Translational Animal Science, 2024, **8**, txae108
https://doi.org/10.1093/tas/txae108
Advance access publication 22 July 2024
Animal Health and Well Being

An analysis of the influence of preslaughter management factors on welfare and meat quality outcomes in fed beef cattle in the United States

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Abstract

During the preslaughter phase, cattle are transported from their place of origin to a slaughter facility, experiencing transportation, lairage, environmental factors, and novel environments. Although research exists that has focused how the preslaughter phase impacts cattle welfare and meat quality, some significant preslaughter management factors and subsequent welfare and meat quality outcomes have not been thoroughly explored. The objective of this study was to assess the effects of preslaughter management factors on welfare and meat quality outcomes in fed beef cattle in the United States. Transportation factors, environmental characteristics, lairage factors, cattle characteristics, and several meat quality variables were collected from 5 federally inspected commercial processing facilities in the United States. After excluding slaughter lots that included <75% complete datasets, a total of 619 slaughter lots representing 84,508 head of cattle were used for further analysis. Predictor variables of interest included processing plant, cattle breed, sex class, operation shift at the plant, distance traveled to the plant, truck waiting time to unload at the plant, lairage duration and space allowance, temperature humidity index, and windspeed. Outcome variables of interest included cattle mobility, carcass bruising, dark cutting (DC), quality grades, and hot carcass weights. Logistic and linear regressions were used to analyze the associations between the predictor and outcome variables of interest. Increased distance traveled and truck waiting time were associated with higher odds of mobility impairment ($P = 0.0009$ and $P = 0.007$, respectively), with each 10 km increase in distance traveled having an odds ratio (OR) of 1.001 (95% confidence interval [CI]: 1.000 to 1.001) and each 1-min increase in waiting time having an OR of 1.003 (CI: 1.001 to 1.004). Conversely, a 10-km increase in distance traveled decreased the odds of carcass bruising (OR: 0.997, CI: 0.996 to 0.998; $P < 0.0001$). Longer lairage was associated with increased odds of DC ($P = 0.0415$), with each 60-min increase in duration having an OR of 1.034 (CI: 1.001 to 1.068). The results demonstrate the importance of truck arrival management (i.e., scheduling, prioritizing unloading) on mobility. Focusing on lairage management (i.e., density and time) may provide some opportunities to improve meat quality.

Lay Summary

Ensuring animal welfare is a critical component of preslaughter animal management. Transportation, handling practices, and facilities can impact both animal welfare indicators and meat quality. Although there is a large body of research investigating the impacts of various preslaughter management practices on cattle welfare and meat quality, many of the studies are limited in scope (e.g., including a small number of influencing factors or welfare and meat quality outcomes). This research assessed the effects of several important management factors, such as distance traveled to the plant, truck wait time at the plant, and space allowance in holding pens on welfare (e.g., mobility) and meat quality (e.g., bruising and dark cutting) outcomes on a large population of fed cattle at commercial slaughter facilities in the United States. Results indicate that the impact on cattle welfare and meat quality during this phase is multifactorial. For example, the plant, breed of cattle, truck waiting time, distance traveled, space allowance, wind speed, and temperature humidity index were all associated with cattle mobility. By understanding these relationships, industry stakeholders can adjust management practices to improve both cattle welfare and ultimate meat quality during this significant phase of the marketing process.

Key words: bruising, dark cutting, lairage, meat quality, mobility, transportation

Introduction

The management of cattle during the preslaughter period has become a process facing increased scrutiny from consumers (Wigham et al., 2018) and supply chain stakeholders due to its cumulative effects on animal welfare and meat quality (Edwards-Callaway and Calvo-Lorenzo, 2020). The preslaughter period includes processes performed (e.g., feed withdrawal, weighing) to prepare cattle to leave their place of origin (e.g., a feedlot), transport of cattle to a slaughter facility, and management of cattle at the slaughter facility until they are processed. During this period, cattle are subjected to a variety of stressors, including increased handling, novel environments, and mixing with unfamiliar cattle that undoubtedly have a cumulative impact on an animal's welfare and subsequent meat quality (Warriss, 1990; Wigham et al., 2018). The intensity and duration of

Received February 3, 2024 Accepted July 20, 2024.

preslaughter processes vary based on environmental characteristics, facility management protocols, and an individual animal's stress response (Ferguson and Warner, 2008). High levels of fear, stress, and discomfort during this process are well documented to negatively impact an animal's welfare state and final product quality (Ferguson and Warner, 2008; Cockram, 2017; Edwards-Callaway and Calvo-Lorenzo, 2020). The meat quality defects (e.g., bruising, dark cutting [DC]) that occur during the preslaughter period result in significant financial losses (Warriss, 1990; Kline et al., 2020).

