final report

Project code: B.FLT. 0387

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Date published: 21 March 2019

PUBLISHED BY
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Evaluation of a heat load model for feedlot cattle

Meat & Livestock Australia acknowledges the matching funds provided by the Australian Government to support the research and development detailed in this publication.

Executive summary

The Heat Load Index (HLI) model (Gaughan et al. 2008) was developed by monitoring panting scores of commercial feedlot cattle across a range of sites in Australia and the United States. When the HLI and Accumulated Heat Load Unit (AHLU) models were first published in 2008 it was always the intention that at some point the models would need to be reviewed. Over the last few years there has been some concern that the models do not always adequately reflect what lot feeders are seeing in the field. In many cases, anecdotal observations suggest the models work very well. However in some cases, the models suggest that cattle should be adversely affected by high levels of accumulated heat load when in reality the cattle cope with no signs of stress. At other times the model underestimates the effects on cattle. While this is not the case for all locations at any given time, false alerts or a failure to alert results in a loss of confidence in the usefulness of the models by the end users. Some of the failures may be due to incorrect siting of the weather station (i.e. not truly representative of conditions in feedlot pens) and incorrect threshold settings (e.g. threshold set as if all pens are unshaded). However at some locations there appears to be a difference between animal responses and the predicted responses based on the models. Further investigation of model adequacy was implemented in this MLA research project.

Over the summer of 2017/18 six commercial feedlots were monitored. The feedlots were selected so that 3 distinct geographical areas would be represented. Two feedlots (Group 1: feedlots 1 and 2) were monitored in the Riverina (to represent a Mediterranean type climate) – one was located in NSW and the other in VIC), two feedlots (Group 2: feedlots 3 and 4) were monitored in the Central/Northern NSW (to represent a hot dry summer climate) and two feedlots (Group 3: feedlots 5 and 6) were monitored in Queensland (to represent a hot humid summer climate). The feedlots varied by SCU, pen size, pen dimensions, pen orientation, shade type, breed types, days on feed, market focus and feedlot terrain – which ranged from flat to hilly.

Two automated weather stations were installed at each feedlot. One station was located in an area central to the observation pens and the other was located in an area close to the office. Data from the weather stations was averaged to calculate the HLI and AHLU.

At each site the following information was collected. *Pen Information*: Pen dimensions (L x W x D), orientation, pen slope, distance from weather station, shade type and area, shade orientation, feed bunk and water trough dimensions (L x W x D) and shade properties (height, location in pen, material, and coverage). *Manure depth:* Manure depth was obtained for each pen once a day (first observation period). *Pen surface moisture:* A pen surface moisture transect across each pen (during first daily observation) was used to determine average pen soil moisture. *Pen temperature and humidity:* Temperature and humidity loggers were placed in most of the monitored pens (ranged from 8 to 16 at each feedlot). *Water trough temperature:* Water temperature loggers were placed in water troughs.

Cattle Information: Origin of cattle, sex, age (dentition), breed type (see following point) and live weight at induction; Breed type (BT) was defined based on the Meat Standards Australia descriptors for tropical breed content. Five breed types were identified BT1 = 100% BT English, BT2 = 100% BT Euro, BT 3 < 25% *Bos indicus* content (e.g. Angus x Santa), BT 4 = 50% (e.g. Santa, Droughtmaster, Brangus), and BT 5 = 100% (e.g. Brahman).

A head count for each breed type was obtained; HGP status; Days on feed at time of monitoring; Morbidity to date at time of monitoring (including diagnosis); Mortality to date at time of monitoring (including necropsy reports); Daily pen as-fed deliveries and ration number for two weeks prior to, during and post visits; Daily pen head counts for pens for two weeks prior to, during and post visits; Times of the day that cattle were fed and a composite sample of each ration used in the observation pens was obtained and frozen for later analysis.

Cattle Visual assessment: Four times per observation day (at approximately 0600, 1000, 1400 and 1800 h). The data collected was:

- Panting scores (PS). The PS system used was as per: Recognising Excessive Heat Load in Feedlot Cattle – In Tips and Tools "Heat Load in Feedlot Cattle".
- Behavioural observations: Number of cattle standing or lying; location in pen (shade, feed bunk, water trough, in sun); activity (eating, drinking), and disposition (agitated, milling around, depressed).

On-site monitoring occurred when: Managers observations suggesting cattle are under or approaching heat stress; Current conditions at yard (AHLU≥30; over the last 24 h HLI_{MAX}>90 and HLI_{MIN}>65; little or no nightime relief) – weather station data from the feedlots was checked at 0700 h daily, and more often if heat load was increasing; Predicted conditions from the Katestone site (next 3 to 5 days at each feedlot) (max and min temperatures, humidity, wind, rainfall, HLI (>90) and AHLU (increasing not returning to 0). Were evaluated each day at 0800 h. The local BOM forecast for each location was also reviewed each day.

The main outcomes from the study are:

Weather station location: The siting of weather stations at feedlots needs careful consideration. Site location had a significant effect on AHLU. Whilst high correlations and agreement between pen and office weather stations were observed at the some feedlots, at some sites agreement was poor. Wind speed was only moderately correlated, whilst agreement for humidity was dependant on feedlot. Attempts should be made to assess conditions in pens relative to the preferred site for the weather station. In the current study, two weather stations and up to 16 pens were used to obtain micro-climate data. The diversity of conditions within feedlots complicates heat load modelling.

Black globe calculations: The data from this study suggests that the calculation of black globe temperature from solar radiation and ambient temperature results in less robust predictions than utilising a weather station with a black globe sensor. Over or underestimation of black globe temperature occurred dependant on feedlot site. Ideally all weather stations should be fitted with a black globe sensor.

Panting score and AHLU: Using breed type classifications in the model in combination with AHLU adjusted for breed (AHL_{ADJ}) a logistic regression model that predicted probability of panting score ≥ 2 was developed. Ninety-five percent confidence intervals were placed around each predicted probability for each breed type. A significant effect of increasing AHL_{ADJ} on the probability of panting score was observed across breeds. Whilst this demonstrates AHLU is a significant variable determining panting of feedlot cattle, relatively wide confidence intervals around predictions necessitate further investigations of feedlot and pen level factors to explain variation in panting score.

Increasing *Bos indicus* content decreased predicted probabilities of panting score exceeding the threshold (≥ 2). Further research is required to evaluate the adequacy of the model on independent data sets.

Weather conditions during the study were mild and modelling of open mouthed panting was not possible. Negligible mortality due to heat load were observed. Further research is required to develop logistic regression models to predict probability of these adverse animal welfare outcomes.

Dry matter intake: Although there were significant effects of AHLU on DMI/energy responses the correlations were very weak. Management practices associated with feed management during time of high heat load may have had an impact here. In addition there were few hot periods during data collection.

The following recommendations have arisen from this study:

1. Accumulated heat load is a significant variable in explaining heat load response of feedlot cattle, however improvement in prediction confidence intervals of panting scores ≥ 2 is required across feedlot sites and breed types.
2. Further independent data is required to evaluate the logistic regression model adequacy developed in this project. Adjustments to the heat load model valuation should be evaluated during the summer of 2018/19.
3. Attempts to obtain additional data from cattle exposed to high heat load (in the field) are required to model probability of open mouth panting due to mild summer conditions experienced during this project.
4. Ideally all weather stations should be fitted with a black globe sensor.
5. There is a need to understand how different pen micro-climates influence predictability of heat load responses of feedlot cattle compared to weather stations located outside of pens.

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1 Background

1.1 Reviewing the heat load index (HLI)

1.1.1 The problem

Managing excessive heat load (EHL) during the summer months is critical to improving animal welfare outcomes and productivity of feedlot cattle. Over the past 15 years, the feedlot industry has invested heavily in research on shade infrastructure, heat stress nutrition and management of feedlot cattle. The industry has proactively promoted the use of heat load forecasting and modelling tools to accurately predict animal responses to periods of EHL and enact early response plans to maximise improved animal welfare outcomes. As part of a continuous improvement process, the feedlot industry wishes to formally evaluate the ability of the Heat Load Index (HLI) model (which includes the HLI and the accumulated heat load units - AHLU) to predict heat load response of cattle under commercial feeding conditions.

The Heat Load Index model and Accumulated Heat Load model (Gaughan et al. 2008) were developed by monitoring panting scores of commercial feedlot cattle across a range of sites in Australia and the United States. When the HLI and AHLU models were first published in 2008 it was always the intention that at some point the models would need to be reviewed. The models are currently used in the weather prediction service provided to the feedlot industry (Katestone: www.katestone.com.au). The prediction service provides a 7 day AHLU risk level alert for specific sites around Australia. Over the last few years there has been some concern that the models do not always adequately reflect what lot feeders are seeing in the field. In many cases anecdotal observations suggest the models work very well. However for some locations at any given time false alerts or a failure to alert results in a loss of confidence in the usefulness of the models by the end users. Some of the failures may be due to incorrect siting of the weather station (i.e. not truly representative of conditions in feedlot pens) and incorrect threshold settings (e.g. threshold set as if all pens are unshaded). However at some locations there appears to be a difference between animal responses and the predicted responses based on the models.

Therefore it is prudent, that the underlying aspects of the model be evaluated scientifically under field conditions.

The aims of this study were:

- Evaluate the accuracy of HLI and AHLU in predicting panting scores and DMI, for various cattle genotypes with variations of days on feed.
- Evaluate the accuracy of the HLI and AHLU against morbidity and mortality.
- Evaluate the placement of weather stations at feedlots to determine the influence of weather station site on the accuracy of pen data (animal responses).
- Evaluate the accuracy of the calculated black globe temperature against the weather station black globe temperature.
- Determine differences between ambient temperature and relative humidity in pens and the weather stations.

2 Project objectives

2.1 Main objectives

In addition to the aims out lined above the main objectives of the study were to:

1. Determine the adequacy of the current heat load model (Gaughan et al. 2008) to predict excessive heat load of commercial feedlot cattle.
2. Determine the adequacy of the current heat load model to explain variation in energy intake of feedlot cattle and cattle mortality.
3. Determine differences in the precision and accuracy of AHLU to explain variation in panting score with weather stations that have a true black globe temperature sensor vs. weather stations that record solar radiation and temperature (and calculate black globe temperature by formula).
4. Determine the precision and accuracy of AHLU to explain variation in panting scores of feedlot cattle for weather stations located near the feedlot office vs. those adjacent to feedlot pens.

3 Methodology

3.1 The study

3.1.1 Feedlots

Six commercial feedlots were monitored during the study. The feedlots were selected so that 3 distinct geographical areas would be represented. Two feedlots (Group 1: feedlots 1 and 2) were monitored in the Riverina (to represent a Mediterranean type climate), two feedlots (Group 2: feedlots 3 and 4) were monitored in the Central/Northern NSW (to represent a hot dry summer climate) and two feedlots (Group 3: feedlots 5 and 6) were monitored in Queensland (to represent a hot humid summer climate). The feedlots varied by SCU, pen size, pen dimensions, pen orientation, shade type, breed types, days on feed, market focus and feedlot terrain – which ranged from flat to hilly.

3.1.2 Market Categories Monitored

At each yard the following market categories were targeted to be monitored in shaded and unshaded pens (when available). However not all feed classes were available at each feedlot at each observation time. Where all of the market combinations were not present extra replicates of market category × DOF intervals were monitored.

1. Domestic cattle: 280 to 350 kg initial LWT; monitored at intervals of 0, 25, and 50 DOF
2. Short-Fed export cattle: 380 to 500 kg initial LWT; monitored at intervals of 0, 50 and 100 DOF
3. Mid-Fed export cattle: 380 to 500 kg initial LWT; monitored at intervals of 150 to 200 DOF

If all classes of cattle were available at a feedlot up to 16 pens were observed. However the actual pen count varied from 8 to 16 across the feedlots.

A pen inventory (with market category and current DOF) were sent from the feedlot to UQ on a weekly basis.

3.1.3 Trigger Points for On-site Monitoring

- Managers observations suggest cattle are under or approaching heat stress.

- Current conditions at yard (AHLU≥30; over the last 24 h HLI_{MAX}>90 and HLI_{MIN}>65; little or no nighttime relief) – weather station data from the feedlots was checked at 0700 h daily, and more often if heat load was increasing.
- Predicted conditions from the Katestone site (next 3 to 5 days at each feedlot) (max and min temperatures, humidity, wind, rainfall, HLI (>90) and AHLU (increasing not returning to 0). Where evaluated each day at 0800 h. The local BOM forecast for each location was also reviewed each day.

3.1.4 Data collected on Pens

For each feedlot the following data was obtained:

- ***Pen Information:*** A pen description for each pen used in the study was obtained before experimental data was collected. This included pen dimensions (L x W x D), orientation, pen slope, distance from weather station, shade type and area, shade orientation, feed bunk and water trough dimensions (L x W x D) and shade properties (height, location in pen, material, and coverage).
- ***Manure depth:*** Manure depth was obtained for each pen once a day (first observation period). A graduated 2 m long PVC conduit was used. The conduit was pressed into the manure and the depth recorded. In addition pen surface was characterised at each observation time: a visual score (dry dusty, smooth, compact, pugged, saturated.
- ***Pen surface moisture:*** A pen surface moisture transect across each pen (during first daily observation) was used to determine average pen soil moisture. Pen surface transects was made diagonally across a pen and soil moisture (depth 6 – 10 mm) was determined every 20 m. Soil moisture was determined using a portable soil moisture meter (MPkit 406, ICT International, Armidale).
- ***Pen temperature and humidity:*** Temperature and humidity loggers (HOBO Pro V2; Onset Computer Corporation) were placed in most of the monitored pens (ranged from 8 to 16 at each feedlot). The loggers were placed in a shaded location in the pens at a height of approximately 2.5 m above the pen surface. Ambient temperature and relative humidity were recorded at 10 min intervals for the duration of the study. Data from these loggers was used to calculate a temperature humidity index (THI: $THI = (0.8 \times T_A) + ((RH/100) \times (T_A - 14.4)) + 46.4$); where T_A is ambient temperature (^oC) and RH is relative humidity (%). These data were then compared to the THI from the weather station. The THI was used for these calculations rather than the HLI because the loggers could only record T_A and RH.
- ***Water trough temperature:*** Water temperature loggers. The loggers used were either a HOBO U12 Stainless Temperature logger (Onset Computer Corporation) or a HOBO Pendant MX temperature logger (Onset Computer Corporation), were placed in 8 to 16 water troughs at each feedlot. In some cases a water trough was shared between pens, hence the lower number.

3.1.5 Animal data

The following data were obtained for each pen at the commencement of the study, when new pens were enrolled after the commencement of the study and at each observation time. Although this was somewhat repetitive if did give allow for consistency of information.

- Origin of cattle, sex, age (teeth), breed type (see next dot point) and live weight at induction

- Breed type (BT): BT was defined based on the Meat Standards Australia descriptors for tropical breed content. Five breed types were identified BT1 = 100% BT English, BT2 = 100% BT Euro, BT 3 < 25% *Bos indicus* content (e.g. Angus x Santa), BT 4 = 50% (e.g. Santa, Droughtmaster, Brangus), and BT 5 = 100% (e.g. Brahman). A head count for each breed type was obtained.
- Hormonal growth promotant (HGP) status
- Days on feed at time of monitoring
- Morbidity to date at time of monitoring (including diagnosis)
- Mortality to date at time of monitoring (including necropsy reports)
- Daily pen as-fed deliveries and ration number for two weeks prior to, during and two weeks post visits
- Daily pen head counts for pens for two weeks prior to, during and post visits
- Times of the day that cattle were fed
- A composite sample of each ration used in the observation pens was obtained and frozen for later analysis. Feed samples were sent to Symbio Laboratory, Brisbane and the following were determined: DM, CP, NDF, Fat, Ash and ME.
- Visual assessment of cattle in the enrolled pens occurred four times per observation day (at approximately 0600, 1000, 1400 and 1800 h). The data collected was:

    - *Panting scores (PS).* The PS system used was as per: Recognising Excessive Heat Load in Feedlot Cattle – In Tips and Tools "Heat Load in Feedlot Cattle".

    - *Behavioural observations*: Number of cattle standing or lying; location in pen (shade, feed bunk, water trough, in sun); activity (eating, drinking), and disposition (agitated, milling around, depressed).

3.1.6 Weather Stations

Two automated weather stations (Weather Maestro 10 channel weather station, Environdata Weather Stations Pty Ltd., Warwick Qld) were installed at each feedlot. Each weather station was calibrated by the supplier and calibration certificates were provided for each weather station.

One station was located in an area close (<50 m) to the office (identified as weather station 1) and the other was located central to the observation pens (identified as weather station 2). In both instances the weather stations located on earth or an unwatered grassed area. Each site was assessed to ensure that the weather data would not be biased by shade, topography, buildings, concrete slabs or asphalt roads.

The weather stations measured the following at 10 min intervals: wind speed (m/s) at a height of 2 m, wind direction, ambient (dry bulb) temperature (T_A, ^oC), relative humidity (RH, %), solar radiation (SR, W/m^2) and black globe temperature (^oC). Rainfall was collected on site and recorded daily at 0900 h.

A web based service WeatherMation LIVE (Environdata Weather Stations Pty Ltd., Warwick Qld): provided real time weather data as well as real time HLI and AHLU values. In addition the service provided 3 hourly 12 hourly and 30 day graphical representation of the data. The quality and integrity of data streams was assessed each day.

3.1.7 Calculation of the heat load index and accumulated heat load units

Heat load index thresholds and the consequent accumulated heat load units were calculated for each breed type were as per Recognising Excessive Heat Load in Feedlot Cattle – In Tips and Tools ”Heat Load in Feedlot Cattle”.

3.1.7.1 Heat Load Index Calculation

Calculation of the Heat Load Index (HLI) requires ambient temperature (T_A; °C), relative humidity (RH; %), wind speed (WS; m/s) and black globe temperature (BGT; °C). Of these, T_A, RH and WS are routinely measured by the majority of weather stations. Although sensors for measuring BGT exist, these are not normally included as part of the standard weather station (however theses were included on the weather stations used in this study) and must be ordered from a suitable supplier. In the absence of a BGT sensor, the BGT can be inferred from measurements of T_A and solar radiation (SR; W/m^2).

The equation for calculating BGT from T_A and SR is:

$BGT = 1.33 \times T_A - 2.65 \times Sqrt(T_A) + 3.21 \times \log(SR + 1) + 3.5$, where: log is the logarithm (base 10) function and Sqrt is the square root function.

$HLI_{LO} = 1.3 \times BGT + 0.28 \times RH - WS + 10.66$, and $HLI_{HI} = 1.55 \times BGT + 0.38 \times RH - 0.5 \times WS + \exp(2.4 - WS) + 8.62$: where: *exp* is the exponentiation function and the HLI value was taken as either HLI_{HI} ($BGT \geq 25$ °C) or HLI_{LO} ($BGT < 25$ °C) depending on the BGT value.

A blending function (S(BGT)) – was used to produce a smooth transition in HLI values calculated using the two different equations. The blending function is: $SBGT = 1 / (1 + \exp(-(BGT - 25) / 2.25))$. Using this blending function, a value of the HLI is calculated as follows:

$HLI = SBGT \times HLI_{HI} + (1 - S(BGT)) \times HLI_{LO}$

3.1.7.2 Accumulated Heat Load Unit Calculation

The Accumulated Heat Load Unit (AHLU) represents the amount of heat accumulated in cattle over a period of time. For this study AHLU were calculated from 1 December 2017 to mid-April 2018 (the actual end date varied between feedlots). The rate of accumulation depends on the current HLI value and the thresholds used. Large HLI values result in a more rapid increase in AHLU, conversely, low HLI values result in a decrease of the AHLU (i.e. the cattle cool down and recover). The thresholds are determined based on: breed type, access to shade, and days on feed (see Gaughan et al. 2008 for details). Whether cattle recover or become heat stressed depends on the value of the thresholds.

The ***base threshold*** occurs at a HLI value of 86 (base AHLU). This threshold is based on a healthy Black Angus steer, 80 days on feed without access to shade. For each breed type used in the study a different HLI threshold was used to calculate the AHLU for that breed type for any given period of time. Firstly a threshold value of +5 was added to each breed type because they had access to shade (86 from the base threshold + 5) (NB: each feedlot had a shade area of 2 to 3 m^2/animal: where no shade was provided in some pens i.e. Feedlot 1, then no adjustments were made for those pens), and then the breed type (BT) adjuster (see Gaughan et al 2008) was added. Thus for BT1 the threshold was 91 (no breed adjustment just shade), for BT2 the upper threshold was 94, for BT3 it was 95, for BT4 it was 98 and for BT5 it was 101. The lower threshold remained at 77 for all breed types. The subsequent AHLUs (AHL_{ADJ}) were then used to evaluate the efficacy of the AHLU to predict PS and DMI.

In the current study the HLI and AHLU were calculated from 10 minute data from the on-site weather stations. The BGT, WS and RH for the two stations were combined and averaged for each 10 min interval and these data were then used to calculate the HLI and AHLU.

3.1.8 Statistical Analysis

Weather data: The relationships between the climatic parameters on the two weather stations located at each feedlot were determined using regression analysis (PROC REG; SAS). Linear and quadratic relationships were evaluated. As there were no quadratic relationships only the linear responses are presented. The climate parameters: ambient temperature, black globe temperature, relative humidity, solar radiation (day light only) and wind speed were assessed. The heat load assessment indices HLI (between weather stations), the AHLU (two data sets were examined – 24 h daily means and daily means for times when AHLU>0), and the THI (between weather stations and in situ pen loggers) were also assessed. Similar analysis was undertaken to determine the relationships between the measured black globe temperature and calculated black globe temperature. Additionally as the black globe temperature is considered to be correct, then a regression of residuals (observed minus predict black globe) on mean centred predicted black globe temperature was undertaken to determine if there was mean or linear bias associated with the black globe temperature prediction. Studentized t-tests were undertake to determine if differences existed between the means of the various weather variables at each feedlot from each weather station. Significance was taken as $P<0.05$

Modelling panting score: Panting score was categorised as a binary outcome variable:

- 0 = normal (original panting score values of 0 or 1)
- 1 = abnormal (original panting score values of 2 or greater)

A mixed effects logistic regression was then used to analyse data with binary panting score as the outcome. Nested random effects were incorporated into all models coding for pen nested within feedlot. This ensured appropriate adjustment for lack of statistical independence associated with individual measurements being clustered within pens and feedlots.

Predictors were then added as fixed effects. These included climatic variables (relative humidity, ambient temperature, black globe temperature, wind speed, solar radiation) and their standardized values with [(x-mean(x))/SD(x)], breed type (BT1: 100% % Bos taurus (English), BT2: 100% % Bos taurus (European); BT3: 25% Bos indicus; BT4: 50% Bos indicus and BT5: 100% Bos indicus), sex (heifers, mixed and steers) and period (Period 1 = 0600 – 0959 h; Period 2 = 1000 – 1359 h; Period 3 = 1400 – 1759 h period 4 >= 1800 h) as well as categorized HLI and AHLU values.

