RH), wind speed (WS) and solar radiation (SR) all influencing apparent temperature. While there are many indices to quantify cold stress in cattle, there are limited indices that directly relate to cattle and account for all the interactions between climatic variables. This makes cold stress difficult to quantify, with on-cattle measures such as core body temperature and shivering difficult metrics to obtain in feedlot cattle. Moreover, individual cattle will react differently to cold conditions based on their production, age, sex, coat characteristics (colour and type), breed and nutrition. While cold stress can be difficult to measure, the production status, behavioural and physiological effects of cold stress have been identified, but generally under what could be considered as extreme cold stress events. Similarly, while mitigation strategies such as shelter, bedding and windbreaks have been investigated, limited information is available surrounding their usefulness in temperate climates. Further research is needed to fully investigate the effects of cold stress and how to mitigate those effects in feedlot cattle under conditions, such as those found in Australia.

1. Introduction

With the global population anticipated to reach 9.687 billion by 2050, agricultural production must also increase to satisfy the needs of the growing population (Norrman, 2023). Livestock industries account for approximately 37% of global food protein and the demand for protein is projected to increase in coming years. This increased protein demand is likely to promote production efficiency and drive increased sustainability in the feedlot industry (Tilman et al., 2002; Greenwood, 2021). Meat provides 21% of global protein, with red meat being 25% of all meat consumed, providing 6% of global protein intake (Smith et al., 2022). Currently, Australian feedlots account for 47% of beef cattle slaughtered and contribute approximately $4.6 billion to Australia's economy (ALFA, 2022; Atkinson, 2023). Feedlots manage large numbers of cattle in pens, resulting in many challenges, with one of the larger challenges being thermal stress (Grandin, 2016). Thermal stress has negative effects on both efficiency of production and welfare of the cattle in feedlots globally (Grandin, 2016). In Australian feedlots, heat stress has received considerable attention and has been identified as a major contributor to reduced performance and wellbeing (Mader, 2003).

However, cold stress also impacts cattle production, but has received limited attention in Australian feedlots (Mader, 2003). This lack of investigation can be attributed with the Australian winters being mild in comparison to feedlots in the northern hemisphere that experience significant snowfall during winter (Wagner, 1988). However, evidence

Abbreviations: **ADG**, Average Daily Gain; **CCI**, Comprehensive Climate Index; **CSI**, Cold Stress Index; **DMI**, Dry Matter Intake; **LCT**, Lower Critical Temperature; **NEFA**, Non-Esterified Fatty Acids; **RH**, Relative Humidity; **SR**, Solar Radiation; **T_3**, Triiodothyronine; **T_4**, Thyroxine; **T_A**, Ambient Temperature; **TRH**, Thyrotropin-Releasing Hormone; **WCI**, Wind Chill Index; **WCT**, Wind Chill Temperature; **WS**, Wind Speed.

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suggests that mild cold conditions can negatively impact feedlot cattle production (Mader et al., 2010). Mader et al. (2010) classified mild cold conditions as those where ambient temperature (T_A) is below 5 °C; however, genetic diversity and multiple environmental factors can impact the T_A threshold where cattle experience mild cold stress. For example, Brahman steers, a heat tolerant breed, have been found to shiver during a tropical low where TA was 24.2 ± 0.1 °C combined with persistent rainfall and low SR. Whereas other more cold tolerant breeds such as Angus and Charolais did not exhibit notable signs of cold stress (Lees et al., 2018). Both WS and precipitation exacerbate cold conditions and can elicit acute cold events, potentially decreasing the apparent temperature below the thermoneutral zone (Joyce and Blaxter, 1964; Angrecka and Herbut, 2015). Overall, mild cold stress will occur at different environmental thresholds for different breeds. However, it is likely that mild cold stress will occur during lower T_A, that are below the 5 °C threshold described by Mader et al. (2010). Australian feedlots in locations classified as temperate by the Köppen climate classification have T_A averaging below 18 °C but generally remain above 0 °C during their coldest months (Cui et al., 2021), with differing amounts of rainfall. This indicates that the cattle in these regions are likely experiencing mild cold stress during the winter season.

This review aims to evaluate current knowledge of acute cold stress and its effects on feedlot cattle specifically in the Australian context and identify future research needs. The review will cover climatic and cattle factors affecting acute cold stress and the responses and impacts that occur in feedlot cattle, along with a brief overview of mitigation options.

2. Cold stress

Cold stress occurs when the environmental conditions are below the thermoneutral zone and beyond the lower critical temperature (LCT), specifically the point where cattle are required to redirect energy towards maintaining or producing heat to maintain homeostasis (Van Laer et al., 2014). However, there are numerous challenges in determining the LCT as it is influenced by both cattle factors and climatic conditions (Young, 1981). While T_A is considered the primary climatic condition in determining cold stress, wind speed (WS) and precipitation can reduce the LCT and exacerbate the impact of cold conditions (Bryant et al., 2007). Equally, the cattle's phenotype, basal metabolic rate, body weight and growth rate influence the cattle's ability to cope with cold conditions, specifically accumulating subcutaneous fat and increasing coat thickness all contribute to an individual's ability to cope extreme cold conditions (Van Laer et al., 2014). These differences in climatic conditions and cattle factors make it difficult to determine when cattle undergo cold stress and highlight the magnitude of individual variation that exists.

Cattle are also capable of seasonal changes to adapt to their current climactic conditions which increases the difficulty in determining the LCT. Seasonal cooling results in acclimatisation to the colder conditions, reducing the LCT (Young, 1981, 1983). These changes include a thicker and longer hair coat and increased subcutaneous fat accumulation for insulation, reducing the cold stress the cattle undergo during winter (Young, 1983; Van Laer et al., 2014). However, when the apparent temperature declines past this adjusted LCT, cattle can experience acute cold stress. This acute cold stress can be caused by rising WS and precipitation, thereby reducing the insulative effects of thicker coats and higher subcutaneous fat depositions (Young, 1981). Acute cold stress generally occurs in Australian temperate feedlots, with weather periodically dropping the apparent temperature below the LCT. In much colder climates, cold stress is chronic, lasting the entire winter, and therefore has a vastly different impact and requires different approaches to management. Therefore, from herein this review will focus on acute cold stress as that is the more abundant form of cold stress that feedlot cattle in temperate climates are exposed to.

It is important to distinguish between the effects of acclimatisation to the cold and acute cold stress, as they have different impacts for cattle. Acclimatisation to cold stress is the adaptive changes that cattle express to cope such as thickening of the hair coat, whereas acute cold stress results in periodic behaviours such as shivering to generate metabolic heat (Young, 1983). Acclimatisation occurs in response to changing ambient conditions during the transition between seasons, and in response to these environmental cues cattle increase their basal metabolic rate and increase dry matter intake (DMI) leading to increased subcutaneous fat deposition, and thickening of hair coats (Young, 1983). These changes allow cattle to manage the effects of colder environmental condition experiences during the winter season without substantive negative physiological effects. By increasing basal metabolic rate, cattle become less susceptible to the acute effects of cold stress, allowing for the preservation of energy for growth and production (Young, 1983), due to the increased basal metabolic rates. Increased basal metabolic rate requires a sufficient increase in DMI to ensure necessary energy resources are available to meet the increased energy demands. Cattle that increase their DMI during cold conditions may maintain their body temperature while maintaining energy availability for growth, a particularly important outcome within a feedlot. Sufficient acclimatisation to the cold prevents production losses when within the adjusted thermoneutral zone.