Federal regulations (Code of Federal Regulations. Humane Slaughter of Livestock., 1979; Twenty-Eight Hour Law, 1994) and industry guidelines were created to ensure proper care throughout the slaughter process. There are several ways to measure animal welfare at slaughter, including mobility scoring (NAMI, 2015). Cattle mobility is an important production and welfare issue; cattle with impaired mobility may be in pain, injured, or distressed due to their inability to keep up with their contemporary group. Previous studies have identified risk factors occurring during the preslaughter phase such as increased temperatures and heat stress (González et al., 2012a; Lee et al., 2018), heavier body weights, handling practices at slaughter (Edwards-Callaway et al., 2017), and transportation conditions (González et al., 2012a) that negatively impact cattle mobility. Scoring mobility has also recently been added to the National Beef Quality Audit (NBQA) benchmarking efforts conducted by the National Cattlemen's Beef Association which occur every few years.

Meat quality issues discovered postmortem, including carcass bruising and DC, can provide some insight into the animal's welfare state antemortem. In the United States, the 2016 NBQA reported that 38.9% of fed steers and heifers, 42.9% of bulls, and 64.1% of cows were bruised (Eastwood et al., 2017), and two additional recent studies found a bruise prevalence of 80.09% (Sullivan et al., 2024) and 69.7% (Davis et al., 2024) in fed cattle. With carcass bruising costing the U.S. beef industry an estimated $35 million each year (Lee et al., 2017), there is a significant need for continued research on bruise risk factors. DC is another quality issue stemming from chronic stressful events antemortem with can result in depletion of muscle glycogen, in turn leading to a high ultimate pH of meat (Scanga et al., 1998; Ponnampalam et al., 2017). The reason for DC is multifactorial and various stressors such as feed and water deprivation, transportation, and lairage (i.e., holding time at the slaughter plant) conditions may impact an individual animal's responses to stress, postmortem metabolism, and final product quality (Ponnampalam et al., 2017; Sullivan et al., 2022). DC beef is not only unfavorable to consumers due to its darker appearance (Ponnampalam et al., 2017), but it also has a shortened shelf-life (Newton and Gill, 1981), and is discounted and downgraded in terms of quality grade accounting for nearly $170 million in losses annually for the U.S. beef industry (Underwood et al., 2007). Findings from Boykin et al. (2017) in the 2016 NBQA, and the benchmarking paper by Davis et al. (2024), identified that 1.9% and 1.6%, respectively, of fed cattle carcasses exhibited signs of DC. Preslaughter stressors such as fasting, transportation, unfamiliar environments also have significant impacts on additional carcass characteristics such as hot carcass weights (HCW) and quality grades (QG) (Smith et al., 1982; Warriss, 1990), which also would likely result in financial losses for the industry.

Several recent review papers have indicated the need for continued research in the preslaughter period focusing specifically on transportation, lairage, and environmental factors due to their cumulative effects on cattle welfare and final product quality (Schwartzkopf-Genswein et al., 2012, 2016; Tucker et al., 2015; Davis et al., 2022; Sullivan et al., 2022). There is far less research on the effects of certain preslaughter management factors on cattle welfare and meat quality following transportation to the plant (i.e., truck waiting time to unload at the plant or animal space allowance in lairage and lairage duration) compared to during transportation. Additionally, there is a limited body of research that provides a comprehensive approach to evaluating multiple management factors together, particularly in the United States. Therefore, the objective of this observational study was to assess the effects of preslaughter management factors on welfare and meat quality outcomes in fed beef cattle in the United States.

Materials and Methods

Ethical Statement

This research was granted an exemption (IACUC Exemption #2019-080-ANSCI) by the Colorado State University Animal Care and Use Committee as all animal data collected was observational.

Data Collection

This article is an extension of a previously published manuscript by Davis et al. (2024).