The categorised HLI values were thermoneutral (TNC), moderate hot, very hot and extreme. The AHLU values were TNC, mild, moderate, hot and extreme (Table 1).

Table 1. Coding used to represent HLI and AHLU categories

HLI	HLI Categories	Variable Name	AHL	AHLU Categories	Variable Name
< 70	TNC	HLIcat	< 1	TNC	AHLcat
70 – 77	Moderate		1 – 10	Mild	
77 – 86	Hot		10 – 20	Moderate	
86 – 96	Very Hot		20 – 50	Hot	
> 96	Extreme		> 50	Extreme	

Preliminary bivariable screening was performed using the same outcome, and screening each predictor one at a time. Screening was used to selected predictors for entry into the initial multivariable model if the predictor was associated with a screening *P<0.2*. All of the predictors met the screening criteria and therefore all candidate predictors were considered in the multivariable models.

Three separate multivariable models were run. First, separate models were run with single fixed effects – adjusted AHLU (AHL_{ADJ}) and then breed type. The third model contained the two fixed effects in the one final model – adjusted AHLU and breed type.

HLI and AHLU variables (AHL_{ADJ}) were added to models as continuous predictors. Initial model checking for linearity in the logit for continuous variables confirmed that a linear fit was reasonable. Model diagnostics for normality of the random effects were performed using QQ plot and density plots. Model fit was checked by plotting the residuals against the fitted probabilities.

Linear regression approach for modelling panting score: Multivariable linear regression was also run with the actual panting score as a continuous outcome variable and HLI, AHL, Breed Type, Sex, and Period as potential predictors.

Modelling dry matter intake (DMI) and energy intake: dry matter intake (DMI), energy intake, HLI, AHL, and DOF data were measured at pen levels for each observation day. Each measurements represents daily level DMI, energy intake, HLI, AHLU and DOF at pen level for randomly selected days (a per head per day basis). To quantify the relationship between DMI and energy intake outcomes, and the daily HLI, AHLU and DOF measurements taken for that specific randomly selected days. Separate multivariable linear models were run with DMI and energy intake as the outcome of interest. For each model outcome, the model was repeated with AHLU presented as a continuous variable and then with AHL presented as a categorical variable.

Modelling mortality and morbidity: There was insufficient data to statistically analysis these parameters.

Statistical packages: All analyses (apart from the weather station and related data which used SAS) were performed using the R software version 3.4.2 and the lme4 R package for fitting the mixed effects logistic regression.

4 Results

4.1 Site visits

At each site baseline (non-heatwave conditions) data (the same data as collected during heat waves) was collected. The number of total site visits was determined by the occurrence of heat wave events. Including the visit to collect baseline data, there were four visits to Feedlot 1, five to Feedlot 2, five to Feedlot 3, three to Feedlot 4, four to Feedlot 5 and six to Feedlot 6. Each visit was for a duration of 4 days (except there was one three day visit at Feedlot 5 due to storms), and data was collected 4 times each day as outline in the Materials and Methods. In total data was collected over 120 days. Animal data was collected from 34 pens at Feedlot 1, 18 at Feedlot 2, 34 at Feedlot 3, 20 at Feedlot 4, 23 at Feedlot 5 and 14 from Feedlot 6. The number of pens used was due to cattle movements (e.g. cattle sold, and new pens enrolled). Climatic data was collected continuously from 1 December 2017 to 30 April 2018.

4.2 Water trough temperature

There was a 10% failure rate with the HOBO Pendant loggers so a full data set of water temperature was not obtained at all feedlots. However there were still in excess of 13,000 data points per feedlot. Water trough temperature across the six feedlots ranged from 8.6 to 40.8 ^{o}C (Table 2). Water trough temperatures rarely exceed 30 ^{o}C, and when this occurred it was for a limited amount of time. For most of the time water temperature was between 20 and 30 ^{o}C, which has a 0 effect on the HLI upper threshold.

Table 2. Water temperature (^{o}C) in water troughs at the six feedlots used in the study

	1	2	3	4	5	6
Mean	23.13 ± 0.02	26.11 ± 0.02	26.70 ± 0.02	22.97 ± 0.02	25.07 ± 0.02	27.37 ± 0.02
Range	8.59 – 33.09	16.88 – 33.46	17.36 – 36.03	14.44 – 40.83	17.34 – 32.41	16.01 – 32.79

4.3 Pen floor moisture

Over the duration of the study there was little rainfall so for the most part pens mostly had a moisture content ≤ 40% (Table 3). One yard had a maximum of 92.3 % pen floor moisture content following a rain event. All yards were feedlot class 1 for manure management and pens were in good repair.

Table 3. Pen floor moisture (%) at the six feedlots used in the study

	1	2	3	4	5	6
Mean	24.53 ± 0.13	16.81 ± 1.02	21.13 ± 0.01	28.91 ± 0.01	26.93 ± 0.01	16.56 ± 0.02
Range	2.10 – 42.67	1.30 – 37.71	1.00 – 35.20	5.90 – 40.40	10.00 – 92.30	1.00 – 37.01

4.4 Weather conditions

The 2017/2018 summer was moderate to normal with only a few heat wave events. A summary of the monthly weather data for each feedlot is presented in Appendix 1.

Weather stations

Siting of the weather stations was undertaken to ensure (i) that one was in close proximity to the feedlot pens (within 10 m of pens), and (ii) that the other was located within 50 m of the feedlot office (ranged from approximately 30 m to 75 m). Distances between office and pen weather stations varied from 250 m to 650 m.

Feedlot 1: The weather stations were approximately 300 m apart. This feedlot is characterised by being on a ridge (172 m in altitude) with pens running from the top of the ridge (east) down the slope towards the west. There is approximately 21 m difference in altitude from the top pen to the lower pens. The laneways (approximately 800 m in length) run down the slope with pens running horizontally off the lanes. The office station was located on the top of a ridge and the pen station at the base of the ridge. The stations were in sight of each other however the pen station was approximately 21 m lower in altitude.
Feedlot 2: This feedlot is characterised as having a relatively flat terrain, with a 7 m fall from the northern end to the southern end of the feedlot. Pens are uniform across the feedlot, and had all had north-south orientation. The laneways were approximately 800 m long. The weather stations were located approximately 750 m apart.

***Feedlot 3*:** This feedlot is characterised as having a flat terrain. Pens are uniform across the feedlot. The weather stations were located approximately 650 m apart.
Feedlot 4: The feedlot is located on a hill. Pens were located on the top of the hill and on the northern and eastern side (basically following contour lines) of the hill. There was considerable variation in pen sizes and orientation. The weather stations were located approximately 550 m apart. The office station was located on the top of the hill. The pen station was out of site of the office station and was approximately 11 m lower in altitude and was located on the north-eastern slope.
Feedlot 5: This feedlot was located on an elevated area that sloped towards the north. The weather stations were located approximately 400 m apart. The office station was on top of the rise, whereas the pen station was located approximately 4 m lower in altitude.
Feedlot 6: The feedlot was on a ridge with pens predominantly on a north-south orientation (sloping towards the south). The laneways varied from approximately 440 m in length to 720 m in length. The distance between the office and pen stations was approximately 400 m. The office station was approximately 13 m higher in altitude than the pen station. The pen area of the feedlot was relatively flat and pens were uniform. The pen weather station was shaded approximately 10 min earlier in the afternoon than the office weather station.

Overall the weather stations and associated software worked to expectations. There was a solar radiation sensor failure at Feedlot 4. While this did not impact on the calculations of the HLI and AHLU it did result in fewer data for the comparison between the measure black globe and the calculated black globe. The transmission of the weather data from feedlots to the web based software and the subsequent use in monitoring feedlots real time worked very well. Weather data for each site was downloaded weekly (as a backup) and also monthly. The monthly data was used in the statistical analysis.

4.4.1 Relationship between weather stations

There were strong correlations (*$P<0.0001$*; $R^2>0.80$) between the weather stations (at four of the feedlots 1, 3, 5 and 6) for ambient temperature, black globe temperature, relative humidity, HLI, AHL, and the THI. There were moderate relationships for wind speed (*$P<0.0001$*; $R^2<0.77$). The regression equations and P-values for the measured weather parameters are presented below (Tables 4 to 7). In addition some graphical representations for Feedlot 6 are presented (Figures 1 and 2).

Table 4. The linear regressions and correlations between the T_A from the two weather stations located at each feedlot used in the study

Feedlot	Regression Equation	R^2	P-value
1	$T_A1 = 0.9651 \times T_A2 – 1.0136$	0.9774	<0.0001
2	$T_A1 = 0.9546 \times T_A2 + 1.1617$	0.8071	<0.0001
3	$T_A1 = 0.9606 \times T_A2 + 1.1167$	0.9740	<0.0001
4	$T_A1 = 0.2310 \times T_A2 + 19.6920$	0.0527	<0.0001
5	$T_A1 = 0.9781 \times T_A2 + 0.5343$	0.9917	<0.0001
6	$T_A1 = 0.9819 \times T_A2 + 0.1971$	0.9848	<0.0001

T_A1 = obtained from weather station 1 (office), T_A2 = obtained from weather station 2 (pen)

Table 5. The linear regressions and correlations between the BG from the two weather stations located at each feedlot used in the study

Feedlot	Regression Equation	R^2	P-value
1	BG1 = 0.9750 × BG2 + 1.1314	0.9853	<0.0001
2	BG1 = 0.9419 × BG2 + 1.3609	0.8778	<0.0001
3	BG1 = 0.9432 × BG2 + 1.4668	0.9261	<0.0001
4	BG1 = 0.0296 × BG2 + 27.0750	0.0008	<0.0001
5	BG1 = 0.9907 × BG2 + 0.4411	0.9826	<0.0001
6	BG1 = 0.9814 × BG2 + 0.5141	0.9683	<0.0001

BG1 = obtained from weather station 1 (office), BG2 = obtained from weather station 2 (pen)

Table 6. The linear regressions and correlations between the RH from the two weather stations located at each feedlot used in the study

Feedlot	Regression Equation	R^2	P-value
1	RH1 = 0.9743 × RH2 - 1. 3691	0.9675	<0.0001
2	RH1 = 0.7874 × RH2 + 4.9338	0.6545	<0.0001
3	RH1 = 0.9482 × RH2 + 6.0906	0.9603	<0.0001
4	RH1 = 0.3199 × RH2 + 35.415	0.1051	<0.0001
5	RH1 = 0.9901 × RH2 + 0.3582	0.9947	<0.0001
6	RH1 = 0.9875 × RH2 - 0.4902	0.9862	<0.0001

RH1 = obtained from weather station 1 (office), RH2 = obtained from weather station 2 (pen)

Table 7. The linear regressions and correlations between the WS from the two weather stations located at each feedlot used in the study

Feedlot	Regression Equation	R^2	P-value
1	WS1 = 0.7752 × WS2 - 0.3642	0.7724	<0.0001
2	WS1 = 0.9320 × WS2 + 0.6638	0.5018	<0.0001
3	WS1 = 0.9098 × WS2 + 0.3350	0.7670	<0.0001
4	WS1 = 0.1512 × WS2 + 1.4040	0.0337	<0.0001
5	WS1 = 0.7626 × WS2 + 0.3329	0.7508	<0.0001
6	WS1 = 0.8913 × WS2 + 0.2978	0.7556	<0.0001

WS1 = obtained from weather station 1 (office), WS2 = obtained from weather station 2 (pen)

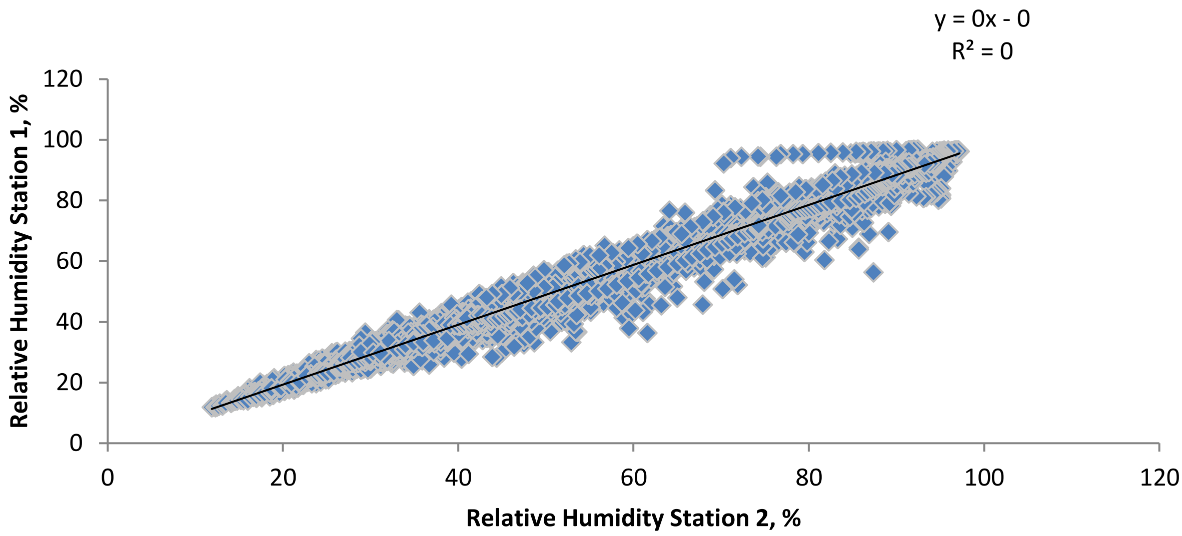


Figure 1. The linear relationship for relative humidity (RH) between the two weather stations (1 = office location and 2 = pen location) at Feedlot 6.

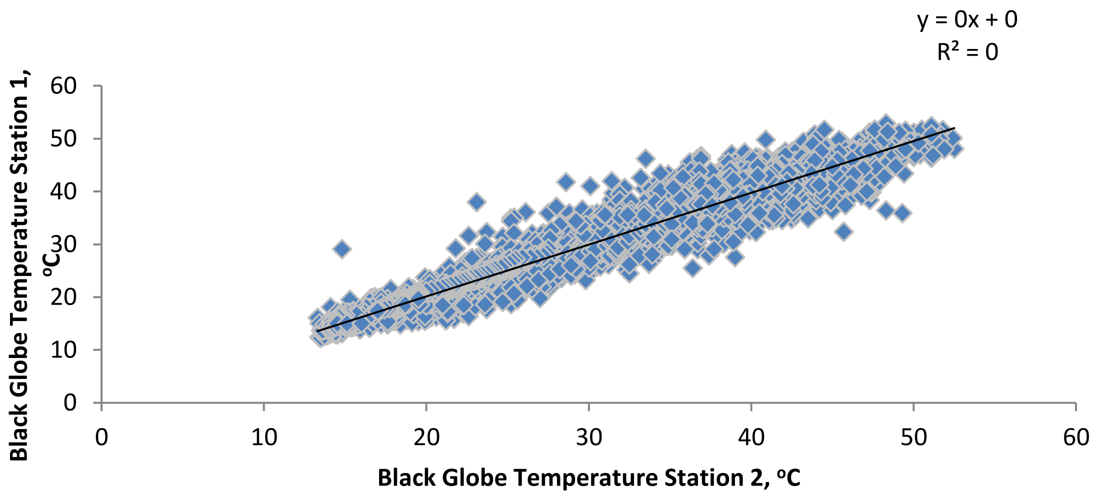


Figure 2. The linear relationship for black globe temperature (BG) between the two weather stations at Feedlot 6.

Linear regressions, R^2 for HLI and AHLU for each feedlot are presented in Tables 8 and 9 respectively. Figures 3 and 4 show a graphical representation of HLI and AHLU for Feedlot 6. Across all feedlots there were differences (*P<0.0001*) between weather stations for HLI and AHLU (with the exception of feedlot 1 for HLI).

Table 8. The linear regressions and correlations between the HLI calculated from the two weather stations located at each feedlot used in the study

Feedlot	Regression Equation	R^2	P-value
1	HLI1 = 0.9902 × HLI2 + 0.7012	0.9796	<0.0001
2	HLI1 = 0.8934 × HLI2 + 4.3071	0.8303	<0.0001
3	HLI1 = 0.9565 × HLI2 + 3.8450	0.9525	<0.0001
4	HLI1 = 0.0868 × HLI2 + 61.859	0.0062	<0.0001
5	HLI1 = 0.9916 × HLI2 + 1.1460	0.9683	<0.0001
6	HLI1 = 0.9739 × HLI2 + 1.3723	0.9542	<0.0001

HLI1 = calculated HLI from weather station 1 (office), HLI2 = calculated HLI from weather station 2 (pen)

Table 9. The linear regressions and correlations between the AHLU calculated from the two weather stations located at each feedlot used in the study

Feedlot	Regression Equation	R^2	P-value
1	AHLU1 = 1.1150 × AHLU2 + 0.4148	0.8336	<0.0001
2	AHLU1 = 0.3008 × AHLU2 + 0.6795	0.2208	<0.0001
3	AHLU1 = 1.1669 × AHLU2 + 0.3102	0.9493	<0.0001
4	AHLU1 = 0.4160 × AHLU2 + 6.2580	0.0648	<0.0001
5	AHLU1 = 1.1034 × AHLU2 + 0.6354	0.9247	<0.0001
6	AHLU1 = 0.7923 × AHLU2 + 0.0530	0.9460	<0.0001

AHLU1 = calculated AHLU from weather station 1 (office), AHLU2 = calculated AHLU from weather station 2 (pen)

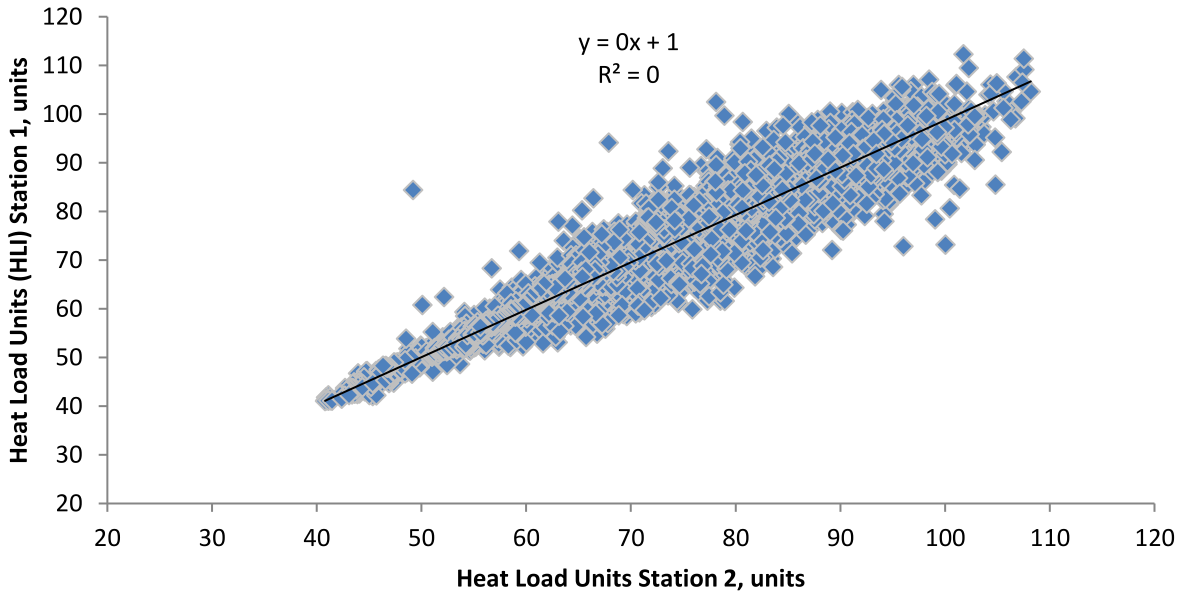


Figure 3. The linear relationship for the heat load index (HLI) between the two weather stations at Feedlot 6.

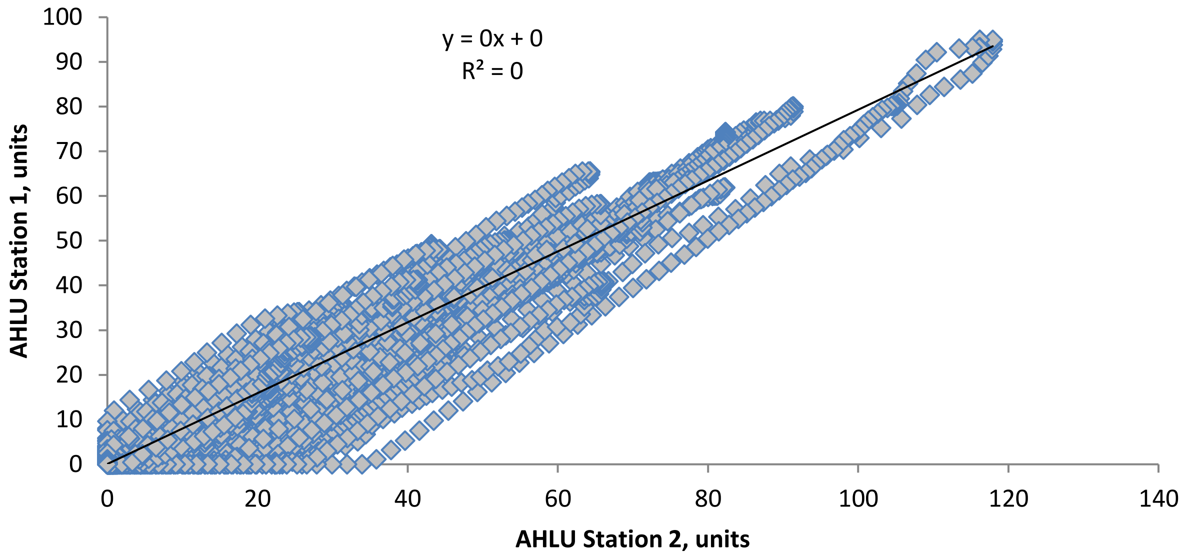


Figure 4. The linear relationship for accumulated heat load units (AHLU) between the two weather stations at Feedlot 6.

The regression analysis shows that there is precision between the two weather stations on each site and the measured parameters. However there were numerous statistical differences (T-test) for the measured weather parameters and the calculated HLI and AHLU between the office weather station and the pen weather station (Table 10). There were no differences (*P>0.05*) between the TA obtained from the two weather stations at four of the feedlots. At five of the feedlots WS differed (*P<0.001*) between the two weather stations, and there was trend (*P=0.0978*) for a difference at the remaining feedlot. The AHLU differed (*P<0.001*) between each weather station (at each site). These data suggest that the siting of the weather station is important as the siting will influence the HLI and AHLU.

