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Effect of weather conditions ante-mortem on the incidence of dark cutting in feedlot finished cattle – A retrospective analysis

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Abstract

The aim of this experiment was to conduct a retrospective analysis of historical Meat Standard Australia (MSA) carcass data in combination with Bureau of Meteorology (BOM) data to assess the impact of climatic conditions prior to consignment on the incidence of dark cutting. MSA data from 2,795,754 carcasses from 20 feedlots over a 6 year period (2012 to 2017 inclusive) was sourced. These cattle were consigned in 27,073 lots at 17 different abattoirs. The BOM data was provided as half-hourly data recordings for each weather station nearest to feedlots 1 to 17 over a 6 year period. The half-hourly data was amalgamated into daily observations and a series of predictors was generated covering different lag period prior to consignment between 24 hours and 28 days. Between 6 months to 6 years of data from feedlot weather stations was also obtained but was deemed too small, unreliable and inaccurate. The amalgamation of the MSA and BOM data sets allowed the percentage of dark cutters per lot to be analysed. The analysis showed that the fixed effects alone (Feedlot, processor, sex and HGP) account for around 21% of variation in dark cutting with feedlot and processor having the largest impacts with a range in dark cutting incidence between the highest and lowest incidence of 10.1% and 8.3% respectively ($P<0.01$). Male and mixed sex consignment groups had around 2% and 0.5% lower incidence of dark cutting than female groups respectively ($P<0.01$). Hormone growth promotants had either no effect or reduced the incidence of dark cutting. The inclusion of the weather terms and THI index into the base model had a minimal impact and explained an estimated 0.1 to 0.2% extra variance in dark cutting. Higher maximum temperatures, humidity and THI indexes all significantly increased the incidence of dark cutting in the 3 to 28 day lag models ($P<0.05$) but not in the 48 hours proceeding consignment. Low minimum temperatures and low THI increase the incidence of dark cutting ($P<0.05$). Increased variation in THI and temperature in the 48 hours prior to consignment increased dark cutting ($P<0.05$) while increased standard deviation of temperature and THI range also increased dark cutting in the 14 and 28 day lag models ($P<0.05$). Smaller minimum ranges in temperature also reduced dark cutting in the 28 day lag model ($P<0.05$). Rainfall in the 48 hours proceeding consignment also reduced dark cutting while average wind speed had no effect on the incidence of dark cutting. In conclusion, environmental conditions have a significant but small impact on the incidence of dark cutting compared to the variation caused by animal/carcass and management factors at the feedlot and processor. This suggests that current management practices at the feedlots negate the majority of the effects of climatic conditions on dark cutting, or that the climatic conditions at feedlots are very different to that experienced at the nearest BOM station or the possibility that climatic impacts on dark cutting are significant but minimal. Strategic assessment and manipulation of individual supply chains will most likely achieve the greatest reductions in dark cutting in the feedlot sector.

Executive summary

Dark cutting or dark, firm and dry (DFD) carcasses in Australia are defined by Meat Standards Australia (MSA) as those with an ultimate pH ≥ 5.71. Although no longer a specification in MSA grading, many domestic and export processors also use an AUSmeat colour score in pricing grids. An AUSmeat colour score >3 is sometimes classified as DFD and producers can be discounted. The audits of MSA data suggest a greater incidence of dark cutting in feedlot cattle during summer due to environmental impacts like heat stress during hot, humid weather. Temperatures in Australia lie outside the normal thermal comfort zones for *bos taurus* beef cattle (15-25 ^{o}C) and for *bos indicus* cattle (16-27^{o}C) many months of the year which is likely to have a physiological impact on the growing animal. It is fundamentally important to understand the impact of high humidity and heat on the heat load of animals, however, the association between heat stress and the rate of dark cutting is yet to be quantified anywhere in the world. Moreover, the impact of environmental conditions and/or time of exposure to these conditions on the incidence of dark cutting has also not be established. This retrospective data analysis aims to discover the relationships between environmental conditions and dark cutting in order to provide evidence-based suggestions for how MSA pH non-compliance and AUSmeat colour scores > 3 can be reduced in grain fed cattle. It is hypothesised that exposure of animals to excessive heat in the days or weeks prior to slaughter will increase the incidence of dark cutting.

Meat Standards Australia data was captured over a 6 year period from 2012 to 2017 inclusive for 21 feedlots totalling just under 2.8 million carcasses that had been MSA graded. These cattle were consigned to slaughter in 27,073 different kill groups or lots which had greater than 10 head. Bureau of Meteorology (BOM) weather data was provided as half-hourly data recordings for weather stations nearest to each feedlot (Table 1). The half-hourly data was amalgamated into daily observations and a massive series of climatic predictors were generated covering different lags between 24 hours out to 28 days prior to consignment. These climatic predictors along with fixed effects for feedlot, processor, sex and HGP were analysed in a stepwise general linear model against the incidence of dark cutting per lot. Data from onsite weather stations at feedlots varying from 3 years to as short as 6 months was captured. It was provided as hourly data recordings which were amalgamated into daily observations and a series of predictors was generated covering different lags. There was substantially less data available than the BOM data set plus large amounts of missing and erroneous data in the weather station data, hence a conservative approach was taken to not to report the findings from that analysis as it is based on a fraction of the lots included in the BOM analysis and over unbalanced periods of time for each feedlot.

The fixed effects in the base model of feedlot, processor, sex and HGP status explained between 19.8% and 24.1% of the variation in dark cutting in the various lag period models of 24 hours to 28 days prior to consignment. Feedlot and processor had the largest effect on the incidence of dark cutting. There was a 10.1% range in the estimated effect of feedlot on the incidence of dark cutting between the lowest incidence feedlot (number 17) and highest incidence feedlot (number 10). The highest incidence feedlot (number 10) had greater dark cutting by 3.5%. There was a 8.3% range in the estimated effect of processing plant on the incidence of dark cutting between the lowest incidence processor (plant 1) and highest incidence processor (plant 17). The highest incidence performing processing plant (plant 17) had greater dark cutting by 2.8%. Male lots had 2% less dark cutting than females ($P<0.01$) and mixed sex lots also had lower rates of dark cutting than straight female lots by 0.5% ($P<0.05$). HGPs caused a

significant decrease ($P<0.05$) in dark cutting by 0.3% and 0.4% in the BOM analysis models for 14 and 28 day lag periods but did not significantly impact the incidence of dark cutting in the other lag period models.

The range of maximum temperatures for all lots spread from 15°C to 47°C. As maximum temperature increased by 10°C, the incidence of dark cutting increased by 0.3 to 1 percent in the 3, 7, 14 and 28 day lag period models ($P<0.01$) but had no effect in the 48 hours prior to consignment. Minimum temperature was significant at all lag times other than 48 hours ($P<0.05$) . As minimum temperature increased by 10°C, DFD% decreased by 0.1 % in the 24 hour lag model, 0.4% in the 3 and 14 day lag models and by 1 percent in the 7 and 28 day lag models. Thus these results show that both heat stress and cold shock impact the incidence of dark cutting in lot fed cattle.

The impact of temperature standard deviation on the incidence of dark cutting was significant ($P<0.05$) but the size of the effect, relationship with the incidence of DFD and significance was variable across the various lag periods. As temperature standard deviation went up by 1°C, the incidence of dark cutting went up by 0.1% in the 2 day lag model and down by 0.1% and 0.3% in the 7 and 28 day lag models. Temperature range per day had a significant effect on the incidence of DFD in the 28 day lag period model which showed that as temperature range increased by 10°C, the incidence of DFD reduced by 1%. Greater variation in temperature range also significantly increased the incidence of DFD in the 14 day lag period model ($P<0.01$). Maximum relative humidity also had a significant effect in the models 3, 7 and 28 days before consignment ($P<0.1$) showing a 10 point increase in humidity increasing DFD by 0.1, 0.2 and 0.4 % respectively.

In separate models, the temperature humidity index (THI) terms were included. Results showed that THI has no impact on DFD% within 48hrs before consignment although a 10 point increase in THI max between 3 and 28 days prior to consignment increased DFD by between 0.3 and 1% ($P<0.01$). On the contrary, an increase of 10 points of the minimum THI caused a reduction in DFD by 0.2 to 0.5% in the 3, 7 and 14 day lag models only ($P<0.05$). This shows that both high and low temperatures and/or humidity can also have a negative effect on dark cutting. The standard deviation in THI over the 48 hours prior to consignment also had a significant effect on the incidence of DFD ($P<0.01$) increasing DFD by 0.1% as THI variation increased by 1 point. This result is also supported by the result which showed that as the standard deviation in the THI range increased by 1 point, dark cutting also increased by 0.1 and 0.2% in the 14 and 28 day lag period models ($P<0.05$).

Rainfall also had a significant effect on the incidence of DFD if it occurred in the 48 hours prior to consignment ($P<0.05$). A 10mm increase in rain in the two days before kill could reduce DFD by 0.1%, while a 10mm increase in the 24 hours prior to consignment reduced DFD by 0.2%. Wind speed did not significantly affect the incidence of DFD per lot probably due to the both negative and positive effects of wind in cold wet and hot humid conditions respectively, cancelling each other out. It is also important to note that the inclusion of the BOM weather terms and THI did not impact the size of effect of the feedlots and processing plants nor did it cause any re-ranking in the feedlots or processing plants, but it did help to explain an extra 0 to 0.4% of variation in DFD across the various lag period models.

These results suggest that both heat stress and cold shock or cold conditions impact the muscle physiology of lot fed cattle, either reducing the rate of glycogen deposition or increasing the rate of glycogen breakdown and overall increasing the incidence of dark cutting. Variation in temperature also has a significant effect suggesting that an animals preparedness for climatic conditions is fundamentally important. Even though many of the weather terms and THI have a significant impact on the incidence of dark cutting, the relative size of the impact compared to the variation caused by animal/carcass and management factors at the feedlot and processor plus sex seems small. Even though the size of impact of climatic conditions on the incidence of DFD is small, this analysis provides insights into when management of cattle needs to change to reduce the pressure/stress on the cattle to minimise dark cutting rates. For example in the 4 weeks post a cold snap, normal practices at a feedlot could be altered or optimised to minimise the stress on those already compromised animals to ensure the rates of dark cutting are not heightened. The small impact of climatic conditions in this analysis suggests 1.) Current industry management practices during heat stress events at feedlots negate the majority of the effects of climatic conditions on dark cutting; 2.) The climatic conditions measured at the BOM stations are vastly different to those in the feedlots or 3.) The impact of climatic conditions on dark cutting are significant but minimal. It is recommended that further analysis of individual poor performing supply chains are completed as the impact of climatic conditions on DFD% might be vastly different at different feedlots. Strategic assessment and manipulation of individual supplychains (feedlot and processor in collaboration) will most likely achieve the greatest reductions in dark cutting in the feedlot sector.

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1 Background

Dark cutting in Australia is defined numerous ways depending on market. For carcasses traded on AUSmeat grain fed (GF) and grainfed yearling (GFYG) ciphers only, any carcass with an AUSmeat colour >3 is classified as a dark cutter while for Meat Standards Australia (MSA), a dark cutting carcass is based on ultimate pH > 5.70. Dark cutting in MSA graded carcasses alone has been estimated to cost the Australian beef industry upwards of $55 million per year, with penalties to producers being worth $19 million per year (Jose *et al.* 2015). Discounts applied to grain-fed beef are typically in the range of 25 – 120 c/kg for high pH, and/or dark meat colour. This partial economic analysis showed that losses to the processing sector were calculated to exceed those of the producer (Jose *et al.* 2015).

Dark cutting is typically a result of lower glycogen stores at slaughter (Tarrant 1989b) which can be caused by poor nutrition on farm (Knee *et al.* 2004) as well as by stress or muscle contraction which utilizes glycogen as an energy source pre and post farm gate (Ferguson and Warner 2008). Thus to reduce dark cutting, it is important for producers to manage feed quality and intake as well as reduce the stress on the animal during the pre-slaughter period. Grain fed cattle are typically on a higher plane of nutrition compared to grass fed cattle, thus have greater glycogen stores and therefore, as expected, produce a lower rate of dark cutting (Warner *et al.* 1988; McGilchrist *et al.* 2012). The 2015 Australian Beef Quality audit produced by MLA/MSA reported that dark cutting of grain-fed cattle averaged between 1.5 and 2.5% with a peak rate of 2.5% in March. The audits of MSA data suggest a greater incidence of dark cutting in feedlot cattle during summer which is suggested to be the result of environmental impacts like heat stress, transport and time in lairage during hot weather. The normal thermal comfort zone for *bos taurus* beef cattle is 15-25 °C and 16-27°C for *bos indicus* cattle, and since regional Australia regularly average a maximum temperature that exceeds these levels during December to March, the conditions in feedlots are likely to have a physiological impact on the growing animal. Furthermore, it is essential for the overnight temperature to drop below 21°C at night for 3-6 hours to sufficiently allow the animal to lose the heat it gained during the day (Igono *et al.* 1992; Muller *et al.* 1994), thus this would put Australian cattle especially at risk. It is fundamentally important to understand the impact of high humidity and heat on the heat load of animals, however, the association with heat stress and the rate of dark cutting is yet to be quantified anywhere in the world. Moreover, the impact of environmental conditions and/or time of exposure to these conditions on the incidence of dark cutting has also not be established, but appropriate management techniques developed through this research project could play a significant role in reducing the rates of dark cutting in the beef industry.

Extreme environmental conditions that prevent the adequate release of heat, result in increased body temperature and thus reduces productivity. Furthermore, grain fed cattle have an inherently higher body temperature than grass-fed cattle due to the large amount heat released from digestion of high energy diets and increased fat cover (Jacob *et al.* 2014), making them more susceptible to heat stress. The first sign of reduced productivity due to heat stress is a decrease in dry matter intake (DMI), a physiological strategy used to reduce the heat increment occurring from feeding and reducing the heat of rumenal fermentation. This will result in a decreased rate of body weight gain (Ray 1989) and reduced metabolic rate (O'Brien *et al.* 2010), having a negative impact on the productivity of the animal and are representative of an animal on a lower nutritional plane. O'Brien *et al.* (2010) found that heat induced dry matter intake reduction essentially explained all of the reduced weight gain in growing calves. It is known that dark cutting is more likely to occur under a poor plane of nutrition, especially in grass fed cattle (Knee *et al.* 2004) due to a decrease in glycogen stores. Indeed both chronic and acute heat stress result in an increase in glycogen utilization due to the effects of catecholamine's and glucose reliance as an energy source (Miova *et al.* 2013). However, it is a combination of decreased input and altered metabolic responses that ultimately effect the growth performance (Belhadj Slimen *et al.* 2016). Chronically heat stressed animals present depressed protein deposition (Geraert *et al.* 1996), increased fat synthesis and deposition with fat tissue catabolism down regulated as a measure to reduce the metabolic heat production (Geraert *et al.* 1996), increased glycogen utilization and a generally ruminants overall favour glucose as a primary fuel source (Belhadj Slimen *et al.* 2016). These physiological changes are all means to reduce the heat production as glucose oxidation is more efficient and thus less heat is produced compared to other fuels (Baldwin *et al.* 1980). However, it is not known what extent, period of exposure and severity of heat stress in feedlot cattle will result in lower glycogen stores and thus dark cutting.

This retrospective data analysis aims to discover the relationships between environmental conditions and dark cutting in order to provide evidence-based suggestions for how MSA non-compliance can be reduced in grain fed cattle. It is hypothesised that exposure of animals to excessive heat in the days or weeks prior to slaughter will increase the incidence of dark cutting.

2 Project objectives

2.1 Objectives

1. Conduct a retrospective analysis of carcasses databases (e.g. Feedlot carcase or MSA databases) to determine factors contributing to variation in dark cutting.
2. Conduct a 12 month slaughter chain audit of grain-fed cattle at a minimum of two processors with a known high incidence of dark cutting, and their supplying feedlots (3 per abattoir), to determine factors contributing to variation in dark cutting.
3. Determine whether time to grading influences meat colour of grain-fed carcasses, and the viability of re-grading at later time intervals as a method to improve meat colour.
4. Make recommendations to minimise the incidence of dark cutting carcasses in Australia.

2.2 Outcomes

1. A greater understanding of the national incidence of dark cutting in grain finished cattle and the seasonality of dark cutting
2. Expanded knowledge about the impact of climate, animal and lairage factors on the incidence of dark cutting
3. Increased profitability for producers through increased compliance to meat colour and pH requirements of slaughter grids
4. Increased understanding of the implications of variation in grading times and recommendations to increase compliance to meat colour and pH standards of slaughter grids.

3 Methodology

3.1 Data sourced

This experiment undertook a retrospective analysis of three datasets for 20 participating feedlots: 1) historic MSA carcass grading data 2) Feedlot weather station data sourced from Katestone 3) Locality weather data sourced from the nearest Bureau of Meteorology weather station.

3.1.1 MSA carcase grading database

Three abattoirs and 20 feedlots were approached (in consultation with MLA and ALFA) to obtain their permission to provide data for the retrospective database analysis. This included data contained in the Meat Standards Australia database, Weather data captured by Katestone from onsite stations at feedlots as well as data from nearby weather stations from the Bureau of Meteorology (BOM).

MSA data was captured over a 6 year period 01/01/2012 - 28/12/2017 for 21 feedlots (Table 1) totalling just under 2.8 million carcasses that had been MSA graded. These cattle were consigned to slaughter in 27,073 different kill groups or lots which had greater than 10 head.

Table 1: The distance from the nearest bureau of meterology (BOM) weather station, the number of cattle MSA graded from each feedlot and the percent that represents of the total data for each feedlot

Feedlot	Distance from BOM station	No. carcasses MSA Graded	Percent
01	23.7km	271639	9.7
02	26.8km	433131	15.5
03	32.93km	29210	1
04	18.40km	38841	1.4
05	26.8km	58879	2.1
06	19.6km	52639	1.9
07	4.48km	175692	6.3
08	36.01km	145973	5.2
09	34.62km	64472	2.3
10	3.16 km	103366	3.7
11	16.58km	31174	1.1
12	35.19km	153061	5.5
13	29.92km	139094	5
14	49.29km	46834	1.7
15	90km	281950	10.1
16	66km	216912	7.8
17	94.17km	10091	0.4
19	26.91km	123235	4.4
20	21km	30698	1.1
21	16.47km	173922	6.2
	Total	**2795754**	

The MSA data came in the form of seven CSV files, with a total file size of 700MB: 62 columns of data for ~2.8 million animals. When aggregating over lots, the following variables were created in R for the following fixed effects:

- n_animal = number of animals in each lot
- dfd_perc = DFD percentage (DFD has meatcolour >= 4 OR ph >= 5.71 or both)
- highmc_perc = percentage with meatcolour >= 4

- highph_perc = percentage with ph >= 5.71
- gradedate_med = the median grade date for that lot
- bodyno_med = the median body number for that lot
- grader_mf = the most frequent grader for that lot
- grader_pct = the percent of animals graded by the most frequent grader
- hang_mf = the most frequent hang method for that lot
- hgp_mf = the most frequent HGP treatment status for that lot
- sex_mf = the most frequent sex in that lot
- sex_perc_m = the proportion of males in that lot
- sex is Male when at least 90% of the animals in a lot are male, Female when at least 90% of the animals in a lot are female and otherwise Mixed.
- mfv_mf = the most frequent MFV in that lot
- rinse_mf = the most frequent rinse in that lot
- saleyard_mf = the most frequent saleyard in that lot
- rib_mf = the most frequent rib in that lot

The numeric grading variables had mean and sd summaries generated for each lot.