Processing facility characteristics

Data were collected from 5 federally inspected commercial processing facilities in the West, Southwest, and Midwest regions of the United States from March 2021 to July 2022. Data were recorded for a total of 637 slaughter lots consisting of 87,220 total head of cattle. Four of the processing plants operated two 8-h shifts per day and slaughtered approximately 4,000 to 5,000 cattle per day, while the fifth plant operated one shift per day and slaughtered approximately 1,200 cattle per day. Lairage pens at each plant provided ad libitum access to water for cattle, and sprinklers were used as heat mitigation by all plants during the warmer months. One plant had shaded holding pens. While most plants had stamped concrete flooring in the handling areas and holding pens, one plant added rubber mats to all handling areas and holding pens except for on the scale and unloading docks. Receiving times for cattle at the plant varied from plant to plant, and slaughter lots (i.e., unique groups of cattle coming from the same origin) of cattle were occasionally held overnight. Slaughter lots of cattle were tracked throughout the preslaughter and slaughter process to obtain ante- and postmortem observational measurements.

Cattle population and preslaughter management factors

Sex class, breed type (*Bos taurus*, *Bos indicus,* or Holstein), number of cattle, and average live weight for each lot were obtained from the plant while on-site. Cattle were recorded as *B. indicus* if greater than 25% of the cattle within the lot had 2 or more breed characteristics consistent with *B. indicus* (e.g., a large hump on their withers, excess skin on their dewlap and/or prepuce, or large droopy ears). Other cattle not possessing the characteristics of *B. indicus* were either categorized as *B. taurus* or were Holsteins. Live weight was either provided by the plant or calculated using the truck net weights and the number of cattle in each truck. The population of animals in this study is a subset of the study population reported in Davis et al. (2024).

Transport distance from the feedlot to the plant for each lot was calculated using Google Maps (Google LLC, Mountain View, CA, USA). Once trucks arrived at a processing facility, each truck's individual arrival time was recorded to calculate truck waiting time before unloading cattle at the facility; these times were then averaged for each lot. Environmental conditions (temperature; °C, humidity; %, precipitation; cm, and wind speed; km/h) were recorded at 3 time points (e.g., arrival, unloading, and at the end of lairage at the time of mobility scoring) for each lot gathered from an online weather service (Weather Underground, San Francisco, CA, USA) and then averaged per lot. Temperature and humidity were then later used to calculate a Temperature Humidity Index (THI) score for each lot using the equation $\mathrm{THI} = 0.8*T + \mathrm{RH}*(T - 14.4) + 46.4$, where T is ambient or dry-bulb temperature in °C, and relative humidity (RH) is expressed as a proportion (LiveCorp and Meat and Livestock Australia, 2023).

Preslaughter outcomes

While in lairage, cattle mobility was scored by trained scorers either on a catwalk or in an alley way as cattle were moved from lairage pens to slaughter. Mobility scores were given for each individual animal using the North American Meat Institute (NAMI) cattle mobility scoring scale (1: no apparent lameness, normal, walks easily; 2: exhibits minor stiffness, shortness of stride, slight limp, keeps up with normal cattle; 3: exhibits obvious stiffness, difficulty taking steps, obvious limp, obvious discomfort, lags behind normal cattle; and 4: extremely reluctant to move, statue-like; NAMI, 2015). The frequency of each mobility score category was then calculated per lot. Individuals were trained to ensure that all scorers received a Kappa coefficient for inter-observer reliability ≥0.80 compared to a gold standard scorer. The total time that cattle slaughter lots spent in lairage (subtracting the time at which the lot was unloaded at the facility from the time the lot was moved for slaughter), and the lairage space allowance (m^2/animal was calculated using the total square meters of the pen and the number of animals in each pen) were also recorded.

Postmortem outcomes

Postmortem, individual carcasses were bruise scored by trained scorers immediately following hide removal using an adapted version of the NBQA bruise scoring system (Eastwood et al., 2017) using 3 mutually exclusive categories (i.e., carcasses were scored as either having no bruises, one bruise that was lesser than equal to the size of a deck of cards, or one bruise that was greater than the size of a deck of cards), and scorers could also report if a carcass had multiple bruises and the assigned bruise category was determined by the size of the largest bruise on the carcass in this case. Individuals were trained to ensure that all scorers received a Kappa coefficient for inter-observer reliability ≥ 0.80 compared to a gold standard scorer. The frequency of each bruise category was then calculated per lot. After carcasses were chilled for approximately 24 h (or according to the plant's specific procedures), carcass characteristics including quality grade (QG), number of DC carcasses, and HCW for each lot were later obtained from each plant's records. DC data was obtained from 3 plants.

Statistical Analysis

All statistical analyses were performed in SAS 9.4 (SAS Institute, Cary, NC). Descriptive statistics for the full dataset of 637 slaughter lots can be found in the study by Davis et al. (2024).