Table 10. Means (±SE) for black globe temperature (BG), ambient temperature (T_A), relative humidity (RH), solar radiation (SR) calculated for daylight hours (SR>1), wind speed (WS), heat load index (HLI), accumulated heat load for the duration of the study ($AHLU^1$) and accumulated heat load for times when accumulated heat load was >0 ($AHLU^2$) for weather stations located at office and pens across six feedlots (1 to 6)

	1	2	3	4	5	6
BG, °C						
Office	26.87 ± 1.16	28.11 ± 3.30	30.23 ± 1.76	27.90 ± 1.76	29.10 ± 1.19	28.99 ± 1.52
Pen	26.39 ± 1.16	28.40 ± 3.30	30.46 ± 1.76	27.75 ± 1.76	28.93 ± 1.19	29.02 ± 1.52
P-value	<0.001	0.0042	0.0181	0.1200	0.0778	0.7812
T_A, °C						
Office	23.88 ± 0.96	25.64 ± 2.91	27.84 ± 0.94	25.59 ± 5.78	25.83 ± 0.49	25.92 ± 0.63
Pen	23.69 ± 0.96	25.64 ± 2.91	27.83 ± 0.94	25.57 ± 5.78	25.86 ± 0.49	26.21 ± 0.63
P-value	0.0073	0.9704	0.7602	0.6178	0.5972	<0.001
RH, %						
Office	50.03 ± 3.31	42.66 ± 11.02	45.34 ± 3.55	52.13 ± 18.74	57.51 ± 1.51	59.48 ± 2.44
Pen	52.75 ± 3.31	47.91 ± 11.02	41.39 ± 3.55	52.24 ± 18.74	57.72 ± 1.51	60.73 ± 2.44
P-value	<0.001	<0.001	<0.001	0.5905	0.3396	<0.001
SR*, W/m²						
Office	472.82 ± 3.54	488.36 ± 3.35	447.57 ± 2.83	504.51 ± 4.62	469.54 ± 3.45	362.67 ± 2.82
Pen	509.51 ± 3.54	470.58 ± 3.35	446.15 ± 2.83	497.46 ± 4.62	432.12 ± 3.45	324.46 ± 2.82
P-value	<0.001	<0.001	0.7326	0.2819	<0.001	<0.001
WS, m/s						
Office	1.97 ± 0.52	2.72 ± 1.14	2.91 ± 0.81	1.74 ± 1.04	2.12 ± 0.55	2.57 ± 0.55
Pen	2.07 ± 0.52	2.21 ± 1.14	2.80 ± 0.81	2.24 ± 1.04	2.35 ± 0.55	2.55 ± 0.55
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	0.0978
HLI						
Office	64.71 ± 2.04	63.74 ± 5.68	68.64 ± 3.00	67.64 ± 14.13	71.02 ± 0.58	70.94 ± 2.71
Pen	64.64 ± 2.04	66.53 ± 5.68	67.69 ± 3.00	66.59 ± 14.13	70.47 ± 0.58	71.43 ± 2.71
P-value	0.6654	<0.001	<0.001	<0.001	<0.001	<0.001
$AHLU^1$						
Office	2.52 ± 3.41	1.64 ± 5.30	3.29 ± 1.76	8.06 ± 19.33	7.29 ± 4.05	6.83 ± 3.35
Pen	1.89 ± 3.41	3.20 ± 5.30	2.53 ± 1.76	4.34 ± 19.33	6.03 ± 4.05	8.54 ± 3.35
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
$AHLU^2$						
Office	12.45 ± 0.23	10.19 ± 0.22	13.39 ± 0.17	25.47 ± 0.35	20.26 ± 0.22	19.04 ± 0.24
Pen	9.34 ± 0.23	19.23 ± 0.22	10.22 ± 0.17	18.68 ± 0.35	16.78 ± 0.22	23.84 ± 0.24
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

*SR daylight hours only; $AHLU^1$ = mean AHLU for duration of study; $AHLU^2$ = mean AHLU for times when AHLU>0. AHLU is the base accumulated heat load derived from when the upper threshold is HLI=86.

The calculation of HLI (and subsequently AHLU) is strongly influenced by wind speed, especially when BG>25 °C. It is not surprising therefore that differences for HLI and AHLU exist between weather stations at a feedlot. The location of the weather stations influenced AHLU for all feedlots and more so for Feedlots 2 and 4. At feedlot 2 the highest AHLU was at the pen weather station, and at feedlot 4 the highest AHLU was obtained at the office weather station (Figure 5 and Figure 6). Feedlot 4 had an undulating layout. The pen weather station was located approximately 11 m lower (in altitude) than the office station which was located in an open area near the top of a hill. However, wind speed was greater (*P<0.001*) at the pen location than the office location (2.24 ± 1.04 m/s vs 1.74 ± 1.04 m/s respectively). Whereas at Feedlot 6 (flat terrain) there were no differences (*P=0.0978*) in wind speed between the weather station located at the office and the pens (2.57 ± 0.55 m/s vs 2.55 ± 0.55 m/s respectively) (Figure 7).

It is clear that location of the weather station will influence the HLI and the AHLU. Location of stations may explain some of the variation seen between feedlots in terms of the differences seen with the predicted HLI/AHLU (e.g. from Katestone) and site obtained AHLU. A 60 unit difference at Feedlot 2 on 06/01/18 (Figure 5) demonstrates the importance of site selection. Whereas the office weather station is returning to 0 AHLU each night the pen station AHLU remains above 0 for a couple of days (no night time relief) between the 6 and 10th January. An underestimation or overestimation of AHLU at the animal level is obviously problematic. In the given example it is not easy to determine which station is the more accurate in modelling AHLU. However in general it is assumed that the station located closest to the cattle more accurately represents the conditions to which the animals are exposed.

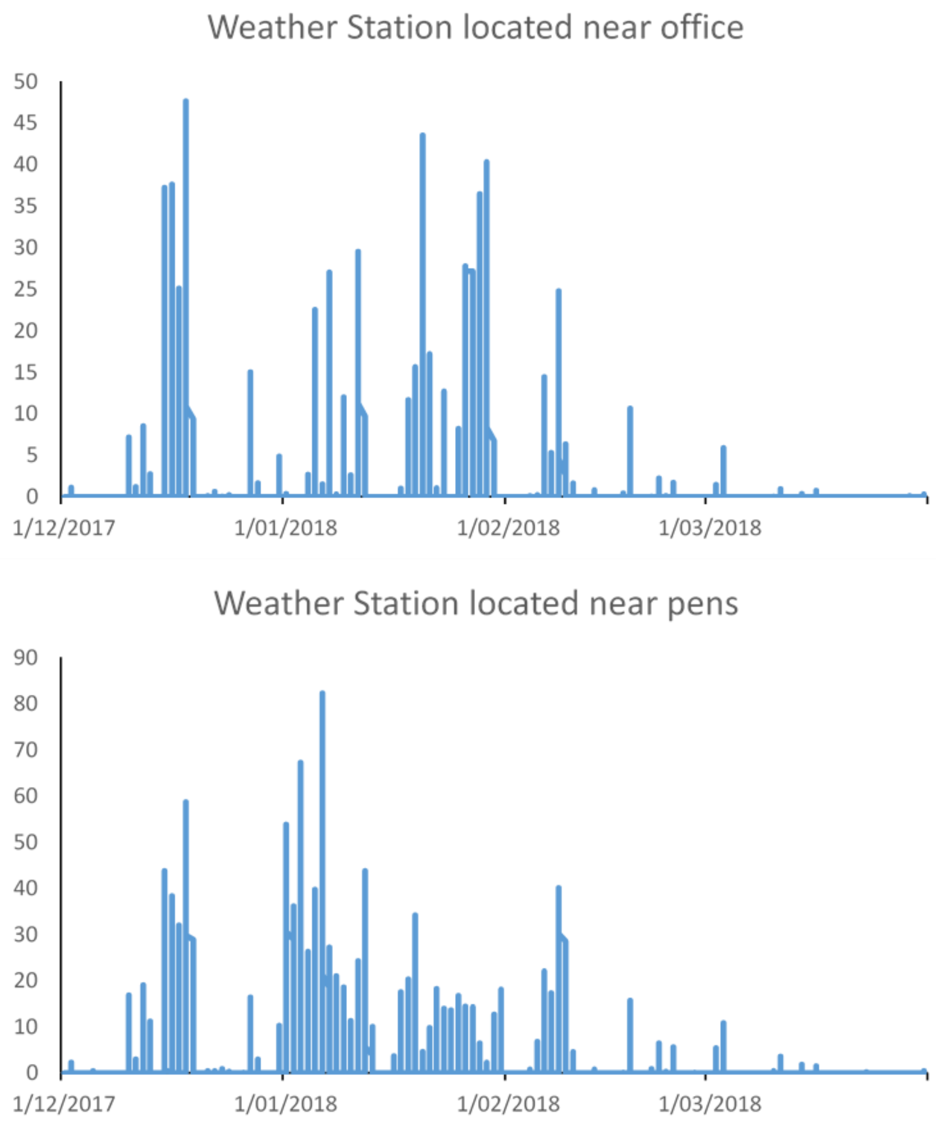
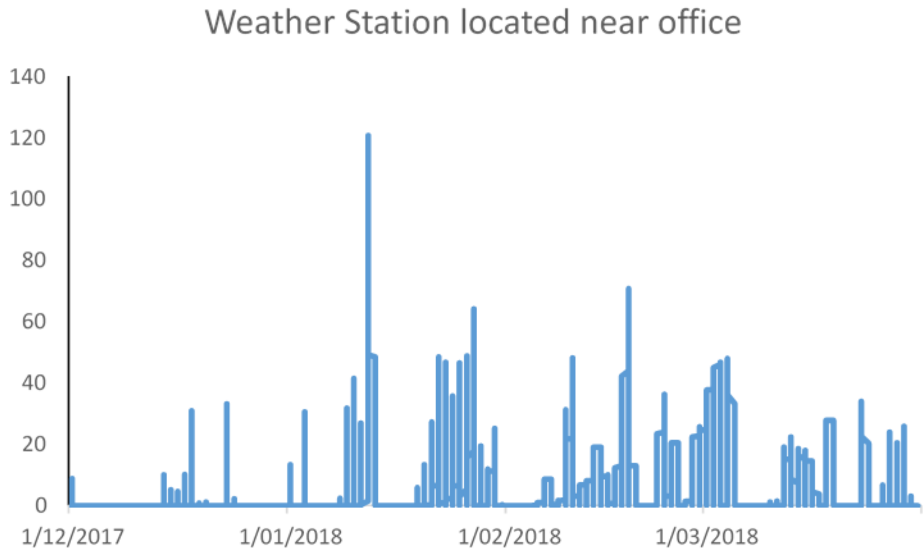


Figure 5. The AHLU (y-axis) for the two weather stations at Feedlot 2.



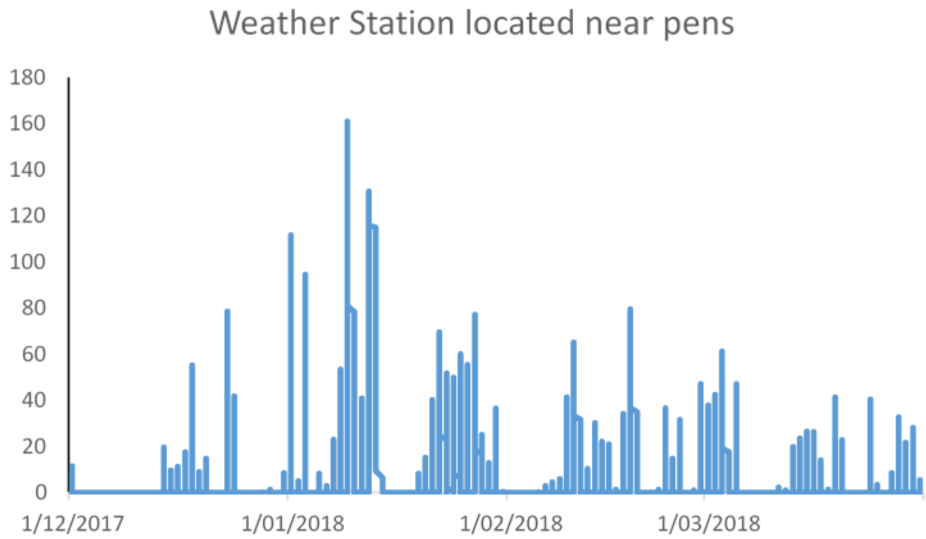
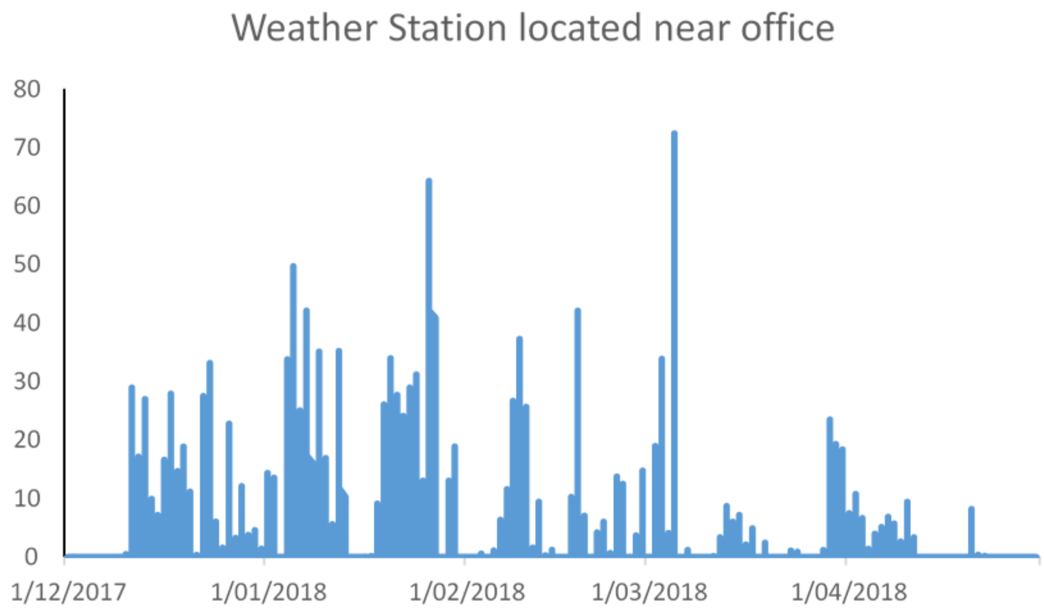


Figure 6. The AHLU (y-axis) for the two weather stations at Feedlot 4.



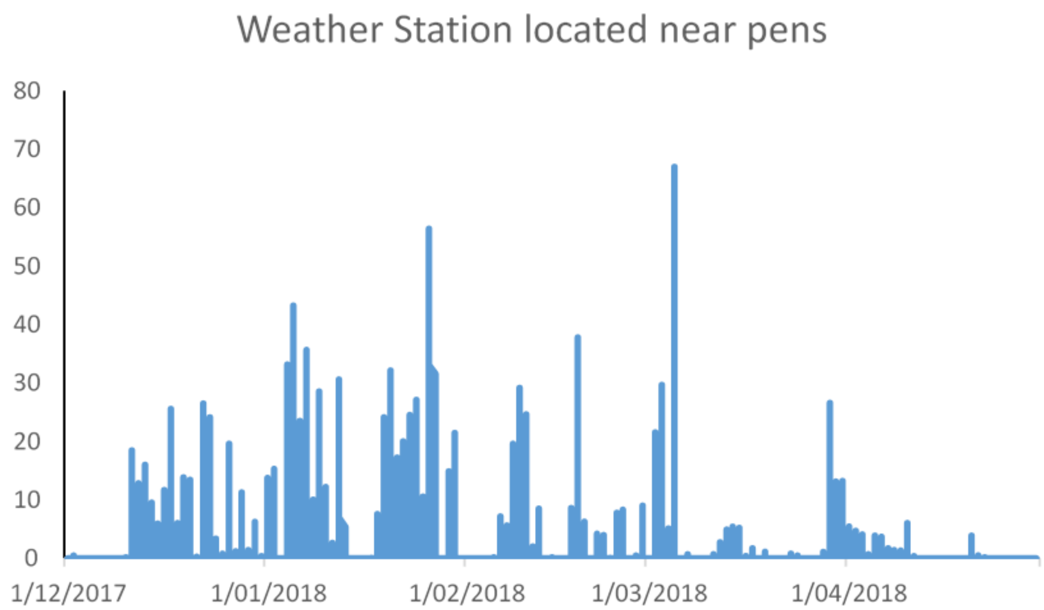


Figure 7. The AHLU (y-axis) from the two weather stations at Feedlot 6.

4.4.2 Relationship between measured black globe temperature (BG) and calculated BG

There was a strong correlations (*$P<0.001$; $R^2 >0.94$*) between the measured BG from the weather stations at each feedlot and the calculated BG (calculated using SR and T_A for each weather station) (Table 11). Approximately 17,400 data points were used for each regression calculation.

Table 11. The linear regressions and correlations between the measured black globe temperature (BG) and calculated BG (BGC) for the 6 feedlots used in the study

Feedlot	Regression Equation	R^2	P-value
1	BG = 0.9686 × BGC + 0.4195	0.9615	<0.0001
2	BG = 0.9697 × BGC + 1.0244	0.9626	<0.0001
3	BG = 0.9458 × BGC + 0.9029	0.9665	<0.0001
4*	BG = 1.0260 × BGC – 0.5307	0.9497	<0.0001
5	BG = 0.9973 × BGC + 0.2684	0.9575	<0.0001
6	BG = 0.9947 × BGC + 0.2718	0.9503	<0.0001

*Based on less data than the other feedlots due to a SR sensor malfunction

Assuming that the data from the black globe on the weather stations is correct then the BG from the weather stations (observed BG) was compared against the calculated BG (predicted). The results of the regressions of observed black globe temperature on calculated black globe temperature are summarised in Table 12. Mean data is presented in Table 13. A plot of the observed BG minus the calculated BG vs men centred calculated BG is presented in Figure 8. The results for two feedlots (Feedlots 2 and 3) are presented graphically in Figures 9 and 10. At all feedlots the equations had significant mean bias (*P<0.001*), and four had significant linear bias (*P<0.001*). Four of the feedlots had negative mean bias which indicates an over prediction of BG. Systematic bias was low across all feedlots. The negative mean bias although small indicate an over prediction of the mean black globe temperature. On face value the under/over predictions are probably of limited biological importance. However small difference can accumulated this will examined further below.

Table 12. Statistics from regression of the BG obtained from the weather station sensor and the calculated BG

Feedlot	1	2	3	4	5	6
Mean bias, °C	-0.03	-0.06	-0.06	0.03	-0.003	-0.01
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	0.0023
Linear bias, °C	-0.42	-0.72	-0.72	0.20	0.19	0.12
P-value	<0.001	<0.001	<0.001	<0.001	0.0849	<0.001
r^2	0.03	0.10	0.09	0.01	0.0	0.00
RMSE, °C	1.97	2.06	1.88	2.22	1.87	1.90
MSPE, °C	3.88	4.23	3.52	4.94	3.49	3.63
MAE, °C	1.45	1.52	1.40	1.64	1.42	1.42
Mean proportional bias	1.01	1.03	1.02	0.98	0.99	0.96
Decomposition of MSPE						
Mean bias, %	4.57	12.09	14.38	0.83	1.03	0.40
Systemic bias, %	2.44	8.43	7.41	1.20	0.02	0.05
Random bias, %	92.99	79.48	78.21	97.97	98.96	99.55
Bias at maximum predicted value, °C	-1.22	-2.30	-1.93	0.75	0.13	0.01
Bias at minimum predicted value, °C	0.26	0.59	0.49	-0.25	0.24	0.21

RSME = root mean square; MSPE = mean square prediction error; MAE = mean absolute error.

Table 13. The mean observed and calculated black globe temperature (BG) for the 6 feedlots used in the study

	1	2	3	4	5	6
BG, °C						
Observed	26.40	28.11	29.09	28.22	29.01	28.99
Calculated	26.82	28.83	29.80	28.02	28.82	28.87
SE	1.89	1.83	1.66	2.20	1.86	1.89
P[1]-value	<0.0001	<0.0001	<0.0001	0.9364	0.0479	0.1843

[1]P-value from two tail T-Test, comparing means of BG-observed and BG-calculated

Approximate prediction intervals were calculated for each site. And these ranged from ± 3.25 °C (Feedlot 3) to ± 7.34 °C (Feedlot 6). The values for Feedlots 1, 2, 4 and 5 were ± 3.72, ± 3.59, ± 4.31 and ± 3.60 °C respectively. This is further evidence of the probable inadequacy of the calculated BG.

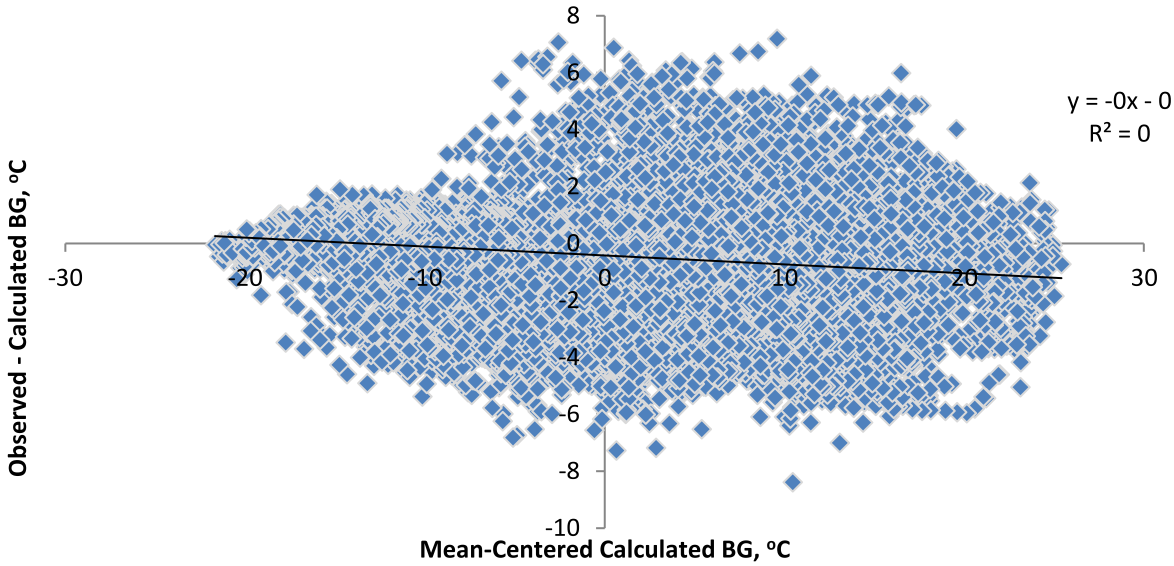


Figure 8. Plot of observed minus calculated BG vs. mean-centered calculated BG for Feedlot 1.