In contrast, during periods of acute cold stress numerous responses are observed including shivering, hypothermia, reduced feed intake due to heavy precipitation, reduced daily gain and during extreme conditions, death can occur (Young, 1983; Mader, 2003). The specific duration of acute cold stress that results in a thermal challenge is largely undefined; however, a study in sheep on the effects of chronic vs acute cold stress, had sheep exposed to cold conditions, −25 °C T_A, for 160 min (Christopherson et al., 1978). In a human study, acute cold stress effects were tested with 10 °C T_A for 4 h (Lieberman et al., 2009). More research is required to precisely define the thresholds of acute cold stress and duration of exposure implications for cattle. Regardless, these periods of acute cold stress increases energy demand further due to increased requirements for thermoregulation, diverting energy from growth towards heat production to ensure survival. During acute cold conditions where energy availability is reduced, cattle will leverage fat reserves to ensure heat production occurs (Mader et al., 1997). Generally, acute cold stress results in a neutral or negative average daily gain (ADG) either due to energy diverted away from production and/or reduced feed intake, reducing energy resources (Birkelo et al., 1991). The differences between acclimatisation and acute cold stress combined with the effect of environmental conditions, genotype and phenotype considerations mean the impacts of cold stress are difficult to quantify.

3. Climatic conditions influencing cold stress

Cattle accumulate and dissipate heat via the four thermal exchange pathways, radiation, conduction, convection and evaporation (Bakken, 1976). Generally, heat can be lost when cattle radiate their heat to the environment and through conduction and evaporation when heat is evaporated from respiratory systems. Moreover, wind currents can remove heat convectively from the body's surface (Neves et al., 2022).

Cold stress cannot be solely attributed to one climatic variable; therefore, it is important to consider the combined effects of climatic variables that influence the thermal exchange pathways. In particular, the combined effects of T_A, WS, precipitation, relative humidity (RH) and solar radiation (SR) need to be considered when determining acute cold stress (Mader et al., 2010). While each of these climatic variables have individual effects on the accumulation and dissipation of heat, the interactions that exist between these climatic variables and housing structures determine the effective ambient conditions that cattle are exposed to, and the apparent temperature they experience (Gwazdauskas, 1985). For example, when T_A is low and the RH is high, the effective ambient conditions on the cattle are colder than the T_A as a singular climatic variable (Fig. 1; Mader et al., 2010). This interaction between T_A and RH means that both need to be considered when

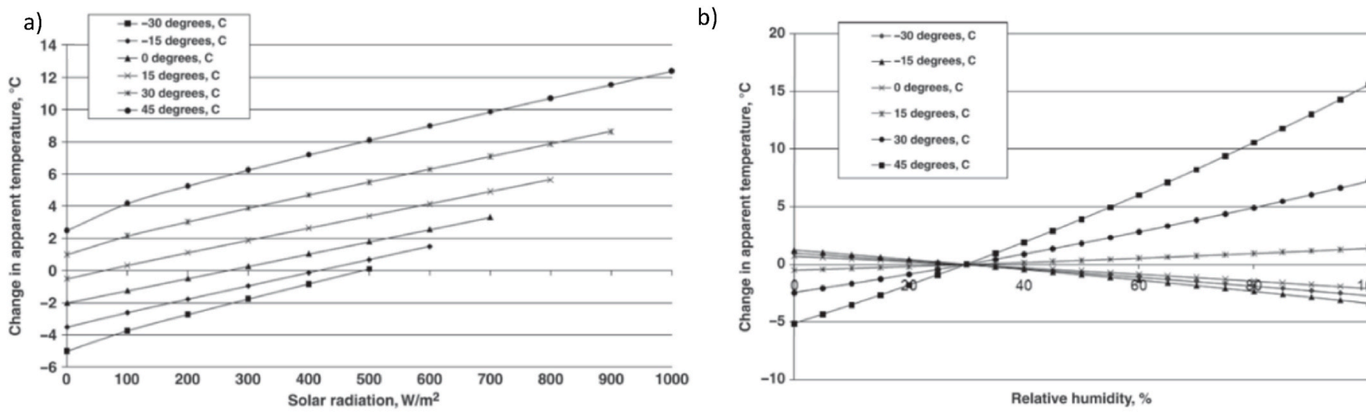

Fig. 1. Apparent temperature changes as (a) solar radiation and (b) relative humidity increases at varying ambient temperatures.
Note. Sourced from *A comprehensive index for assessing environmental stress in animals*, by T. L. Mader, L. J. Johnson, and J. Gaughan, 2010, *Journal of Animal Science*, 88(6) pp 2155-2156.

assessing the severity of cold conditions. Colder conditions experienced by the cattle can be attributed to high RH, and precipitation which reduce the ability of the coat to insulate. Reduced insulation then exacerbates cattle's exposure to cold stress by increasing the evaporative heat lost from the skin and coat surface (Angrecka and Herbut, 2015). Moreover, cold water on the skin conducts heat from the skin at a faster rate than air (Mader et al., 2010). This means wet cattle will lose heat faster than dry cattle, thus with increased air moisture the severity of cold stress conditions can become exacerbated. The effects of RH on the apparent temperature changes at different T_A with more change seen in the apparent temperature when T_A is high, creating a positive linear relationship between RH and T_A (Fig. 1; Mader et al., 2010).

Opposingly, WS has a negative effect on apparent temperature as it increases convective loss from the skin, increasing exposure to cold stress (Joyce and Blaxter, 1964). Wind speeds exponential relationship with T_A is negative, with increases in WS from 0 to 7 m/s results in a decline in apparent temperature by 11 °C. However, when WS increases from 8 to 25 m/s, there is a drop in apparent temperature by 4 °C (Fig. 2; Mader et al., 2010). The variation to apparent temperature with changing WS and RH highlights that a dynamic model is needed to assess the effect of cold conditions on cattle.

Conversely, higher levels of SR increase the heat gained through the hair coat and skin, reducing cold stress. Solar radiation during cold conditions can offset cold conditions, more than during higher T_A, making the apparent temperature higher; however, the radiant load is reduced during winter conditions due to reduced photoperiod duration (Fig. 1; Joyce and Blaxter, 1964). Furthermore, due to interactions that exist between climatic variables, determining the impact of acute cold

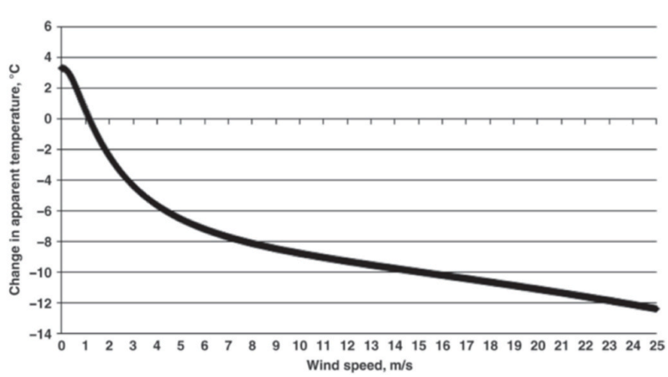

Fig. 2. Apparent temperature changes as wind speed increases.
Note. Sourced *A comprehensive index for assessing environmental stress in animals*, by T. L. Mader, L. J. Johnson, and J. Gaughan, 2010, *Journal of Animal Science*, 88(6) pp 2156.

stress alone can be challenging. It requires an understanding of the thermal exchange mechanisms and the impact that climatic variables, and their interactions have on these mechanisms (Holmér, 1994; Mader et al., 2010). In an attempt to overcome these challenges, numerous climatic indices to assess acute cold stress have been developed.

4. Climatic indices for cold stress

Over the years numerous cold stress climatic indices have been developed to help identify when cold stress for livestock. In most circumstances these climatic indices typically incorporate several climatic variables to account for the interactions between climatic variables and the associated impact on thermal exchange pathways. The wind chill index (WCI) was originally developed for human application (Siple and Passel, 1945). The WCI was also known as the wind chill temperature index (WCT) and was subsequently revised by Tew et al. (2002). The original WCI was based on the dry-shade cooling rates of the atmosphere using a neutral human skin temperature of 33 °C and was developed in Antarctica (Siple and Passel, 1945), using equation [1].

$$K_0 = \left(\sqrt{v \times 100} + 10.45 - v\right)(33 - T_a) \qquad [1]$$

Where v = wind velocity, meters/second; T_a = temperature of the air, °C; K_0 = cooling power of the atmosphere in kilogram calories per hour per square metre, kg cal/hr/m^2

However, it is important to consider that this index does not consider the effects of wet weather as it was specifically designed for cold dry conditions. Moreover, there are limitations in its calculation due to unspecified variables by Siple and Passel (1945) such as air temperature. It could be referring to apparent temperature, wet bulb temperature, dry bulb temperature or T_A; however, the most logical assumption is that this would refer to T_A.