3.1.2 Feedlot Weather Data

Weather data from the feedlot weather stations was collected from Katestone. A multitude of different weather factors (Table 2) could be analysed to determine which has an impact on the percent dark cutting per lot. Data from onsite weather stations at feedlots was captured from Katestone varying from 3 years to as short as 6 months. It was provided as hourly data recordings in the form of 19 Microsoft Excel files (68MB) which was imported into R and merged into one data frame. The hourly data was amalgamated into daily observations and a series of predictors was generated covering different lags. There was substantial missing data in the weather station data. A conservative approach was taken to the data amalgamation process such that if any data was missing over the period for which the statistic is to be calculated a NA is reported. This results in longer lag periods having less data available than shorter lag periods as the wider the lag window the greater the chance of a missing observation.

Table 2: Weather variables analysed over lag periods for 24hrs, 2, 3, 7, 14 and 28 days prior to slaughter

Weather Term
Ave Temp (AveTA, ˚C)
Max Temp (MaxTA, ˚C)
Min Temp (MinTA, ˚C)
SD (Range Temp)
Max Daily Temp range
Min Daily Temp range
SD Daily Temp range
Ave Relative Humidity (RH, %)
Max RH, %
Min RH, %
SD (Range RH)

Wind Speed (WS, m/s)
Ave Solar Radiation between 9am and 3pm (SR, W/m) #
Ave Calc Black Globe Temperature (BG, ˚ C) #
Max Calc BG, ˚C #
Min Calc BG, ˚ C #
SD (Calc Black Globe) #
Total Rainfall (mm)
Calculated Values
Temperature Humidity Index (THI)
Ave THI=(0.8*TA)+ [(RH/100)*(TA-14.4)]+46.4
Max THI=(0.8*TA)+ [(RH/100)*(TA-14.4)]+46.4
Min THI=(0.8*TA)+ [(RH/100)*(TA-14.4)]+46.4
SD THI
SD (Range) THI
Heat Load Index (HLI)
HLIHI (BG > 25 ˚C) = 8.62 + (0.38 * RH)+(1.55*BG)-(0.5*WS)+[e(2.4-WS)] #
HLILO (BG < 25 ˚C)=10.66+(0.28*RH)+(1.3*BG)-WS #
Max Smooth BG = 1/(1+e(-(BG-25)/2.25)) #
Max HLI Corrected = S(BG)*HLIHI+(1-S(BG))*HILILO #
Accumulated Heat Load Units (AHLU)
Max AHLU86 #
SD ADHL86 #
Range AHLU86 #
Total time AHLU86 >0 (hrs) #

#These terms were not able to be analysed from BOM data

3.1.3 Bureau of meteorology data

The Bureau of Meteorology (BOM) weather data was provided as half-hourly data recordings for each weather station nearest to the feedlot (Table 1) in the form of 16 Microsoft Excel files (210MB) which was imported into R and merged into one data frame. The half-hourly data was amalgamated into daily observations and a series of predictors was generated covering different lags. A conservative approach was taken to the data amalgamation process such that if any data was missing over the period for which the statistic is to be calculated a NA is reported. This results in longer lag periods having less data available than shorter lag periods as the wider the lag window, the greater the chance of a missing observations. BOM locations were linked to the geographically closest producer location (Table 1). Data in Table 2 with a # could not be analysed from BOM data as the data was not available from any weather station managed by BOM. Data without a # was analysed for all feedlots where BOM data was available for 24 hours, 2, 3, 7, 14 and 28 day lag periods before slaughter.

3.1.4 Statistical Methodology

Dark, Firm, and dry (DFD) percentage per lot was calculated using the number of carcasses in a lot which had meatcolour ≥ 4 OR pH ≥ 5.71 or both divided by the number in each lot. Lots with 10 head or less were removed from the analysis as the size of the impact from 1 animal being DFD becomes to large.

Following an extensive data integration and variable creation process, DFD percentage per lot was regressed on the weather predictors of a certain lag, as well as with fixed effects for feedlot, processor, sex and HGP status. A stepwise model selection procedure was performed starting at the full model and progressing both backwards and forwards through the model space using the Akaike information criterion to evaluate competing models and stopping when a minimum is reached (Akaike 1974).

The initial base model run included fixed effects for feedlot, processor, HGP status and sex with no weather terms or indexes included. The weather term models including max, min and standard deviation for temperature, relative humidity, daily temperature range plus average windspeed and rainfall were added to the base model. The third analysis using the BOM weather data was the THI index model where max, min and standard deviation of THI, plus average windspeed and rainfall were added to the base model. Throughout the 3 models for BOM data, the lots analysed were restricted to the same bounds, hence the number of observations used in the analysis for each lag period were exactly the same. The MSA carcass grading data provided information on 27073 lots of carcasses which had greater than 10 head. If there was missing weather data in the analysis for a lot, then that lot was dropped from the analysis hence there was greater attrition of lots as the lag period increased from 24 hours (19,563 lots in analysis, Table 7) to 28 days (9,167 lots in analysis, Table 7).

While the dependent variable, DFD percentage, and model residuals are not normally distributed, valid p-value based inferences on the model coefficients can still be obtained through the application of the central limit theorem given the large sample sizes.

Data integration and modelling was performed using the R statistical program (RCoreTeam 2018). Estimated marginal means were calculated using the emmeans package (Lenth 2018) and estimated coefficients and standardised coefficients visualised with the sjPlot package (Lüdecke 2018).

4 Results

4.1 MSA carcass data descriptive stats

Table 3: The number of observations, mean, standard deviation (sd), minimium, 25th percentile value (P25), median, 75th percentile (P75) and maximum value for lots per producer, lot size, AUSmeat marbling, MSA marbling, carcass weight, ossification score, days on feed (DOF), pH, % high meat colour, % high pH, MSA index and % dark cutting based on pH and colour.

Variable	n	mean	sd	min	25th Percentile	median	75th Percentile	max
Lot Size	27073	98	90	11	43	72	120	871
AUSmeat marbling	27073	1	0.9	0	0.8	1	2	8
MSA marbling	27073	364	88	109	321	356	395	1099
Carcass Weight	27073	330	57	158	279	337	375	518
Ossification Score	27073	167	23	116	152	166	178	547
Days On Feed	27073	115	55	0	100	100	130	806
pH	27073	5.53	4.42	5.33	5.50	5.53	5.55	5.98
% High Meat Colour	27073	2.25	5.24	0	0	0	2.35	95.2
% High pH	27073	1.97	4.53	0	0	0	2.04	90.9
MSA Index	27073	55.9	3.45	42.7	54.1	55.8	57.5	68.9
% Dark Cutting	27073	2.37	5.50	0	0	0	2.50	100

4.1.1 Lot size

There is a large range in lot sizes consigned to slaughter from the 20 feedlots in the weather analysis between start 2012 and end 2017. Some feedlots like number 2 and 15 consistently have higher lot sizes compared to others like number 20 whom has lower and very consistent numbers consigned. There are also some periods from certain feedlots when cattle were not consigned to processors where MSA grading occurred.

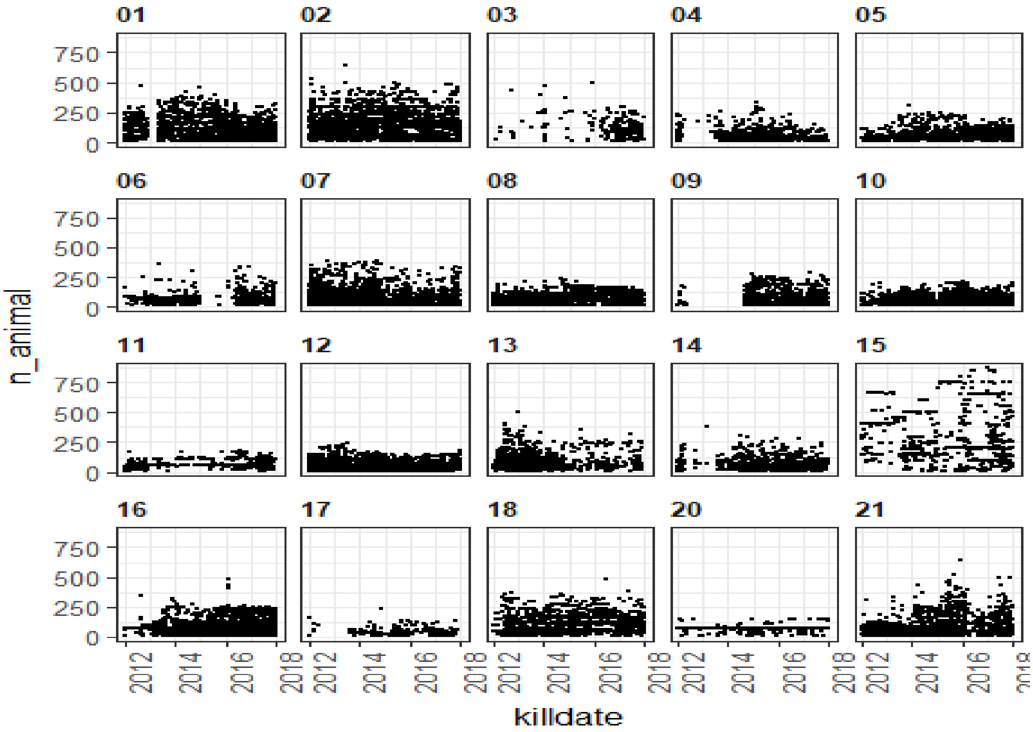

Figure 1. The number of cattle per lot from feedlots that had MSA data for lots killed across multiple years. Some have gap periods and less coverage across the 6 years.

4.1.2 Dark cutting

There is large variation in the incidence of DFD between the 20 feedlots. Some feedlots like feedlots 4, 7, 9, 14 and 17 have consistently low rates of dark cutting while others like 10 and 16 have consistently higher rates of dark cutting.

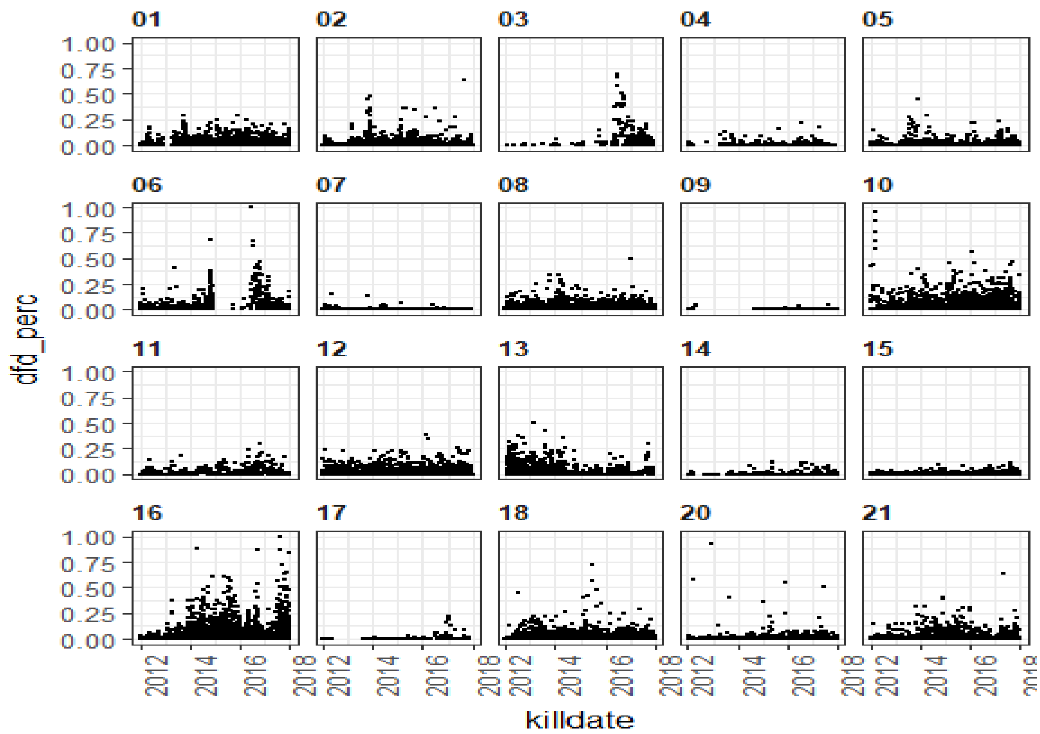

Figure 2. Incidence of dark cutting (dfd_perc) by feedlot location and kill date

4.1.3 pH

The range in pH measured at MSA grading are consistent with the rates of dark cutting as seen in Figure 2. Those feedlots with more dark cutting have a wider range in ultimate pH.

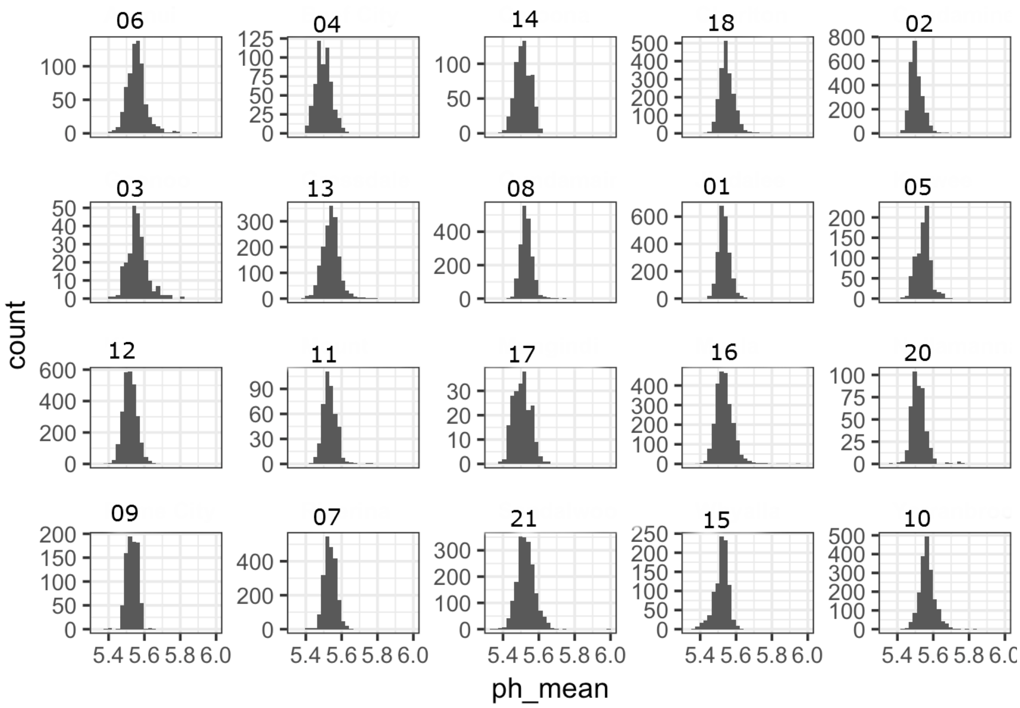

Figure 3. Mean pH per lot across Feedlots. A score of 5.71 or greater is non-compliant and classified as a dark cutter.

4.1.4 Estimated Percentage *Bos Indicus*

Plants appear to be grading high numbers of carcasses on X which means that it is a mob with variable amounts of *bos indicus* in the herd. It could also mean that there are a few cattle with *bos indicus* content in a mob of *bos taurus* animals. This is not necessary as X (which denotes unknown BI content) should be used only when the *bos indicus* content of cattle is variable or can't be declared. Some feedlots with high values for the number graded on X feed very low numbers of *bos indicus* cattle.

Why is grading *bos taurus* cattle on X an issue? It is because the MSA model, as it stands, will assume that all cattle have some percentage of *bos indicus* so grading on X will artificially reduce the MSA eating quality prediction for some cut by cook combinations. Hence this will reduce the MSA index's of cattle from these feedlots being graded on X due to apparent low levels of *bos indicus* in all cattle in the majority of lots.

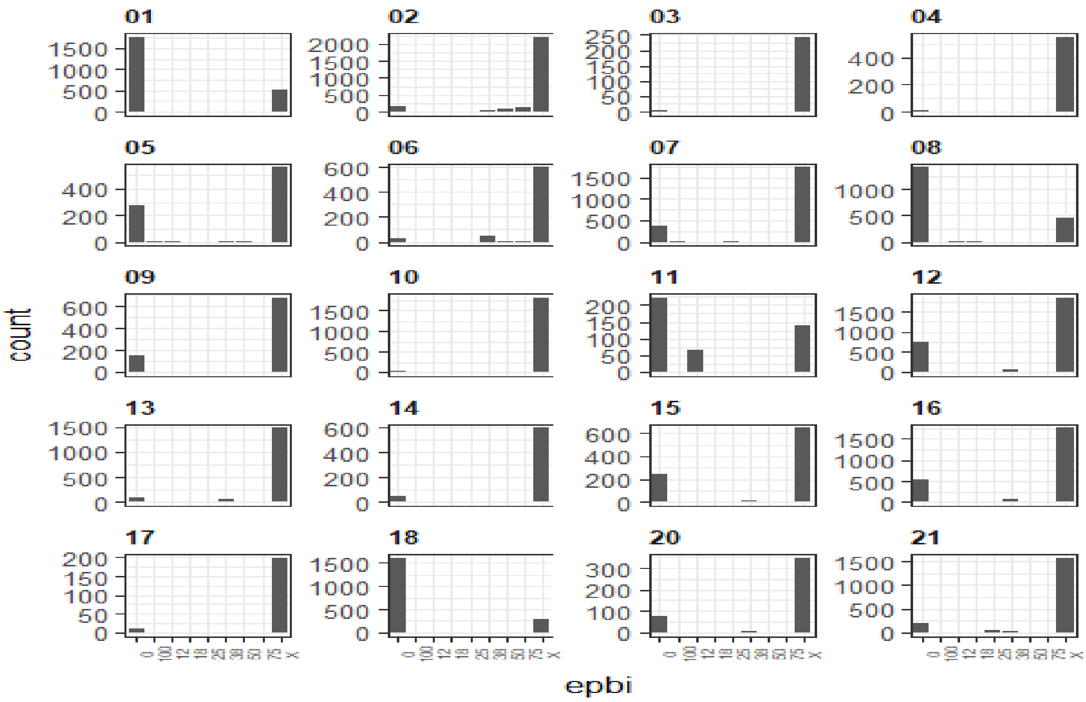

Figure 4. The count of lots at each *Bos indicus* content across 6 years of MSA data for each feedlot

4.1.5 HSCW

The bimodal distributions of HSCW for some feedlots clearly shows that they feed for different end markets, while some feedlots have a very narrow distribution in their HSCW's.