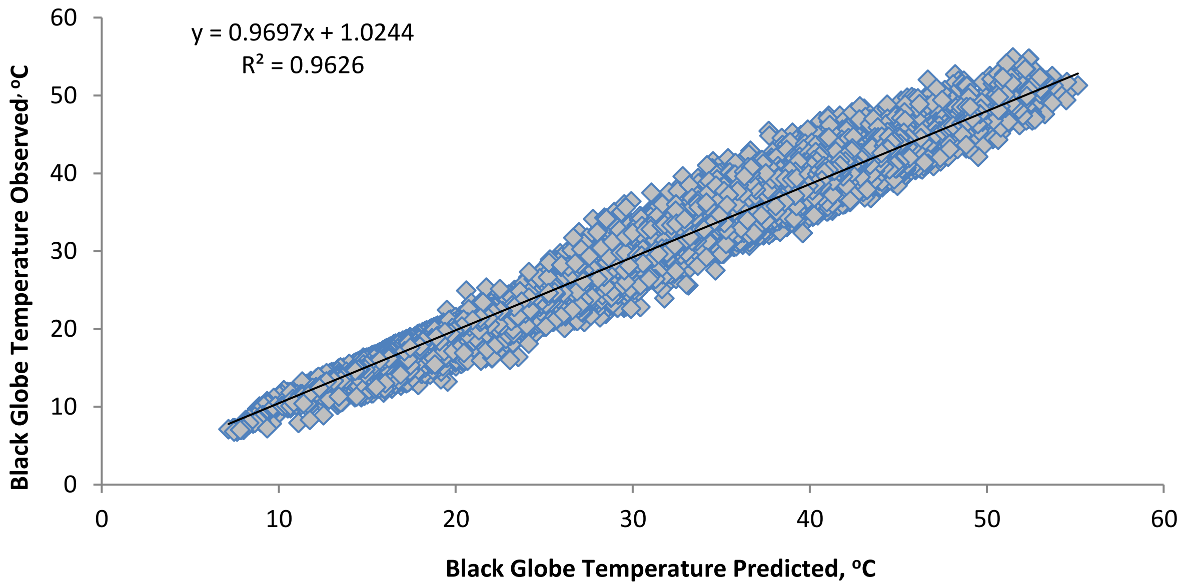


Figure 9. The relationship between the measured black globe temperature and the calculated black globe temperature at Feedlot 2.

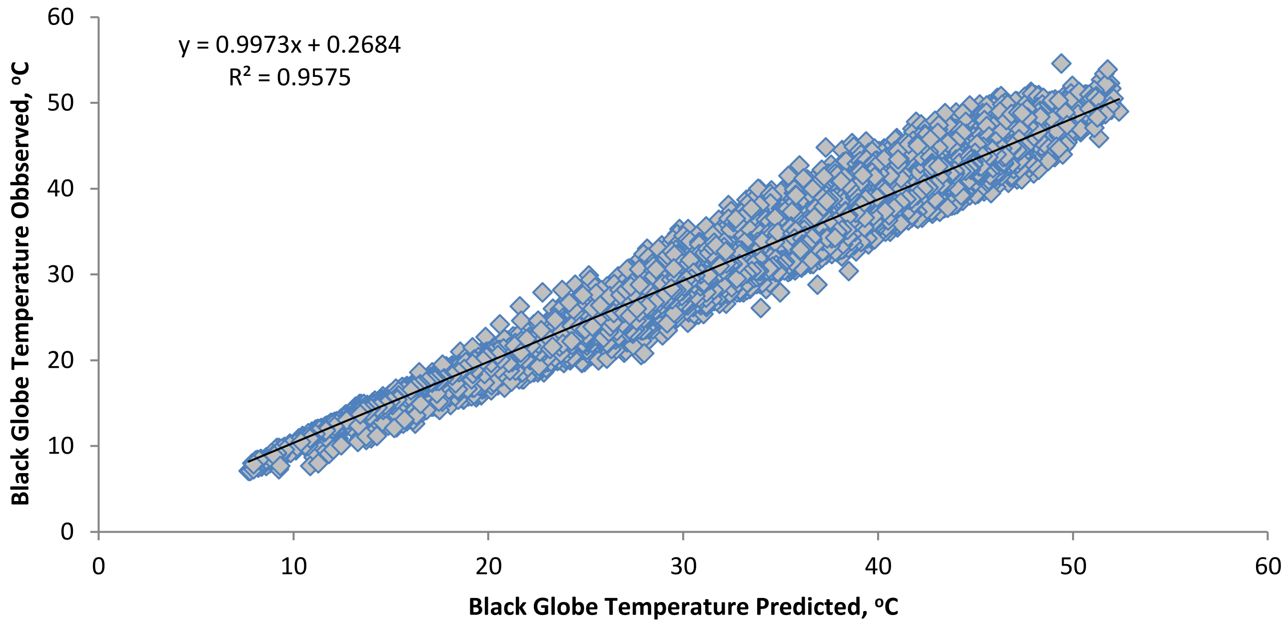


Figure 10. The relationship between the measured black globe temperature and the calculated black globe temperature at Feedlot 3.

4.4.3 How is AHLU affected by the calculated black globe?

There were differences (*P<0.001*) between the mean AHLU determined from the black globe sensor located on the weather stations and the AHLU determined from the calculated black globe (BG Calc) (Table 14). At four of the feedlots the AHLU obtained using BG Calc were lower than that obtained from the black globe sensor temperature. The differences between the maximum AHLU determined from the black globe sensor and the calculated black globe for feedlots 4, 5 and 6 were large. The largest disparity was at feedlot 4 (130.62 vs 74.57 units) for the sensor and calculated respectively. At feedlot 5 the values where 91.68 vs 66.52 units, and 94.93 vs 70.82 units for feedlot 6. Assuming that the black globe sensor is correct the underestimation of AHLU when using the calculated black globe at these feedlots would be of concern.

Table 14. The mean accumulated heat load for all data collected during the study (AHLU[1]) and the mean AHLU (AHLU[2]) when AHLU>0 for the six feedlots used in the study

	1	2	3	4	5	6
AHLU[1]						
WS BG[A]	2.52	1.64	2.73	8.21	7.29	6.83
BG Calc[B]	1.88	1.99	3.37	2.78	3.59	3.59
SE	3.73	4.01	5.18	7.21	8.48	7.53
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
AHLU[2]						
WS BG	17.22	10.94	12.25	31.84	24.15	24.93
BG Calc	13.16	13.29	15.14	11.21	12.10	13.44
SE	0.30	0.27	0.19	0.36	0.22	0.24
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

AHLU[1] = mean AHLU all data; AHLU[2] = mean AHLU when AHLU>0; WS BG[A] = black globe from the weather station sensor used to calculate HLI; BG Calc[B] = black globe calculated used to calculate HLI. AHLU is the base accumulated heat load derived from when the upper threshold is HLI=86.

4.4.4 Relationship between weather station THI and pen THI

The relationships between the THI values obtained from the weather stations located near the pen (y) and from the within pen loggers (x) were highly variable (Table 15). The best correlations were for Feedlots 5 (Figure 11) and 6 (*P<0.001*; R^2>0.98), and the lowest was for Feedlot 1 (*P<0.001*; R^2 = 0.36) (Figure 12).

Table 15. The regression equations for THI calculated from the pen weather station and within pen THI for the six feedlots in the study

	Regression Equation	R^2	P-value
1	y = 0.8378x + 10.8060	0.36	<0.001
2	y = 0.7034x + 21.8435	0.66	<0.001
3	y = 0.4684x + 38.6278	0.42	<0.001
4	y = 0.7418x +19.0070	0.76	<0.001
5	y = 1.0027x – 0.9193	0.98	<0.001
6	y = 0.9888x + 1.1788	0.98	<0.001

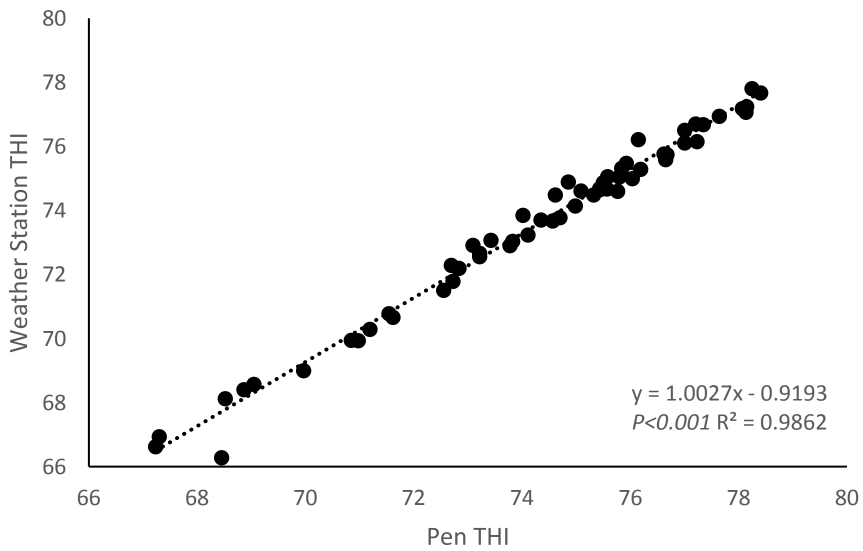


Figure 11. The linear relationship between the THI of the weather station (y-axis) and the THI from the pens (x-axis) for Feedlot 5.

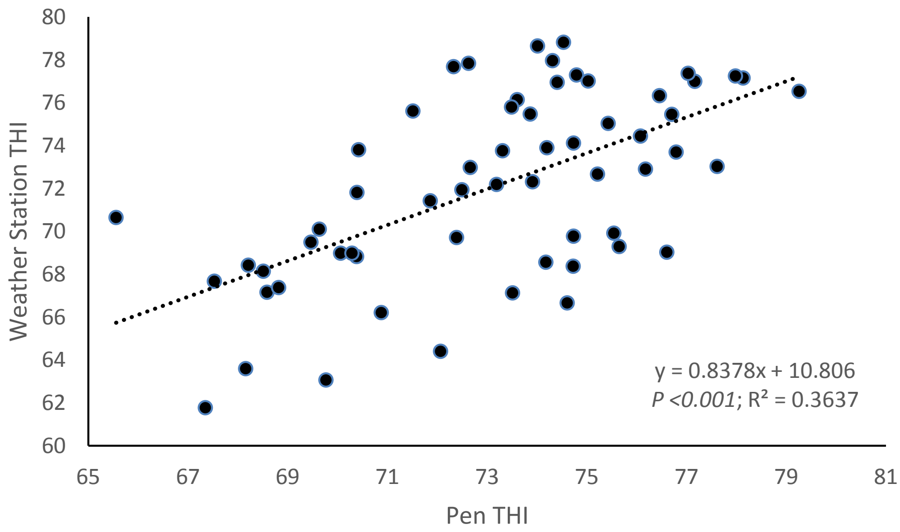


Figure 12. The linear relationship between the THI of the weather station (y-axis) and the THI from the pens (x-axis) for Feedlot 1.

The mean daily THI, T_A and RH for each feedlot over the duration of the study are presented in Table NN. There were no differences (*P>0.05*) between the THI obtained from loggers placed in the pens, and the THI obtained from the weather stations for five of the feedlots. There were differences between the RH from pens and weather stations at four of the feedlots. There were no differences between pens and weather stations for T_A.

Table 16. Mean daily temperature humidity index (THI), ambient temperature (TA) and relative humidity (RH) for the six feedlots used in the study

	1	2	3	4	5	6
THI						
WS	73.15	73.17	73.18	73.01	74.28	74.70
Pens	71.73	72.97	73.78	72.80	73.56	74.36
SE	0.35	0.33	0.51	0.36	0.27	0.27
MAE	2.81	1.90	2.31	1.53	0.73	0.36
P-value	0.0479	0.7641	0.5708	0.7672	0.1785	0.5375
TA						
WS	27.36	27.46	27.79	27.00	27.32	27.50
Pens	26.13	27.10	27.90	26.37	26.85	27.05
SE	0.32	0.32	0.48	0.31	0.20	0.24
P-value	0.0529	0.3884	0.9108	0.3111	0.2548	0.3558
RH						
WS	39.93	41.95	37.51	44.77	54.35	54.75
Pens	48.39	46.09	44.07	50.07	52.87	55.77
SE	1.09	0.93	1.33	1.20	0.90	1.07
P-value	>0.001	0.0283	0.0124	0.0234	0.4003	0.6609

4.5 Panting Scores

Over 980,000 panting score counts were obtained (Table 17). The majority of the counts were in the 0/1 panting score range (88.2%), followed by panting score 2 at 11.2%. The remaining panting scores (2.5, 3, 3.5 4 and 4.5) accounted for 0.6% of the panting score counts. Thus the data is heavily biased towards the lower panting scores. This is not unexpected given that the summer conditions were overly hot.

Table 17. Distribution of panting score counts by feedlot and number of pens

			Panting Score Categories								
Feedlot		**No. of Pens**	**0/1**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**Total PS Count**	**% of Total**
1	n	34	123,574	4,501	226	213	22	0	0	128,536	13.1%
	%		96.1%	3.5%	0.2%	0.2%	0.0%	0.0%	0.0%	100.0%	
2	n	18	221,241	23,821	1,780	888	401	28	0	248,159	25.3%
	%		89.2%	9.6%	0.7%	0.4%	0.2%	0.0%	0.0%	100.0%	
3	n	34	144,593	19,851	263	151	37	60	0	164,955	16.8%
	%		87.7%	12.0%	0.2%	0.1%	0.0%	0.0%	0.0%	100.0%	
4	n	20	100,527	6,708	94	21	9	0	0	107,359	10.9%
	%		93.6%	6.2%	0.1%	0.0%	0.0%	0.0%	0.0%	100.0%	
5	n	23	72,910	16,516	291	234	103	0	0	90,054	9.2%
	%		81.0%	18.3%	0.3%	0.3%	0.1%	0.0%	0.0%	100.0%	
6	n	14	202,290	38,890	385	218	129	5	10	241,927	24.7%
	%		83.6%	16.1%	0.2%	0.1%	0.1%	0.0%	0.0%	100.0%	
Total	**n**	**143**	**865,135**	**110,287**	**3,039**	**1725**	**701**	**93**	**10**	**980,990**	**100.0%**
	%		**88.2%**	**11.2%**	**0.3%**	**0.2%**	**0.1%**	**0.0%**	**0.0%**	**100.0%**	

More than 95% of the counts were from steers and the rest of the panting score counts were from mixed gender pens and pens with only heifers. Most of the observations (77.9%) were from BT1, and 7.6% and 7.2% of the panting score counts, respectively, were made on BT4 and BT5.

Almost half (49.2%) of the panting score counts were observed in the moderate (24.8%) and thermo-neutral category (TNC) (24.4%) categories of HLI. Nearly one third (28.6%) of the panting score counts were observed in the Hot category of HLI and 19.4% were in the Very Hot category. The rest of the panting score counts (2.9%) were observed in the Extreme category.

More than half (55.6%) of the panting score counts were observed in the TNC category of AHLU and 17.7% were from the Mild category of AHLU. The remainder of the panting score counts were observed in the Hot (11.5%), Extreme (6.8%) categories of AHLU (Table 18).

Table 18. Distribution of panting score counts by panting score categories, sex, breed type, period and HLI and AHLU categories

Variables	Categories	PS Count	(%)
Panting Score	0/1	865,135	88.2
	2	110,287	11.2
	2.5	3,039	0.3
	3	1,725	0.2
	3.5	701	0.1
	4	93	0.0
	4.5	10	0.0
PS Binary	Clinically Affected	115,855	11.8
	Normal	865,135	88.2
Sex	Heifers	12,726	1.3
	Mixed	27,493	2.8
	Steers	940,771	95.9
Period	1 = 0600 – 0959 h	221,535	22.6
	2 = 1000 – 1359 h	260,517	26.5
	3 = 1400 – 1759 h	332,806	33.9
	4 = 1800 – 2410 h	166,132	16.9
Breed Type (BT)	1 = 100% *Bos taurus* (British)	764,069	77.9
	2 = 100% *Bos taurus* (European)	40,549	4.1
	3 = 25% *Bos indicus*	31,854	3.5
	4 = 50% *Bos indicus*	74,398	7.6
	5 = 100% *Bos indicus*	70,120	7.2
HLI	TNC[1]	239,570	24.4
	Moderate	242,829	24.8
	Hot	280,143	28.6
	Very Hot	190,046	19.4
	Extreme	28,402	2.9
AHLU	TNC	545,228	55.6
	Mild	173,586	17.7
	Moderate	82,679	8.4
	Hot	112,476	11.5
	Extreme	67,021	6.8
	Total	**980,990**	100.00

[1]TNC = thermoneutral conditions i.e. no heat load

4.5.1 Multivariable mixed effects logistic regression model

Three separate multivariable models have been run. First, separate models were run with single fixed effects – adjusted AHLU (AHL_{ADJ}) and then breed type. The third model contained the two fixed effects in the one final model – adjusted AHLU and breed type.

Model 1: **Outcome:** PS (0/1 versus 2+), **Predictors:** $AHLU_{ADJ}$. The model outcomes are presented in Table 19.

Table 19. Multivariable random effects logistic regression with $AHLU_{ADJ}$ as fixed effect predictor. Var = Animal level variance, PenID:Yard = Variance due pens within Feedlots, Yard = Variability due to Feedlot, ICC = Intraclass Correlation Coefficient

	PS Outcome		
Predictors	*Odds Ratios*	*CI*	*P-value*
(Intercept)	0.02	0.00 – 0.06	<0.001
$AHLU_{ADJ}$	1.12	1.11 – 1.14	<0.001
Random Effects			
Var - animal	3.29		
Var - PenID:Yard	0.45		
Var - Yard	2.41		
$ICC_{PenID:Yard}$	0.07		
ICC_{Yard}	0.39		
Observations	91552		
Marginal R^2 / Conditional R^2	0.078 / 0.507		

Breed type adjusted AHLU ($AHLU_{ADJ}$) was significantly associated with higher panting score (panting score ≥ 2). A one-unit increase in adjusted AHLU ($AHLU_{ADJ}$) level was accompanied by 12% increase in the odds of higher panting score. That is, the odds of higher panting score increased for a one-unit increase in breed type adjusted AHLU.

An illustrative example is given to aid interpretation of Figure 13. Breed type adjusted AHLU ($AHLU_{ADJ}$) level of 40 was associated with a predicted probability of elevated panting score of 62.5% with a 95% confidence interval ranging from about 28% to 88%. This suggests that if an observer were to scan a large number of pens of cattle across different feedlots when $AHLU_{ADJ}$ was 40, then the average % of cattle observed across all pens with panting scores of 2 or greater would be 62.5%.

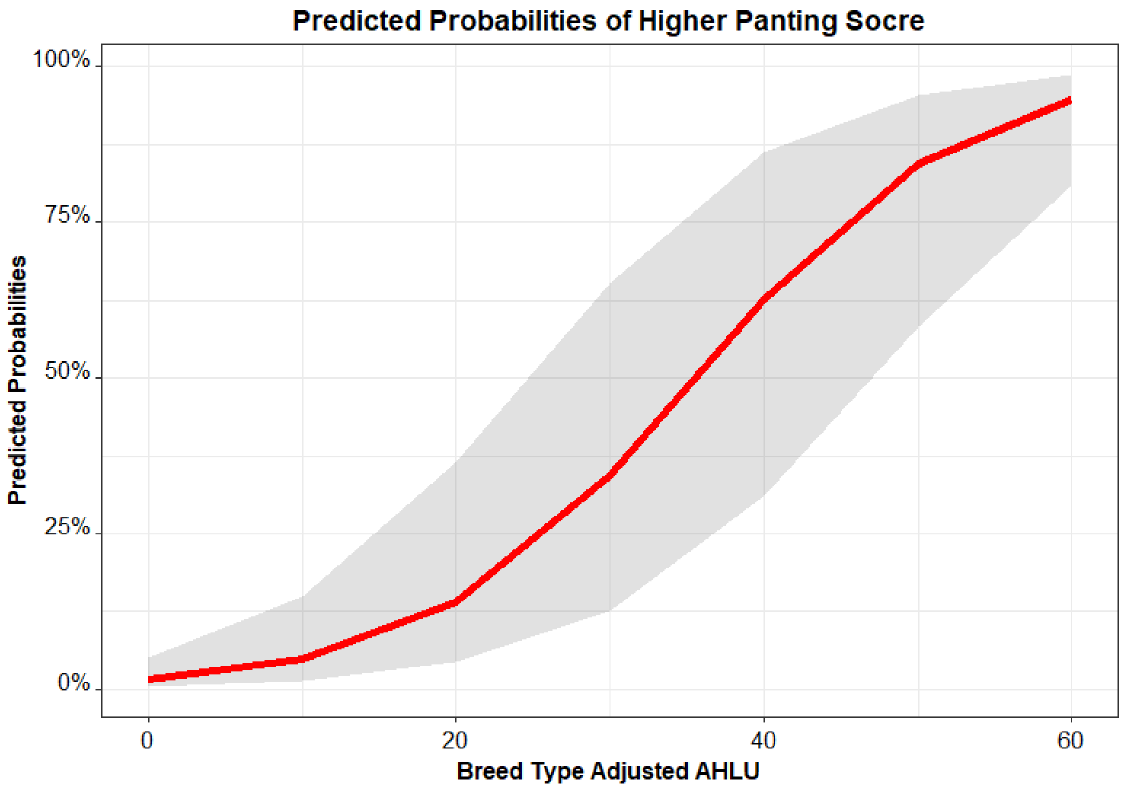


Figure 13. Predicted probability of elevated panting score (PS ≥2) for "$AHLU_{ADJ}$" levels. The shaded bands represent 95% confidence intervals. Predicted probabilities derived from a multivariable mixed effects logistic regression model.

Random effects

Random effects have been plotted as caterpillar plots, sorted in ascending order and shown with 95% confidence intervals. The plots provide a visual measure of unexplained or residual variance in the outcome of interest (proportion of animals with elevated panting score), derived from the multivariable model. Explained variance is the variance in the outcome of interest that has been explained by the addition of fixed effects to the model. At a conceptual level we assume that the total variance in the outcome (for a dataset) is constant. When fixed effects are added to a multilevel model they will be expected to explain some of the variance in the outcome and the residual (or unexplained) variance will be reduced. In a mythical, perfect model where fixed effects explain almost all of the variance in the outcome, there would be almost zero unexplained (residual) variance. In most models, fixed effects explain some of the variance and the remaining variance is then distributed amongst the random effects. Interpretive value can be assigned to the random effects.

The caterpillar plot for pen-level variance are presented in Figure 14. Looking at Figure 14, where the confidence intervals for the plotted variance cross the zero line, the unexplained variance for that individual pen is not different to the unexplained variance averaged over all pens. Where the entire confidence interval is below the zero line, the proportion of animals with elevated panting score in that pen is expected to be significantly lower than the average across all pens. Where the entire confidence interval for a pen is above the zero line (at the right end of Figure 14), the pen has a significantly higher proportion of animals with elevated panting score compared to the average across pens.

The residual or unexplained variance in the outcome at the pen level, after fitting a specific multivariable model is displayed in Figure 14. A different model would be expected to have different amounts of unexplained variance at various levels (fixed effect, random effects at animal, pen and yard levels). Most of the individual pen estimates shown in Figure 14 have confidence intervals that cross the zero line, meaning that for these pens there is no significant variation in proportion of animals with elevated panting score – they are all within the confidence limits of the overall average. For most pens there is little pen-level effect on the probability of having an elevated panting score (Figure 14). There were then a small number of pens that either had a lower (or higher) probability of elevated panting score than the average across all pens. Further work to collect more detailed data on other pen-level variables might allow identification of what factors could be driving this pen level variability.