The effects of different K_0 values were outlined for humans with 0 representing no WS and 2600 representing the freezing of flesh (Siple and Passel, 1945). With advancing technology, the WCI was able to be refined by Tew et al. (2002) as noted in the equation defined below.

$$WCI = 35.74 + 0.6215T - 35.75(V \times 0.16) + 0.4275T(V \times 0.16) \qquad [2]$$

Where T = air temperature, °F; V = wind speed, mph.

Both the K_0 and WCI are based on how heat is lost from the body to its surroundings and the subsequent influence of WS on the rate of heat dissipation (Siple and Passel, 1945; Tew et al., 2002). While the WCI provides insight regarding the impact of WS on the severity of cold stress, it does not consider the impact of precipitation or SR. These are important considerations as these climatic factors are known to have considerable impacts on the accumulation and dissipation of heat from the body (Mader et al., 2010). Finally, the WCI is not specific for cattle, more specifically feedlot cattle, in temperate winters. In an attempt to account for this Mader et al. (2010) developed the comprehensive climate index (CCI). The CCI incorporates the net effects of WS, RH, SR and T_A and considers their interactions, to produce a singular unit value.

The CCI was developed to encompass both hot and cold conditions, and defines the severity of cold stress conditions across six 'stress' categories: (1) No stress, CCI $\geq$0; (2) Mild, CCI 0 ≤ -10.0; (3) Moderate, CCI -10.1 ≤ -20.0; (4) Severe, CCI -20.1 ≤ -30.0; (5) Extreme, CCI -30.1 ≤ -40.0; and (6) Extreme danger, CCI ≤ -40.1 (Mader et al., 2010), where the index takes the following form:

$$CCI = TA + EQ1 + EQ2 + EQ3 \quad [3]$$

Where;

EQ (1) presents a correction factor for RH;

$$EQ1 = e^{(0.00182\times RH + 1.8\times 10^{-5}\times TA\times RH)} \times \left(0.000054 \times TA^2 + 0.00192 \times TA - 0.0246\right) \times (RH - 30) \quad [4]$$

EQ (2) presents a correction factor for WS;

$$EQ2 = \left(- \frac{6.56}{e^{\left(\left(1/\left(2.26\times WS + 0.23\right)^{0.45}\right)\times\left(2.9 + 1.14\times 10^{-6}\times WS^{2.5} - \log_{0.3}\left(2.6\times WS + 0.33\right)^{-2}\right)\right)}} \right) - 0.00566 \times WS^2 + 3.33 \quad [5]$$

EQ (3) presents a correction factor for SR;

$$EQ3 = 0.0076 \times SR - 0.00002 \times SR \times TA + 0.00005 \times TA^2 \times \sqrt[2]{SR} + 0.1 \times TA - 2 \quad [6]$$

Where e = natural log; RH = relative humidity, %; TA = ambient temperature, °C; WS = wind speed, m/s; and RAD = solar radiation, W/m2.

The CCI was developed using cattle responses under different environmental conditions encompassing both cold ($\geq$-30 °C) and hot ($\leq$45 °C) climatic conditions. Within the CCI, panting scores were used as a biological indicator of heat stress, while DMI was the primary indicator for cold stress (Mader et al., 2010). Panting scores provide a visual assessment to assess the heat load status of cattle as it evaluates respiratory dynamics of cattle (Gaughan and Mader, 2014; Lees et al., 2019). Dry mater intake is a good indicator of cold conditions, as cattle will increase their DMI to compensate for their increased energy requirements (Wagner, 1988), specifically Kang et al. (2020) shows that DMI increased to 0.45 kg/day during cold conditions where T_A was approximately -2.96 °C. At T_A below -5 °C, the CCI relied on the WCI as the basis model for model development.

The cold stress index (CSI) is another climatic model targeted as a management tool for cold stress conditions, one is the cold stress index (CSI) (Bryant et al., 2007). The CSI was developed initially by Nixon--Smith (1972), based on climatic observations of sheep by Alexander (1962) and was foundational for the development of the sheep graziers warnings provided via the Australian Bureau of Meteorology (Donnelly, 1984). This index is based on the theory that T_A and WS have large effects of heat loss in lambs. In addition, the evaporation of moisture is another cooling effect. The equation reported by Donnelly (1984) is:

$$C = \left(11.7 + 3.1v^{0.5}\right)(40 - T) + 481 + R \quad [7]$$

Where C = potential heat loss, kJ/m^2/h^1; v = average daily wind velocity, m/s; T = average daily air temperature, °C; R = $418\left(1 - e^{-0.04x}\right)$; and x = total daily rainfall, mm

While the CSI is an effective cold stress index for lambs, it does not suit cattle production, specifically feedlots, as newborn lambs, like many newborn mammals, have brown adipose tissue which allows them to generate metabolic heat without shivering due to the presence of thermogenin (Symonds et al., 1992). The index validated for quantifying cold stress in feedlot cattle is the CCI which incorporates the climactic variables that influence cold stress (Mader et al., 2010).

One limitation to the current available models is that there is no index for cold stress that examines the duration of exposure to cold events, a factor that significantly contributes to the severity of cold stress on cattle (Van Laer et al., 2014). In fact, in heat stress, chronic and acute heat stress have been shown to impact cattle differently and as such, the accumulated heat index takes this into account (Gaughan et al., 2008). To overcome some of the limitations of current cold stress indices, Fu et al. (2022) investigated combining thermal environment, physiological and air quality factors using a multilevel fuzzy comprehensive evaluation utilising an analytical hierarchy prosses and a genetic algorithm to provide objective index weights. Current understanding of physiological changes that occur during cold stress, such as decreased respiratory rate, along with the effects of poor air quality, which in turn can reduce the functionality of the immune system resulting in reduced resistance to cold stress, were assessed. These were combined with the current understanding of how the thermal environment influences cattle, enabling the amount of cold stress to be quantified more clearly (Fu et al., 2022). This new method utilises T_A, RH, WS and SR for the thermal environment factors; respiratory rate and ventral surface temperature for physiological factors; and, carbon dioxide, ammonia and inhalable particulate matter as air quality factors (Fu et al., 2022). By combining environmental and cattle factors, this model may be able to best quantify the cold stress cattle are experiencing. However, the matrix developed is complex, developed using first and second lactation dairy cattle and currently is only a research tool.

The determination of acute cold stress in feedlot cattle in temperate winter is possible using the CCI or the matrix developed by Fu et al. (2022); however, the complexity of these indices make them difficult to use outside of research, reducing their usefulness in commercial feedlots or other commercial operations. Additionally, there are several cattle factors that affect their ability to cope during cold stress, further increasing the difficulty in determining when cattle are undergoing cold stress.

5. Cattle factors influencing thermal comfort

Cattle characteristics such as their age, coat characteristics, nutrition, production status, body condition and breed influence their thermoneutral zone. However, one of the initial and main factors determining susceptibility to cold stress is surface to volume ratio (Van Laer et al., 2014). As such, weaner cattle are more susceptible to cold stress than grower cattle due to their higher surface area to volume ratio. Calves and weaner cattle experience faster heat loss from the body to the environment when compared with grower cattle that have a lower surface to volume ratio; therefore, yearling steers entering a feedlot would be the most susceptible to the cold. As the surface of cattle is a primary factor in heat lost to the environment, the more insulation on that surface, the more heat that can be retained (Fu et al., 2022). Thus, the physiological requirement for the coat changes during the winter as longer and denser coats provide greater insulation (Young, 1981; Brandle et al., 1994). These changes provide insulation for dry cattle, as a wet coat results in increased heat lost via conduction and evaporation (Angrecka and Herbut, 2015).