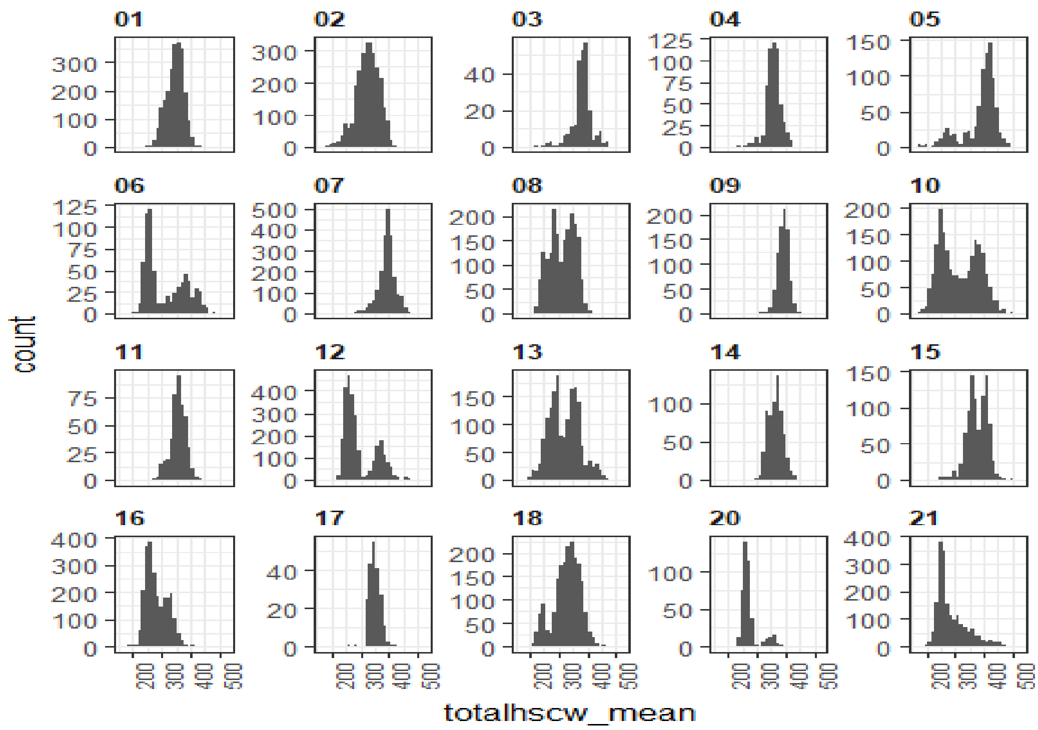

Figure 5. Mean HSCW scores per lot across feedlots

4.1.6 Ossification

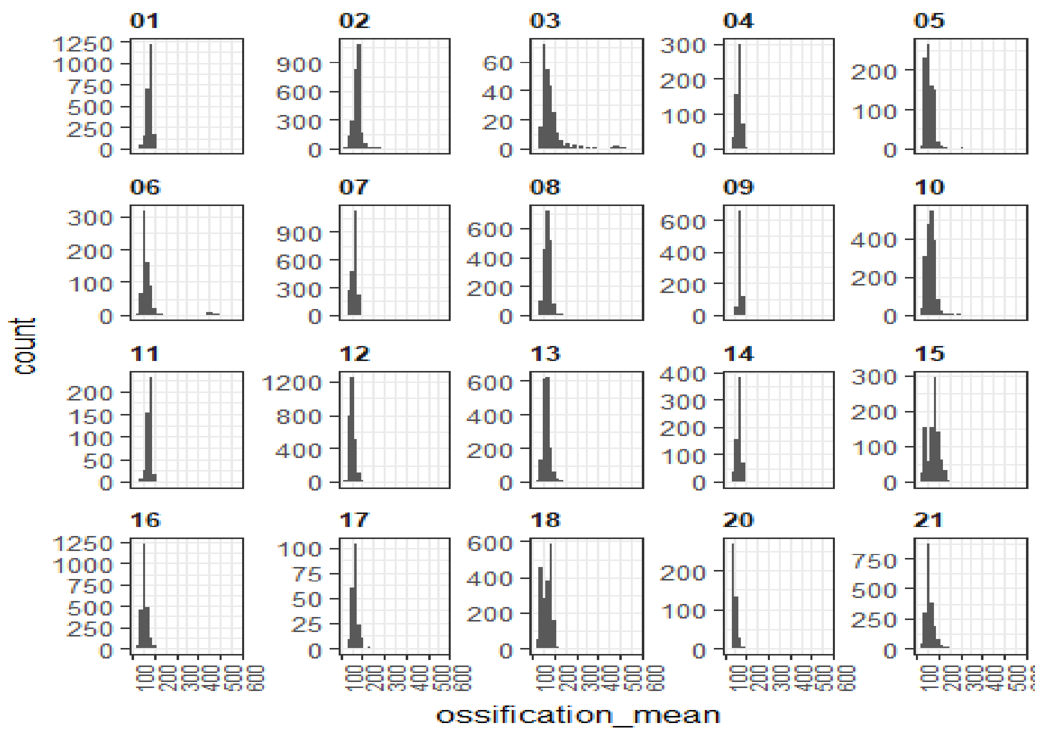

Figure 6. Mean Ossification scores per lot across feedlots

4.1.7 MSA Marbling

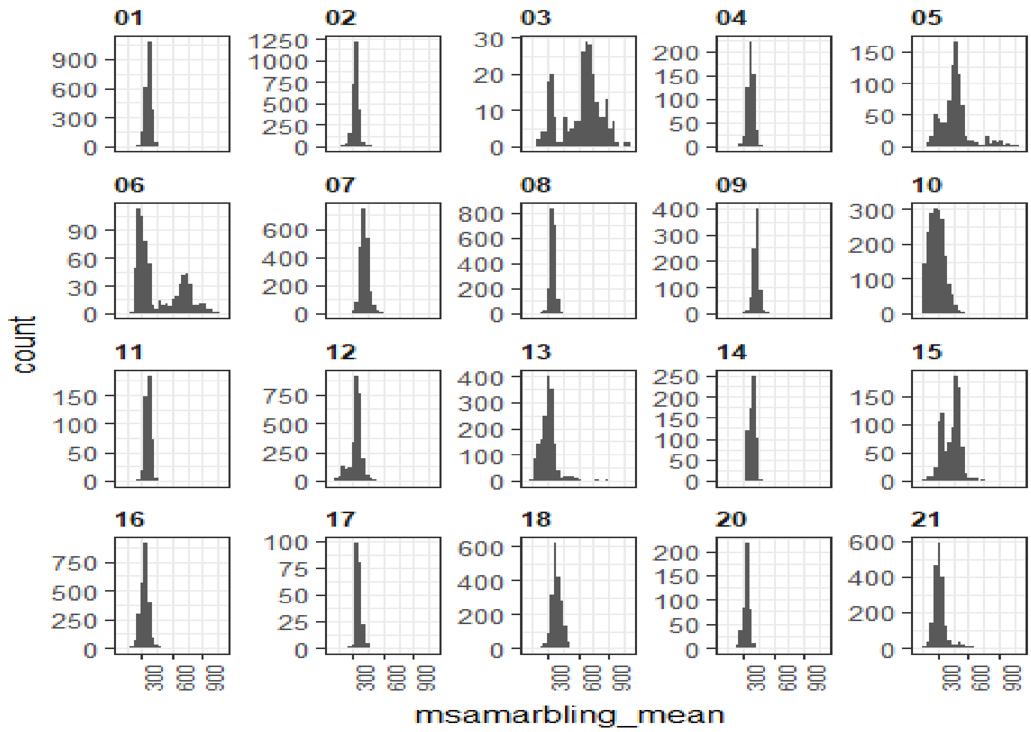

Figure 7. Mean MSA marbling score counts per lot across feedlots

4.1.8 MSA Index

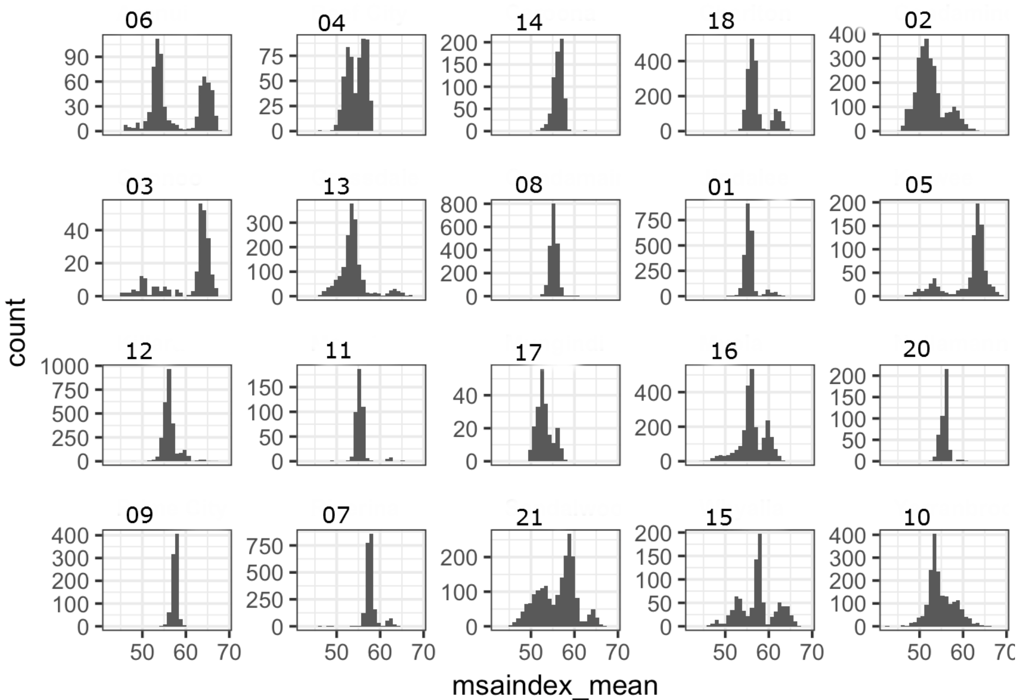

Figure 8. Mean MSA index counts per lot across feedlots. This does not include non-compliant carcasses as they grade as N/A and not numerical.

4.1.9 Days on Feed

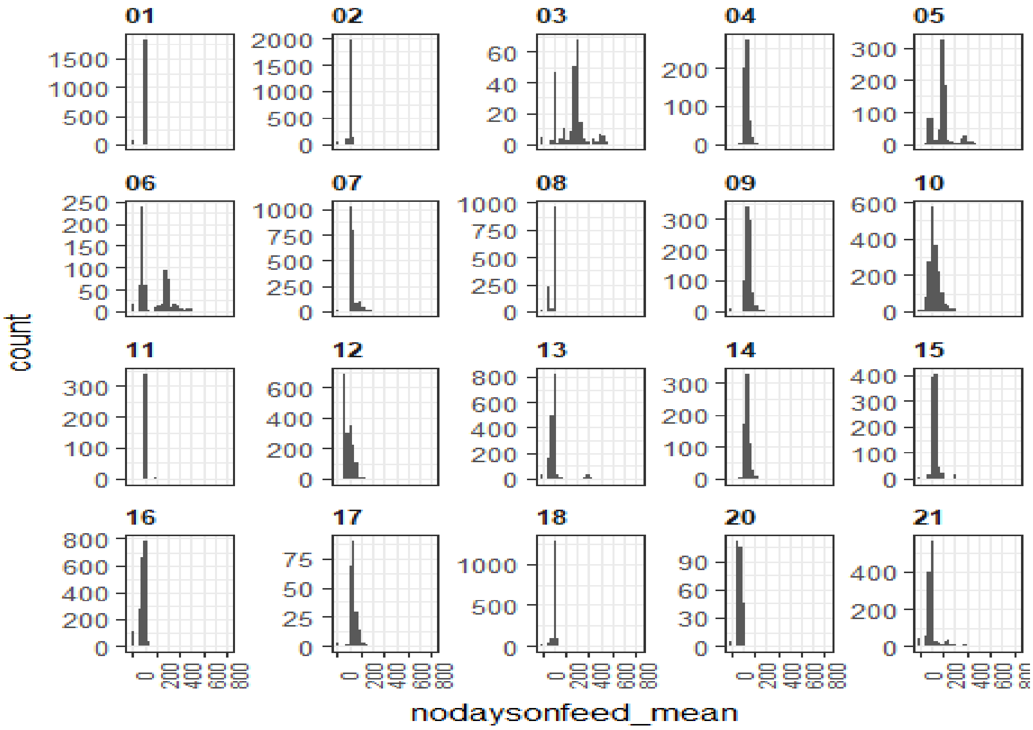

Figure 9. Mean days on feed per lot across feedlots

4.2 Fixed effect data analysis

The analysis presented in the results section of this report was conducted based on a dark cutting carcass which had either high pH at grading (>5.7), high AUSmeat colour at grading (>3) or both. The analysis of pH alone and meat colour alone is included in the appendix of this final report. Correlation between pH and meat colour is also included in the appendix of the report

4.2.1 Hormone growth promotants

Out of the 2.8 million cattle in the MSA carcass data set, 82.4% had been treated with a hormone growth promotant (HGP) (Table 4), 17.1% were not treated with HGPs and 0.5% of carcasses were unclassified in the MSA database. In the statistical analysis, HGPs caused a significant decrease ($P<0.05$) in dark cutting by 0.3% and 0.4% in the BOM analysis models for 14 and 28 day lag periods. HGPs did not significantly impact the incidence of dark cutting in the other lag period models. This indicates that HGPs have either no effect on the incidence of dark cutting or slightly reduce the incidence.

Table 4. The usage rates of hormone growth promotants in MSA graded carcasses

HGP	N	Percentage
N	472,186	17.1%
Y	2,210,022	82.4%

4.2.2 Sex

Out of the 2.8 million cattle in the MSA carcass data set, 77.6% were males and 22.4% were females (Table 5). The statistical analysis of MSA lot based data in the base model showed that male lots had 2% less dark cutting than females in the 24 hour, 2 and 3 day lag period models (P<0.01, Table 6). However in the 7, 14 and 28 day lag period models, the incidence for male lots was 1.9%, 1.7% and 1.5% lower (P<0.01, Table 6). Mixed sex lots also had lower rates of dark cutting than straight female lots by 0.5% in the 24hr, 2 day and 3 day base model analyses (P<0.05, Table 6) but no difference to female lots in the 7, 14 and 28 day lag analysis (Table 6).

Table 5. The proportion and number of male and female MSA graded carcasses

Sex	N	Percentage
F	600,723	22.4%
M	2,081,485	77.6%

Table 6: Estimated coefficients from the base model for the effect of fixed effects at 24 hours, 2, 3, 7, 14 and 28 days prior to slaughter on the incidence of dark cutting per lot with standard errors in brackets

	Dependent variable: DFD percentage per lot					
Lag Time	1	2	3	7	14	28
sexMale	-0.020***	-0.020***	-0.020***	-0.019***	-0.017***	-0.015***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
sexMixed	-0.005**	-0.005**	-0.005**	-0.004	-0.005	-0.002
	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.003)
hgp_mfY	-0.001	-0.001	-0.001	-0.001	-0.003*	-0.004**
	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)	(0.002)
plant02	0.006	0.006	0.005	0.006	0.008	0.005
	(0.005)	(0.006)	(0.006)	(0.006)	(0.007)	(0.009)
plant03	0.015**	0.015**	0.010	0.014**	0.012	0.009
	(0.006)	(0.006)	(0.006)	(0.007)	(0.008)	(0.008)
plant04	0.055***	0.056***	0.054***	0.054***	0.058***	0.043***
	(0.003)	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)
plant05	0.025***	0.024***	0.022***	0.026***	0.025***	0.021***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)
plant06	0.043***	0.044***	0.042***	0.043***	0.048***	0.034***
	(0.005)	(0.005)	(0.005)	(0.006)	(0.006)	(0.007)
plant07	0.022***	0.022***	0.021***	0.027***	0.025***	0.018***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)
plant08	0.021***	0.020***	0.018***	0.021***	0.021***	0.015**
	(0.005)	(0.005)	(0.006)	(0.006)	(0.007)	(0.007)
plant09	0.049***	0.048***	0.047***	0.053***	0.047***	0.034***
	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)	(0.007)
plant10	0.043***	0.042***	0.041***	0.044***	0.046***	0.042***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.005)
plant11	0.013***	0.014***	0.011**	0.019***	0.012*	-0.018**

	(0.004)	(0.005)	(0.005)	(0.005)	(0.006)	(0.008)
plant12	0.012***	0.011***	0.010**	0.010**	0.011**	0.005
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)
plant13	0.034***	0.034***	0.031***	0.036***	0.037***	0.028***
	(0.005)	(0.005)	(0.005)	(0.005)	(0.006)	(0.007)
plant14	0.020***	0.019***	0.016***	0.020***	0.018***	0.016**
	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)	(0.006)
plant15	0.023***	0.022***	0.020***	0.026***	0.025***	0.020***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)
plant17	0.083***	0.082***	0.079***	0.083***	0.079***	0.066***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.005)	(0.005)
Feedlot02	-0.006**	-0.006**	-0.005*	-0.005	-0.003	-0.002
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.005)
Feedlot 03	0.023***	0.023***	0.023***	0.026***	0.024***	0.031***
	(0.005)	(0.005)	(0.005)	(0.006)	(0.006)	(0.007)
Feedlot 04	-0.041***	-0.043***	-0.042***	-0.040***	-0.043***	-0.030***
	(0.005)	(0.005)	(0.005)	(0.006)	(0.006)	(0.007)
Feedlot 05	-0.016***	-0.017***	-0.018***	-0.016***	-0.022***	-0.023***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)
Feedlot 06	0.024***	0.023***	0.021***	0.025***	0.025***	0.011*
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)
Feedlot 07	-0.035***	-0.036***	-0.036***	-0.034***	-0.039***	-0.028***
	(0.005)	(0.005)	(0.006)	(0.006)	(0.007)	(0.007)
Feedlot 08	-0.0003	0.0002	0.0003	-0.0001	0.001	0.002
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Feedlot 09	-0.036***	-0.037***	-0.037***	-0.035***	-0.039***	-0.028***
	(0.006)	(0.006)	(0.006)	(0.006)	(0.007)	(0.008)
Feedlot 10	0.059***	0.064***	0.063***	0.070***	0.135***	0.287***
	(0.005)	(0.006)	(0.006)	(0.007)	(0.009)	(0.012)
Feedlot 11	0.009***	0.009***	0.009***	0.010***	0.010***	0.009***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)
Feedlot 12	-0.012***	-0.012***	-0.012***	-0.013***	-0.011***	-0.008**
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)
Feedlot 13	0.010***	0.010***	0.009***	0.011***	0.011**	0.014***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)
Feedlot 14	-0.040***	-0.041***	-0.041***	-0.038***	-0.041***	-0.030***
	(0.005)	(0.005)	(0.005)	(0.005)	(0.006)	(0.007)
Feedlot 15	0.002	0.003	0.001	0.004	0.004	0.007
	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)	(0.006)
Feedlot 16	0.005	0.005	0.005	0.003	0.007*	0.016***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)
Feedlot 17	-0.042***	-0.043***	-0.042***	-0.038***	-0.045***	-0.037***
	(0.006)	(0.006)	(0.006)	(0.007)	(0.008)	(0.010)
Constant	0.013***	0.013***	0.015***	0.010**	0.011**	0.012*
	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)	(0.006)

NB: *P<0.1; **P<0.05; ***P<0.01

4.2.3 Feedlot effect

The feedlot from which cattle came from had a significant effect on the incidence of dark cutting (Table 6) in the base model analysis. The effect of feedlot can be best estimated in the 24 hour lag period analysis as this analysis contains the greatest number of lots of cattle (Table 7). There was a 10.1% range in the estimated effect of feedlot on the incidence of dark cutting between the lowest (number 17) and highest incidence feedlot (number 10). The highest incidence feedlot (number 10) had greater dark cutting by 3.5% (Figure 10).