Figure 15 shows the caterpillar plot for yard (or feedlot). There are only six estimates because there were only six feedlots in the analysis. Again the estimates have been sorted in ascending order to aid interpretation. There was more substantial unexplained variation at the feedlot level. One feedlot (Feedlot 4) was associated with a reduction in proportion of elevated panting scores while four feedlots were associated with an increased proportion of elevated panting scores. The effect at the feedlot level appears more marked than the unexplained variance at the pen level. Assigning unexplained variance to the feedlot level means that the effect is at the feedlot level, or that all animals in that specific feedlot share the same effect. Significant residual variance at the feedlot level indicates that there are attributes at the feedlot level (location, topography etc.) that are influencing probability of elevated panting scores.

Further work to collect more detailed data on other feedlot-level variables might allow identification of what factors could be driving this feedlot level variability. The feedlot level effect appears more prominent than the pen level effect (unexplained variance). This suggests that work to explore additional feedlot-level variables might be more rewarding than work to explore additional pen-level variables that could explain additional variability in elevated panting scores.

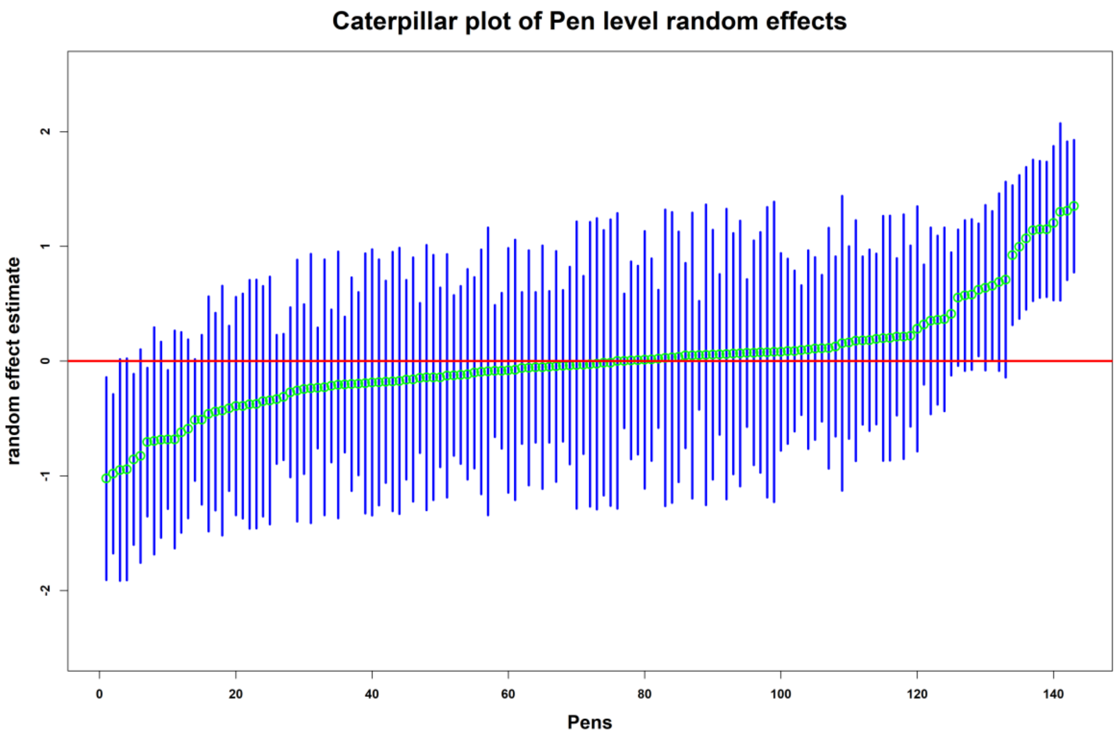


Figure 14. Caterpillar plot of the pen level random effects. It represents the unobserved variance that could be attributed to variation between pens.

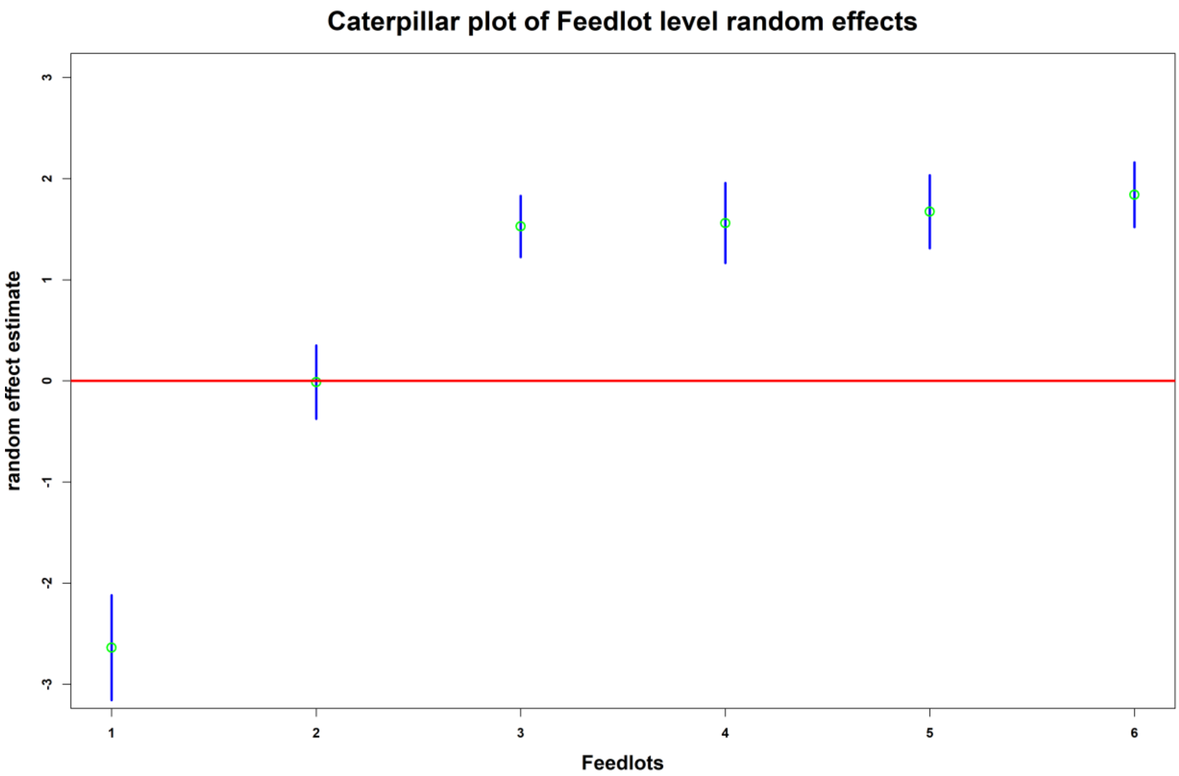


Figure 15. Caterpillar plot of the feedlot level random effects. It represents the unobserved variance that could be attributed to variation between feedlots. *NB: The feedlot numbers in this figure are different to the rest of the report in that they are in a sequential range. For clarity in this figure feedlot 1 is feedlot 3 in the rest of the report, feedlot 2 is feedlot 4, feedlot 3 is feedlot 1, feedlot 4 is feedlot 2, feedlot 5 is feedlot 6, and feedlot 6 is feedlot 5.*

Model 2: Outcome: PS (0/1 versus 2+), **Predictors:** Breed Type. The outcomes from Model 2 are presented in Table 20.

Table 20. Multivariable random effects logistic regression with Breed Type as fixed effect predictor. Var = Animal level variance, PenID:Yard = Variance due pens within Feedlots, Yard = Variability due to Feedlot, ICC = Intraclass Correlation Coefficient

	PS Outcome		
Predictors	*Odds Ratios*	*CI*	*P-value*
(Intercept)	0.08	0.05 – 0.14	<0.001
100% *Bos taurus*	reference		
100% *Euro*	0.25	0.17 – 0.36	<0.001
25% *Bos indicus*	0.17	0.10 – 0.30	<0.001
50% *Bos indicus*	0.01	0.00 – 0.04	<0.001
100% *Bos indicus*	0.00	0.00 – 52.87	0.107
Random Effects			
Var	3.29		
PenID:Yard	0.09		
Yard	0.43		
$ICC_{PenID:Yard}$	0.02		
ICC_{Yard}	0.11		
Observations	91552		
Marginal R^2 / Conditional R^2	0.821 / 0.846		

Breed type was found to be statistically significantly associated with higher panting score. Compared to the reference breed type category (Breed 1: 100% *Bos taurus*), the odds of higher panting score decreases for breed type 2 (100% Euro), breed type 3 (25% *Bos indicus*) and breed type 4 (50% *Bos indicus*). Respectively, the odds of higher panting score were 75%, 83% and 99% lower for 100% Euro, 25% *Bos indicus* and 50% *Bos indicus* compared to 100% *Bos taurus*.

An illustrative example is given to aid interpretation of Figure 16. For Breed 1 (100% *Bos taurus*) is associated with a predicted probability of elevated panting score of 8% with a 95% confidence interval ranging from about 5% to 12%. This suggests that if an observer were to scan a large number of pens of 100% *Bos taurus* cattle across different feedlots, then the average % of cattle with panting scores of 2 or greater would be 8%.

The very small number of observations involving 100% *Bos indicus* cattle is the main reason why the 95% confidence interval for the predicted probability for this breed type is so wide (covering the entire predicted probability range). More observations from *Bos indicus* cattle in future studies would aid in producing more precise estimates for 100% *Bos indicus* cattle.

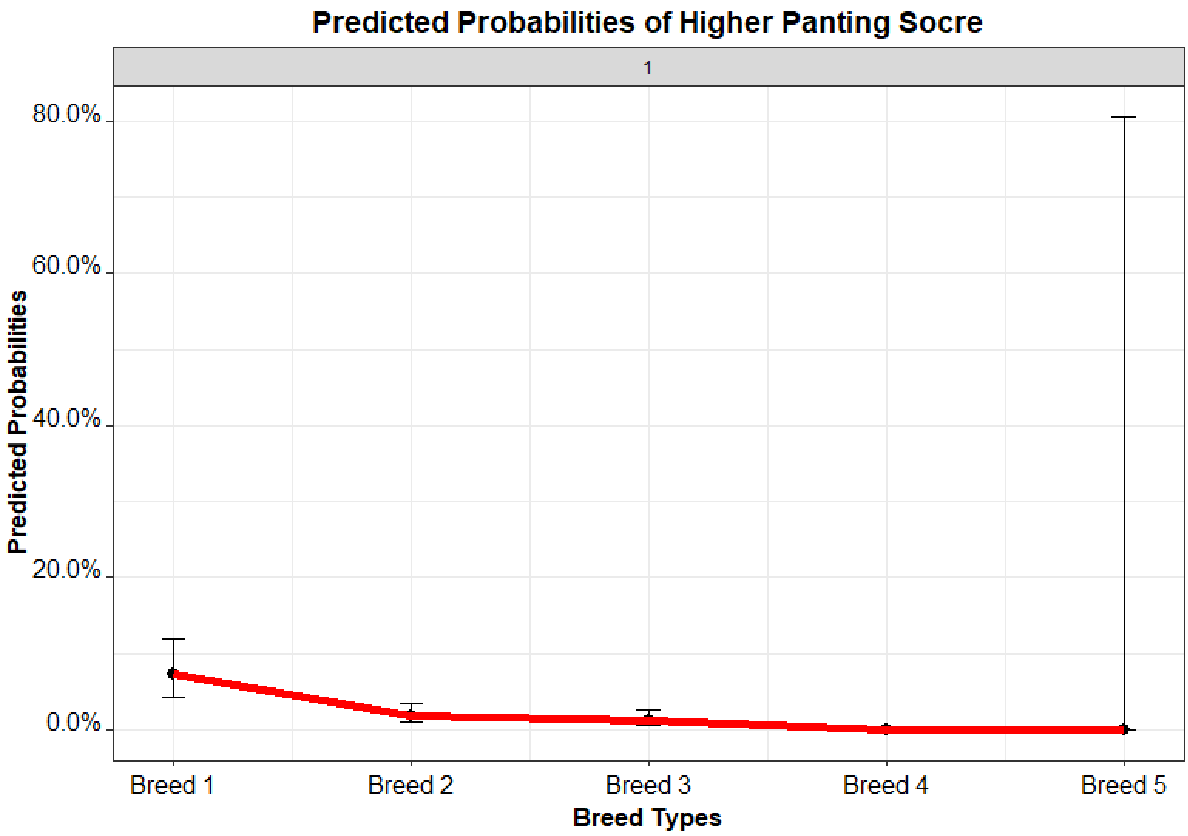


Figure 16. Predicted probability of higher panting score for each combination of "$AHLU_{ADJ}$" and "Breed Type" levels. The error bars represent 95% confidence intervals. Predicted probabilities derived from a multivariable mixed effects logistic regression model.

A more detailed discussion of interpreting caterpillar plots was provided in the previous pages. Figure 17 shows relatively little evidence for significant pen level variation in proportion elevated panting scores (for the model with breed type as a fixed effect). Figure 18 shows significant feedlot level variation in the proportion of elevated panting scores.

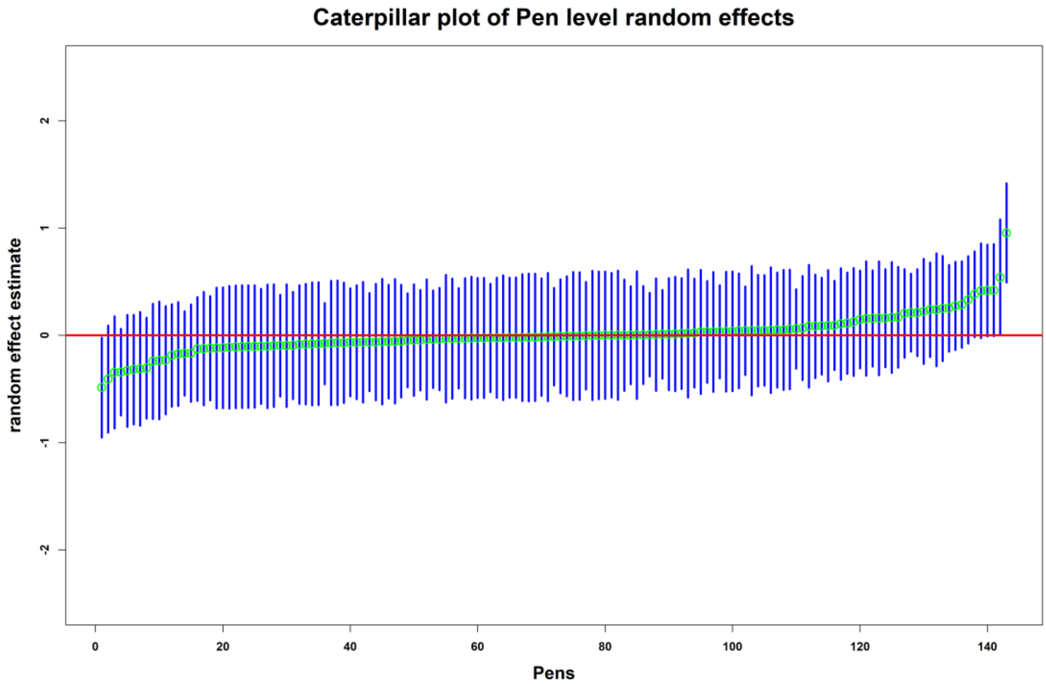


Figure 17. Caterpillar plot of the pen level random effects. It represents the unobserved variance that could be attributed to variation between pens.

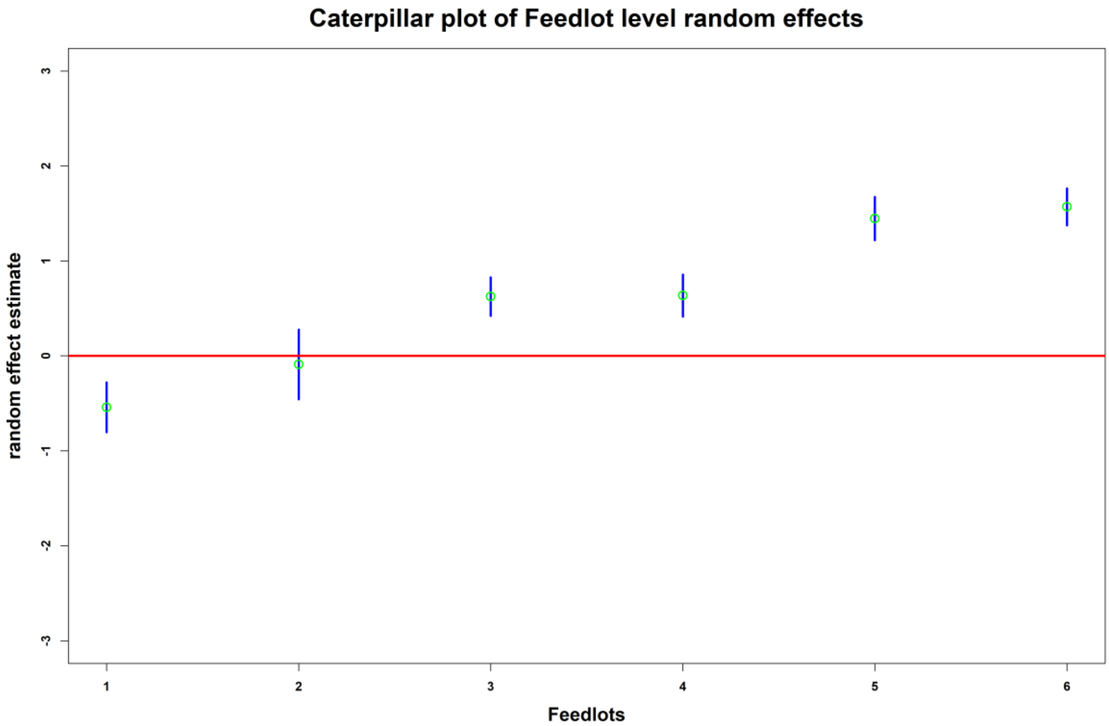


Figure 18. Caterpillar plot of the feedlot level random effects. It represents the unobserved variance that could be attributed to variation between feedlots. ***NB: The feedlot numbers in this figure are different to the rest of the report in that they are in a sequential range. For clarity in this figure feedlot 1 is feedlot 3 in the rest of the report, feedlot 2 is feedlot 4, feedlot 3 is feedlot 1, feedlot 4 is feedlot 2, feedlot 5 is feedlot 6, and feedlot 6 is feedlot 5.***

Model 3: **Outcome:** PS (0/1 versus 2+), **Predictors:** $AHLU_{ADJ}$, Breed Type. Model 3 outcomes are presented in Table 21. This model is expected to provide the most useful inference because it includes fixed effects for both adjusted AHLU and for breed type.

Table 21. Multivariable random effects logistic regression with $AHLU_{ADJ}$ and Breed Type as predictors. Var = Animal level variance, PenID:Yard = Variance due pens within Feedlots, Yard = Variability due to Feedlot, ICC = Intraclass Correlation Coefficient

		PS Outcome		
Predictors	*Categories*	*Odds Ratios*	*CI*	*P-value*
(Intercept)		0.04	0.01 – 0.11	<0.001
$AHLU_{ADJ}$		1.10	1.08 – 1.11	<0.001
Breed Type	100% *Bos taurus*	0.31	0.22 – 0.45	<0.001
	100% Euro	0.25	0.14 – 0.42	<0.001
	25% *Bos indicus*	0.01	0.00 – 0.07	<0.001
	50% *Bos indicus*	0.00	0.00 – 2512.97	0.173
	100% *Bos indicus*	reference		
Random Effects				
Var		3.29		
PenID:Yard		0.11		
Yard		1.86		
$ICC_{PenID:Yard}$		0.02		
ICC_{Yard}		0.35		
Observations		91552		
Marginal R^2 / Conditional R^2		0.767 / 0.854		

The Model 3 outcomes indicated that the model assumptions were met. The model was then used to generate predicted probabilities at the pen level of animals having panting scores of 2 or greater across a range of $AHLU_{ADJ}$ values and for each level of breed type. These results clearly show the impact of breed type at a given $AHLU_{ADJ}$ and provide useful estimates of the predicted outcomes (proportion of animals with elevated panting scores) for different combinations of adjusted AHLU and breed type.

An illustrative example is given to aid interpretation of Figure 19. For Breed 1 (100% *Bos taurus*), $AHLU_{ADJ}$ levels of 40 are associated with a predicted probability of elevated panting score of about 60% with a 95% confidence interval ranging from about 28% to 78%. This suggests that if an observer were to scan a large number of pens of 100% *Bos taurus* cattle across different feedlots when $AHLU_{ADJ}$ was 40, then the average % of cattle with panting scores of 2 or greater would be 60%.

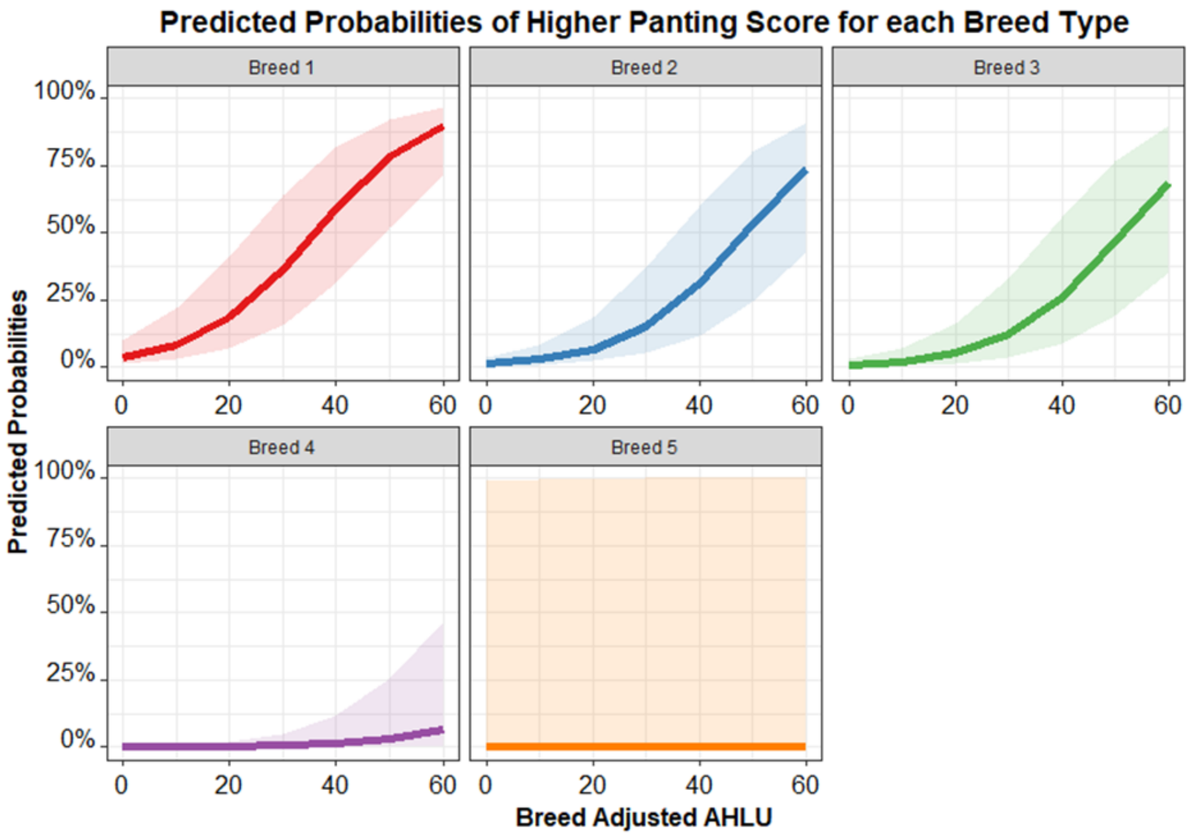


Figure 19. Predicted probability of higher panting score for each combination of "AHLU$_{ADJ}$" and "Breed Type" levels. The shaded bands represent 95% confidence intervals. Predicted probabilities derived from a multivariable mixed effects logistic regression model.