As cattle experience cold stress, they divert energy from growth and production towards thermoregulation, resulting in high energy demanding cattle being more affected by cold stress (Van Laer et al., 2014). Feedlot cattle have high energy requirements for growth so when cold stress restricts energy availability, growth is reduced (Girma and Gebremariam, 2019). To support the higher energy requirements associated with the increased basal metabolic rate, feed intake can be increased (Young, 1983; Mader, 2003). The energy needed for thermoregulation can also be leveraged from their body reserves; thus, if cattle have been on high energy feed longer, subcutaneous fat reserves may be greater (Cartes et al., 2021). This augmented subcutaneous insulation can increase their ability to tolerate cold stress and can be mobilised for energy production through beta oxidation and the tricarboxylic acid cycle (Young, 1981). Differences in subcutaneous fat reserves between breeds of cattle has been noted (Ledger, 1959), where *Bos taurus* cattle are more adapted to cooler climates, increasing their thermal tolerance to cold conditions (Mader et al., 1997; Salvin et al., 2020). This is in part due to their ability to deposit subcutaneous fat for insulation, in conjunction their faster metabolism which generates more body heat (Ledger, 1959; Frisch and Vercoe, 1977). Furthermore, *Bos indicus* cattle are known to have thinner coats, more suitable for hotter climates, reducing their ability to tolerate cool conditions (Carvalho et al., 1995).

Feedlot cattle will experience their thermal environment differently depending on their specific factors. Understanding which cattle will be more susceptible to the cold, enables producers to know which cattle will be most likely to experience detrimental effects of acute cold stress as conditions drop below the LCT.

6. Responses and impacts of acute cold stress

Acute cold stress in cattle has an impact on welfare, behaviour and production; however, the magnitude depends upon the severity of conditions and the duration of the exposure. Acute cold stress events are associated with the temporary drop in climatic conditions below the LCT and as such can occur for variable amounts of time and severity (Young, 1983), albeit short periods, i.e., days. The impact of acute cold stress on feedlot cattle in temperate environments is difficult to quantify due to the variations in duration and severity. Acute cold stress has numerous effects on cattle that require a range of physiological and behavioural responses to maintain body temperature and homeostasis (Fig. 3). However, there are issues assessing the responses and impacts of acute cold stress in commercial feedlots. Firstly, the exact responses of feedlot cattle to acute cold stress in temperate conditions are largely unknown, as most research focuses on extreme chronic cold conditions. Secondly, it is difficult to identify when cattle are undergoing those responses and to measure the magnitude of the impact on production and welfare. There is no panting score equivalent to measure cold stress, and as such there is no developed scale to indicate the severity of the cold stress on individual cattle, thus resulting in the reliance on DMI (Mader et al., 2010). Other physical responses to cold stress such as shivering and decreased body temperature are challenging to evaluate under commercial conditions.

6.1. Welfare impacts

Animal welfare in particular is a difficult metric to define and measure (Ventura et al., 2016); however, it encompasses aspects of health, productivity, reduction of pain and consideration of natural behaviours (von Keyserlingk et al., 2009). Acute cold stress is likely to negatively affect health and productivity and reduce the expression of natural behaviours. This review will focus on more measurable behavioural and production effects from acute cold stress, acknowledging that those changes will negatively impact the welfare of cattle.

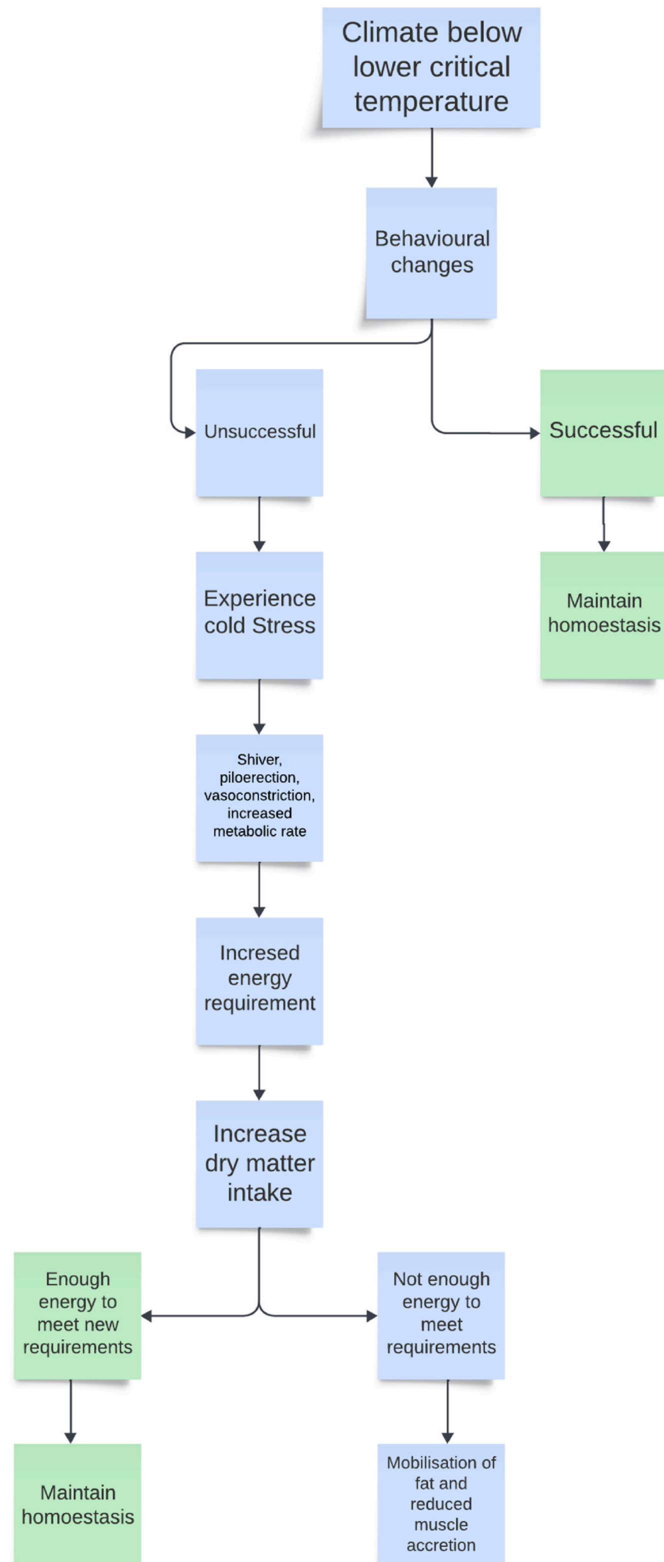

Fig. 3. Flow chart of the responses to acute cold stress in cattle. Green indicates successful mitigation of acute cold stress; blue indicates acute cold stress is occurring. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

6.2. Behavioural responses

Behavioural changes to increase heat gained or retained are the first changes observed and are typically the most effective response to cold stress (Willmer et al., 2009). Cattle will often bask in the sunlight and/or change their posture to expose a greater proportion of their body surface area directly to the sun increasing their radiated heat gain (Yáñez-Pizaña et al., 2020). In contrast, WS and precipitation have been shown to elicit shelter seeking responses and modify lying patterns, when compared to low T_A (Table 1; Beaver and Olson, 1997; Graunke et al., 2011). Shelter seeking behaviours are likely to occur to reduce exposure to wet conditions, as a mechanism to reduce heat dissipation from the surface (Webster et al., 2008). During wet and cold conditions, cattle reduce lying time, either due to the wet conditions or the lack of a dry space to lie down (Webster et al., 2008), which can be considered a welfare concern as cattle are unable to display their natural behaviours (von Keyserlingk et al., 2009; Cartes et al., 2021). The availability of shelter during cold and rainy conditions, T_A between −2 and 16 °C and 10.3 mm/day rain, has been shown to increase the duration of lying by 189.9 min/day (Cartes et al., 2021). Interestingly, shelter was utilised more by cattle that had previously experienced cold stress, T_A between 1.4 and 7.3 °C, when compared to younger, inexperienced cattle, suggesting that older experienced cattle should be mixed with younger cattle to support the social transfer of this learnt behaviour (Beaver and Olson, 1997; Graunke et al., 2011), in grazing context but presents challenges in a feedlot environment. Within a feedlot context this is not possible as animals are managed as pen groups to ensure nutritional management targets can be maintained. Other behaviours include cattle huddling together while standing to decrease the surface area exposed to the cold environment (Yáñez-Pizaña et al., 2020), thus effectively managing the thermal exchange pathways via behavioural changes.