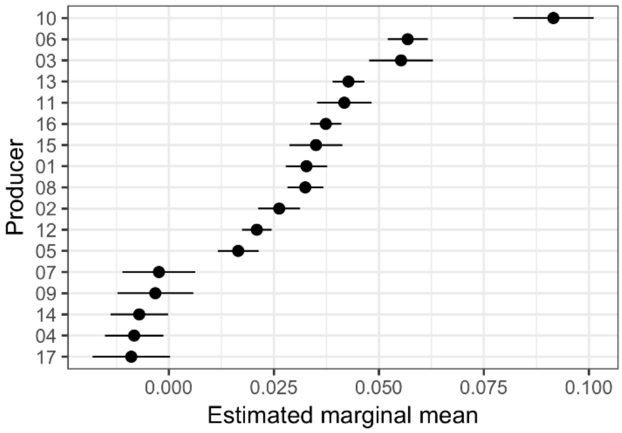

Figure 10: The estimated marginal means for the effect of each feedlot (producer) on the incidence of dark cutting in the 24 hours pre-consignment lag period analysis

4.2.4 Plant effect

The plant at which cattle were slaughtered had a significant effect on the incidence of dark cutting (Table 6) in the base model analysis. The effect of plant can be best estimated in the 24 hour lag period analysis as this analysis contains the greatest number of lots of cattle (Table 7). There was a 8.3% range in the estimated effect of processing plant on the incidence of dark cutting between the lowest incidence processor (plant 1) and highest incidence processor (plant 17). The highest incidence processing (plant 17) had greater dark cutting by 2.8% (Figure 10).

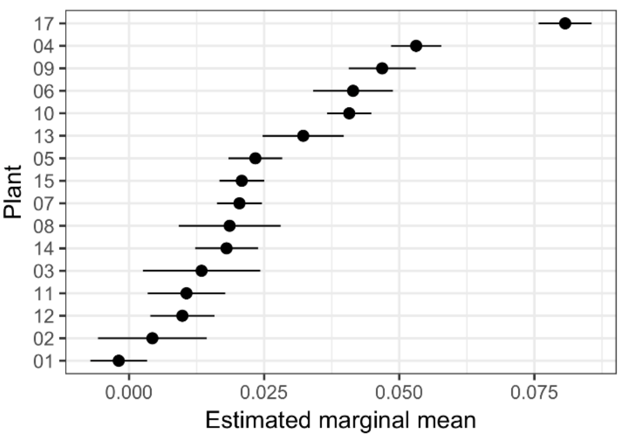

Figure 11: The estimated marginal means for the effect of each processor (plant) on the incidence of dark cutting in the 24 hours pre-consignment lag period analysis

Table 7: The R^2, adjusted R^2, residual standard error and F statistic for the base model, BOM weather terms model and THI model

		Lag period prior to feedlot departure					
		24 hours	**2 days**	**3 days**	**7 days**	**14 days**	**28 days**
	Observations	19,563	18,852	18,224	15,637	12,782	9,167
Base Model (fixed effects only)	R^2	0.202	0.204	0.201	0.198	0.204	0.241
	Adjusted R^2	0.201	0.202	0.199	0.196	0.202	0.238
	Residual Std. Error	0.049 (df = 19528)	0.049 (df = 18817)	0.050 (df = 18189)	0.051 (df = 15602)	0.051 (df = 12747)	0.048 (df = 9132)
	F Statistic	145.401*** (df = 34; 19528)	141.718*** (df = 34; 18817)	134.423*** (df = 34; 18189)	112.947*** (df = 34; 15602)	95.883*** (df = 34; 12747)	85.354*** (df = 34; 9132)
BOM Weather term model	R^2	0.203	0.204	0.202	0.199	0.205	0.245
	Adjusted R^2	0.201	0.203	0.2	0.197	0.203	0.241
	Residual Std. Error	0.049 (df = 19526)	0.049 (df = 18816)	0.050 (df = 18187)	0.051 (df = 15599)	0.051 (df = 12744)	0.048 (df = 9127)
	F Statistic	137.746*** (df = 36; 19526)	138.000*** (df = 35; 18816)	127.548*** (df = 36; 18187)	104.704*** (df = 37; 15599)	89.077*** (df = 37; 12744)	75.808*** (df = 39; 9127)
BOM THI Model	R^2	0.202	0.204	0.202	0.199	0.205	0.242
	Adjusted R^2	0.201	0.203	0.2	0.197	0.203	0.239
	Residual Std. Error	0.049 (df = 19528)	0.049 (df = 18816)	0.050 (df = 18188)	0.051 (df = 15600)	0.051 (df = 12744)	0.048 (df = 9130)
	F Statistic	145.657*** (df = 34; 19528)	138.087*** (df = 35; 18816)	131.148*** (df = 35; 18188)	107.671*** (df = 36; 15600)	88.806*** (df = 37; 12744)	81.063*** (df = 36; 9130)

4.3 Bureau of meteorology data analysis

The base model with fixed effects only explained between 19.8% (7 day lag model) and 24.1% (28 day lag model) of the variation in the incidence of DFD per lot (Table 7). Adding in the BOM weather variables increased the R^2 by between 0% (2 day lag period model), 0.1% (24 hr, 3, 7, 14 day models) and by 0.4% in the 28 day lag model (Table 7). Adding THI terms to the base model also only explained an extra 0.1% of variation in DFD per lot for the 3, 7, 14 and 28 day lag period models only (Table 7). This demonstrates that across lots from all producers over the 6 years of grading data, BOM weather terms and THI could only help explain a further 0.1% of the variation in DFD carcasses over and above that explained by sex, producer, processor and HGP status alone.

4.3.1 BOM individual weather trait analysis

Maximum temperature had a significant effect on the incidence of dark cutting in the 3, 7, 14 and 28 day lag period models (P<0.01, Table 8) but was not significant within 48 hours of consignment (Table 8). An increase of 10 degrees maximum temp between 3 to 28 days correlated with a 0.3 to 1 percent increase in DFD incidence (Table 8). This relationship was linear across the range of maximum temperatures for all lots which were spread from 15°C to 47°C.

Minimum temperature was significant at all lag times (P<0.05) except 48 hours. As minimum temperature increased by 10°C, DFD% decreased by 0.1 % in the 24 hour lag model, 0.4% in the 3 and 14 day lag models and by 1 percent in the 7 and 28 day lag models (Table 8).

Temperature standard deviation also had a significant effect (P<0.05) the incidence of dark cutting but the size of the effect, relationship with the incidence of DFD and significance was variable across the various lag periods (Table 8). As temperature standard deviation went up by 1°C, the incidence of dark cutting went up by 0.1% in the 2 day lag model and down by 0.1% and 0.3% in the 7 and 28 day lag models (Table 8). Temperature range per day also had a significant effect on the incidence of DFD but only in the 28 day lag period model (Table 8) which showed that as temperature range increased by 10°C the incidence of DFD reduced by 1%. The standard deviation of temp range was also only significant in the 14 day lag period model (P<0.01).

Maximum relative humidity (RH) was only significant in the models for 3, 7 and 28 days before consignment (P<0.1). A 10 point increase in RH corresponded with an increase in DFD by 0.1, 0.2 and 0.4 % respectively.

A 10mm increase in rainfall had a 0.01% reduction in DFD if it occurred in the 48 hours prior to consignment from the feedlot (P<0.1, Table 8).

Wind speed did not have a significant effect on the incidence of dark cutting. It is also important to note that the inclusion of the BOM weather terms did not impact the size of effect of the feedlots and processing plants nor did it cause any re-ranking in the feedlots or processing plants (Table 6 and 8).

Table 8: Estimated coefficients for the effect of bureau of meteorology weather terms at 24 hours, 2, 3, 7, 14 and 28 days prior to consignment plus sex, HGP, feedlot and processor on the incidence of dark cutting per lot with standard errors in brackets

	Dependent variable: DFD percentage per lot					
Lag Time	1	2	3	7	14	28
temp_max			0.0003***	0.001***	0.0003***	0.001***
			(0.0001)	(0.0001)	(0.0001)	(0.0002)
temp_min	-0.0001**		-0.0004***	-0.001***	-0.0004***	-0.001***
	(0.0001)		(0.0001)	(0.0001)	(0.0001)	(0.0002)
rh_min	-0.00003					
	(0.00002)					
temp_sd		0.001**		-0.001**		-0.003***
		(0.0003)		(0.001)		(0.001)
rain	-0.0001*	-0.0001**				
	(0.0001)	(0.00005)				
temp_range_min						-0.001***
						(0.0002)
rh_max			0.0001*	0.0002**		0.0004*
			(0.00005)	(0.0001)		(0.0003)
temp_range_sd					0.002***	
					(0.001)	
sexMale	-0.020***	-0.020***	-0.020***	-0.019***	-0.017***	-0.014***

	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
sexMixed	-0.005**	-0.005**	-0.005**	-0.004	-0.005	-0.002
	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.003)
hgp_mfY					-0.003*	-0.004**
					(0.002)	(0.002)
plant02	0.006	0.006	0.005	0.007	0.010	0.008
	(0.005)	(0.006)	(0.006)	(0.006)	(0.007)	(0.009)
plant03	0.016***	0.015**	0.011*	0.016**	0.015*	0.012
	(0.006)	(0.006)	(0.006)	(0.007)	(0.008)	(0.008)
plant04	0.056***	0.056***	0.054***	0.055***	0.058***	0.045***
	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)	(0.005)
plant05	0.025***	0.025***	0.023***	0.026***	0.026***	0.023***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)
plant06	0.044***	0.044***	0.042***	0.044***	0.048***	0.037***
	(0.005)	(0.005)	(0.005)	(0.006)	(0.006)	(0.007)
plant07	0.023***	0.023***	0.021***	0.028***	0.025***	0.020***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)
plant08	0.021***	0.020***	0.019***	0.022***	0.022***	0.016**
	(0.005)	(0.005)	(0.006)	(0.006)	(0.007)	(0.007)
plant09	0.049***	0.049***	0.048***	0.053***	0.048***	0.036***
	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)	(0.007)
plant10	0.043***	0.043***	0.042***	0.046***	0.047***	0.044***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.005)
plant11	0.014***	0.015***	0.013***	0.021***	0.014**	-0.018**
	(0.004)	(0.004)	(0.005)	(0.005)	(0.006)	(0.008)
plant12	0.012***	0.011***	0.010***	0.011**	0.012**	0.007
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)
plant13	0.035***	0.034***	0.032***	0.038***	0.039***	0.031***
	(0.005)	(0.005)	(0.005)	(0.006)	(0.006)	(0.007)
plant14	0.020***	0.019***	0.016***	0.021***	0.019***	0.018***
	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)	(0.006)
plant15	0.023***	0.022***	0.021***	0.026***	0.026***	0.022***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)
plant17	0.083***	0.082***	0.079***	0.083***	0.079***	0.068***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.005)	(0.005)
Feedlot02	-0.006**	-0.006**	-0.005*	-0.005	-0.0004	0.001
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.005)
Feedlot 03	0.023***	0.024***	0.025***	0.028***	0.029***	0.036***
	(0.005)	(0.005)	(0.005)	(0.006)	(0.006)	(0.007)
Feedlot 04	-0.041***	-0.043***	-0.042***	-0.040***	-0.040***	-0.028***
	(0.004)	(0.005)	(0.005)	(0.005)	(0.006)	(0.007)
Feedlot 05	-0.016***	-0.016***	-0.018***	-0.016***	-0.021***	-0.022***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)
Feedlot 06	0.024***	0.024***	0.021***	0.026***	0.027***	0.015***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)
Feedlot 07	-0.035***	-0.036***	-0.035***	-0.031***	-0.034***	-0.025***

	(0.005)	(0.005)	(0.006)	(0.006)	(0.007)	(0.008)
Feedlot 08	-0.0003	0.0001	0.001	0.0004	0.002	0.004*
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)
Feedlot 09	-0.036***	-0.037***	-0.036***	-0.033***	-0.036***	-0.026***
	(0.005)	(0.006)	(0.006)	(0.006)	(0.007)	(0.008)
Feedlot 10	0.058***	0.064***	0.063***	0.070***	0.138***	0.294***
	(0.005)	(0.006)	(0.006)	(0.007)	(0.009)	(0.012)
Feedlot 11	0.009***	0.009***	0.010***	0.010***	0.011***	0.011***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)
Feedlot 12	-0.011***	-0.012***	-0.010***	-0.009***	-0.005	-0.0004
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)
Feedlot 13	0.010***	0.010***	0.009***	0.012***	0.012***	0.016***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)
Feedlot 14	-0.040***	-0.041***	-0.041***	-0.038***	-0.039***	-0.027***
	(0.004)	(0.005)	(0.005)	(0.005)	(0.006)	(0.007)
Feedlot 15	0.003	0.003	0.002	0.006	0.007	0.010
	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)	(0.006)
Feedlot 16	0.005	0.005*	0.006**	0.006*	0.010***	0.021***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)
Feedlot 17	-0.042***	-0.043***	-0.041***	-0.036***	-0.043***	-0.032***
	(0.005)	(0.006)	(0.006)	(0.007)	(0.008)	(0.010)
Constant	0.014***	0.011***	-0.0002	-0.018*	-0.004	-0.053*
	(0.004)	(0.004)	(0.007)	(0.010)	(0.006)	(0.027)

NB: *P<0.1; **P<0.05; ***P<0.01

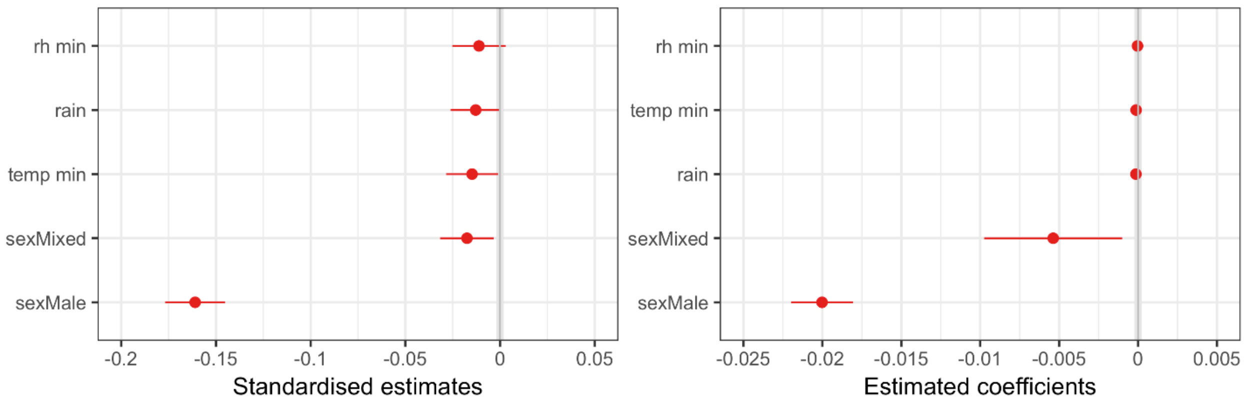

Figure 12: The estimated coefficients and standardised estimates for significant terms in the 24 hour lag period model using bureau of meteorology data

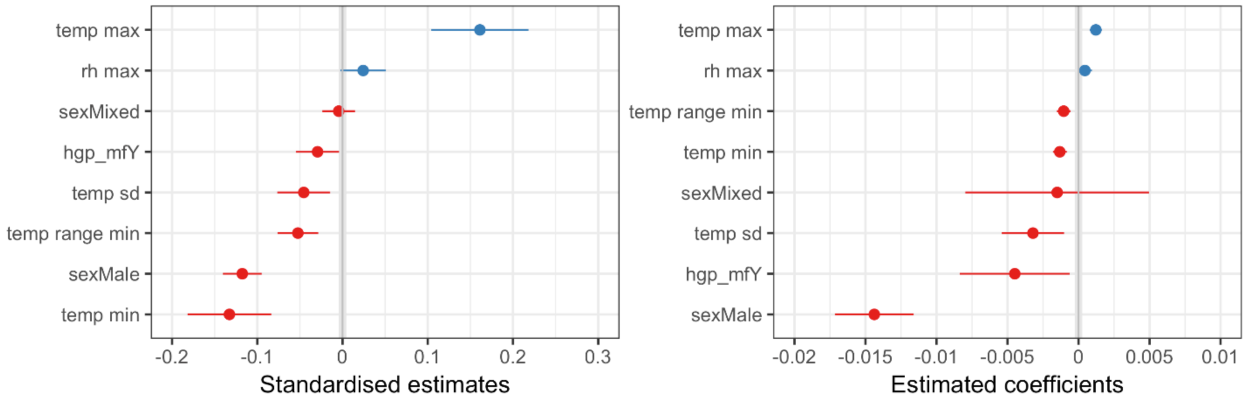

Figure 13: The estimated coefficients and standardised estimates for significant terms in the 28 day lag period model using bureau of meteorology data

4.3.2 Temperature Humidity Index analysis using BOM data

THI had no effect within 48hrs before slaughter although a 10 point increase in THI max between 3 and 28 days prior to consignment increased DFD by between 0.3 and 1% (P<0.01, Table 9). On the contrary, an increase of 10 points of the minimum THI caused a reduction in DFD by 0.2 to 0.5% in the 3, 7 and 14 day lag models only (P<0.05, Table 9). This shows that low temperatures and/or low humidity can also have a negative effect on dark cutting, however it is known from Table 8 that low temperatures do cause an increase in DFD % per lot. The standard deviation in THI over the 48 hours prior to consignment also had a significant effect on the incidence of DFD (P<0.01, Table 9). As the variation/standard deviation in THI increased over the 48 hour period by 1 point, dark cutting increased by 0.1%. This result is also supported by the significance of the standard deviation of the daily range in THI in the 14 (P<0.1) and 28 day models (P<0.01, Table 9). As the standard deviation in the THI range increase by 1 point, dark cutting also increased by 0.1 and 0.2% in the 14 and 28 day lag period models.

Rainfall also had a significant effect on the incidence of DFD if it occurred in the 48 hours prior to consignment (P<0.05, Table 9). A 10mm increase in rain in the two days before kill could reduce DFD by 0.1%, while a 10mm increase in the 24 hours prior to consignment reduced DFD by 0.2%. Wind speed did not significantly affect the incidence of DFD per lot.

Although THI was significant in the prediction of DFD; when compared across years to producer and processor effect, the magnitude of effect of THI on the incidence of DFD is minimal. Adding THI terms into the model didn't reduce the effect of processing plants or feedlots, nor did it cause any re-ranking between plants and feedlots.