Scanning across the predicted plots for other breed types clearly shows that the predicted probability of having elevated panting score for a given AHLU$_{ADJ}$ is reduced as breed type moves from 100% *Bos taurus* to 100% Euro and then through increasing *Bos indicus* percentage. The very small number of observations involving 100% *Bos indicus* cattle is the main reason why the 95% confidence interval for the predicted probability for this breed type is so wide (covering the entire predicted probability range). More observations from *Bos indicus* cattle in future studies would aid in producing more precise estimates for 100% *Bos indicus* cattle.

Random effects

The random intercept plots (Figure 20 and Figure 21) show the variation among pens to be minimal – suggesting that pen level variability may be less important as an explanatory factor for panting score. It is apparent that there were a very small number of pens that had an elevated likelihood of elevated panting score but the overall impact was small. This finding has important ramifications. If there were substantial unexplained variance in the outcome (elevated panting score) at the pen level, then this would direct more attention to understanding particular pen attributes within a feedlot. Some pens may have different attributes (elevation, shade, wind, etc.) that are associated with lower or higher risk of elevated panting scores. However, the fact that the model suggests there is little pen level variation suggests that this is not a major explanatory factor in heat stress. Further work is needed to confirm this finding.

In contrast there is substantial unexplained variation in elevated panting scores at the feedlot level. One feedlot (Feedlot 4) was associated with a reduction in likelihood of elevated panting score while other feedlots were associated with an increased likelihood of elevated panting score. The random effect for a particular feedlot is a quantitative measure of how much higher or lower the log-odds values are in the model for pens in that feedlot. These findings suggest that further work is needed to identify characteristics at the feedlot level that may be contributing to the unexplained variance between feedlots as shown in Figure 21. Identifying specific attributes that explain this variance will provide the opportunity to develop risk mitigation strategies to counter the effects of these drivers.

An attempt was made to explore the generation of predicted probability plots (as shown in Figure 19) for each feedlot location using the multivariable model – in order to try and understand more deeply the impact of feedlot-specific variability on predicted probability of elevated panting scores. The plots are not shown in this report because the model estimates were numerically unstable. The results were considered to be consistent with Figure 19 in that there was substantial variation in predicted probability of elevated panting score between individual feedlots. There were also patterns that were consistent with the biological complexity of causal weather-related factors that may drive panting in animals. For example, there were occasions where pens of *Bos taurus* cattle were observed to have elevated percentages of cattle with panting scores ≥ 2 even in the presence of very low AHLU values. In these occasions the HLI values were invariably high – reflecting short term, hot conditions that have not been present for long enough to drive elevated AHLU values.

The authors also noted that the outcome used in these models was proportion of cattle in a pen with panting scores of 2 or higher – classified as elevated panting score. In fact it may be that panting scores of 3 or higher may be a better reflection of high risk. In the datasets we used for analysis there were so few animals that had panting scores of 3 or higher that we were unable to complete statistical analyses with this as the outcome. This is likely to have interfered with our findings in that perhaps animals were more likely to show periods of panting score of 2 or higher even when AHLU values were relatively low.

In summary, the authors felt that the approach used for modeling to explore relationships between AHLU and panting score was sound and that data limitations have constrained the usefulness of the findings. It will be useful to continue to develop and apply these methods to more extensive datasets collected during periods of more extreme heat and when some cattle are showing panting scores of 3 or higher.

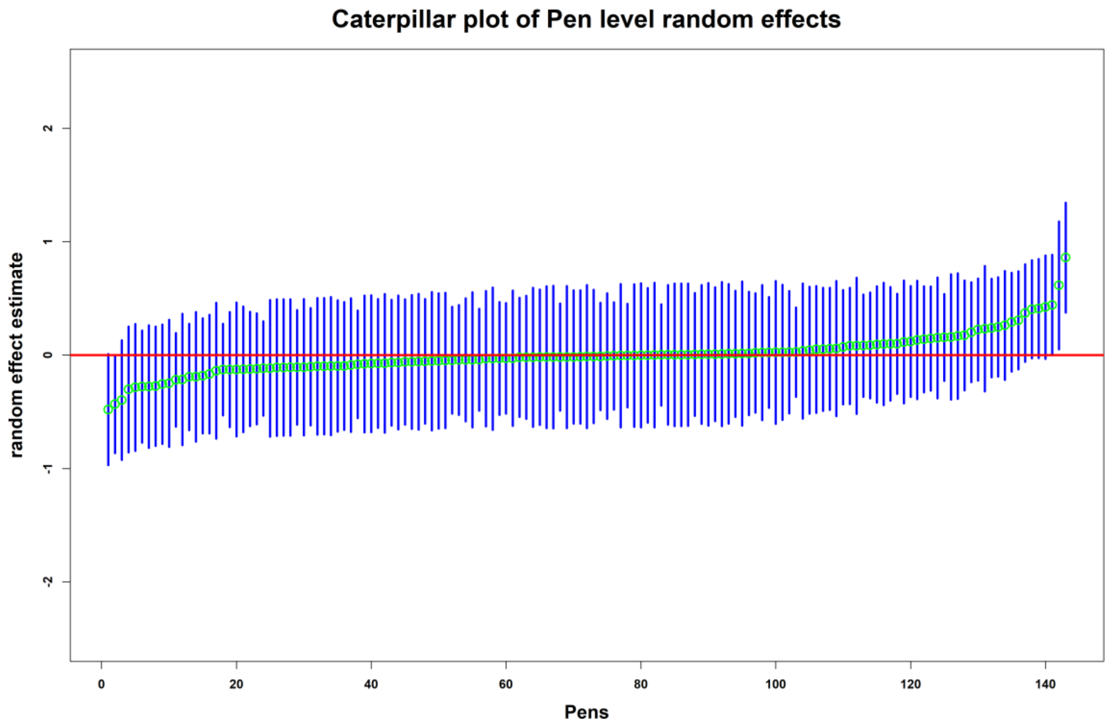


Figure 20. Caterpillar plot of the pen level random effects. It represents the unobserved variance that could be attributed to variation between pens.

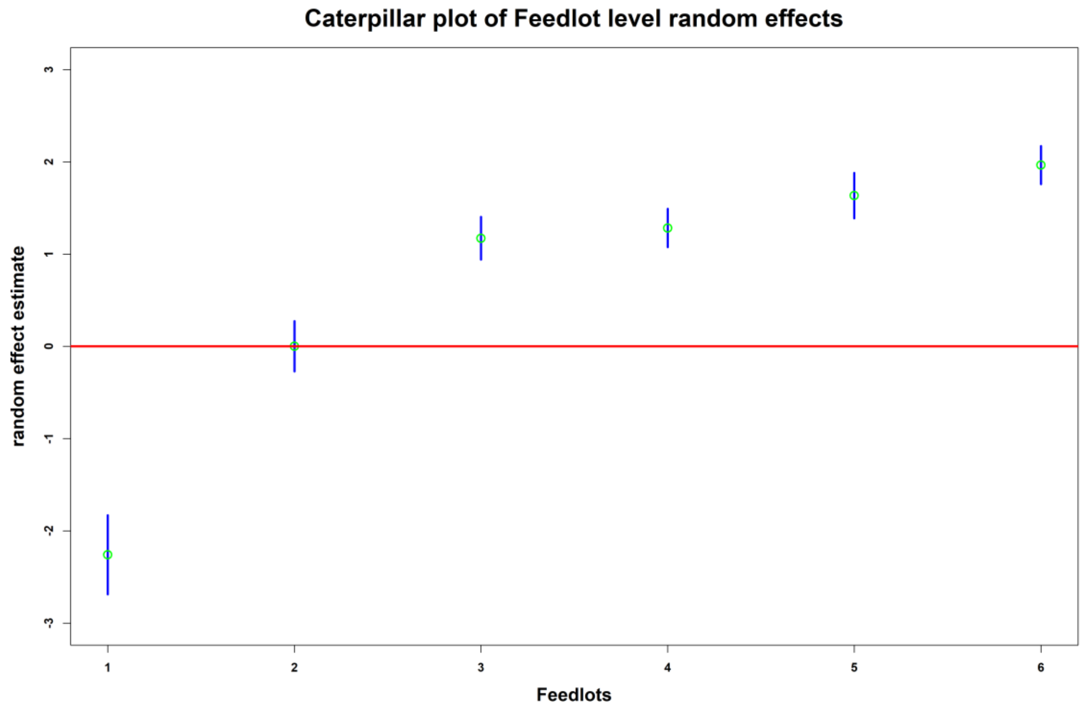


Figure 21. Caterpillar plot of the feedlot level random effects. It represents the unobserved variance that could be attributed to variation between feedlots. *NB: The feedlot numbers in this figure are different to the rest of the report in that they are in a sequential range. For clarity in this figure feedlot 1 is feedlot 3 in the rest of the report, feedlot 2 is feedlot 4, feedlot 3 is feedlot 1, feedlot 4 is feedlot 2, feedlot 5 is feedlot 6, and feedlot 6 is feedlot 5.*

Model selection

Model selection statistics using Akaike Information Criteria shows that Model 3, that, the model which includes the fixed effect of both "$AHLU_{ADJ}$" and "Breed Type" performed better than the two models each with a single explanatory variable (Table 22). This is based on the general rule that in a set of models the preferred model is the one with the minimum AIC value.

Table 22. Model comparison using Akaike Information Criteria (AIC)

Model	DF	AIC
Model 1	**4**	3045.825
Model 2	**7**	3084.391
Model 3	**8**	2848.680

Model equation
Denote π = probability of panting score ≥ 2 for a given animal.

logit (odds) = $log(\frac{\pi}{1-\pi})$ = $\beta_0 + \beta_1$*Breedtype + β_2*$AHLU_{ADJ}$ + u + ε,

Where, $u_j \sim N(0, \sigma^2_u)$ and $\varepsilon \sim N(0, \sigma^2_\varepsilon)$; u is the effect of pen on the log-odds that panting score ≥ 2; also known as a level 2 residual; σ^2_u is the level 2 (residual) variance, or the between-pen variance in the log-odds that panting score ≥ 2after accounting for fixed effects: "$AHLU_{ADJ}$" and "Breed Type."; σ^2_ε is animal level variance.

Since, the odds ratios in Table 19, Table 20 and Table 21 are in exponentiated coefficients, the β_k's for k =1,2,3 can be obtained by taking the natural logarithm of the corresponding odds ratios.

4.5.2 Dry Matter Intake and Energy Intake

Dry matter intake (DMI), energy intake, HLI, AHLU, and DOF data were measured at pen levels for each observation day. Each measurements represents daily level DMI, energy intake, HLI, AHLU and DOF at pen level for randomly selected days (a per head per day basis). To quantify the relationship between DMI and energy intake outcomes, and the daily HLI, AHLU and DOF measurements taken for that specific randomly selected days. Separate multivariable linear models were run with dry matter intake and energy intake as the outcome of interest. For each model outcome, the model was repeated with AHL presented as a continuous variable and then with AHLU presented as a categorical variable.

Model: DMI = $\beta_0 + \beta_1$*AHLU + β_2*HLI + β_3*Class + ε
Where, $\varepsilon \sim N(0, \sigma^2_\varepsilon)$ is the error term

The model results are presented in Table 23 and Table 24. Plots of observed and predicted DMI from the multilinear regression model are presented in Figures 22 and 23. The multivariable linear regression model results summarized in Table 23: AHLU, Class and DOF predictors were statistically significant predictors of DMI. AHLU had a negative effect on DMI, that is, for a unit increase in AHLU, DMI intake decreased by a rate of 0.01 adjusted for HLI, and Class predictors in the model. In addition, compared to 75 DOF class of animals, those in 100 DOF and 150 DOF classes had increased DMI. Those animals 100 DOF class had 2.48 times increased rate of DMI compared to 75 DOF class of animals. Moreover, those animals 150 DOF class had 1.81 times increased rate of DMI compared to 75 DOF class of animals. However, the model is inadequate to predict the variation in the expected DMI as the adjusted R^2 was only 12.5%.

Table 23. Coefficients for the multivariable linear model with DMI as the outcome and with fixed effects representing DOF, AHLU, HLI and feedlot class. Model A shows results for a model including AHLU presented as a continuous variable. Model B shows results for a model with AHLU presented as a categorical variable

Outcome = DMI	Model A			Model B		
Predictors	Estimates	CI	P-value	Estimates	CI	P-value
Intercept	9.21	8.65 – 9.78	<0.001	9.31	9.06 – 9.57	<0.001
DOF	0.00	-0.00 – 0.00	0.684	0.00	-0.00 – 0.00	0.552
AHLU	-0.01	-0.01 – -0.00	0.001			
HLI	0.00	-0.00 – 0.01	0.648			
Class 150 DOF	1.81	1.55 – 2.07	<0.001	1.78	1.52 – 2.04	<0.001
Class 100 DOF	2.48	2.24 – 2.73	<0.001	2.45	2.21 – 2.70	<0.001
Class 75 DOF	reference					
AHLU Extreme				-0.43	-0.88 – 0.01	0.057
AHLU Hot				-0.49	-0.77 – -0.21	0.001
AHLU Moderate				-0.20	-0.38 – -0.02	0.031
AHLU Mild				0.05	-0.07 – 0.17	0.445
AHLU TNC	reference					
HLI Hot				0.23	-0.04 – 0.50	0.094
HLI Moderate				0.03	-0.09 – 0.15	0.622
HLI TNC	reference					
Observations	3903			3903		
R^2 / adjusted R^2	0.126 / 0.125			0.129 / 0.127		

Model A (above) incorporated a continuous variable representing AHLU and HLI. The model assumes a linear and constant relationship between AHLU and the outcome in that a one unit increase in AHLU is expected to have the same impact on the outcome at any point along the continuum of AHLU values. It is perhaps reasonable to expect that the underlying true biological relationship between AHLU and outcome may not be linear and constant across the plausible range of AHLU values. For this reason the authors are inclined to apply more interpretive value to the second model where AHLU is presented as a categorical explanatory variable.

The results of both models appear to be consistent with plausible underlying expectations in that as AHLU moves from thermos-neutral range through levels to extreme heat, there is an increasing negative association with DMI.

Figure 22 shows a visual representation of predicted DMI and AHLU which is consistent with the small negative association.

The datasets used for these analyses involved an outcome aggregated at the pen level (DMI) and only measured once per day. When coupled with the understanding that even in hot weather and in pens with heat affected animals, there may be other animals who are behaving normally and potentially easting normally. Under these conditions it is reasonable to expect that the statistical models may struggle to detect a strong relationship or association between daily aggregated measures of pen level DMI and pen level panting scores.

It is possible that detailed understanding of the association between heat (HLI and AHLU) and panting scores and DMI, may require individual animal monitoring – made possible by advances such as RFID and GrowSafe technology. More detailed data would also allow exploration of non-linear associations between the explanatory factors and the outcomes of interest.

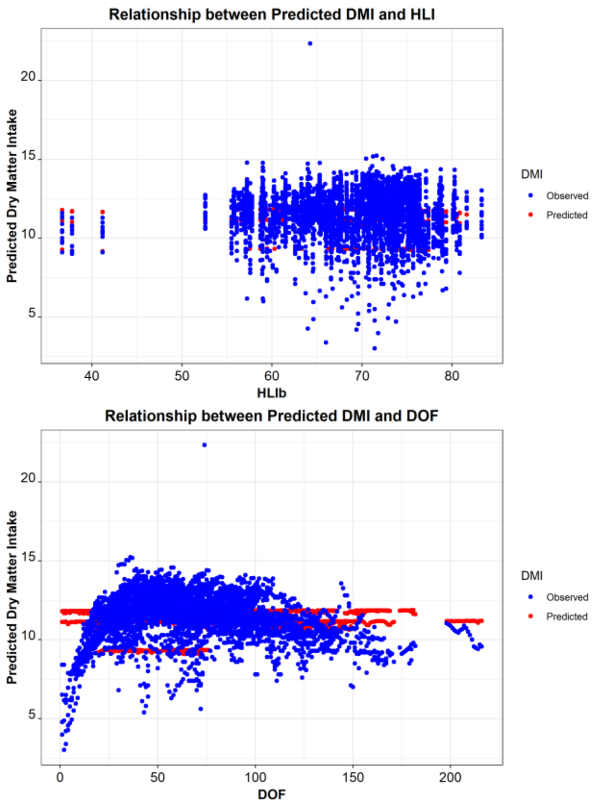


Figure 22. Plots of predicted (red points) and observed (blue points) DMI from multivariable linear regression model with HLI, AHLU, DOF and Class variables as predictors of DMI.

Energy Intake – ME.MJ.Kg

Model: ME.MJ.Kg = $\beta_0 + \beta_1$*AHLU + β_2*HLI + β_3*Class + ε

Where, $\varepsilon \sim N(0, \sigma^2_\varepsilon)$ is the error term

Results of the multivariable linear regression model using AHLU, HLI and Class predictors are presented in Table 24. DOF, HLI and Class variables were statistically significant predictors of energy intake (ME.MJ.kg). However, the model is estimates are unstable for HLI and DOF with zero point estimates and the corresponding 95% CIs have zero lower and upper limits. This could be because the values of energy intake are very similar for most of the observations.

Table 24. The multivariable linear regression model for ME MJ/kg using AHL, HLI and Class predictors

	ME MJ kg			ME MJ kg		
Predictors	Estimates	CI	P	Estimates	CI	P
Intercept	13.01	12.94 – 13.08	<0.001	13.17	13.14 – 13.20	<0.001
DOF	0.00	0.00 – 0.00	<0.001	0.00	0.00 – 0.00	<0.001
AHLU	-0.00	-0.00 – 0.00	0.555			
HLI	0.00	0.00 – 0.00	<0.001			
Class 150 DOF	0.01	-0.03 – 0.04	0.737	0.01	-0.02 – 0.04	0.502
Class 100 DOF	-0.23	-0.26 – -0.20	<0.001	-0.22	-0.25 – -0.18	<0.001
Class 75 DOF	reference					
AHLU Extreme				-0.03	-0.08 – 0.03	0.360
AHLU Hot				0.10	0.07 – 0.14	<0.001
AHLU Moderate				0.05	0.03 – 0.08	<0.001
AHLU Mild				-0.01	-0.02 – 0.01	0.517
AHLU TNC	reference					
HLI Hot				-0.05	-0.08 – -0.01	0.009
HLI Moderate				0.01	-0.01 – 0.02	0.345
HLI TNC	reference					
Observations	3903			3903		
R^2 / adjusted R^2	0.340 / 0.339			0.349 / 0.347		

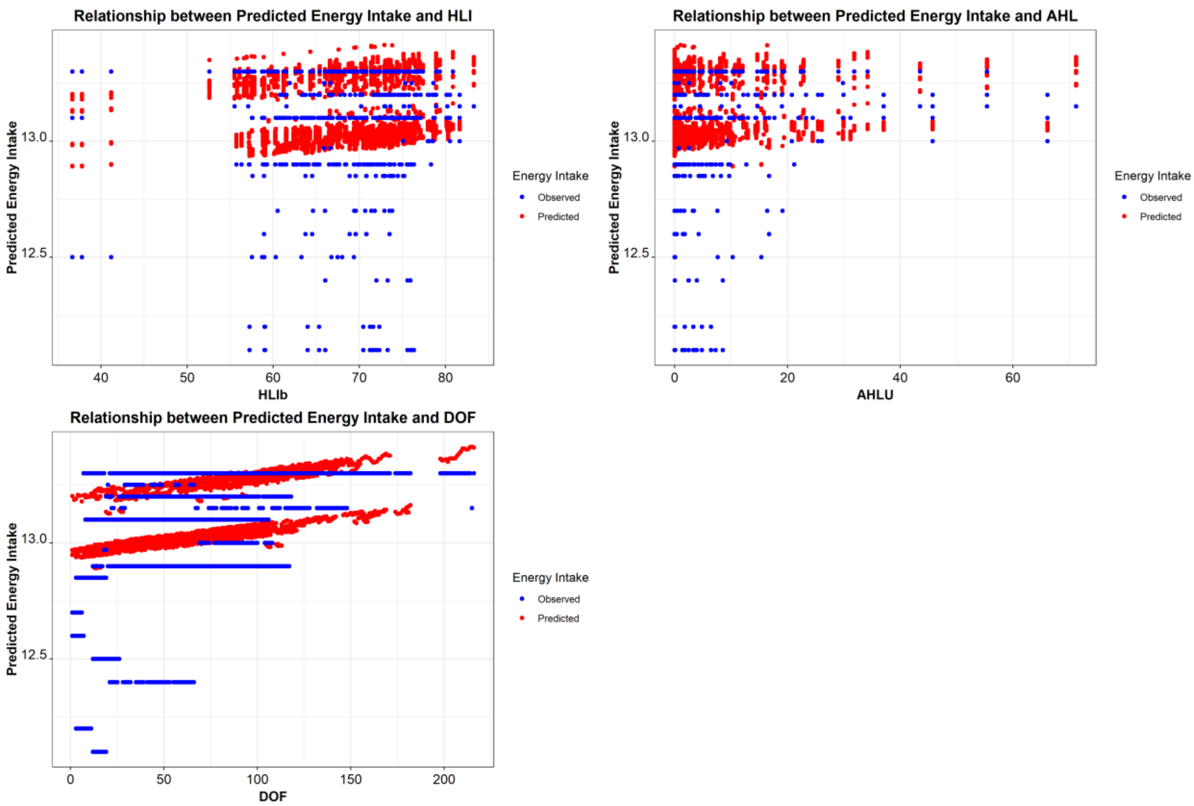


Figure 23. Plots of predicted (red points) and observed (blue points) of energy intake from multivariable linear regression model with HLI, AHLU, DOF and Class variables as predictors of energy intake.