6.3. Metabolic rate and energy partitioning impacts

During temperate winters, cattle acclimatise to the cooler conditions by increasing their basal metabolic rates to support increased energy requirements to cope with cold conditions (Young, 1983). During acute cold stress, if the increased metabolic activity from acclimatisation is not enough to maintain their core body temperature, energy gets diverted to thermoregulatory processes, altering energy partitioning. However, there is some conjecture regarding the exact basal metabolic rate changes due to cold stress (Table 1). Both acclimatisation to cold stress and acute cold stress were found to have no effects upon the metabolisable energy demands of Hereford steers during winter with T_A averaging −2.8 °C (Birkelo et al., 1991). However, this disagrees with previous work by Christopherson et al. (1979) which found basal metabolic rates in Herefords higher in winter ($P < 0.05$), T_A between −30 and 10 °C, than summer or autumn and peaked in spring. The addition of 5.35 m/s of WS to extreme cold conditions (−30 °C) was associated with further increases to metabolic rate (Christopherson et al., 1979). The metabolism peak that occurs during spring can potentially be associated with the loss of the winter coat when the cattle can still be exposed to cool conditions, particularly at nighttime.

Regardless, to compensate for higher metabolic rates during winter due to cold stress, energy requirements increase (Mader, 2003; Graunke et al., 2011; Kang et al., 2020). This is primarily managed via the increased DMI. Acclimatisation to cold conditions of −7.37 to 6.22 °C increased DMI by 0.45 kg/day, however ADG reduced by 0.19 kg/day during cold stress ($P < 0.001$; Kang et al., 2020), showing that the increased energy intake was not sufficient to maintain accelerated growth. Overall, with increased energy being diverted toward maintaining homeostasis, there is a reduction in feed conversion efficiency (Young, 1981). Acute cold stress further increases the energy required for thermoregulation, increasing DMI further as seen when feed intake increased during mild cold conditions of 5 °C (Mader et al., 2010). Interestingly, while DMI was seen to increase by around 9% during the first acute cold event of the season, the subsequent cold conditions resulted in a 3% DMI increase, potentially due to acclimatising to the acute cold conditions (Brouček et al., 1991). As cattle require more energy during acute cold conditions, increased metabolisable energy provided in the diet can be a suitable management tool without increasing total feed intake to provide the extra energy required (Wagner, 1988). However, when acute cold stress is associated with the presence of storms (Mader, 2003), DMI may decrease, exacerbating the effects of cold stress on production and wellbeing (Young, 1983). While energy requirements increase during cold conditions, resulting in a greater feed intake, another reason DMI can increase is likely associated with the metabolic heat produced during fermentation, whereby increased DMI produces more metabolic heat (MacRae and Lobley, 1982; Kang et al., 2020).

The increased energy requirements during acclimatisation and acute cold stress can result in changes to fat deposition and mobilisation. Due to the differences in cattle responses to acute versus acclimatisation to the cold, as well as the severity of the cold, there are differing results surrounding the impact of cold stress on fat deposition and mobilisation in cattle. During acclimatisation to cold conditions, cattle may deposit more subcutaneous fat in an attempt to increase insulation across the body (Mader et al., 1997). This phenomenon of increased subcutaneous fat deposition during acclimatisation was observed in Nebraska, USA which consistently experiences an extremely cold winter, average winter snowfall of 27 cm and T_A persistently below 0 °C. In a temperate winter, subcutaneous fat may not need to be deposited to provide an insulative layer. However, body fat can be mobilised during acute cold stress as body fat reservoirs become important resources to cope with inclement climatic conditions. The sudden onset of stress on the body results in fat reserves to be leveraged as energy to manage the sudden changes to energy demand for thermoregulation (Graunke et al., 2011; Cartes et al., 2021). Circulating non-esterified fatty acids (NEFA) increased by 0.27 mmol/L ($P < 0.001$) when grazing cattle were exposed to T_A between −2 and 16 °C in Chile, suggesting increased fat mobilisation (Cartes et al., 2021). Similarly, when comparing moderate cold stress, T_A averaging −1.05 ± 0.733 °C, to extreme cold stress, T_A averaging −4.33 ± 0.733 °C, NEFA increased by 40 ± 7.948 μEq/L, indicating the rise in fat mobilisation, to divert energy to thermoregulation (Kim et al., 2023). If cattle have sufficient energy from their feed and fat is not mobilised as an energy source, further fat deposition may not occur during acute cold stress as there is reduced energy availability for fat tissue accretion, due to the increased metabolic demands of thermoregulation (Graunke et al., 2011).

In addition, during periods of cold stress there is an adjustment to the ratio of saturated to unsaturated fatty acids contained within subcutaneous fat. During cold stress, unsaturated fats increase to reduce the viscosity of membranes, reducing the negative metabolic effects cold stress causes (Kelly, 1999). However, there appears to be a delayed initiation of this change, with the highest concentration of unsaturated fatty acids occurring during spring. Nutritional changes can also influence fatty acid composition with saturated fats in feedlot cattle not fluctuating seasonally (Kelly, 1999), likely associated with consistency in ration quality and composition.

In Australian temperate feedlot cattle systems, the effects acute cold stress has on subcutaneous fat deposition and mobilisation have not yet been elucidated; however, it is expected that any sudden requirement of energy for thermoregulation will result in fat mobilisation to increase energy availability for the system.

6.4. Physiological thermoregulation responses

Acute cold stress diverts energy towards thermoregulatory responses when peripheral and central thermoreceptors signal that the external and/or internal environment is cold (Yáñez-Pizaña et al., 2020). These thermoreceptors signal the hypothalamus to coordinate with the cardiovascular and metabolic responses (Young, 1981). Thermoregulatory

Table 1
Physiological and behavioural effects of cold stress on cattle in different environments.