Table 9: Estimated coefficients for the effect of Temperature Humidity Index calculated using bureau of meteorology data at 24 hours, 2, 3, 7, 14 and 28 days prior to consignment plus sex, HGP, feedlot and processor on the incidence of dark cutting per lot with standard errors in brackets

Dependent variable: DFD percentage per lot						
Lag Time	1	2	3	7	14	28
thi_sd		0.001***		-0.001		
		(0.0003)		(0.0004)		
rain	-0.0002***	-0.0001**				

	(0.0001)	(0.00005)				
thi_max			0.0004***	0.001***	0.0004***	0.0003***
			(0.0001)	(0.0001)	(0.0001)	(0.0001)
thi_min			-0.0003***	-0.0005***	-0.0002**	
			(0.0001)	(0.0001)	(0.0001)	
thi_range_sd					0.001*	0.002***
					(0.0005)	(0.001)
sexMale	-0.020***	-0.020***	-0.020***	-0.019***	-0.017***	-0.015***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
sexMixed	-0.005**	-0.005**	-0.005**	-0.004*	-0.005	-0.002
	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.003)
hgp_mfY					-0.003*	-0.004**
					(0.002)	(0.002)
plant02	0.006	0.006	0.005	0.007	0.010	0.006
	(0.005)	(0.006)	(0.006)	(0.006)	(0.007)	(0.009)
plant03	0.015**	0.015**	0.011*	0.015**	0.015*	0.011
	(0.006)	(0.006)	(0.006)	(0.007)	(0.008)	(0.008)
plant04	0.056***	0.056***	0.054***	0.055***	0.058***	0.044***
	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)	(0.005)
plant05	0.025***	0.025***	0.023***	0.026***	0.025***	0.021***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)
plant06	0.044***	0.044***	0.042***	0.043***	0.048***	0.035***
	(0.005)	(0.005)	(0.005)	(0.006)	(0.006)	(0.007)
plant07	0.023***	0.023***	0.021***	0.028***	0.025***	0.019***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)
plant08	0.021***	0.020***	0.019***	0.021***	0.022***	0.015**
	(0.005)	(0.005)	(0.006)	(0.006)	(0.007)	(0.007)
plant09	0.049***	0.049***	0.047***	0.053***	0.048***	0.035***
	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)	(0.006)
plant10	0.043***	0.043***	0.042***	0.045***	0.046***	0.042***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.005)
plant11	0.013***	0.015***	0.013***	0.021***	0.013**	-0.018**
	(0.004)	(0.004)	(0.005)	(0.005)	(0.006)	(0.008)
plant12	0.012***	0.011***	0.010***	0.011**	0.012**	0.005
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)
plant13	0.034***	0.034***	0.032***	0.038***	0.039***	0.029***
	(0.005)	(0.005)	(0.005)	(0.006)	(0.006)	(0.007)
plant14	0.020***	0.019***	0.016***	0.021***	0.019***	0.017***
	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)	(0.006)
plant15	0.023***	0.022***	0.021***	0.026***	0.025***	0.020***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)
plant17	0.083***	0.082***	0.079***	0.083***	0.079***	0.066***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.005)	(0.005)
Feedlot02	-0.007**	-0.006**	-0.005*	-0.004	-0.001	-0.001
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.005)

Feedlot 03	0.023***	0.024***	0.025***	0.028***	0.028***	0.034***
	(0.005)	(0.005)	(0.005)	(0.006)	(0.006)	(0.007)
Feedlot 04	-0.042***	-0.042***	-0.042***	-0.040***	-0.042***	-0.029***
	(0.004)	(0.005)	(0.005)	(0.005)	(0.006)	(0.007)
Feedlot 05	-0.016***	-0.016***	-0.018***	-0.016***	-0.021***	-0.023***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)
Feedlot 06	0.024***	0.024***	0.021***	0.025***	0.027***	0.013**
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)
Feedlot 07	-0.036***	-0.036***	-0.035***	-0.031***	-0.035***	-0.025***
	(0.005)	(0.005)	(0.006)	(0.006)	(0.007)	(0.008)
Feedlot 08	-0.0003	0.0001	0.0004	0.00004	0.001	0.003
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Feedlot 09	-0.036***	-0.037***	-0.036***	-0.033***	-0.037***	-0.026***
	(0.005)	(0.006)	(0.006)	(0.006)	(0.007)	(0.008)
Feedlot 10	0.058***	0.064***	0.063***	0.071***	0.137***	0.291***
	(0.005)	(0.006)	(0.006)	(0.007)	(0.009)	(0.012)
Feedlot 11	0.009***	0.009***	0.010***	0.010***	0.010***	0.010***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)
Feedlot 12	-0.012***	-0.012***	-0.010***	-0.009***	-0.006*	-0.003
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)
Feedlot 13	0.010***	0.011***	0.009***	0.012***	0.012***	0.015***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)
Feedlot 14	-0.040***	-0.041***	-0.041***	-0.038***	-0.040***	-0.029***
	(0.004)	(0.005)	(0.005)	(0.005)	(0.006)	(0.007)
Feedlot 15	0.003	0.003	0.003	0.006	0.006	0.009
	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)	(0.006)
Feedlot 16	0.004	0.005*	0.006*	0.005	0.009**	0.019***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)
Feedlot 17	-0.042***	-0.043***	-0.042***	-0.038***	-0.043***	-0.034***
	(0.005)	(0.006)	(0.006)	(0.007)	(0.008)	(0.010)
Constant	0.012***	0.011***	0.001	-0.016**	-0.017*	-0.020*
	(0.004)	(0.004)	(0.006)	(0.008)	(0.009)	(0.012)

NB: *P<0.1; **P<0.05; ***P<0.01

4.4 Feedlot weather station analysis

Of the 27,073 different kill groups or lots which had greater than 10 head available for the analysis, only 16.2% or 4390 lots had full data sets for all terms in the 24 hour lag period feedlot weather station analysis. This number also declined down to 8.4% or 2,268 lots as the lag period before consignment increased out to 28 days. As with the other models, the longer lag time models do explain a greater amount of the variation in the incidence of DFD compared with the shorter lag periods (Table 10). The amount of variation explained in the feedlot weather station models is lower than that explained by the other 3 models discussed above (Table 7).

Table 10: The number of observations used, R^2, adjusted R^2, residual standard error and F statistic for the feedlot weather station analysis model

	Lag period prior to feedlot departure					
	24 hours	2 days	3 days	7 days	14 days	28 days
Observations	4,390	4,135	3,928	3,475	2,969	2,268
R^2	0.163	0.164	0.179	0.188	0.206	0.232
Adjusted R^2	0.156	0.157	0.171	0.179	0.195	0.217
Residual Std. Error	0.045 (df = 4355)	0.046 (df = 4100)	0.044 (df = 3891)	0.045 (df = 3434)	0.046 (df = 2926)	0.046 (df = 2223)
F Statistic	24.937*** (df = 34; 4355)	23.594*** (df = 34; 4100)	23.530*** (df = 36; 3891)	19.936*** (df = 40; 3434)	18.099*** (df = 42; 2926)	15.263*** (df = 44; 2223

5 Discussion

5.1 Effect of weather conditions on DFD Incidence

Many of the weather terms had a significant impact on the incidence of dark, frim and dry beef (DFD). However the quantity of additional variation in DFD that the weather terms explained over and above that accounted for in the base model was minimal. This could be due to feedlotters and processors already having management systems in place to negate the majority of the effects of heat and humidity on cattle or it could suggest that weather has a significant but small effect on the incidence of DFD.

5.1.1 Effect of cold weather

The data analysis shows that cold temperatures have a negative impact on DFD or that higher minimum temperatures or higher minimum THI's reduce the incidence of DFD. As with heat stress, cattle will respond both physiologically and through behaviour to temperatures below the thermal neutral zone. Hypothermia occurs once the body's temperature drops below normal range, in cattle this can be mild, moderate and severe with temperature ranges of 30-32, 22-29 and 20 degrees Celsius respectively (Tarr 2007).

In response to lowered temperature below the body's critical set point, cattle will increase metabolic heat production, increase cardiac output while redistributing blood flow and mobilising metabolic substrates. This includes mobilising free fatty acids from adipose and glucose from glycogen stores in the liver by hepatic gluconeogenesis (Broucek *et al.* 1991). This adaption and diversion of energy to maintaining temperature can begin to occur with no obvious signs of hypothermia. Feed intake will increase to accommodate the higher energy needs and if additional feed is not available or of low quality, body condition will reduce.

Shivering is the first obvious physical sign of cold stress in cattle as the muscle contractions are used to produce heat (Bell *et al.* 1974; Gonyou *et al.* 1979). This would likely increase the rate of glycogenolysis caused by the increases in contractions and activity in the muscle (Tarrant 1989a). This effect would be amplified in cattle with higher glycolytic potential (Monin 1981; Lacourt and Tarrant 1985).

As with heat stress, cold shock acclimation also stimulates increased amounts of heat shock proteins (Hsp) (Archana *et al.* 2016). These hsp's have a range of effects on muscle metabolism and protein structure, resulting in increased toughness and reduced effects of ageing (Pulford *et al.* 2009).

5.1.2 Effect of high temperatures and humidity

Max Temp, Max Humidity and Max THI had no significant effect on the incidence of DFD % in the first 48 hours before consignment. An explanation for this might be that there is a delay in body temperature responses to a heat challenge during the first 3-4 days of exposure, the animal will only enter a chronic response stage after more than 3 days (Gaughan *et al.* 2009). Long term heat acclimation only occurs after multiple days to weeks, this involves the release of heat shock proteins that enable reprogrammed gene expression and altered endocrine systems to decrease metabolic heat production (Bernabucci *et al.* 2010). This long term response may have a higher impact on DFD % than the more immediate homeostatic responses due to catecholamine's during acute and chronic HS. The autonomic response promotes energy utilization from stores and supress energy storage. After adrenaline binds to β-receptors on muscle, a cascade reaction mediated by cyclic adenosine phosphate (cAMP) is initiated. This reaction activates glycogen phosphorylase and inhibits glycogen synthase which leads to activation of glycogenolysis, gluconeogenesis and inhibition of glycogenogenesis, hence why the maximum THI, maximum temperature and maximum humidity terms all have a significant impact on the incidence of DFD in the 3 to 28 days before consignment models. Heat stress reduces dry matter intake in order to reduce the heat increment occurring from feeding and reducing the heat of ruminal fermentation. Reduced intakes and decreased rate of gain (Ray 1989) and reduced metabolic rate (O'Brien *et al.* 2010) are likely to be directly linked to metabolisable energy (ME) intake and therefore glycogen deposition. Cattle with lower ME intakes have decreased glycogen deposition (Pethick *et al.* 1999; Knee *et al.* 2004) plus chronic and acute heat stress result in an increase in glycogen utilization (Miova *et al.* 2013). Glycogen utilisation is increased in heat stress animals as ruminants overall favour glucose as a primary fuel source (Belhadj Slimen *et al.* 2016) to minimise heat production from other biochemical processes. Thus this combination of decreased glycogenesis and an altered metabolic response is the likely cause of increased DFD in the feedlot cattle that underwent a heat event or events in the 3 to 28 days prior to consignment.

5.1.3 Effect of temperature and THI range

An animals adaptation to temperature, be it high or low, is a very important coping mechanism. For this reason sudden changes or large variations in temperature on a daily basis or over a period prior to consignment was analysed. Larger variation in temperature and THI (Temp SD and THI SD) in the 48 hours prior to consignment increased the levels of dark cutting. This result implies that large variations in temperature have a short term impact on muscle glycogen and therefore dark cutting. The results could be impacted equally by the mechanisms discussed with cold shock and heat stress in sections 5.1.1 and 5.1.2 above. An anomaly of this data analysis is that a larger variation in temperature over the 7 and 28 days preceding consignment actually improve DFD or reduce the percentage. The mechanisms underpinning this result are unknown but may be due to the possible effects of having cool nights (below 23 C) after very hot days. This would allow for heat accumulated by cattle during the day to be dissipated therefore preventing heat stress and allowing the animal to eat more during the night and following day.

Another way to look at the impact of temperature and THI is to look at the variation or standard deviation of the range in temperature and THI. Range per day was simply calculated as the highest versus lowest temp of THI score for that day. Increasing standard deviation in the temp range over 14 days pre-consignment and in THI range over 14 and 28 days caused an increase in dark cutting. Thus these results suggest that large variations in temperature and THI in the 4 weeks prior to consignment do impact the usage of muscle glycogen and therefore the incidence rates of dark cutting.

5.1.4 Effect of wind and rainfall

Wind was not significant in any model. This was unexpected as air movement aids in evaporative cooling from the skin and respiratory tract (Vermunt and P. Tranter 2011). Wind speed may have not been significant due to the antagonistic relationship between wind on cold days and wind on hot days cancelling each other out. Wind on cold wet days would be thought to increase DFD due to increasing the cold shock of the animals. While on hot humid days, wind is known to reduce heat stress.

Increased rainfall in the 48 hours prior to consignment caused a reduction in the incidence of DFD in both the weather and THI statistical models. However higher rainfall from 3 to 28 days prior to consignment did not have a positive or negative effect on the incidence of DFD. The mechanism why increased rainfall reduces dark cutting can only be speculated but it is plausible that the changed weather conditions that go with a normal rainfall event have a positive effect on cattle. Increased cloud cover may reduce solar radiation, and animal dehydration which improves the measurement of pH in the carcass (Gardner 2001). Rainfall could also stimulate cattle to eat more feed, ensuring that muscle glycogen concentration pre-slaughter is maximised.

5.1.5 Effect of heat shock on meat quality

Small heat shock proteins (HSP) existing within living muscle are responsible for cell maintenance and repair. They are responsible for the protection against hyperthermia and circulatory shock through the manipulation of the folding, unfolding and refolding of stress-denatured proteins (Gade *et al.* 2010). They are upregulated through heat stress or oxidative shock (Treweek *et al.* 2015). Some types including HSP27 and alpha β-crystallin (ABC) have been correlated with improved tenderness, juiciness and flavour in beef when down regulated. Vermunt and P. Tranter (2011) showed that the HSP 40 family coding gene (DNAJA1) which had a very strong negative correlation with tenderness and explained 63% of its variability (R -0.66, P<0.01). This protein helps the interaction of HSP 70 in the regulation of ATP hydrolisis (Hafizur *et al.* 2004). The heat shock protein (ABC) binds to myofibrillar proteins much like desmin and buffers the degredation effects of endopeptidases such as calpains and cathepsins on beef structure from ageing (Pulford *et al.* 2009), hence why heat stressed animals produce tough meat.

5.2 Effect of sex on DFD incidence

Slaughter groups of mixed sex had higher incidences of DFD carcasses than slaughter groups of either castrates. Females also had a higher incidence of DFD carcasses than castrates. These results are supported by Warren *et al.* (2010) who found that DFD prevalence was highest in mixed loads where heifers and steers were in the same compartment on the truck, followed by heifers penned separately and then castrates.

When females or mixed sex lots are transported, glycogen-depleting sexual activities such as mounting could account for this increased incidence in DFD carcasses in these slaughter groups (Kenny and Tarrant 1988; Broom 2008). This activity is escalated when females are in oestrus (Warren *et al.* 2010).

These results are supported by numerous other studies that also found steers to have lower incidences of DFD carcasses than females (Voisinet *et al.* 1997; Wulf *et al.* 1997; Scanga *et al.* 1998; Warren *et al.* 2010; Romero *et al.* 2013). However these findings have been contradicted by a study done by Page *et al.* (2001) who found no difference in muscle pH between steers and heifers. This was attributed to the heifers being fatter than the steers and it was suggested that at equal levels of fat cover, there may have been a difference in muscle colour.

The sex effect on the incidence of DFD may also result from differences in stresses experienced by females versus castrates which may be driven by an animal's predisposition to stress as well as hormonal fluctuations. Studies have found that there is a significant association between gender and temperament (Voisinet *et al.* 1997) and that heifers tend to be more excitable and more fearful than steers (Voisinet *et al.* 1997b) and therefore more susceptible to stress and DFD syndrome. From this evidence, it seems that by selecting for animals, particularly heifers with calmer temperaments, the likelihood of DFD carcasses occuring can be reduced but this is yet to be scientifically proven.

5.3 Effect of hormonal growth promotants on DFD incidence

Hormonal growth promotants have been under the suspicion of having adverse effects on carcass quality since they were first introduced (Grandin 1992). However the use of HGPs in this study had no impact or a positive impact on the incidence of DFD in grain fed cattle.

This result is contradicted by the findings of previous studies which concluded that use of HGPs will increase the incidence of DFD syndrome (Morgan 1997; Scanga *et al.* 1998; Dikeman 2003; Miller 2007; Hunter 2010). These authors also stressed that the degree of this affect depends on the type of hormone used, the timing of its use, whether it was incorrectly implanted and if over-dosing occurred. Aggressive use of HGPs (Morgan 1997) or false implant strategies can increase the susceptibility of cattle to stress, making them more prone to DFD syndrome when exposed to unusually stressful circumstances (Dikeman 2007). Thus it can be assumed also that all cattle in this data set are slaughtered after the HGP has stopped secreting significant amounts of the hormone or the 'pay-out period' has completed (Hunter 2010). Adhering to the warnings and recommendations given by the manufacturers of HGPs is important to minimise the chance of adverse effects on the incidence of DFD syndrome caused by HGPs.

5.4 Effect of feedlot on the incidence of DFD

Feedlot has a very large effect on the incidence of dark cutting. There is a 10.1% difference in the estimated coefficients from the base model between the best and worst feedlots, with the worst feedlot being 3.5% higher than all other feedlots. Therefore clearly there is a producer effect on the incidence of dark cutting which could be due to an endless list of factors or any combination of those factors for any given lot of cattle. Very little of the variation in dark cutting explained by producer in the base model was then attributed to the weather terms or THI when they were included in the model (an extra 0.1 to 0.3% of variation). This suggests that either producers already have management systems in place to negate the majority of the effects of heat and humidity on cattle or weather has a minimal impact on the incidence of dark cutting. In a retrospective data analysis like this one, these confounding factors cannot be drawn apart. However what is shown, is that regardless of heat stress management strategies, variation between feedlots is still massive.

Variation between feedlots could be due to animals purchased, producers of cattle, breeds selected, mineral deficiencies of cattle, handling techniques of all stockmen at feedlot, time on feed, opportunity for habituation to humans, confinement and machinery, density of cattle in pens, drafting, weighing, washing and pre-consignment management, stock transporter used, distance to abattoir, health and weather management strategies.

5.5 Effect of processing plant on the percentage of DFD carcasses

There was very significant variation in the incidence of dark cutting recorded between the 17 different processing plants analysed in this study. One plant exhibited a substantially higher DFD occurrence (2.8%) than the rest of the plants and there was still significant variation among the other plants. Variation between processing plants could be caused by a plethora of factors, all of which are explained in this statistical model by the term plant. The true impact of each of these factors is difficult and very costly to tease apart, but it can be assumed that the impact of all these factors would vary between slaughter groups on a daily basis.