Energy Intake – ME.Tot

Model: $ME.Tot = \beta_0 + \beta_1*AHLU + \beta_2*HLI + \beta_3*Class + \varepsilon$
Where, $\varepsilon \sim N(0, \sigma^2_\varepsilon)$ is the error term

The results of the multivariable linear regression model using AHLU, HLI and Class predictors are presented in Table 25. Plots of observed and predicted energy intake from the multilinear regression model are presented in Figure 24. In the model, AHLU and Class variables were statistically significant predictors of energy intake (ME.Tot). AHLU had negative effect on energy intake, that is, for a unit increase in AHLU, energy intake will decrease by a rate of 0.11 adjusted for HLI, DOF and Class predictors in the model. In addition, compared to 75 DOF class of animals, those in 100 DOF and 150 DOF classes had increased energy intake. Those animals 100 DAY class had 30.22 times increased rate of energy intake compared to 75 DOF class of animals. Moreover, those animals 150 DOF class had 24.07 times increased rate of energy intake compared to 75 DOF class of animals. However, the model is inadequate to predict the variation in the expected energy intake as the adjusted R^2 was only 9.4%.

The discussion presented above for the DMI model is also considered to apply for the ME model.

Table 25. The multivariable linear regression model for ME total using AHLU, HLI and Class predictors

	ME Tot			ME Tot		
Predictors	Estimates	CI	P-value	Estimates	CI	P-value
Intercept	119.82	112.36 – 127.29	<0.001	122.76	119.38 – 126.14	<0.001
DOF	0.01	-0.01 – 0.03	0.210	0.01	-0.01 – 0.03	0.161
AHLU	-0.11	-0.17 – -0.04	0.001			
HLI	0.05	-0.05 – 0.15	0.335			
Class 150 DOF	24.07	20.60 – 27.54	<0.001	23.79	20.32 – 27.26	<0.001
Class 100 DOF	30.22	26.97 – 33.48	<0.001	29.97	26.71 – 33.23	<0.001
Class 75 DOF	reference					
AHLU Extreme				-5.94	-11.84 – -0.03	0.049
AHLU Hot				-5.25	-8.97 – -1.53	0.006
AHLU Moderate				-2.00	-4.42 – 0.43	0.106
AHLU Mild				0.54	-1.10 – 2.17	0.520
AHLU TNC	reference					
HLI Hot				2.55	-1.05 – 6.15	0.165
HLI Moderate				0.48	-1.14 – 2.10	0.561
HLI TNC	reference					
Observations	3903			3903		
R^2 / adjusted R^2	0.095 / 0.094			0.096 / 0.094		

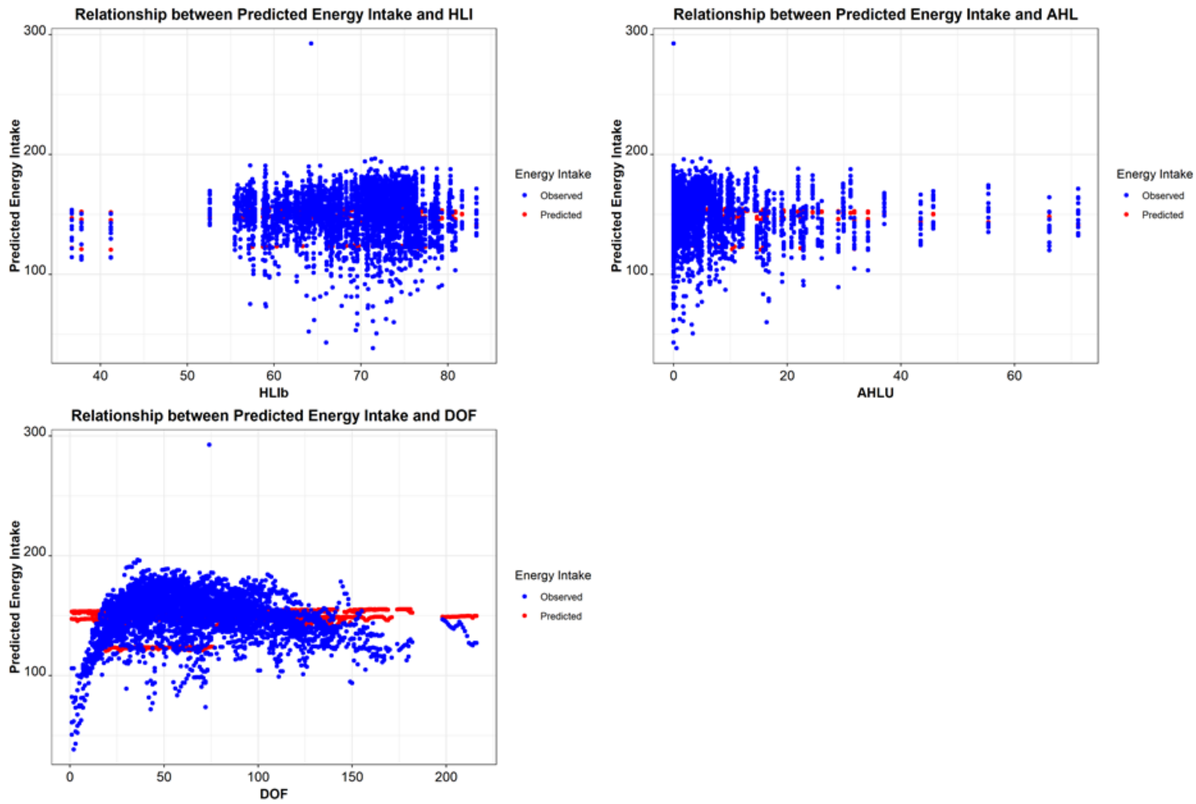


Figure 24. Plots of predicted (red points) and observed (blue points) of energy intake from multivariable linear regression model with HLI, AHLU, DOF and Class variables as predictors of energy intake.

5 Discussion

5.1 Weather stations

Weather data was collected from two weather stations at each feedlot, and the relationships between the various weather parameters from each weather station were explored. One station was located close to the office and the other close to the pens. There were differences (*P<0.001*) between the weather stations for BG at 3 feedlots, T_A at 2 feedlots, RH at 4 feedlots, SR at 2 feedlots and WS at 5 feedlots. These data confirm even over short distances there can be considerable variation in measured weather parameters especially wind speed. An on-site weather station should be located so that WS at the weather station will have airflows similar to what would be expected at pen level. Wind flow has a significant influence on HLI (and hence AHLU) so placing weather stations at a location at a feedlot that has greater or lesser wind speed then the pens will lead to error (see below).

5.2 Calculated black globe temperature

Ideally a black globe temperature sensor should be used on weather stations. However where this is not possible a calculated black globe temperature has been used. There has been some debate as to the reliability of the algorithm used to calculate black globe temperature. To test the accuracy of the calculated BG against measured black globe model precision was evaluated. All sites showed significant mean and linear bias. Systemic bias (as a % of MSPE) was low across all sites, with most of the bias (as a % of MSPE) being random error. There was no consistency between feedlots in terms of model accuracy. For example, the accuracy of calculated BG at 3 of the feedlots was that BG was under-predicted, and at the other 3 it was over predicted. The under and over predictions were not great with means across feedlots differing by 0.12 to 0.72 ^{o}C. However at three of the feedlots (1, 2 and 3) the differences between the observed BG and the calculated BG were significant (*P<0.001*). It is not clear if these differences will impact accuracy of predicted AHLU at a particular site. The approximate prediction intervals ranged from ± 3.25 ^{o}C to ± 7.34 ^{o}C, suggesting errors can be high. The current algorithm does not appear to be a reasonable predictor of black globe temperature.

5.3 THI comparisons (weather station vs pens)

The temperature humidity index was used to assess the micro-climate in pens and relate this back to weather station data. The THI was used rather than the HLI because black globe temperature, solar radiation and wind speed where not available at the pen level.

The relationships between weather station THI and pen THI ranged from very good (R^2>0.98 to very poor R^2 = 0.03). While two of the feedlots (5 and 6) showed a very strong correlation between the THI from the weather station and THI from pen loggers the others were moderate to low. If the weather stations are to truly represent pen conditions (and hence cattle responses to predicted HLI and AHLU) then there needs to be a strong correlation between pen micro climate and weather station data. However this was not the case for 4 of the 6 feedlots used in this study. These results highlight the importance of knowing the differences between pens and weather station data. Ideally pen conditions need to be assessed on a regular basis to determine deviations at least for temperature and humidity between pens and weather stations. Not knowing differences between pens and the weather station could result in an over or underestimate of animal responses to current and predicted HLI and AHLU. However at this stage it is probably best to situate the weather station as close to the animal as possible. Future heat load modelling needs to incorporate as much pen data as possible.

5.4 Heat load index and accumulated heat load units

The location of the weather stations influenced (significant difference between pen and office weather stations) the HLI calculations at feedlots 2, 3, 4, 5 and 6. The AHLU was significantly different between the pen and office weather station at all sites. Wind speed differed (*P<0.001*) between the two weather stations at each site. Generally lower mean WS (5 of the 6 feedlots) resulted in greater AHLU. At Feedlot 4 for example the wind speed was greater at the pen location than at the office location (2.24 ± 1.04 m/s vs 1.74 ± 1.04 m/s respectively). At feedlot 4 the AHLU were at various times 20 to 70 units greater at the office weather station compared with the pen weather station. For Feedlot 2 the AHLU on hot days was 10 to 20 units greater at the pen weather station than at the office weather station. As with Feedlot 4 the differences appear to be primarily due to wind speed.

As stated in Section 5.1 the correlations between the weather stations (at each feedlot) for wind speed were strong for Feedlots 1, 3, 5 and 6, moderate for Feedlot 2 and weak for Feedlot 4. The feedlots with the greatest variation in wind speed between the two weather stations had the greatest variation in AHLUs. A difference of 20 to 70 units (e.g. 30 vs. 100 units – which was seen at Feedlot 4) is enough variation for predicted AHLU to seriously under or overestimate the impact on cattle. If the measure AHLU is 30 and the actual at pen level is 100 there is a considerable underestimation of the climatic impacts on the animals.

Not knowing climatic differences between pens and the weather stations could result in an over or underestimate of current and predicted HLI and AHLU.

It is clear that the siting of the weather station could over or underestimate HLI and AHLU relative to animal location. This could explain some of the variance seen between commercial feedlots in terms of the perceived accuracy of the HLI and AHLU.

5.5 Panting score

As previously mentioned summer conditions were not extreme. As such we were not able to obtain a large number of panting scores greater than 2.5. Thus the data set for the extreme events is limited. Nevertheless over 980,000 panting score counts were obtained over 5 breed types.

Three multivariable logistic regression models were used to assess the AHLU and breed type. First, separate models were run with single fixed effects – adjusted AHLU ($AHLU_{ADJ}$) and then breed type. The third model contained the two fixed effects in the one final model – adjusted AHLU and breed type. The best model was then determined using Akaike Information Criteria (AIC).

Model 1: A breed type adjusted AHLU ($AHLU_{ADJ}$) level of 40 was associated with a predicted probability of elevated panting score of 62.5% with a 95% confidence interval ranging from about 28% to 88% (Figure 13). This suggests that if an observer were to scan a large number of pens of cattle across different feedlots when $AHLU_{ADJ}$ was 40, then the average % of cattle observed across all pens with panting scores of 2 or greater would be 62.5%.

Model 2: Breed type was significantly associated with higher panting score. Compared to the reference breed type category (BT 1: 100% *Bos taurus*), the odds of higher panting score decreases for BT 2 (100% Euro), BT 3 (25% *Bos indicus*) and BT 4 (50% *Bos indicus*). The odds of a higher panting score were 75%, 83% and 99% lower respectively for BT2, BT3 and BT4 compared to BT1. BT1 is associated with a predicted probability of an elevated panting score of 8% with a 95% confidence interval ranging from about 5% to 12% (Figure16). This suggests that if an observer were to scan a large number of pens of 100*% Bos taurus* cattle across different feedlots, then the average % of cattle with panting scores of 2 or greater would be 8%.

The very small number of observations involving 100% *Bos indicus* cattle is the main reason why the 95% confidence interval for the predicted probability for this breed type is so wide (covering the entire predicted probability range). More observations from *Bos indicus* cattle in future studies would aid in producing more precise estimates for 100% *Bos indicus* cattle.

Model 3: The model was then used to generate predicted probabilities at the pen level with animals having panting scores of 2 or greater across a range of $AHLU_{ADJ}$ values and for each breed type. The results from this model clearly show the impact of breed type at a given $AHLU_{ADJ}$ and provide useful estimates of the predicted outcomes (proportion of animals with elevated panting scores) for different combinations of adjusted AHLU and breed type.

For BT 1, $AHLU_{ADJ}$ levels of 40 are associated with a predicted probability of elevated panting score of about 60% with a 95% confidence interval ranging from about 28% to 78% (Figure 19). This suggests that if an observer were to scan a large number of pens of 100% *Bos taurus* cattle across different feedlots when the $AHLU_{ADJ}$ was 40, then the average percentage of cattle with panting scores of 2 or greater would be 60%.

AIC: The model comparison suggests that Model 3 performed better that Models 1 and 2.

Summary: The variation in panting score among pens is minimal – suggesting that pen level variability may be less important as an explanatory factor for panting score. However a small number of pens had an elevated likelihood of elevated panting score but the overall impact was small. This finding has important ramifications. If there were substantial unexplained variance in terms of elevated panting score at the pen level, then this would direct more attention to understanding particular pen attributes within a feedlot. However, the fact that the model suggests there is little pen level variation suggests that this is not a major explanatory factor in heat stress. Further work is needed to confirm this finding.

In contrast there is substantial unexplained variation in elevated panting scores at the feedlot level. These findings suggest that further work is needed to identify characteristics at the feedlot level that may be contributing to the unexplained variance between feedlots (see Figure 21). Identifying specific attributes that explain this variance will provide the opportunity to develop risk mitigation strategies to counter the effects of these drivers.

Understanding why there is variation is important if any deficiencies in the heat load model are to be determined. Variations in cattle response may be due to pens (although the data presented in this study suggests that pen had only a minor impact), the feedlot (a moderate effect on panting score) and breed type (major effect). However factors such as degree of adaptation, health status and growth performance play a role.

5.6 Dry matter and energy intake

The effect of HLI and AHLU on dry matter and energy intake were examined. DMI was negatively affected by AHLU (*$P<0.001$*) with DMI decreasing by 0.01 kg per unit increase in accumulated heat load. However the R^2 was only 12.5% so the model is inadequate in predicting variations in DMI. Similarly for metabolisable energy (ME) intake (MJ/kg DMI) and total energy intake (MJ) the models were inadequate in explaining variations in energy intake. AHLU had a negative effect on ME intake decreased by 0.11 MJ per one unit increase in AHLU.
As previously mentioned there were only a few heat load periods over the duration of the study. Further to this management practices in regards to heat load feeding strategies have probably impacted on the results. Changes in the amount of feed offered prior to and following a heat event when AHLU may be decreasing (during the post heat event) have masked some of the responses.

5.7 Meeting project objectives

1. ***Determine the adequacy of the current heat load model (Gaughan et al. 2008) to predict excessive heat load of commercial feedlot cattle.*** Based on the results from objective 3 and 4 this objective has been partially met. A lack of very hot to extreme conditions over the 2017/18 summer at the study locations limited panting score >2.5 data across all breed types. Given that there was sufficient data to determine that increasing AHLU resulted in an increased probability of PS>2.

2\. ***Determine the adequacy of the current heat load model to explain variation in energy intake of feedlot cattle and cattle mortality***. There was insufficient data in relation to mortality and morbidity to fully explore this objective. Although this objective was not met it is not necessarily a failure of the project as such. More importantly it demonstrated that overall cattle health over the data collection period was very good.

3. ***Determine differences in the precision and accuracy of AHLU to explain variation in panting score with weather stations that have a true black globe temperature sensor vs. weather stations that record solar radiation and temperature (and calculate black globe temperature by formula).*** This objective has been met. Data from the study has shown that there is a need to change the algorithm for calculating black globe temperature.

4\. ***Determine the precision and accuracy of AHLU to explain variation in panting scores of feedlot cattle for weather stations located near the feedlot office vs. those adjacent to***

feedlot pens. Data from this study has shown that the location of the weather station is more important on some feedlots compared to others. The study has also demonstrated that the location of the weather station could have a significant effect on AHLU if the weather station is located in an area with less or more wind than observed in the pens. It was also demonstrated using THI that pen conditions (e.g. temperature and humidity) can vary significantly from these data obtained from weather stations. Siting is probably somewhat feedlot specific.

6 Conclusions/recommendations

6.1 Conclusions

6.1.1 Weather station location

The siting of weather stations at feedlots needs careful consideration. Site location had a significant effect on AHLU. Whilst high correlations and agreement between pen and office weather stations were observed at the some feedlots, at some sites agreement was poor. Wind speed was only moderately correlated, whilst agreement for humidity was dependant on feedlot. Attempts should be made to assess conditions in pens relative to the preferred site for the weather station. In the current study, two weather stations and up to 16 pens were used to obtain micro-climate data. The diversity of conditions within feedlots complicates heat load modelling.

6.1.2 Black globe calculations

The data from this study suggests that the calculation of black globe temperature from solar radiation and ambient temperature results in less robust predictions than utilising a weather station with a black globe sensor. Over or underestimation of black globe temperature occurred dependant on feedlot site. Ideally all weather stations should be fitted with a black globe sensor.

6.1.3 Panting score and AHLU

Panting score and AHLU: Using breed type classifications in the model in combination with AHLU adjusted for breed ($AHLU_{ADJ}$) a logistic regression model that predicted probability of panting score ≥ 2 was developed. Ninety-five percent confidence intervals were placed around each predicted probability for each breed type. A significant effect of increasing $AHLU_{ADJ}$ on the probability of panting score was observed across breeds. Whilst this demonstrates AHLU is a significant variable determining panting of feedlot cattle, relatively wide confidence intervals around predictions necessitate further investigations of feedlot and pen level factors to explain variation in panting score.

Increasing *Bos indicus* content decreased predicted probabilities of panting score exceeding the threshold (≥ 2). Further research is required to evaluate the adequacy of the model on independent data sets.

Weather conditions during the study were mild and modelling of open mouthed panting was not possible. Negligible mortality due to heat load were observed. Further research is required to develop logistic regression models to predict probability of these adverse animal welfare outcomes.

6.1.4 Dry matter intake

Although there were significant effects of AHLU on DMI/energy responses the correlations were very weak. Management practices associated with feed management during time of high heat load may have had an impact here. In addition there were few hot periods during data collection.

6.2 Recommendations

The following recommendations have arisen from this study

1. Accumulated heat load is a significant variable in explaining heat load response of feedlot cattle, however improvement in prediction confidence intervals of panting scores ≥ 2 is required across feedlot sites and breed types.
2. Further independent data is required to evaluate the logistic regression model adequacy developed in this project. Adjustments to the heat load model valuation should be evaluated during the summer of 2018/19.
3. Attempts to obtain additional data from cattle exposed to high heat load (in the field) are required to model probability of open mouth panting due to mild summer conditions experienced during this project.
4. Ideally all weather stations should be fitted with a black globe sensor.
5. There is a need to understand how different pen micro-climates influence predictability of heat load responses of feedlot cattle compared to weather stations located outside of pens.

7 Bibliography

Gaughan et al. 2008. A new heat load index for feedlot cattle. Journal of Animal Science 86:226 – 234.

8 Appendix 1

Table 1A. Monthly weather data – Feedlot 5 (pen)

Pen	Dec	Jan	Feb	Mar	Apr
TA					
Mean	25.8 ± 0.08	27.6 ± 0.08	24.7 ± 0.09	24.3 ± 0.07	21.6 ± 0.07
Max	38.8	39.4	41.0	35.7	33.0
Min	10.8	14.6	14.8	14.4	9.5
RH					
Mean	56.1 ± 0.31	51.1 ± 0.31	60.9 ± 0.33	63.1 ± 0.29	59.2 ± 0.28
Max	95.3	93.6	95.3	96.6	93.3
Min	16.1	10.8	15.0	22.5	22.9
SR					
Mean	266.9 ± 5.11	280.6 ± 5.22	215.2 ± 4.67	190.5 ± 3.91	164.4 ± 3.48
Max	1193.6	1209.0	1111.6	1002.1	792.8
Min	0.0	0.0	0.0	0.0	0.0
WS					
Mean	2.4 ± 0.02	2.4 ± 0.02	2.4 ± 0.02	2.1 ± 0.02	1.8 ± 0.02
Max	9.0	10.4	6.6	6.8	6.0
Min	0.0	0.0	0.1	0.0	0.0
BGT					
Mean	29.1 ± 0.14	31.2 ± 0.14	28.4 ± 0.14	27.0 ± 0.12	24.2 ± 0.13
Max	49.8	53.3	53.4	49.7	46.1
Min	9.4	12.4	13.6	13.0	7.9
HLI					
Mean	70.1 ± 0.20	72.5 ± 0.20	70.4 ± 0.20	68.9 ± 0.20	63.0 ± 0.20
Max	102.5	108.1	107.6	104.7	94.7
Min	42.3	42.3	50.7	49.7	42.5
AHLU					
Mean	5.1 ± 0.17	7.7 ± 0.22	6.8 ± 0.22	4.6 ± 0.22	0.3 ± 0.20
Max	102.5	82.5	68.2	74.0	11.0
Min	0.0	0.0	0.0	0.0	0.0
THI					
Mean	77.5 ± 0.09	74.4 ± 0.09	72.8 ± 0.09	71.3 ± 0.08	67.2 ± 0.09
Max	83.3	83.4	85.3	83.2	77.7
Min	52.4	58.2	58.6	57.9	49.7

Table 2A. Monthly weather data – Feedlot 5 (office)

Pen	Dec	Jan	Feb	Mar	Apr
TA					
Mean	25.7 ± 0.08	27.6 ± 0.07	25.7 ± 0.09	24.3 ± 0.07	21.6 ± 0.07
Max	38.6	39.5	40.3	35.8	32.9
Min	12.9	15.3	15.0	13.8	9.8
RH					
Mean	55.9 ± 0.31	50.9 ± 0.30	60.7 ± 0.33	62.8 ± 0.29	58.9 ± 0.28
Max	95.4	93.1	95.9	96.8	94.3
Min	16.2	11.1	15.2	22.8	22.8
SR					
Mean	284.7 ± 5.47	303.4 ± 5.66	234.4 ± 5.10	211.0 ± 4.34	184.4 ± 3.90
Max	1220.1	1296.3	1210.8	1082.4	881.4
Min	0.0	0.0	0.0	0.0	0.0
WS					
Mean	2.2 ± 0.02	2.1 ± 0.02	2.3 ± 0.02	2.0 ± 0.02	1.8 ± 0.02
Max	6.9	8.2	7.0	7.6	5.9
Min	0.0	0.0	0.1	0.0	0.0
BGT					
Mean	29.2 ± 0.14	31.5 ± 0.13	28.6 ± 0.14	27.3 ± 0.13	24.3 ± 0.13
Max	49.9	54.0	52.3	49.4	44.5
Min	11.1	13.0	13.5	12.5	8.0
HLI					
Mean	70.5 ± 0.20	73.4 ± 0.20	70.8 ± 0.20	69.4 ± 0.19	63.0 ± 0.20
Max	103.4	109.2	104.1	105.0	93.9
Min	42.7	42.1	51.3	50.5	42.7
AHLU					
Mean	5.5 ± 0.17	11.1 ± 0.28	7.3 ± 0.23	5.2 ± 0.19	0.3 ± 0.20
Max	57.5	91.7	72.7	66.5	10.6
Min	0.0	0.0	0.0	0.0	0.0
THI					
Mean	72.4 ± 0.09	74.3 ± 0.07	72.4 ± 0.09	71.2 ± 0.08	67.2 ± 0.09
Max	83.1	84.4	74.9	82.9	77.4
Min	55.7	59.3	58.9	56.9	50.2