Location	Climate	Cattle breed and Experimental Design	Effects of cold stress				Reference
			Fat Depth/ mobilisation	Weight/Average Daily Gain (ADG)	Metabolic rates and metabolisable energy	Behaviour	
Northern Colorado, United States of America	AT: 2.8 °C WS: 3.0 m/s Precipitation: 38.9 cm/year Cold stress index: WCT	Hereford steers in a feedlot and a calorimetry chamber was used.	NA	ADG reduced during winter (−0.6 kg ADG, $P < 0.05$) on both planes of nutrition compared to summer (0.4 kg ADG).	No changes were found during winter to metabolisable energy due to acclimatisation to the cold (even though weight gain dropped (−0.6 kg ADG)). Acute cold stress was not found to have an effect on metabolic rate due to insulation and surface to volume ratio.	NA	Birkelo et al. (1991)
Valdivia, Chile	AT: 2 – 16 °C RH: 40–99.9% WS: 0.1–7.3 m/s Precipitation: 85% days during experiment and averaged 10.3 mm/day	Holstein-Friesian cattle (prepartum not lactating) in open paddock or paddock with artificial shelter (fed daily)	Higher levels of NEFA plasma concentrations in unsheltered cattle by 0.27 mmol/L (more cold stress) as a measure of negative energy balance. Therefore, sheltered cattle were mobilising less fat than unsheltered cattle (more exposed to wet and cold conditions).	NA	NA	Sheltered cattle spent more time lying down than unsheltered cattle (by 189.9 min/day) which could be an indicator of welfare issues. The weather did not affect the usage of shelter.	Cartes et al. (2021)
Sweden	AT: 1.4–7.3 °C WS: 2.4 – 3 m/s Cold stress index: WCT	Black Angus-Charolais or black Angus cows and heifers. Shelter (trees) was provided in paddocks to analyse behaviour.	NA	NA	Higher energy demands during the lower temperatures led to more feeding.	Cattle seek protection when it rained and was windy, but rainfall reduced lying down behaviours. Group cattle of different ages can teach younger cattle to utilise shelter with the older cattle showing the younger cattle to use shelter during windy and wet weather.	Graunke et al. (2011)
Montana, United States of America	Cold Stress Index: standard operative temperature[a].	Angus x Hereford cows (one group experienced cold, one group had never been in cold conditions).	Cattle (no exposed to cold stress before) lost back fat due to greater effect of cold exposure.	Cattle (not exposed to cold stress before) lost weight due to greater exposure to the cold.	NA	Experienced cattle utilised shelter during windy and wet conditions.	Beaver and Olson (1997)
Nebraska, United States of America	AT: 4.2 °C RH: 66% Precipitation: 3.3cm/winter (3 months) Snow: 27.2 cm WS: 5.35 m/s	Steers (British and British X Continental crossbred). Feedlot pens (overhead shelter, no shelter or southeast shelter).	Increased back fat and marbling during winter for cattle with no shelter (fat provides insulation during winter).	NA	NA	Shelter was found to be more important for *Bos indicus* cattle than *Bos taurus* cattle.	Mader et al. (1997)
Edmonton, Canada	AT: 30 – 10 °C	Hereford cattle. Fed grain; in a climate chamber	NA	NA	Thermoneutral metabolic rates were lower in winter and peaked in spring due to a loss of winter coat but still cool conditions. Metabolic rate was still higher in winter than in summer or autumn. Wind increased metabolic rate at −30 °C	NA	Christopherson et al. (1979)
Australia	Not Stated	Angus, Hereford, Murray Grey, Shorthorn, Brahman, Santa Gertrudis & Belmont Red.	Found an increase in unsaturated fats in subcutaneous fat after winter occurred (a delayed effect) with	NA	NA	NA	Kelly (1999)

(continued on next page)

Table 1 (*continued*)

Location	Climate	Cattle breed and Experimental Design	Effects of cold stress				Reference
			Fat Depth/ mobilisation	Weight/Average Daily Gain (ADG)	Metabolic rates and metabolisable energy	Behaviour	
		Compared cattle slaughtered in the south of Australia comparing year round data.	C18:1c9 and C16:1c9 beginning to increase during winter and peaking during summer. A difference in fatty acid changes occurred between pasture and grain fed cattle.				
Korea	AT: 8.79 – 5.75 °C	Korean steers fed control vs 8 g/kg added ruminal protected fat during winter.	NA	Diet did not affect growth parameters; however, the cold month of January showed increased feed intake.	NA	NA	Kang et al. (2020)
Korea	Threshold: AT: 4.66 °C RH 62.24% Mild: AT: 1.05 °C RH: 64.32% Extreme: AT: 4.33 °C RH: 44.74%	Korean steers. Examined physiological, blood and behaviour under mild and extreme cold conditions compared with threshold	No increase in NEFA levels during mild conditions, but under extreme cold conditions, NEFA increased by 41.75 k/µL compared to threshold conditions.	NA	NA	Mild cold conditions increased standing time by 25 min/day riving a 25 min/day reduction in laying time	Kim et al. (2023)

AT = ambient temperature; RH = relative humidity; WS = wind speed; WCT = wind chill temperature.

[a] Standard operative temperature = $T_b - [r_{bs} + r_{es})/(r_b + r_e)](T_b - T_e)$ where, T_b = body temperature; r_b = thermal resistance of skin and insulation with ambient wind speed (s/m); r_e = thermal resistance between outer surface and environment with ambient wind speed (s/m); $r_{bs} = r_b$ and $r_{es} = r_e$ but in a controlled environment with wind speed less than 1 m/s; T_e = operative temperature.

processes such as shivering and non-shivering heat production; cardiovascular exchangers and counter currents; insulation and piloerection; and, nervous and hormonal changes occur simultaneously (Willmer et al., 2009). Then, if the acute cold stress continues and/or increases where the body cannot maintain thermal homeostasis, cellular damage can occur, including increased viscosity of membranes (Hochachka and Somero, 1984).

Shivering produces heat through repetitive muscular contractions by myosin cross-bridge cycling, where the intensity of heat produced depends on myofibril density (Herpin et al., 2002). Shivering can have a four to five fold increase in heat production (Yáñez-Pizaña et al., 2020). This is more effective than doing voluntary exercise, which can reduce insulation and cause sweating, increasing conductive heat loss from the skin (Willmer et al., 2009). Non-shivering heat production requires brown adipose tissue, which has high quantities of mitochondria. When stimulated by norepinephrine, derived from the sympathetic nerves, the mitochondria utilise a different proton route caused by the activity of uncoupling proteins (Willmer et al., 2009). This route allows protons to flow back into the mitochondrial matrix via proton translocase channels rather than the ATP synthase enzyme, allowing all energy to become heat (Willmer et al., 2009). However, this mechanism has been studied more in younger animals, especially lambs, and there is no evidence to show that adult cattle are able to utilise this pathway, potentially due to a lack of investigation rather than the pathway not existing (Symonds et al., 1992).

Cardiovascular changes are also occurring to keep the temperature of core organs stable, which can sometimes occur at the cost of extremities (Willmer et al., 2009). Initially, peripheral vasoconstriction occurs, limiting blood flow from reaching the extremities to reduce the temperature difference between the skin and the external environment (Yáñez-Pizaña et al., 2020). Counter current heat exchangers also work to keep the core body temperature stable by decreasing blood temperature prior to reaching the periphery, then rewarming the blood upon its return to the core (Scholander and Schevill, 1955). Another physiological change is insulation and piloerection. In preparation for winter, cattle increase their coat hair density and subcutaneous fat, insulating them against the cold (Van Laer et al., 2014). To further increase the insulative effects of the coat during acute cold stress, piloerection occurs. The muscles at the base of the hair follicle contract, changing the angle of the hair (Willmer et al., 2009). This erect hair encapsulates a layer of air, a poor conductor, to reduce the heat lost to the environment (Yáñez-Pizaña et al., 2020), by creating a temperature gradient between skin surface and the outer most layer of the coat. Piloerection is coordinated by the posterior hypothalamus when a decrease in core body temperature is detected by central thermoreceptors (Yáñez-Pizaña et al., 2020).

Nervous and hormonal changes are occurring simultaneously with these behavioural and physiological changes. Research suggests that neurons and the hypothalamus are responsible for behavioural, vascular, and muscular changes due to the detection of cold stress (Willmer et al., 2009). When the posterior hypothalamus is stimulated by peripheral and central thermoreceptors, several hormonal changes can occur that result in calorigenic effects, increasing the metabolic rate, boosting heat production and increasing body temperature (Willmer et al., 2009). Production of thyrotropin-releasing hormone (TRH) stimulates the thyroid to secrete thyrotropin, stimulating the release of triiodothyronine (T_3) and thyroxine (T_4; Yáñez-Pizaña et al., 2020). Triiodothyronine and T4 increase the metabolic rate of cells and thermogenesis (Willmer et al., 2009), and epinephrine released from the adrenal medulla, results in thermogenesis to produce heat in response to cold stress (Willmer et al., 2009).