Further research is required to identify plant factors that contribute to dark cutting. Although unidentified by this study, possible sources of variation for further investigation could include the following. The measurement of colour between plant graders could vary which is partially supported by a study done by Page *et al.* (2001) who found differences in colorimeter readings between plants. Differences in the handling practices of cattle and carcasses at different processing plants may impact on the rate of ultimate pH decline in carcasses which can affect colour readings (Page *et al.* 2001) and thus potentially impact on the incidence of DFD syndrome recorded across plants. The size of the plant, differences in the type of animals slaughtered to meet specific orders and differences in protocols for the grading of carcasses and the delivery of animals may be impacting on the percentage of DFD carcasses (Brown *et al.* 1990).

Other potential causes for the variation in DFD incidence across the processing plants could be differences in the level of stress animals are exposed to prior to slaughter (Grandin and Gallo 2007). Time in lairage and environmental factors could be investigated. Audit of accuracy of pH meters across processing plants could be investigated to ensure calibration errors are not contributing to dark cutting. The time between slaughter and grading, the temperature of the carcass at grading and the rate of pH/temperature decline or temperature at pH6 could also all effect the pH and colour measurement of the loin and should be investigated in future research (Hughes *et al.* 2014).

5.6 Effects of weather on high meat colour or high pH percentage per lot

The same analysis as that discussed above was also run using models with carcasses classified as having high meat colour or high ultimate pH alone. These 2 analyses, presented and discussed in the appendix of this report produced very similar results. This was expected as the two variables were strongly correlated with a Pearson r value of 0.88 (See Appendix section 9.1). This shows that the majority of those that are non-compliant for either meat colour or pH are non-compliant for the other trait also. The impact of weather on high meat colour or high pH percentages per lot were also markedly similar with the models producing very similar results for both total impact and the significance of time periods prior to exiting feedlot (See Appendix section 9.2.2 to 9.2.5). This means that the recommendations and implications from all the analyses are the same, making extension and adoption of the results from this report more straight forward which is a great outcome.

6 Conclusions/recommendations

6.1 Conclusions

The factors having the greatest impact on the incidence of dark cutting per lot are the feedlot, processor and sex of the lot which explain around 20 to 24% of the variation in DFD%. Climatic conditions do have a significant but small impact on the incidence of dark cutting explaining a further 0.1 to 0.4% of variance across the different lag period models. Both high and low temperatures and THI along with big variations in temperature and THI all increased the incidence of dark cutting due to their impact on the animals rate of glycogen deposition or glycogen breakdown. Rainfall in the 48 hours pre-consignment had a positive impact on DFD% while the average wind speed had no impact on the incidence of DFD.

6.2 Recommendations

- High temperatures and THI, low temperatures and THI, high humidity, and increased daily temp and THI ranges all increase the incidence of dark cutting. If these events occur at a feedlot, management could alter normal practices for the 4 weeks following these events to ensure there is no additive impact of 'normal' practices – for example if it is normal to sort lots of cattle onto the truck then this should be avoided or if departure time is normally morning, move it to later in the day to reduce time in lairage etc.
- After a weather event, an industry system (like Katestone) could warn lot feeders that their cattle are at higher risk of dark cutting and suggest ways to minimise the prevalence of dark cutting. A risk awareness and information delivery mechanism could be built into existing industry warning frameworks.
- Analyse weather data again without feedlots 4, 7, 9, 14 and 17 included as these feedlots have very low incidences of DFD. These feedlots do prove that regardless of weather, their cattle outperform the compliance rates of all others. It could be worthwhile for industry to assess how these feedlots prepare their cattle for consignment and also the processing that they undergo. It is likely that the low incidences are a combination of exemplary management at both the feedlot and abattoir for these cattle and carcasses.
- Time below 23°C per day needs inclusion in a separate model as a curve linear term. Animals need time below 23°C to dissipate heat but the current models also show us that cold temperatures also cause DFD. Hence it is hypothesised that 24hrs less than 23°C will cause high DFD, the rate will get lower as those hours dissipate and the incidence of DFD will be high again at 0 hours less than 23°C
- This analysis identifies the variation in dark cutting among feedlots. It is recommended to conduct strategic systems analyses of these feedlots and the processors they supply to help eliminate dark cutting as it is clearly a within value chain issue.
- This analysis identifies variation in dark cutting among processors. The industry needs to work strategically with these processors to assess why their rates and incidences of dark cutting are high.
- Recommended to complete the supply chain audits and analysis of 3 processors to help identify the factors at both the feedlot and processor levels that could be driving the high DFD incidences.
- Set an industry target of less than 1% dark cutting for all cattle finished on grain based diets and work tirelessly with value chains to achieve this national level of compliance.

7 Key messages

- Sex type of the lot has a large impact on the incidence of dark cutting. Heifers perform the worst suggesting that heifers need to be managed differently to steers to avoid the opportunity for mounting behaviour during the pre-slaughter period. Reduced drafting, reduced time in lairage and optimised feed management during periods of extreme weather could help to minimise the heifer effect.
- HGPs have no impact on the incidence of dark cutting. The recommendation is to continue with perfect placement of HGPs in the ears to avoid buller behaviour and consign cattle to slaughter after the payout period.
- Conduct audits across supplychains (feedlots and processors) with more than 1.5% dark cutting to identify factors that are most likely causing dark cutting. Manipulate 1 factor at a time to see if compliance rates for pH and/or meat colour improve then make the next change picking off the low hanging fruit 1st.
- Understand what climatic conditions impact the rates of dark cutting and manage cattle optimally or more favourable after those events to ensure the rates of DFD are not exacerbated further.

8 Bibliography

Akaike, H (1974) A new look at the statistical model identification. *IEEE Transactions on Automatic Control* **19**, 716-723.

Archana, P, Joy, A, Prathap, P, Sejian, V, Madiajagan, B, Krishnan, G, Lees, A, Manimaran, A, V, B, E K, K, Varma, G, J B, G, R, B (2016) 'Role of heat shock proteins for livestock adaptation against heat stress.'

Baldwin, RL, Smith, NE, Taylor, J, Sharp, M (1980) Manipulating Metabolic Parameters to Improve Growth Rate and Milk Secretion1. *Journal of Animal Science* **51**, 1416-1428.

Belhadj Slimen, I, Najar, T, Ghram, A, Abdrrabba, M (2016) Heat stress effects on livestock: molecular, cellular and metabolic aspects, a review. *Journal of Animal Physiology and Animal Nutrition* **100**, 401-412.

Bell, A, Thompson, G, Findlay, J (1974) The contribution of the shivering hind leg to the metabolic response to cold of the young ox (Bos taurus). *Pflügers Archiv* **346**, 341-350.

Bernabucci, U, Lacetera, N, Baumgard, LH, Rhoads, RP, Ronchi, B, Nardone, A (2010) Metabolic and hormonal acclimation to heat stress in domesticated ruminants. *Animal* **4**, 1167-83.

Broom, D (2008) The welfare of livestock during road transport. In 'Long distance transport and welfare of farm animals.' (Eds Appleby CM, Cussen AV, Garcés L, Lambert AL, Turner J.) (C.A.B. International: Wallingford, England). Available at http://books.google.com.au/books?hl=en&lr=&id=HixNfhRQAscC&oi=fnd&pg=PA157&dq=Long+distance+transport+and+welfare+of+farm+animals&ots=Y2CVMxlNo-&sig=CjU_9xV7rHa1HPcDWb1iyvf4UZo#v=onepage&q=dark&f=false [Accessed

Broucek, J, Letkovicova, M, Kovalcuj, K (1991) Estimation of cold stress effect on dairy cows. *Int J Biometeorol* **35**, 29-32.

Brown, S, Bevis, E, Warriss, P (1990) An estimate of the incidence of dark cutting beef in the United Kingdom. *Meat Science* **27**, 249-258.

Dikeman, ME (2003) Metabolic modifiers and genetics: Effects on carcass traits and meat quality. *International Congress of Meat Science and Technology* **49**, 1-38.

Dikeman, ME (2007) Effects of metabolic modifiers on carcass traits and meat quality. *Meat Science* **77**, 121-135.

Ferguson, DM, Warner, RD (2008) Have we underestimated the impact of pre-slaughter stress on meat quality in ruminants? *Meat Sci* **80**, 12-9.

Gade, N, Mahapatra, RK, Sonawane, A, Singh, VK, Doreswamy, R, Saini, M (2010) Molecular Characterization of Heat Shock Protein 70-1 Gene of Goat (Capra hircus). *Molecular Biology International* **2010**,

Gardner, GE (2001) Nutritional regulation of glycogen metabolism in cattle and sheep. Murdoch University.

Gaughan, J, Lacetera, N, E. Valtorta, S, Khalifa, H, Hahn, L, Mader, T (2009) 'Response of Domestic Animals to Climate Challenges.'

Geraert, PA, Padilha, JCF, Guillaumin, S (1996) Metabolic and endocrine changes induced by chronic heatexposure in broiler chickens: growth performance, body composition and energy retention. *British Journal of Nutrition* **75**, 195-204.

Gonyou, H, Christopherson, R, Young, B (1979) Effects of cold temperature and winter conditions on some aspects of behaviour of feedlot cattle. *Applied Animal Ethology* **5**, 113-124.

Grandin, T (1992) Problems with bruises and dark cutters in harvest steers/heifers. *Improving the consistency and competitiveness of beef-A blueprint for total quality management in the feed-beef industry-The final report of national beef quality audit-1991. Colorado State University, Fort Collins*

Grandin, T, Gallo, C (2007) Cattle Transport. In 'Livestock handling and transport.' (Ed. T Grandin.) pp. 134-154. (CAB International Wallingford, UK)

Hafizur, RM, Yano, M, Gotoh, T, Mori, M, Terada, K (2004) Modulation of chaperone activities of Hsp70 and Hsp70-2 by a mammalian DnaJ/Hsp40 homolog, DjA4. *J Biochem* **135**, 193-200.

Hughes, JM, Kearney, G, Warner, RD (2014) Improving beef meat colour scores at carcass grading. *Animal Production Science* **54**, 422-429.

Hunter, RA (2010) Hormonal growth promotant use in the Australian beef industry. *Animal Production Science* **50**, 637-659.

Igono, MO, Bjotvedt, G, Sanford-Crane, HT (1992) Environmental profile and critical temperature effects on milk production of Holstein cows in desert climate. *International Journal of Biometeorology* **36**, 77-87.

Jacob, RH, Surridge, VSM, Beatty, DT, Gardner, GE, Warner, RD (2014) Grain feeding increases core body temperature of beef cattle. *Animal Production Science* **54**, 444-449.

Jose, C, McGilchrist, P, Perovic, JL, Gardner, GE, Pethick, DW (2015a) The economic impact of dark cutting beef in Australia. In 'International Congress of Meat Science and Technology. Clermont-Ferrand, France'.

Jose, CG, McGilchrist, P, Perovic, JL, Gardner, GE, Pethick, DW Sante-Lhoutellier, G Gandemer (Eds) (2015b) 'The economic impact of dark cutting beef in Australia, 61st International Congress of Meat Science and Technology.' Clermont-Ferrand, France.

Kenny, F, Tarrant, P (1988) The effect of oestrus behaviour on muscle glycogen concentration and dark-cutting in beef heifers. *Meat Science* **22**, 21-31.

Knee, BW, Cummins, LJ, Walker, P, Warner, R (2004) Seasonal variation in muscle glycogen in beef steers. *Australian Journal of Experimental Agriculture* **44**, 729-734.

Lacourt, A, Tarrant, PV (1985) Glycogen depletion patterns in myofibres of cattle during stress. *Meat Science* **15**, 85-100.

Lenth, R, 2018. emmeans: Estimated Marginal Means, aka Least-Squares Means. . R package version 1.1.3. https://CRAN.R-project.org/package=emmeans.

Lüdecke, D, 2018. sjPlot: Data Visualization for Statistics in Social Science. R package version 2.4.1. https://CRAN.R-project.org/package=sjPlot.

McGilchrist, P, Alston, CL, Gardener, GE, Thomson, KL, Pethick, DW (2012) Beef carcasses with larger eye muscle areas, lower ossification scores and improved nutrition have a lower incidence of dark cutting *Meat Science* **92**, 474-480.

Miller, M (2007) Dark, firm and dry beef. *National Cattlemen's Beef Association, Centennial, CO*

Miova, B, Dinevska-Kjovkarovska, S, Cvetkovska, F, Mitev, S, Dzimervska, A, Dimitrovska, M (2013) Liver Carbohydrate Metabolism in Rats in the Period of Recovery after Acute Heat Stress. *Macedonian journal of medical sciences* **6**, 16-23.

Monin, G (1981) Muscle metabolic type and the DFD condition. In 'The problem of dark cutting beef. Current topics in veterinary medicine and animal science.' (Eds DE Hood, PV Tarrant.) Vol. 10 pp. 63 - 85. (Martinus Nijhoff: The Hague)

Morgan, J (1997) 'Implant program effects on USDA beef carcass quality grade traits and meat tenderness, Proc. Symp. Impact Implants Perform. Carcass Value Beef Cattle, Oklahoma State Univ., Stillwater.'

Muller, CJC, Botha, JA, Coetzer, WA, Smith, WA (1994) Effect of shade on various parameters of Friesian cows in a Mediterranean climate in South Africa. 2. Physiological responses. *South African Journal of Animal Science* **24**, 56-60.

O'Brien, MD, Rhoads, RP, Sanders, SR, Duff, GC, Baumgard, LH (2010) Metabolic adaptations to heat stress in growing cattle. *Domestic Animal Endocrinology* **38**, 86-94.

Page, J, Wulf, D, Schwotzer, T (2001) A survey of beef muscle color and pH. *Journal of Animal Science* **79**, 678-687.

Pethick, DW, Cummins, L, Gardner, GE, Knee, BW, McDowell, M, McIntyre, BL, Tudor, G, Walker, PJ, Warner, RD (1999) The regulation by nutrition of glycogen in the muscle of ruminants. *Recent Advances in Animal Nutrition in Australia* **12**, 145-151.

Pulford, DJ, Dobbie, P, Fraga Vazquez, S, Fraser-Smith, E, Frost, DA, Morris, CA (2009) Variation in bull beef quality due to ultimate muscle pH is correlated to endopeptidase and small heat shock protein levels. *Meat Sci* **83**, 1-9.

Ray, DE (1989) Interrelationships among Water Quality, Climate and Diet on Feedlot Performance of Steer Calves1,2. *Journal of Animal Science* **67**, 357-363.

RCoreTeam, 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing. https://www.R-project.org, Vienna, Austria.

Romero, M, Uribe-Velásquez, L, Sánchez, J, Miranda-de la Lama, G (2013) Risk factors influencing bruising and high muscle pH in Colombian cattle carcasses due to transport and pre-slaughter operations. *Meat Science* 256-263.

Scanga, JA, Belk, KE, Tatum, JD, Grandin, T, Smith, GC (1998) Factors contributing to the incidence of dark cutting beef. *Journal of Animal Science* **76**, 2040-7.

Tarrant, PV (1989a) Animal behaviour and environment in the dark-cutting condition. In 'Dark cutting in sheep and cattle. Sydney'. (Eds SU Fabiansson, WR Shorthose, RD Warner) pp. 8 - 18. (Australian Meat and Livestock Research and Development Corporation:

Tarrant, PV (1989b) Animal Behaviour and Environment in the Dark-Cutting Condition in Beef - A Review. *Irish Journal of Food Science and Technology* **13**, 1-21.

Treweek, T, Meehan, S, Ecroyd, H, Carver, J (2015) Small heat-shock proteins: important players in regulating cellular proteostasis. *Cellular and Molecular Life Sciences* **72**, 429-451.

Vermunt, J, P. Tranter, B (2011) 'Heat stress in dairy cattle – a review, and some of the potential risks associated with the nutritional management of this condition.'

Voisinet, B, Grandin, T, Tatum, J, O'connor, S, Struthers, J (1997b) Feedlot cattle with calm temperaments have higher average daily gains than cattle with excitable temperaments. *Journal of Animal Science* **75**, 892-896.

Voisinet, BD, Grandin, T, O'Connor, SF, Tatum, JD, Deesing, MJ (1997) Bos indicus-cross feedlot cattle with excitable temperaments have tougher meat and a higher incidence of borderline dark cutters. *Meat Science* **46**, 367-377.

Warner, RD, Truscott, TG, Eldridge, GA, Franz, PR (1988) A Survey of the incidence of high pH beef meat in Victorian abattoirs. *International Congress of Meat Science and Technology, Brisbane, Australia* **34**, 150-151.

Warren, LA, Mandell, IB, Bateman, KG (2010) Road transport conditions of slaughter cattle: Effects on the prevalence of dark, firm and dry beef. *Canadian Journal of Animal Science* **90**, 471-482.

Wulf, DM, O'Connor, SF, Tatum, JD, Smith, GC (1997) Using objective measures of muscle color to predict beef longissimus tenderness. *Journal of Animal Science* **75**, 684-692.

9 Appendix

9.1 Correlation between high meat colour and high pH percentage per lot

High meat colour and high pH were strongly correlated with a Pearson r value of 0.88 in this data set. This shows that the majority of those that are non-compliant for either meat colour or pH are non-compliant for the other trait also.

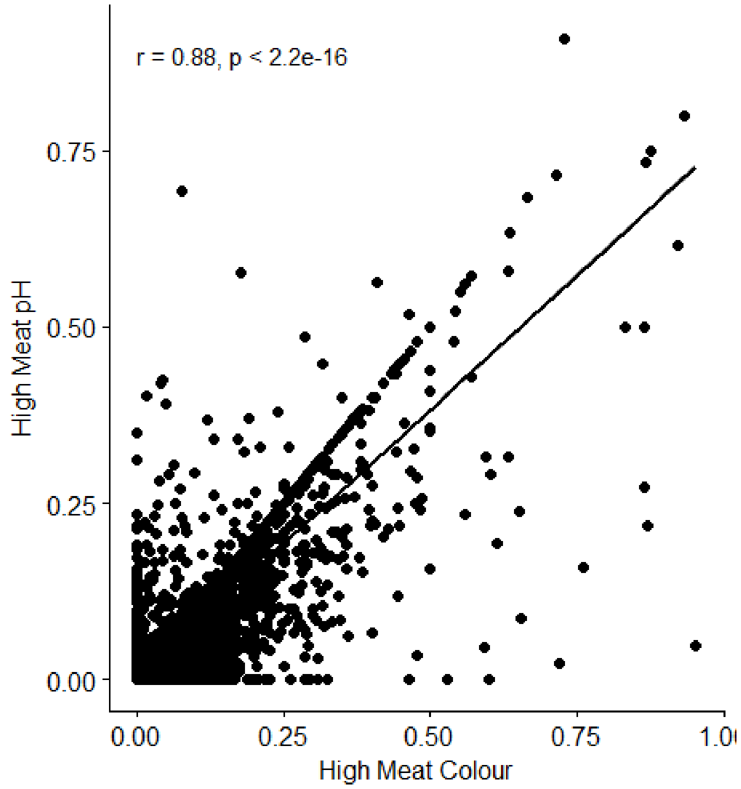

Figure 1. Correlation between high meat colour (>4) and high pH (>5.7) percentage per lot
t = 302.74, df = 27217, p-value < 2.2e-16 Pearson Corr = 0.88

9.2 Bureau of meteorology data analysis

The MSA carcass grading data analysed was the same as that analysed in the report with percentage of carcasses per lot with high meat colour and pH run as separate dependant variables.