Table 3A. Monthly weather data – Feedlot 6 (pen)

Pen	Dec	Jan	Feb	Mar	Apr
TA					
Mean	26.5 ± 0.08	28.0 ± 0.08	25.7 ± 0.09	24.6 ± 0.07	22.2 ± 0.07
Max	39.3	39.3	41.5	35.0	33.1
Min	15.5	15.5	14.5	15.4	11.6
RH					
Mean	52.2 ± 0.30	53.8 ± 0.31	67.0 ± 0.34	66.5 ± 0.26	61.3 ± 0.28
Max	96.6	96.1	97.2	95.3	95.0
Min	16.1	11.9	16.8	26.1	21.4
SR					
Mean	292.0 ± 5.38	295.0 ± 5.43	229.3 ± 5.00	210.6 ± 4.30	191.6 ± 4.00
Max	1172.4	1247.5	1212.3	1204.5	902.7
Min	0.0	0.0	0.0	0.0	0.0
WS					
Mean	2.6 ± 0.02	2.5 ± 0.01	2.7 ± 0.02	2.5 ± 0.02	2.2 ± 0.02
Max	10.1	7.3	10.6	7.6	7.0
Min	0.0	0.0	0.4	0.0	0.0
BGT					
Mean	29.7 ± 0.13	31.3 ± 0.13	28.1 ± 0.14	26.9 ± 0.11	24.4 ± 0.12
Max	51.7	48.5	52.5	49.5	44.2
Min	13.3	15.0	13.5	13.7	10.2
HLI					
Mean	71.2 ± 0.19	73.7 ± 0.20	71.5 ± 0.20	69.4 ± 0.18	63.3 ± 0.19
Max	105.9	108.2	107.6	106.3	99.2
Min	43.3	40.8	48.5	51.3	43.8
AHLU					
Mean	5.7 ± 0.19	7.6 ± 0.21	14.2 ± 0.39	7.1 ± 0.24	0.5 ± 0.04
Max	74.2	82.3	117.9	91.4	33.1
Min	0.0	0.0	0.0	0.0	0.0
THI					
Mean	73.6 ± 0.08	75.2 ± 0.06	73.5 ± 0.09	72.2 ± 0.08	68.3 ± 0.08
Max	84.4	85.3	86.0	83.1	79.1
Min	59.4	61.4	58.1	59.7	53.5

Table 4A. Monthly weather data – Feedlot 6 (office)

Pen	Dec	Jan	Feb	Mar	Apr
TA					
Mean	26.2 ± 0.07	27.7 ± 0.07	25.4 ± 0.09	24.4 ± 0.07	22.0 ± 0.07
Max	37.9	39.5	41.2	34.9	32.7
Min	14.0	16.4	14.3	15.2	11.3
RH					
Mean	55.5 ± 0.30	52.2 ± 0.31	65.5 ± 0.34	65.2 ± 0.26	59.7 ± 0.28
Max	96.7	94.8	96.5	94.5	94.2
Min	16.3	11.9	15.6	25.1	21.1
SR					
Mean	286.9 ± 5.41	304.2 ± 5.73	221.9 ± 4.94	209.5 ± 4.30	188.5 ± 4.00
Max	1289.0	1217.9	1152.4	1217.0	961.3
Min	0.0	0.0	0.0	0.0	0.0
WS					
Mean	2.6 ± 0.02	2.5 ± 0.02	2.7 ± 0.02	2.5 ± 0.02	2.2 ± 0.02
Max	13.0	8.5	10.6	7.3	7.1
Min	0.0	0.0	0.4	0.0	0.0
BGT					
Mean	29.6 ± 0.13	31.3 ± 0.13	28.0 ± 0.14	26.9 ± 0.12	24.4 ± 0.12
Max	52.9	49.4	52.4	51.7	44.5
Min	12.3	15.0	13.6	13.8	10.1
HLI					
Mean	70.8 ± 0.19	73.0 ± 0.19	70.9 ± 0.20	69.0 ± 0.18	62.8 ± 0.19
Max	107.1	106.1	111.4	112.3	99.0
Min	42.1	41.0	48.4	51.0	42.0
AHLU					
Mean	4.9 ± 0.17	5.8 ± 0.16	10.8 ± 0.31	6.1 ± 0.21	0.6 ± 0.04
Max	63.5	61.9	94.9	80.0	34.4
Min	0.0	0.0	0.0	0.0	0.0
THI					
Mean	73.0 ± 0.07	74.7 ± 0.06	73.0 ± 0.09	71.7 ± 0.07	67.8 ± 0.08
Max	83.7	83.8	85.5	82.4	78.4
Min	57.4	60.8	57.7	59.3	52.9

Table 5A. Monthly weather data – Feedlot 2 (pen)

Pen	Dec	Jan	Feb	Mar	Apr
TA					
Mean	25.3 ± 0.10	28.0 ± 0.07	26.3 ± 0.10	23.2 ± 0.09	20.8 ± 0.10
Max	41.1	40.6	43.0	37.6	37.9
Min	11.5	16.8	12.4	8.1	12.0
RH					
Mean	51.0 ± 0.32	53.8 ± 0.31	45.5 ± 0.24	44.7 ± 0.24	47.1 ± 0.26
Max	95.7	96.1	83.9	88.0	84.6
Min	11.0	11.9	12.9	10.7	22.7
SR					
Mean	287.0 ± 5.50	294.9 ± 5.43	269.6 ± 5.39	223.7 ± 4.34	151.7 ± 3.27
Max	1417.5	1247.5	1159.1	930.1	743.0
Min	0.0	0.0	0.0	0.0	0.0
WS					
Mean	2.1 ± 0.02	2.5 ± 0.01	2.2 ± 0.02	2.1 ± 0.02	1.7 ± 0.02
Max	6.5	7.3	9.0	7.2	8.4
Min	0.0	0.0	0.0	0.0	0.0
BGT					
Mean	28.1 ± 0.15	31.3 ± 0.13	28.8 ± 0.14	25.5 ± 0.14	22.4 ± 0.14
Max	52.9	48.5	55.7	46.5	44.4
Min	10.0	15.0	11.1	6.6	10.9
HLI					
Mean	67.0 ± 0.20	73.7 ± 0.20	65.3 ± 0.21	60.1 ± 0.20	56.0 ± 0.20
Max	102.8	108.2	102.5	92.7	90.3
Min	41.5	40.8	40.2	39.0	42.5
AHLU					
Mean	3.3 ± 0.14	7.6 ± 0.21	1.5 ± 0.09	0.2 ± 0.02	0.01 ± 0.00
Max	58.7	82.3	40.1	10.8	2.3
Min	0.0	0.0	0.0	0.0	0.0
THI					
Mean	70.9 ± 0.11	75.2 ± 0.06	71.6 ± 0.10	68.0 ± 0.09	65.0 ± 0.11
Max	84.6	85.3	84.9	80.1	80.0
Min	53.2	61.4	54.7	48.1	54.3

Table 6A. Monthly weather data – feedlot 2 (office)

Pen	Dec	Jan	Feb	Mar	Apr
TA					
Mean	25.1 ± 0.10	28.1 ± 0.10	26.2 ± 0.10	23.3 ± 0.09	21.1 ± 0.10
Max	39.4	44.8	42.4	37.2	37.4
Min	11.5	11.3	12.1	8.4	7.1
RH					
Mean	49.1 ± 0.32	41.5 ± 0.30	38.5 ± 0.23	41.2 ± 0.24	42.8 ± 0.25
Max	95.8	95.1	84.8	87.9	83.9
Min	11.5	11.3	12.6	9.2	10.0
SR					
Mean	298.9 ± 5.69	302.7 ± 5.71	279.2 ± 5.53	234.5 ± 4.59	164.2 ± 3.48
Max	1387.0	1173.6	1259.1	1013.4	827.5
Min	0.0	0.0	0.0	0.0	0.0
WS					
Mean	2.5 ± 0.02	2.9 ± 0.02	2.7 ± 0.03	2.8 ± 0.03	2.2 ± 0.03
Max	9.4	11.0	11.9	10.6	11.2
Min	0.0	0.0	0.0	0.0	0.0
BGT					
Mean	27.7 ± 0.14	30.7 ± 0.14	28.6 ± 0.14	25.5 ± 0.13	22.7 ± 0.14
Max	52.7	54.9	54.1	47.0	44.5
Min	10.3	10.5	9.8	6.8	5.5
HLI					
Mean	65.2 ± 0.20	68.1 ± 0.21	63.4 ± 0.21	58.3 ± 0.19	54.3 ± 0.19
Max	101.4	100.6	100.4	91.8	89.4
Min	40.5	38.3	38.1	35.7	36.6
AHLU					
Mean	2.3 ± 0.11	3.5 ± 0.13	0.6 ± 0.05	0.1 ± 0.01	0.01 ± 0.00
Max	47.6	43.5	24.8	5.9	0.9
Min	0.0	0.0	0.0	0.0	0.0
THI					
Mean	70.5 ± 0.10	73.6 ± 0.10	71.3 ± 0.09	67.9 ± 0.09	65.2 ± 0.10
Max	84.0	86.9	83.9	79.5	79.4
Min	53.2	53.1	54.4	48.7	46.3

Table 7A. Monthly weather data – Feedlot 1 (pen)

Pen	Dec	Jan	Feb	Mar	Apr
TA					
Mean	23.0 ± 0.09	26.5 ± 0.10	24.2 ± 0.09	21.1 ± 0.09	18.6 ± 0.09
Max	37.6	42.4	39.7	35.5	36.0
Min	9.0	10.3	8.7	6.2	3.8
RH					
Mean	57.5 ± 0.31	49.7 ± 0.28	49.4 ± 0.24	54.0 ± 0.26	59.7 ± 0.25
Max	96.7	94.2	88.6	94.8	93.2
Min	15.3	13.4	19.3	21.3	20.8
SR					
Mean	313.4 ± 6.05	336.7 ± 6.23	287.1 ± 5.82	234.3 ± 4.75	164.4 ± 3.62
Max	1367.5	1288.2	1238.9	1121.9	833.7
Min	0.0	0.0	0.0	0.0	0.0
WS					
Mean	2.1 ± 0.02	2.3 ± 0.02	2.0 ± 0.02	2.0 ± 0.02	1.7 ± 0.02
Max	9.6	7.2	8.6	8.5	7.9
Min	0.0	0.0	0.0	0.0	0.0
BGT					
Mean	25.6 ± 0.14	29.5 ± 0.15	26.9 ± 0.14	23.6 ± 0.14	20.5 ± 0.14
Max	48.9	52.7	49.5	44.3	46.8
Min	7.6	9.2	7.4	4.9	2.8
HLI					
Mean	64.7 ± 0.20	69.3 ± 0.22	64.8 ± 0.22	59.8 ± 0.21	56.6 ± 0.20
Max	101.1	102.8	96.0	91.3	95.5
Min	41.2	41.2	39.1	34.7	38.1
AHLU					
Mean	1.6 ± 0.10	4.9 ± 0.16	0.8 ± 0.05	0.1 ± 0.01	0.1 ± 0.00
Max	52.5	48.2	26.4	4.5	4.2
Min	0.0	0.0	0.0	0.0	0.0
THI					
Mean	68.7 ± 0.11	72.7 ± 0.11	69.8 ± 0.10	66.1 ± 0.10	62.9 ± 0.11
Max	83.4	84.6	83.7	79.4	80.0
Min	48.9	51.0	49.2	44.1	39.9

Table 8A. Monthly weather data – Feedlot 1 (office)

Pen	Dec	Jan	Feb	Mar	Apr
TA					
Mean	23.2 ± 0.09	26.7 ± 0.10	24.3 ± 0.09	21.4 ± 0.08	19.1 ± 0.09
Max	38.4	43.3	39.6	35.5	36.0
Min	10.3	10.5	10.9	7.6	7.3
RH					
Mean	54.6 ± 0.31	47.0 ± 0.28	46.6 ± 0.23	51.5 ± 0.25	56.4 ± 0.24
Max	96.1	93.8	88.0	94.5	90.8
Min	13.4	11.7	18.2	20.3	20.5
SR					
Mean	289.4 ± 5.58	309.1 ± 5.71	268.6 ± 5.43	218.7 ± 4.42	149.9 ± 3.29
Max	1232.0	1177.6	1168.3	1008.0	759.4
Min	0.0	0.0	0.0	0.0	0.0
WS					
Mean	2.0 ± 0.02	2.1 ± 0.02	2.0 ± 0.02	1.9 ± 0.02	1.8 ± 0.02
Max	10.8	6.7	9.6	8.9	8.8
Min	0.0	0.0	0.0	0.0	0.0
BGT					
Mean	26.0 ± 0.14	30.0 ± 0.15	27.4 ± 0.14	24.1 ± 0.13	21.2 ± 0.13
Max	48.9	55.0	51.4	44.8	46.9
Min	8.3	9.3	9.9	6.8	5.8
HLI					
Mean	64.5 ± 0.20	69.6 ± 0.22	64.8 ± 0.22	60.0 ± 0.21	56.5 ± 0.20
Max	99.7	102.3	97.5	93.3	91.3
Min	40.7	41.6	39.2	35.6	39.2
AHLU					
Mean	1.5 ± 0.09	7.0 ± 0.21	1.2 ± 0.06	0.2 ± 0.01	0.1 ± 0.00
Max	44.0	69.9	30.1	7.3	3.1
Min	0.0	0.0	0.0	0.0	0.0
THI					
Mean	68.7 ± 0.10	72.6 ± 0.11	69.8 ± 0.10	66.3 ± 0.10	63.5 ± 0.10
Max	83.6	84.9	83.5	79.3	79.6
Min	51.5	51.3	52.9	46.3	46.5

Table 9A. Monthly weather data – Feedlot 4 (pen)

Pen	Dec	Jan	Feb	Mar	Apr
TA					
Mean	26.0 ± 0.09	27.3 ± 0.09	25.3 ± 0.10	23.7 ± 0.08	20.6 ± 0.08
Max	40.4	40.5	38.6	38.1	32.3
Min	13.5	8.0	13.4	11.7	10.0
RH					
Mean	53.4 ± 0.30	47.3 ± 0.30	50.3 ± 0.10	57.8 ± 0.28	60.3 ± 0.26
Max	95.0	95.5	94.1	93.0	94.2
Min	18.8	9.1	5.4	16.9	23.6
SR					
Mean	-	-	282.8 ± 5.82	229.9 ± 4.77	190.5 ± 4.02
Max	-	-	1262.0	1181.4	935.3
Min	-	-	0.0	0.0	0.0
WS					
Mean	2.2 ± 0.02	2.2 ± 0.02	2.4 ± 0.02	2.2 ± 0.02	2.0 ± 0.02
Max	7.5	7.8	8.8	7.1	8.9
Min	0.1	0.2	0.1	0.1	0.1
BGT					
Mean	-	-	28.3 ± 0.15	26.5 ± 0.14	23.0 ± 0.13
Max	-	-	50.5	50.4	45.4
Min	-	-	12.0	11.5	8.4
HLI					
Mean	-	-	66.7 ± 0.22	65.8 ± 0.21	60.7 ± 0.20
Max	-	-	101.4	103.1	97.9
Min	-	-	38.1	42.3	42.7
AHLU					
Mean	-	-	4.2 ± 0.17	3.9 ± 0.13	0.9 ± 0.05
Max	-	-	70.7	47.9	29.0
Min	-	-	0.0	0.0	0.0
THI					
Mean	72.4 ± 0.09	73.4 ± 0.09	71.1 ± 0.09	68.9 ± 0.08	65.8 ± 0.09
Max	84.5	84.7	83.0	82.0	77.7
Min	56.6	50.4	56.3	53.6	50.6

Table 10A. Monthly weather data – Feedlot 4 (office)

Pen	Dec	Jan	Feb	Mar	Apr
TA					
Mean	26.0 ± 0.09	27.3 ± 0.09	25.4 ± 0.10	23.7 ± 0.09	20.5 ± 0.08
Max	39.7	40.6	38.5	37.7	32.3
Min	13.5	18.2	12.9	12.3	8.5
RH					
Mean	53.1 ± 0.29	47.2 ± 0.29	50.1 ± 0.32	57.7 ± 0.23	60.0 ± 0.26
Max	94.3	94.6	93.4	91.6	93.8
Min	18.0	9.0	4.9	16.5	22.2
SR					
Mean	-	-	287.6 ± 5.94	234.2 ± 4.88	192.6 ± 4.09
Max	-	-	1347.0	1243.1	981.1
Min	-	-	0.0	0.0	0.0
WS					
Mean	1.8 ± 0.02	1.7 ± 0.02	1.9 ± 0.02	1.7 ± 0.02	1.4 ± 0.01
Max	5.7	6.9	6.6	5.9	5.0
Min	0.0	0.0	0.0	0.0	0.0
BGT					
Mean	-	-	28.5 ± 0.16	26.6 ± 0.14	23.1 ± 0.14
Max	-	-	51.7	49.0	44.4
Min	-	-	11.1	10.6	6.6
HLI					
Mean	-	-	67.8 ± 0.23	66.8 ± 0.21	61.5 ± 0.21
Max	-	-	99.0	103.4	95.3
Min	-	-	37.5	41.6	42.9
AHLU					
Mean	-	-	6.0 ± 0.21	5.7 ± 0.18	0.1 ± 0.05
Max	-	-	79.5	61.2	30.9
Min	-	-	0.0	0.0	0.0
THI					
Mean	73.4 ± 0.09	73.5 ± 0.09	71.2 ± 0.09	69.9 ± 0.08	65.7 ± 0.10
Max	84.0	84.8	82.9	82.0	77.9
Min	56.6	56.2	55.5	54.5	48.2

Table 11A. Monthly weather data – Feedlot 3 (pen)

Pen	Dec	Jan	Feb	Mar	Apr
TA					
Mean	27.8 ± 0.10	29.6 ± 0.09	27.8 ± 0.09	26.0 ± 0.08	22.4 ± 0.09
Max	43.0	43.0	43.1	39.1	35.3
Min	12.3	12.8	15.1	12.1	7.5
RH					
Mean	43.0 ± 0.27	38.2 ± 0.28	38.5 ± 0.28	45.5 ± 0.28	46.7 ± 0.23
Max	93.0	90.2	87.7	91.2	90.9
Min	8.4	3.7	4.9	11.7	13.9
SR					
Mean	294.3 ± 5.42	288.6 ± 5.30	247.1 ± 5.02	215.9 ± 4.26	166.6 ± 3.50
Max	1202.6	1150.0	1022.0	1041.3	787.7
Min	0.0	0.0	0.0	0.0	0.0
WS					
Mean	3.0 ± 0.02	2.9 ± 0.03	2.8 ± 0.02	2.5 ± 0.02	2.0 ± 0.02
Max	8.3	10.9	7.7	9.6	9.4
Min	0.0	0.0	0.0	0.0	0.0
BGT					
Mean	30.5 ± 0.14	32.5 ± 0.14	30.4 ± 0.14	28.5 ± 0.13	25.5 ± 0.14
Max	53.7	53.1	53.2	50.1	46.7
Min	10.9	12.0	14.2	10.9	5.8
HLI					
Mean	68.1 ± 0.19	70.4 ± 0.21	66.8 ± 0.21	65.4 ± 0.21	59.3 ± 0.21
Max	100.8	101.0	99.2	103.9	93.0
Min	43.0	41.0	37.5	36.6	37.1
AHLU					
Mean	1.8 ± 0.07	4.7 ± 0.14	1.7 ± 0.08	1.8 ± 0.11	0.2 ± 0.01
Max	26.5	56.4	37.8	67.0	6.1
Min	0.0	0.0	0.0	0.0	0.0
THI					
Mean	73.5 ± 0.09	75.3 ± 0.08	73.2 ± 0.08	71.8 ± 0.08	67.4 ± 0.10
Max	85.4	85.3	84.1	82.6	79.3
Min	54.5	55.7	59.0	54.7	47.2

Table 12A. Monthly weather data – Feedlot 3 (office)

Pen	Dec	Jan	Feb	Mar	Apr
TA					
Mean	27.7 ± 0.10	29.7 ± 0.08	27.9 ± 0.09	26.1 ± 0.08	22.6 ± 0.08
Max	42.5	42.5	42.7	38.5	35.3
Min	12.5	13.5	16.2	12.5	8.7
RH					
Mean	46.3 ± 0.27	42.4 ± 0.27	43.1 ± 0.26	49.3 ± 0.27	50.7 ± 0.22
Max	95.7	92.9	91.0	96.9	93.5
Min	12.8	9.7	10.4	15.7	19.1
SR					
Mean	289.8 ± 5.35	288.9 ± 5.30	250.5 ± 5.08	218.1 ± 4.33	169.7 ± 3.57
Max	1191.1	1120.4	1105.5	1002.2	784.2
Min	0.0	0.0	0.0	0.0	0.0
WS					
Mean	3.2 ± 0.02	3.1 ± 0.03	2.8 ± 0.02	2.5 ± 0.02	2.1 ± 0.02
Max	9.4	13.0	8.4	10.0	8.6
Min	0.0	0.0	0.0	0.0	0.0
BGT					
Mean	30.3 ± 0.14	32.2 ± 0.13	30.3 ± 0.13	28.2 ± 0.13	24.5 ± 0.13
Max	54.6	53.9	51.1	49.0	46.2
Min	10.9	13.0	15.3	11.2	7.1
HLI					
Mean	68.8 ± 0.19	71.4 ± 0.20	68.1 ± 0.21	66.2 ± 0.20	60.4 ± 0.21
Max	102.5	100.9	99.3	102.9	96.9
Min	43.5	41.6	38.6	37.9	38.5
AHLU					
Mean	2.5 ± 0.09	6.5 ± 0.17	2.4 ± 0.10	2.1 ± 0.12	0.4 ± 0.02
Max	33.1	64.3	42.1	72.4	10.8
Min	0.0	0.0	0.0	0.0	0.0
THI					
Mean	73.9 ± 0.10	76.0 ± 0.08	73.9 ± 0.08	72.4 ± 0.08	68.0 ± 0.10
Max	86.2	86.2	85.2	83.0	79.9
Min	54.3	56.7	60.6	55.2	49.1