As cattle are endotherms and homeotherms, they must keep their core body temperature stable to ensure the efficacy of normal bodily function. Thermoregulatory responses aim to keep body temperature stable; however, if they fail to do so, changes can occur in the cattle. During reduced core body temperatures, chemical reactions slow down, and cellular membranes become more viscous, making it difficult for enzymes to enter and exit cells (Hochachka and Somero, 1984). Cells internal temperature can drop so low the cells begin to freeze, and the ice crystals can puncture cell membranes causing irreparable damage (Drobnis et al., 1993). To keep membranes in a normal viscous state, homeoviscous adaptation can occur which changes saturated to unsaturated fatty acids (Willmer et al., 2009). By increasing the number of unsaturated fats in cell membranes when cold stress occurs, cell membrane viscosity can be maintained and normal cellular function can occur (Hochachka and Somero, 1984). These fatty acid changes are the result of desaturase enzymes whose activity is temperature dependent (Willmer et al., 2009). The rate of transcription levels of these desaturase enzymes increases eight to ten fold as T_A decline (Willmer et al., 2009). While the effects of cold T_A on physiological changes can be seen, the exact mechanism from detection of the cold to the changes seen are unclear due to the complexity and length of the mechanisms (Willmer et al., 2009). It would take extreme acute cold stress in temperate winter for cattle to need to implement homeoviscous adaptation. It is hypothesised temperate Australian feedlot cattle will more likely experience a temporary loss of production during acute cold stress, associated with the diversion of energy towards maintaining thermal comfort. In addition, cold exposure in the Australian environment is simply not comparable with other regions of the world.

6.5. Production impacts

Acute cold stress influences production efficiencies, which can be attributed to the changes to energy partitioning, with increased energy being diverted towards thermoregulation. These metabolic activities can then be associated with reduced body weight gain and/or growth performance because of reduced energy availability for muscle maintenance and tissue accretion (Graunke et al., 2011). During winters with T_A averaging -2.8 °C, ADG dropped by -0.6 kg/day whereas in summer, T_A averaging 20.9 °C, ADG was 0.4 kg/day ($P < 0.05$) (Birkelo et al., 1991). The reduced energy availability for muscle accretion is indicated by reduced liveweights (Beaver and Olson, 1997) and reductions in ADG, across different planes of nutrition (Birkelo et al., 1991, Table 1). Examining differences between older and younger cattle during winter, 3-year-old cattle lost approximately double the weight of 7- to 8-year-old cattle ($P = 0.0003$) (Beaver and Olson, 1997). However, this was examining weight over the course of a winter, rather than during periods of acute cold stress. Examining acute cold stress in feedlot cattle has received limited attention; however, the effects of acute cold stress on production in dairy cattle may be used to highlight the potential effects of the energy diversion to support thermoregulation. During an acute cold event where, average T_A were -9.2 to -4.3 °C, milk yield dropped from 15.01 kg to 12.80 kg ($P < 0.01$), despite a 9% feed intake increase (Brouček et al., 1991). This type of acute cold events occur during periods of extreme cold T_A, which temperate Australia may only experience occasionally. However, the impact of WS and precipitation on apparent temperature and the thermoregulatory abilities of cattle would place temperate feedlot cattle in acute cold conditions more consistently. The exact decline in production remains undefined for feedlot cattle.

Interestingly, acute cold stress may not just negatively impact cattle weight gains, but also the quality of the meat and increase the incidence of dark cutting. Recent studies have shown that cold climatic conditions can increase the prevalence of dark cutting (Steel et al., 2022b). However, the effect is small only accounting for 0.1–0.2% of the incidence of dark cutting in Australian conditions (Steel et al., 2022a). An increase in the minimum T_A by 10 °C, 28 days before feedlot departure, resulted in a reduction in dark cutting by up to 1% (Steel et al., 2022a). Moreover, a 1 mm increase in rain in the week prior to departure resulted in a 1.013 increase in the odds in the incidence of dark cutting ($P < 0.001$) (Steel et al., 2022b). These associations with the incidence of dark cutting due to acute cold conditions can potentially be attributed to the cattle undergoing glycogenolysis and breaking down glycogen stores to glucose to maintain core body temperature (Steel et al., 2022a). When cattle were exposed to windy and wet conditions during lairage, their incidence of dark cutting also increased (Steel et al., 2021). However, it has been postulated that the wet and windy conditions made the new environment more stressful for the cattle due to reduced visibility and hearing, rather than increasing their acute cold stress directly (Steel et al., 2021).

There is a clear need to explore the exact production effects of acute cold stress on temperate feedlot cattle and to determine how to identify when cattle are experiencing acute cold stress. There is a general understanding that cattle respond behaviourally and physiologically to acute cold stress; however, how to measure these responses and the effect they have on production is an area for further research.

7. Mitigation opportunities

As the effects of acute cold stress have production and welfare implications, it is important to mitigate the effects of cold stress as much as possible. Most research surrounding shelter in feedlots is conducted during summer when shade is utilised as a heat load mitigation tool (Salvin et al., 2020). However, in Iowa feedlots, it has been found that shelter or roofs can decrease the number of days that cattle experience cold stress by 5–17%, depending on which cold stress index is used to determine the severity of the conditions (Euken, 2016). There is further evidence highlighting that waterproof shelter can be useful to protect cattle from cold stress (Van Laer et al., 2014). An issue with providing shelter in feedlots is the cost associated with construction, and each feedlot may need different types of shelter due to differing thermal environments, i.e. subtropical versus temperate climates, feedlot design and layout (Young, 1981). However, the production efficiencies that can be gained with the provision of shelter need to be considered when assessing the required investment (Young, 1981). In pasture-based systems, shelter has been seen to increase lying down time, improve cleanliness and reduce adipose mobilisation (Cartes et al., 2021). However, the use of shelters may not protect cattle from the WS due to their height (Mader et al., 1997). Greenhouse roofs have been investigated as a form of shelter in temperate environments, T_A of 15.9 °C and average RH of 64.1%, and have been found to decrease DMI by 0.16 kg/animal/day, and increase the ADG by 0.04 kg/day and the feed:gain during winter by 0.007 ($P < 0.01$) (Hidalgo et al., 2022). This suggests that these cattle were more efficiently utilising the feed for muscle accretion and fat deposition while consuming less feed.

Wind breaks can also be used to reduce the effects of WS on cold stressed cattle, leading to lower energy demand and minimising the increase in DMI (Brandle et al., 1994). Windbreaks can be used in feedlot systems if they are perpendicular to the winter winds. However, these shelter belts, while being seen to protect cattle during winter, can negatively impact cattle production during summer by limiting air flow (Mader et al., 1997).

In addition, bedding can offer multiple benefits including increasing the insulation cattle have and protecting cattle from acute cold stress (Mader, 2003). Bedding has also been found to help dry coats and reduce the conductive heat loss from a wet coat (Mader and Griffin, 2015). Mader (2003) concluded that providing 1 kg of straw bedding daily improved gains by 7% and improved efficiency by 6%; however, this also increases the waste that needs to be cleaned from the pens. Similarly, feedlot cattle fed 109 days during a temperate Australian winter showed the addition of 30 cm of woodchip bedding increased ADG by 0.22 ± 0.21 kg body weight/head/d ($P < 0.001$) and DMI by 0.2 ± 1.34 kg dry matter/head/d ($P < 0.049$; Tait et al., 2023). Finally, bedding can reduce muddy conditions of the pen, keeping cattle clean and dry and improving their ability to tolerate colder temperatures (Tucker et al., 2015; Salvin et al., 2020; Tait et al., 2023). As mud can further increase the energy requirements of cold stressed cattle, keeping cattle clean through the use of bedding or even wind breaks can improve production and welfare (Grandin, 2016).