9.2.1 Statistical Modeling

High meat colour or high pH percentage per lot were calculated using the number of carcasses in a lot which had meat colour ≥ 4 OR pH ≥ 5.71 divided by the number in each lot. The high pH and high meat colour analyses were run as separate dependent variables. Lots with 10 head or less were removed from the analysis as the size of the impact from 1 animal being high meat colour or high pH becomes too large.

Following an extensive data integration and variable creation process, high meat colour and high pH percentage per lot were regressed in separate models on the weather predictors of a certain lag, as well as with fixed effects for feedlot, processor, sex and HGP status. A stepwise model selection procedure was performed starting at the full model and progressing both backwards and forwards through the model space using the Akaike information criterion to evaluate competing models and stopping when a minimum is reached (Akaike 1974).

The initial base models run included fixed effects for feedlot, processor, HGP status and sex with no weather terms or indexes included as per the base model in report above. The weather term models including max, min and standard deviation for temperature, relative humidity, daily temperature range plus average wind speed and rainfall were added to the base model. The third analysis using the BOM weather data was the THI index model where max, min and standard deviation of THI, plus average wind speed and rainfall were added to the base model. Throughout the 3 models for BOM data, the lots analysed were restricted to the same bounds, hence the number of observations used in the analysis for each lag period were exactly the same. The MSA carcass grading data provided information on 27073 lots of carcasses which had greater than 10 head. If there was missing weather data in the analysis for a lot, then that lot was dropped from the analysis hence there was greater attrition of lots as the lag period increased from 24 hours (19,563 lots in analysis, Table 7) to 28 days (9,167 lots in analysis, Table 7) due to a greater possibility of missing weather data over a 28 day period.

While the dependent variables, high meat colour or high pH percentage, and model residuals are not normally distributed, valid p-value based inferences on the model coefficients can still be obtained through the application of the central limit theorem given the large sample sizes.

Data integration and modelling was performed using the R statistical program (RCoreTeam 2018). Estimated marginal means were calculated using the emmeans package (Lenth 2018) and estimated coefficients and standardised coefficients visualised with the sjPlot package (Lüdecke 2018).

9.2.2 High pH Temperature Model

Maximum temperature had a significant effect on the incidence of dark cutting in the 3 ($P<0.1$), 7, 14 and 28 day lag period models ($P<0.01$, Table 1) but was not significant within 48 hours of consignment. An increase of 10 degrees maximum temp between 3 to 28 days correlated with a 0.1 to 0.5 percent increase in high pH incidence (Table 1). This relationship was linear across the range of maximum temperatures for all lots which were spread from 15°C to 47°C.

Minimum temperature was only significant at 7, 14 and 28 days ($P<0.01$). As minimum temperature increased by 10°C, the prevalence of high pH carcasses decreased by 0.3% in the 7 and 14 day lag models and by 0.5 percent in the 28 day lag models (Table 1).

Temperature standard deviation also had a significant effect at 2 and 3 days prior to consignment ($P<0.01$) (Table 1). As temperature standard deviation went up by 1°C, the incidence of carcasses with high pH went up by 0.1% in the 2 and 3 day lag model (Table 1). Minimum temperature range per day also had a significant effect on the incidence of high pH but only in the 28 day lag period model (Table 1) which showed that as temperature range increased by 10°C the incidence of high pH reduced by 0.4%. The standard deviation of temp range was also only significant in the 14 day lag period model ($P<0.01$).

Maximum relative humidity (RH) was only significant in the models for 3, 7 ($P<0.1$) and 28 days before consignment ($P<0.05$). A 10 point increase in RH corresponded with an increase in high pH by 0.1, 0.1 and 0.5 % respectively.

A 10mm increase in rainfall had a 0.1-0.2% reduction in high pH if it occurred between 1-3 days prior to consignment from the feedlot (P<0.01, Table 1). Wind speed did not have a significant effect on the incidence of high pH.

These results are almost identical to the analysis of the incidence of DFD when carcasses are categorised using pH and meat colour.

Table 1: Estimated coefficients for the effect of weather variables on high pH calculated using bureau of meteorology data at 24 hours, 2, 3, 7, 14 and 28 days prior to consignment plus sex, HGP, feedlot and processor on the incidence of dark cutting per lot with standard errors in brackets

	Dependent variable: High pH Percent					
Lag Time	1	2	3	7	14	28
temp_max			0.0001*	0.0003***	0.0003***	0.0005***
			(0.0001)	(0.0001)	(0.0001)	(0.0001)
temp_sd		0.001***	0.001***			
		(0.0003)	(0.0003)			
temp_min				-0.0003***	-0.0003**	-0.0005***
				(0.0001)	(0.0001)	(0.0001)
temp_range_min						-0.0004**
						(0.0002)
rh_max			0.0001*	0.0001*		0.0005**
			(0.00004)	(0.0001)		(0.0002)
rain	-0.0002***	-0.0001***	-0.0001**			
	(0.0001)	(0.00004)	(0.00003)			
temp_range_sd					0.001***	
					(0.0004)	
sexMale	-0.019***	-0.019***	-0.019***	-0.018***	-0.017***	-0.016***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
sexMixed	-0.006***	-0.006***	-0.006***	-0.005**	-0.005**	-0.003
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)
plant02	0.005	0.005	0.004	0.006	0.008	0.008
	(0.004)	(0.004)	(0.005)	(0.005)	(0.006)	(0.007)
plant03	0.016***	0.015***	0.011**	0.016***	0.016***	0.016**
	(0.005)	(0.005)	(0.005)	(0.006)	(0.006)	(0.007)
plant04	0.047***	0.047***	0.045***	0.045***	0.049***	0.043***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)
plant05	0.020***	0.019***	0.017***	0.021***	0.021***	0.019***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)
plant06	0.037***	0.037***	0.035***	0.035***	0.040***	0.035***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)
plant07	0.023***	0.023***	0.021***	0.027***	0.028***	0.024***
	(0.002)	(0.002)	(0.003)	(0.003)	(0.003)	(0.004)
plant08	0.019***	0.018***	0.017***	0.020***	0.021***	0.017***
	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)	(0.005)

plant09	0.042***	0.042***	0.041***	0.047***	0.044***	0.035***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)
plant10	0.042***	0.042***	0.041***	0.044***	0.046***	0.045***
	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.004)
plant11	0.019***	0.019***	0.018***	0.026***	0.023***	-0.005
	(0.003)	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)
plant12	0.011***	0.010***	0.009***	0.010***	0.010***	0.007
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)
plant13	0.023***	0.023***	0.020***	0.026***	0.026***	0.022***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)
plant14	0.020***	0.019***	0.016***	0.021***	0.021***	0.022***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)
plant15	0.022***	0.022***	0.020***	0.025***	0.025***	0.022***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)
plant17	0.043***	0.042***	0.040***	0.046***	0.043***	0.034***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)
location02	-0.010***	-0.009***	-0.009***	-0.009***	-0.006*	-0.006*
	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.004)
location03	0.017***	0.018***	0.018***	0.022***	0.024***	0.027***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)
location04	-0.036***	-0.037***	-0.037***	-0.033***	-0.035***	-0.029***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)
location05	-0.018***	-0.019***	-0.020***	-0.018***	-0.020***	-0.022***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.005)
location06	0.020***	0.020***	0.017***	0.021***	0.022***	0.013***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)
location07	-0.031***	-0.032***	-0.031***	-0.027***	-0.030***	-0.028***
	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)	(0.006)
location08	-0.001	-0.001	-0.001	-0.001	-0.0004	0.001
	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)	(0.002)
location09	-0.032***	-0.033***	-0.033***	-0.029***	-0.032***	-0.028***
	(0.004)	(0.004)	(0.005)	(0.005)	(0.005)	(0.006)
location10	0.020***	0.023***	0.018***	0.017***	0.028***	0.058***
	(0.004)	(0.005)	(0.005)	(0.005)	(0.007)	(0.009)
location11	0.009***	0.010***	0.009***	0.010***	0.010***	0.009***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)
location12	-0.013***	-0.013***	-0.013***	-0.012***	-0.009***	-0.007**
	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)
location13	0.008***	0.009***	0.008***	0.010***	0.010***	0.014***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)
location14	-0.035***	-0.036***	-0.035***	-0.031***	-0.034***	-0.027***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)
location15	0.001	0.001	-0.00003	0.003	0.005	0.007
	(0.003)	(0.003)	(0.004)	(0.004)	(0.004)	(0.005)
location16	-0.001	-0.0004	-0.0003	-0.001	0.003	0.011***

	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.003)
location17	-0.037***	-0.037***	-0.036***	-0.031***	-0.037***	-0.032***
	(0.004)	(0.005)	(0.005)	(0.005)	(0.006)	(0.008)
Constant	0.014***	0.013***	0.006	-0.007	-0.002	-0.051**
	(0.003)	(0.003)	(0.006)	(0.008)	(0.005)	(0.021)
Observations	19,563	18,852	18,224	15,637	12,782	9,167
R^2	0.159	0.161	0.158	0.158	0.157	0.159
Adjusted R^2	0.158	0.160	0.157	0.156	0.155	0.156
Residual Std. Error	0.040 (df = 19528)	0.040 (df = 18816)	0.040 (df = 18186)	0.040 (df = 15600)	0.040 (df = 12745)	0.037 (df = 9129)
F Statistic	108.798*** (df = 34; 19528)	103.524*** (df = 35; 18816)	92.455*** (df = 37; 18186)	81.545*** (df = 36; 15600)	65.904*** (df = 36; 12745)	46.743*** (df = 37; 9129)
Note:	*p**p***p<0.01					

9.2.3 High pH THI Model

THI had no effect on high pH within 48hrs before slaughter although a 10 point increase in THI max between 3 and 28 days prior to consignment increased high meat pH by between 0.3 and 1% (P<0.01, Table 2). On the contrary, an increase of 10 points of the minimum THI caused a reduction in high meat pH by 0.2 to 0.1% in the 7 and 14 day lag models only (P<0.05, Table 2). This varied from the DFD model as it was not significant at 3 days and had a lower than 0.5% effect.

The standard deviation in THI 2-3 days prior to consignment also had a significant effect on the incidence of high pH (P<0.01, Table 2). As the variation/standard deviation in THI increased the period by 1 point, high pH increased by 0.1%. This result is also supported by the significance of the standard deviation of the daily range in THI in the 7 (P<.05), 14 (P<0.1) and 28 day models (P<0.01, Table 9). As the standard deviation in the THI range increase by 1 point, high pH also increased by 0.004, 0.1 and 0.2% in the 14 and 28 day lag period models.

Rainfall also had a significant effect on the incidence of high pH if it occurred up to 3 days prior to consignment (P<0.05, Table 2). A 10mm increase in rain 2-3 days before kill could reduce the prevalence of high pH carcasses by 0.1%, while a 10mm increase in the 24 hours prior to consignment reduced high pH carcasses by 0.2%

Table 2: Estimated coefficients for the effect of Temperature Humidity Index on high pH calculated using bureau of meteorology data at 24 hours, 2, 3, 7, 14 and 28 days prior to consignment plus sex, HGP, feedlot and processor on the incidence of dark cutting per lot with standard errors in brackets

	Dependent variable: High pH Percent					
Lag Time	1	2	3	7	14	28
thi_max			0.0001**	0.0004***	0.0004***	0.0003***
			(0.00004)	(0.0001)	(0.0001)	(0.0001)
thi_sd		0.001***	0.001***			
		(0.0002)	(0.0002)			
rain	-0.0002***	-0.0001***	-0.0001*			
	(0.0001)	(0.00004)	(0.00003)			
thi_min				-0.0002***	-0.0001*	

				(0.0001)	(0.0001)	
thi_range_sd				0.0004*	0.001**	0.002***
				(0.0002)	(0.0004)	(0.0004)
ws_avg						-0.0003
						(0.0002)
sexMale	-0.019***	-0.019***	-0.019***	-0.018***	-0.017***	-0.016***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
sexMixed	-0.006***	-0.006***	-0.006***	-0.005**	-0.005**	-0.003
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)
plant02	0.005	0.005	0.004	0.006	0.008	0.007
	(0.004)	(0.004)	(0.005)	(0.005)	(0.006)	(0.007)
plant03	0.016***	0.015***	0.010**	0.016***	0.016***	0.015**
	(0.005)	(0.005)	(0.005)	(0.006)	(0.006)	(0.007)
plant04	0.047***	0.047***	0.045***	0.045***	0.049***	0.042***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)
plant05	0.020***	0.019***	0.017***	0.021***	0.021***	0.018***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)
plant06	0.037***	0.037***	0.034***	0.035***	0.040***	0.034***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)
plant07	0.023***	0.023***	0.021***	0.027***	0.028***	0.024***
	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.004)
plant08	0.019***	0.018***	0.017***	0.020***	0.021***	0.016***
	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)	(0.005)
plant09	0.042***	0.042***	0.041***	0.046***	0.044***	0.034***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)
plant10	0.042***	0.042***	0.041***	0.044***	0.046***	0.044***
	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.004)
plant11	0.019***	0.019***	0.017***	0.026***	0.023***	-0.004
	(0.003)	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)
plant12	0.011***	0.010***	0.008***	0.010***	0.011***	0.006
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)
plant13	0.023***	0.023***	0.020***	0.026***	0.026***	0.021***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)
plant14	0.020***	0.020***	0.016***	0.021***	0.021***	0.021***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)
plant15	0.022***	0.022***	0.020***	0.025***	0.025***	0.021***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)
plant17	0.043***	0.042***	0.040***	0.046***	0.043***	0.033***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)
location02	-0.010***	-0.009***	-0.009***	-0.008***	-0.006**	-0.009**
	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.004)
location03	0.017***	0.018***	0.018***	0.023***	0.024***	0.026***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)
location04	-0.036***	-0.037***	-0.037***	-0.033***	-0.036***	-0.029***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)
location05	-0.018***	-0.019***	-0.020***	-0.018***	-0.021***	-0.022***

	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.005)
location06	0.020***	0.020***	0.017***	0.021***	0.022***	0.011**
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.004)
location07	-0.031***	-0.032***	-0.031***	-0.027***	-0.030***	-0.026***
	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)	(0.006)
location08	-0.001	-0.001	-0.001	-0.001	-0.0005	0.0004
	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)	(0.002)
location09	-0.032***	-0.033***	-0.033***	-0.028***	-0.032***	-0.027***
	(0.004)	(0.004)	(0.005)	(0.005)	(0.005)	(0.006)
location10	0.020***	0.023***	0.019***	0.018***	0.028***	0.058***
	(0.004)	(0.005)	(0.005)	(0.005)	(0.007)	(0.009)
location11	0.009***	0.010***	0.009***	0.010***	0.010***	0.009***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)
location12	-0.013***	-0.013***	-0.013***	-0.011***	-0.008***	-0.003
	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.004)
location13	0.008***	0.009***	0.007***	0.010***	0.010***	0.012***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)
location14	-0.035***	-0.036***	-0.035***	-0.031***	-0.034***	-0.030***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)
location15	0.001	0.001	0.0002	0.004	0.005	0.005
	(0.003)	(0.003)	(0.004)	(0.004)	(0.004)	(0.005)
location16	-0.001	-0.0003	-0.001	-0.001	0.003	0.011***
	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.003)
location17	-0.037***	-0.037***	-0.036***	-0.031***	-0.037***	-0.035***
	(0.004)	(0.005)	(0.005)	(0.005)	(0.006)	(0.008)
Constant	0.014***	0.013***	0.008*	-0.012**	-0.017**	-0.019**
	(0.003)	(0.003)	(0.004)	(0.006)	(0.007)	(0.009)
Observations	19,563	18,852	18,224	15,637	12,782	9,167
R^2	0.159	0.161	0.158	0.159	0.157	0.159
Adjusted R^2	0.158	0.160	0.157	0.157	0.155	0.155
Residual Std. Error	0.040 (df = 19528)	0.040 (df = 18816)	0.040 (df = 18187)	0.040 (df = 15600)	0.040 (df = 12745)	0.037 (df = 9130)
F Statistic	108.798*** (df = 34; 19528)	103.503*** (df = 35; 18816)	95.052*** (df = 36; 18187)	81.916*** (df = 36; 15600)	65.989*** (df = 36; 12745)	47.880*** (df = 36; 9130)
Note:	NB: *P<0.1; **P<0.05; ***P<0.01					

9.2.4 High meat colour weather temperature model

Maximum temperature had a significant effect on the incidence of high meat colour in the 1 (P<0.1), 3, 7, 14 and 28 day lag period models (P<0.01, Table 3) but was not significant within 48 hours of consignment (Table 3). An increase of 10 degrees maximum temp for all days correlated with a 0.1 to 1 percent increase in high meat colour incidence (Table 3).

Minimum temperature was significant at all lag times (P<0.01) except the first 2 days prior to consignment (Table 3). As minimum temperature increased by 10°C, high meat colour % decreased by 0.3% in the 3 day lag model and by 1% in the 7-28 day lag models (Table 3).

Temperature standard deviation also had a significant effect (P<0.05 – P<0.01) the incidence of high meat colour but the size of the effect, relationship with the incidence of high colour and significance was variable across the various lag periods (Table 3). As temperature standard deviation went up by 1°C, the incidence of dark cutting went up by 0.1% in the 2 day lag model and down by 0.2% at 7 and 14 days and 0.4% in the 28 day lag model (Table 3). Max temperature range per day also had a significant effect on the incidence of high colour but only in the 7 day lag period model (Table 3) which showed that as max temperature range increased by 10°C the incidence of high meat colour reduced by 0.4%. The standard deviation of temp range was also significant in the 14 day lag period model (P<0.01).

Maximum relative humidity (RH) was only significant in the models for 3 and 28 days before consignment (P<0.1 and P<0.05). A 10 point increase in RH corresponded with an increase in high colour by 0.1 and 0.2% respectively. Minimum RH was also significant at the 1 day lag period (P<0.1) with a 10 point increase decreasing the incidence of high meat colour by 0.1%.

A 10mm increase in rainfall had a 0.1% reduction in high meat colour if it occurred in the 48 hours prior to consignment from the feedlot (P<0.1, Table 3).

Average Wind speed did have a significant effect on the incidence of high meat colour at 28 days lag period (P<0.05, Table 3). An increase of 10ms in average wind speed decreased high meat colour percentage by 1%.

Table 3: Estimated coefficients for the effect of weather variables on high meat colour calculated using bureau of meteorology data at 24 hours, 2, 3, 7, 14 and 28 days prior to consignment plus sex, HGP, feedlot and processor on the incidence of dark cutting per lot with standard errors in brackets

Dependent variable: High Meat Colour Percentage

Lag Time	1	2	3	7	14	28
temp_max	-0.0001^{*}		0.0003^{***}	0.001^{***}	0.001^{***}	0.001^{***}
	(0.0001)		(0.0001)	(0.0003)	(0.0001)	(0.0002)
rh_min	-0.0001^{*}					
	(0.00003)					
temp_sd		0.001^{*}		-0.002^{***}	-0.002^{**}	-0.004^{***}
		(0.0003)		(0.001)	(0.001)	(0.001)
rain	-0.0001	-0.0001^{*}				
	(0.0001)	(0.00004)				
temp_range_max				-0.0004		
				(0.0003)		

temp_range_sd					0.001**	
					(0.001)	
temp_range_min						-0.001***
						(0.0002)
ws_avg						-0.001**
						(0.0003)
temp_min			-0.0003***	-0.001***	-0.001***	-0.001***
			(0.0001)	(0.0003)	(0.0002)	(0.0002)
rh_max			0.0001*	0.0002**		
			(0.00005)	(0.0001)		
sexMale	-0.019***	-0.019***	-0.019***	-0.018***	-0.016***	-0.014***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
sexMixed	-0.002	-0.002	-0.002	-0.002	-0.003	-0.0002
	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)
hgp_mfY	0.002	0.002				
	(0.001)	(0.001)				
plant02	0.002	0.001	0.001	0.003	0.006	0.004
	(0.005)	(0.005)	(0.005)	(0.006)	(0.007)	(0.009)
plant03	0.012**	0.011*	0.008	0.013**	0.012	0.008
	(0.006)	(0.006)	(0.006)	(0.007)	(0.007)	(0.008)
plant04	0.019***	0.019***	0.018***	0.022***	0.025***	0.014***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)
plant05	0.021***	0.020***	0.019***	0.024***	0.023***	0.019***
	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)	(0.005)
plant06	0.016***	0.016***	0.015***	0.019***	0.023***	0.013**
	(0.005)	(0.005)	(0.005)	(0.005)	(0.006)	(0.006)
plant07	0.021***	0.021***	0.018***	0.025***	0.025***	0.020***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.005)
plant08	0.017***	0.016***	0.015***	0.019***	0.019***	0.013**
	(0.005)	(0.005)	(0.005)	(0.006)	(0.006)	(0.007)
plant09	0.042***	0.042***	0.041***	0.049***	0.043***	0.030***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)
plant10	0.040***	0.040***	0.039***	0.043***	0.045***	0.042***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)
plant11	0.011**	0.012***	0.009**	0.017***	0.012**	-0.018**
	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)	(0.007)
plant12	0.009***	0.008**	0.007**	0.010**	0.010**	0.004
	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)	(0.005)
plant13	0.030***	0.030***	0.028***	0.035***	0.035***	0.027***
	(0.004)	(0.004)	(0.005)	(0.005)	(0.006)	(0.007)
plant14	0.016***	0.016***	0.013***	0.019***	0.017***	0.014**
	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)	(0.006)
plant15	0.019***	0.019***	0.017***	0.024***	0.023***	0.019***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)
plant17	0.076***	0.076***	0.073***	0.079***	0.075***	0.062***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)

location02	-0.007***	-0.006**	-0.005**	-0.005*	-0.002	-0.003
	(0.002)	(0.003)	(0.003)	(0.003)	(0.004)	(0.005)
location03	0.012***	0.012***	0.012**	0.013**	0.013**	0.020***
	(0.005)	(0.005)	(0.005)	(0.005)	(0.006)	(0.007)
location04	-0.014***	-0.015***	-0.015***	-0.014***	-0.016***	-0.007
	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)	(0.007)
location05	-0.016***	-0.016***	-0.018***	-0.016***	-0.020***	-0.020***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.005)	(0.006)
location06	0.013***	0.013***	0.012***	0.019***	0.019***	0.007
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)
location07	-0.012**	-0.013**	-0.012**	-0.011*	-0.012*	-0.007
	(0.005)	(0.005)	(0.005)	(0.006)	(0.006)	(0.007)
location08	-0.001	-0.00004	0.001	0.0003	0.001	0.003
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
location09	-0.013**	-0.014***	-0.013**	-0.012**	-0.014**	-0.006
	(0.005)	(0.005)	(0.005)	(0.006)	(0.007)	(0.007)
location10	0.057***	0.063***	0.062***	0.069***	0.136***	0.289***
	(0.005)	(0.005)	(0.005)	(0.006)	(0.008)	(0.011)
location11	0.009***	0.009***	0.009***	0.010***	0.010***	0.010***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
location12	-0.012***	-0.012***	-0.010***	-0.010***	-0.005	0.004
	(0.002)	(0.002)	(0.003)	(0.003)	(0.003)	(0.005)
location13	0.009***	0.010***	0.010***	0.012***	0.011***	0.014***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)
location14	-0.014***	-0.015***	-0.015***	-0.014***	-0.017***	-0.009
	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)	(0.006)
location15	0.001	0.002	0.001	0.004	0.005	0.005
	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)	(0.006)
location16	0.005*	0.006**	0.007**	0.006*	0.010***	0.020***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)
location17	-0.016***	-0.016***	-0.015***	-0.013**	-0.018**	-0.011
	(0.005)	(0.005)	(0.005)	(0.006)	(0.008)	(0.010)
Constant	0.018***	0.013***	0.002	-0.017*	-0.005	-0.002
	(0.004)	(0.004)	(0.007)	(0.010)	(0.006)	(0.007)
Observations	19,563	18,852	18,224	15,637	12,782	9,167
R^2	0.198	0.200	0.198	0.195	0.200	0.248
Adjusted R^2	0.197	0.198	0.197	0.194	0.198	0.245
Residual Std. Error	0.046 (df = 19525)	0.047 (df = 18815)	0.047 (df = 18187)	0.048 (df = 15598)	0.048 (df = 12744)	0.045 (df = 9128)
F Statistic	130.499*** (df = 37; 19525)	130.597*** (df = 36; 18815)	124.797*** (df = 36; 18187)	99.736*** (df = 38; 15598)	86.280*** (df = 37; 12744)	79.085*** (df = 38; 9128)

Note: NB: *P<0.1; **P<0.05; ***P<0.01

9.2.5 High meat colour THI model

THI had no effect within 48hrs before slaughter although a 10 point increase in THI max between 3 and 28 days prior to consignment increased high colour by between 0.3 and 1% ($P<0.01$, Table 4). On the contrary, an increase of 10 points of the minimum THI caused a reduction in high colour by 0.2 to 0.4% in the 3, 7 and 14 day lag models only ($P<0.05$, Table 4). This is close to the results for DFD% with a 0.1% lower reduction in high meat colour.

The standard deviation in THI over the 48 hours prior to consignment also had a significant effect on the incidence of high colour ($P<0.01$, Table 4). As the variation/standard deviation in THI increased over the 48 hour period by 1 point, carcasses high in colour increased by 0.1%. THI range was not significant when only using high meat colour as the dependant variable.

Rainfall also had a significant effect on the incidence of high colour if it occurred in the 48 hours prior to consignment ($P<0.05$, Table 4). A 10mm increase in rain in the two days before kill could reduce the incidence of high colour by 0.1%.

Table 4: Estimated coefficients for the effect of Temperature Humidity Index on high meat colour calculated using bureau of meteorology data at 24 hours, 2, 3, 7, 14 and 28 days prior to consignment plus sex, HGP, feedlot and processor on the incidence of dark cutting per lot with standard errors in brackets

	Dependent variable: High Meat Colour Percentage					
Lag Time	1	2	3	7	14	28
thi_sd		0.001**		-0.001**		
		(0.0002)		(0.0004)		
Rain	-0.0001**	-0.0001*				
	(0.0001)	(0.00004)				
thi_max			0.0003***	0.001***	0.0004***	0.0004***
			(0.0001)	(0.0001)	(0.0001)	(0.0001)
thi_min			-0.0002***	-0.0004***	-0.0002***	-0.0002
			(0.0001)	(0.0001)	(0.0001)	(0.0001)
ws_avg						-0.0004
						(0.0003)
plant02	0.001	0.001	0.001	0.004	0.005	0.003
	(0.005)	(0.005)	(0.005)	(0.006)	(0.007)	(0.009)
plant03	0.011**	0.011*	0.008	0.013**	0.011	0.008
	(0.006)	(0.006)	(0.006)	(0.007)	(0.007)	(0.008)
plant04	0.019***	0.019***	0.018***	0.021***	0.024***	0.013***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)
plant05	0.021***	0.020***	0.019***	0.023***	0.022***	0.018***
	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)	(0.005)
plant06	0.016***	0.016***	0.015***	0.019***	0.022***	0.012*
	(0.005)	(0.005)	(0.005)	(0.005)	(0.006)	(0.006)
plant07	0.021***	0.021***	0.018***	0.025***	0.025***	0.019***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.005)
plant08	0.017***	0.016***	0.015***	0.019***	0.019***	0.012*

	(0.005)	(0.005)	(0.005)	(0.006)	(0.006)	(0.007)
plant09	0.042***	0.042***	0.041***	0.048***	0.043***	0.029***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)
plant10	0.040***	0.040***	0.039***	0.043***	0.044***	0.041***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)
plant11	0.010**	0.012***	0.008*	0.017***	0.012**	-0.019**
	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)	(0.007)
plant12	0.009***	0.008**	0.007**	0.009**	0.010**	0.004
	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)	(0.005)
plant13	0.030***	0.030***	0.028***	0.034***	0.035***	0.027***
	(0.004)	(0.004)	(0.005)	(0.005)	(0.006)	(0.007)
plant14	0.016***	0.016***	0.013***	0.018***	0.016***	0.014**
	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)	(0.006)
plant15	0.019***	0.019***	0.017***	0.024***	0.023***	0.018***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)
plant17	0.076***	0.076***	0.073***	0.078***	0.074***	0.061***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)	(0.005)
sexMale	-0.019***	-0.019***	-0.019***	-0.018***	-0.016***	-0.014***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
sexMixed	-0.002	-0.002	-0.002	-0.003	-0.003	-0.001
	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)
hgp_mfY	0.002	0.002				
	(0.001)	(0.001)				
location02	-0.007***	-0.006**	-0.005**	-0.005	-0.003	-0.005
	(0.002)	(0.003)	(0.003)	(0.003)	(0.004)	(0.005)
location03	0.012***	0.013***	0.011**	0.013**	0.012**	0.018***
	(0.005)	(0.005)	(0.005)	(0.005)	(0.006)	(0.007)
location04	-0.014***	-0.015***	-0.015***	-0.014***	-0.017***	-0.008
	(0.004)	(0.004)	(0.004)	(0.005)	(0.006)	(0.007)
location05	-0.016***	-0.016***	-0.018***	-0.016***	-0.021***	-0.021***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.005)	(0.006)
location06	0.013***	0.013***	0.012***	0.019***	0.019***	0.005
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)
location07	-0.012**	-0.013**	-0.012**	-0.010*	-0.014**	-0.008
	(0.005)	(0.005)	(0.005)	(0.006)	(0.006)	(0.007)
location08	-0.0005	-0.00005	0.0004	0.0001	0.001	0.002
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
location09	-0.013**	-0.014**	-0.013**	-0.011*	-0.015**	-0.007
	(0.005)	(0.005)	(0.005)	(0.006)	(0.007)	(0.007)
location10	0.057***	0.063***	0.063***	0.070***	0.134***	0.284***
	(0.005)	(0.005)	(0.005)	(0.006)	(0.008)	(0.011)
location11	0.009***	0.009***	0.009***	0.010***	0.010***	0.009***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
location12	-0.012***	-0.012***	-0.010***	-0.009***	-0.009***	-0.002
	(0.002)	(0.002)	(0.003)	(0.003)	(0.003)	(0.004)
location13	0.009***	0.010***	0.010***	0.012***	0.011***	0.013***

	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.005)
location14	-0.014***	-0.015***	-0.015***	-0.014***	-0.017***	-0.009
	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)	(0.006)
location15	0.001	0.002	0.001	0.005	0.004	0.005
	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)	(0.006)
location16	0.005*	0.006**	0.006**	0.006*	0.009**	0.018***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)
location17	-0.016***	-0.016***	-0.016***	-0.015**	-0.019**	-0.011
	(0.005)	(0.005)	(0.005)	(0.006)	(0.008)	(0.010)
Constant	0.014***	0.013***	0.004	-0.014*	-0.009	-0.008
	(0.004)	(0.004)	(0.006)	(0.007)	(0.008)	(0.010)
Observations	19,563	18,852	18,224	15,637	12,782	9,167
R^2	0.198	0.200	0.198	0.195	0.200	0.245
Adjusted R^2	0.197	0.198	0.196	0.193	0.197	0.242
Residual Std. Error	0.046 (df = 19527)	0.047 (df = 18815)	0.047 (df = 18188)	0.048 (df = 15600)	0.048 (df = 12746)	0.045 (df = 9130)
F Statistic	137.824*** (df = 35; 19527)	130.645*** (df = 36; 18815)	128.291*** (df = 35; 18188)	105.170*** (df = 36; 15600)	90.796*** (df = 35; 12746)	82.422*** (df = 36; 9130)
Note:	NB: *P<0.1; **P<0.05; ***P<0.01					

9.3 Individual Animal Data

9.3.1 Data summary

Table 5. Total number, mean, standard deviation and quartiles for variables.

Variable	n	mean	sd	Min	25th Percentile	Median	75th Percentile	Max
AUS marbling	2805443	1.35	1.09	0	1	1	2	9
Eye muscle area	2717285	74.11	12.46	20	68	76	82	150
Perc. *Bos Indicus*	914500	4.76	15.99	0	0	0	0	100
Fat colour	2805443	0.88	0.71	0	0	1	1	9
Hump	2805443	75.1	27.97	15	60	70	85	350
Meat colour	2805443	1.81	0.89	-1	1	2	2	7
MSA marbling	2804323	367.94	110.37	100	310	350	420	1190
Days on feed	2402598	114.52	46.94	0	100	100	128	806
Ossification	2805443	169.88	30.67	100	150	170	180	590
Rib fat	2144964	10.94	2.2	5	10	12	12	13
Total HSCW	2058456	335.11	61.03	52	288	337	380	798
Loin temp	2805443	6.18	1.84	0	4.9	6.1	7.5	15.5
MSA index	2744873	55.57	3.96	34.13	53.5	55.7	57.68	72.67
pH	2805443	5.53	0.09	5.2	5.47	5.53	5.57	7.25

Both high meat colour and high pH had an average incidences of 2.01% ± 0.14 and 1.91% ± 0.137 across all 2,805,443 bodies (Table 5). The DFD incidence averaged 1.62% ± 0.126. This highlights the strong correlation between dark meat and high pH in the data set across all bodies.

When high pH was used as a predictor of high meat colour in a linear model it returned an R^2 of 0.6749 ($P<0.001$) with 2805441 DF and RSE of 0.08005. This shows that animals with high colour scores of ≥4 are more likely to have a higher ultimate pH (Figure 2 and 3). This was expected as it is well known in the literature and there was similar results from the initial lot based analysis (Figure 1).

9.3.2 Correlation between high meat colour and pH

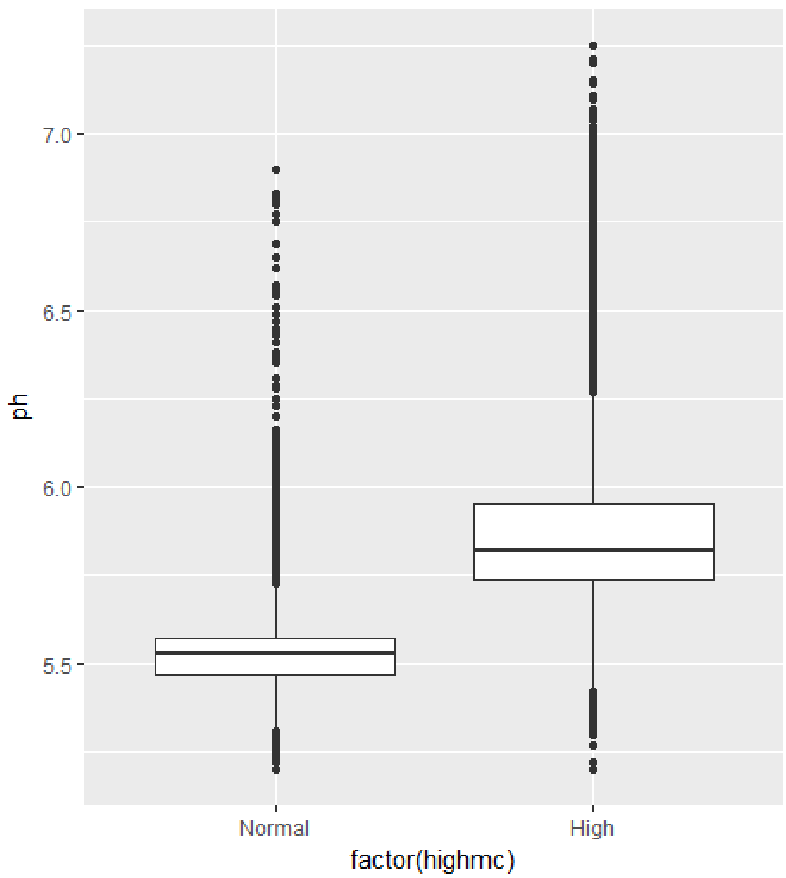

Figure 2. Correlation of individual animal data for high meat colour and pH R = .51 p<.001

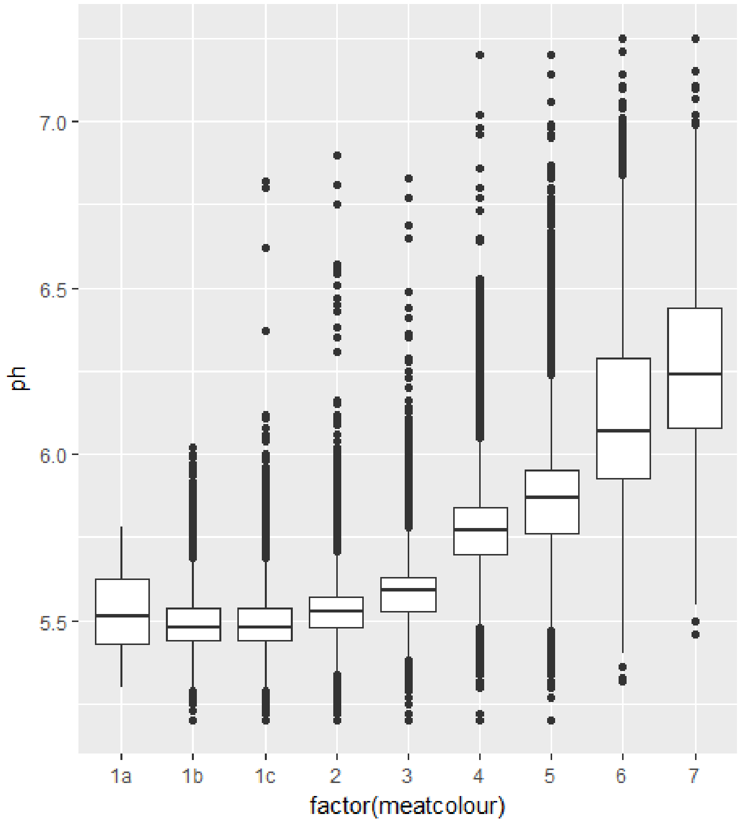

Figure 3. Correlation of individual animal data for meat colour and pH