Nutritional strategies, such as increasing metabolisable energy in diets, have been proposed to help mitigate the effects of acute cold stress. Providing cattle with sufficient energy to maintain production reduces the impact to production during acute cold challenges (Wagner et al., 1988). However, differing results have been seen when adjusting diets in feedlot cattle. Kang et al. (2020) added 8 g/kg ruminal protected fats, a palm oil mixture containing free fatty acids, and found no differences in production when compared to control steers at average T_A of −8.79 to 5.75 °C. Similarly, another study found that DMI decreased with increasing corn grain in the diets, during average T_A approximately 12.4 °C; however, metabolisable energy intake tended to be increased on higher grain diets, even with lower DMI levels (Muhamad et al., 1983). If cattle can meet their metabolisable energy requirements through increasing their DMI, higher energy diets may not be required to combat acute cold stress in Australia. Moreover, given the sporadic and short-lived nature of acute cold stress, implementation of nutritional strategies such as increasing metabolisable energy may be impractical for feedlots. The provision of additional DMI during acute cold events may be a more viable solution for Australian feedlots.

8. Opportunities for the Australian environment

The temperate Australian environment is an unusual climate in which to investigate cold stress, simply because it does not receive the snowfall that regions of the northern hemisphere experience. Furthermore, T_A do not typically decline below −30 °C, or further. Hence, most research into cold stress has been conducted in the northern hemisphere,

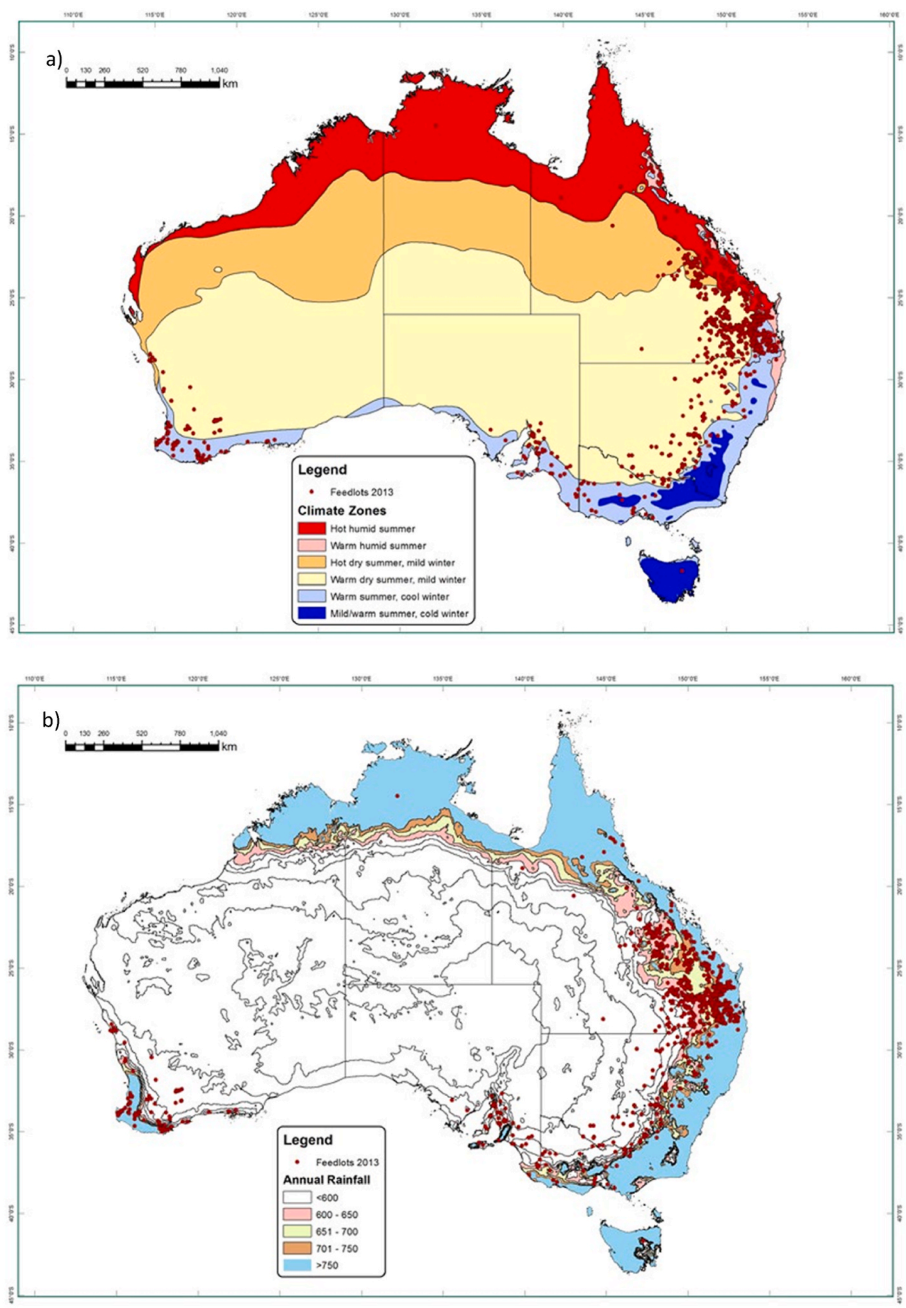

Fig. 4. Climate zones (a) and annual rainfall (b) compared to the location of feedlots in 2013.
Note. Sourced from *Beef cattle feedlots: design and construction*. by Watts, P. J., R. J. Davis, O. B. Keane, M. M. Luttrell, R. W. Tucker, R. Stafford, and S. Janke, 2016, *Meat and Livestock Australia*, pp 2.

and as such the effects of acute cold stress in temperate feedlots, both in Australia and elsewhere has received limited attention. However, temperate regions of Australia have a large amplitude of temperature ranges that result in acute cold stress events, especially when winter conditions are coupled with precipitation and raised WS (Fig. 4). As climate change continues to disrupt historical seasonal patterns, there is a possibility that cattle will be exposed to cold stress during warmer seasons (IPCC et al., 2022), even in mild climate regions. This will result in cattle that are not acclimatised to cold conditions placed in environmental situations that have the potential to have negative welfare and production outcomes. It has been shown that low SR and T_A coupled with precipitation during summer resulted in cold conditions leading to Brahman steers experiencing acute cold stress, as indicated by observations of shivering (Lees et al., 2018), in a subtropical climate. As cattle do change their basal metabolic rate diurnally, these random acute cold stress events outside of winter will increase the effects of cold stress. While climate change is expected to increase T_A, it is also likely to increase storms outside of normal patterns, potentially resulting in acute cold stress during unexpected times of the year (IPCC et al., 2022).

As such, the implications of acute cold stress need to be determined in temperate Australian feedlots and suitable mitigation strategies need to be identified and tested. Moreover, the specific conditions that induce acute cold stress in different regions of temperate Australia need to be isolated. Therefore, more research needs to be conducted into acute cold stress in temperate climates, both in Australia and elsewhere globally.

9. Conclusions

Acute cold stress in temperate feedlots is influenced by a multitude of factors such as climatic conditions, cattle condition and mitigation strategies. As such, the effects on feedlot cattle of acute cold stress are difficult to define clearly. In Australian feedlots, even with mild cold conditions, production efficiency may be compromised due to changing energy requirements for homeostasis. However, further investigation is needed to determine the extent of the reduction in productivity. Further, research needs to focus on the identification of cold stress in feedlots, based on both climactic conditions and cattle responses. With cold conditions expected to occur at unexpected times, cold stress frequency may increase, leading to a need to investigate strategies to mitigate the cold conditions for Australian feedlots. While there are clear impacts of chronic cold stress, the exact effects of acute cold stress on feedlot cattle are unclear in a temperate Australian environment.

Data accessibility statement

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CRediT authorship contribution statement

Pippa J. Pryor: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Billie Standfield:** Writing – review & editing. **Janelle Wilkes:** Writing – review & editing. **Léa Labeur:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Angela M. Lees:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

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

Data availability

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