Regression analysis and model selection

Prior to model selection, slaughter lots with no response variables or lots with <75% of predictor variables were excluded from further analysis resulting in a total of 619 slaughter lots (the number of slaughter lots for each variable varies based on missing data) consisting of 84,508 head of cattle for data analysis. The descriptive statistics for this subset of lots for the predictor and outcome variables of interest used for regression analyses are presented in Tables 1, 2, and 3. Predictor variables of interest included: plant, breed, sex class, operation shift at the plant (i.e., 1 or 2), distance traveled, truck waiting time to unload cattle at the plant, lairage duration, space allowance in lairage, THI, and wind speed. Primary response variables of interest included mobility, bruising, DC, QG, and HCW. Bruise scoring categories were collapsed into a binary variable (Not Bruised/Bruised). Regression analyses were used to assess relationships between the predictor variables of interest (preslaughter management factors and animal characteristics) and the response variables of interest (mobility, bruising, DC, QG, and HCW) that were chosen for analysis based on their known relationships with preslaughter stress. Bruising and DC were analyzed using binary logistic regressions (Bruised/Not Bruised; Dark Cutter/Not a Dark Cutter with Bruised and Dark Cutter as the event; PROC LOGISTIC). Mobility and QG were analyzed using ordinal logistic regression (in the directions of increased mobility impairment and poorer quality grade; PROC GLIMMIX with the Laplace method). The continuous variable, HCW, was analyzed using a multiple linear mixed-effects regression

Table 1. Descriptive statistics of categorical fed cattle slaughter lot characteristics used for regression analyses

Characteristic	*n* lots	Frequency (%)
Sex class ($n = 594$)		
Steers	335	56.4
Heifers	190	32.0
Mix[1]	69	11.6
Breed type[2] ($n = 582$)		
B. taurus or <25% *B. indicus* influence	517	88.8
≥25% *B. indicus* influence	44	7.6
Holstein	21	3.6
Shift ($n = 617$)		
1	353	57.2
2	264	42.8

[1] Slaughter lots with steers and heifers mixed together were considered a mix lot.

[2] Cattle were recorded as *B. indicus* if ≥ 25% of the cattle within the lot had 2 or more of the breed's characteristics (e.g., a large hump on their withers, excess skin on their dewlap or prepuce, and large, droopy ears).

Table 2. Descriptive predictor statistics of transportation, lairage, and environmental characteristics of the slaughter lots used in regression analyses

Variable	*n*	Minimum	Mean	Maximum	SD
Transportation					
Distance traveled, km	598	2.7	155.4	1,332.5	210.2
Truck waiting time, min	603	0.0	30.3	574.0	39.7
Lairage					
Lairage duration, min	572	4.0	200.8	1,072.0	195.0
Space allowance, m^2/animal	606	0.6	3.1	31.7	2.0
Environmental characteristics					
Temperature humidity index (THI)[1,2]	619	18.9	60.4	81.5	13.6
Wind speed[2], km/h	619	0.0	18.1	56.3	10.1

[1] THI value was calculated as $THI = 0.8*T + RH*(T - 14.4) + 46.4$, where T is the ambient temperature in °C and RH is the relative humidity proportion (LiveCorp and Meat and Livestock Australia, 2023).

[2] Temperature and humidity used to calculate THI, and wind speed were recorded from a commercial weather service online (Weather Underground).

Table 3. Descriptive statistics of specific cattle welfare and meat quality outcomes used for regression analyses

Categorical variables

Variable	*n lots*	Frequency (%)
Mobility scores[1]	610	
1		91.8
2		7.8
3		0.3
4		0.002
Bruise scores[2]	598	
None		30.2
≤Deck of cards		27.2
>Deck of cards		42.6
Multiple[3]		65.2
Bruise prevalence[4]	598	
Bruised		69.8
Not bruised		30.2
Dark cutting	361	1.7
Quality grades	604	
Prime		8.6
Choice		70.6
Select		19.0
Standard		0.5
Other		1.3

Continuous variable

Variable	*n*	Minimum	Mean	Maximum	SD
Hot carcass weight, kg	597	301.6	396.5	513.8	36.9

[1] Mobility scores were defined as 1 = normal, no apparent lameness; 2 = exhibits minor stiffness, keeps up with normal cattle; 3 = exhibits obvious stiffness, lags behind normal cattle; and 4 = extremely reluctant to move, statue-like (NAMI, 2015).

[2] Individual carcasses were scored as either having no bruises (none), one bruise that was lesser than or equal to the size of a deck of cards, one bruise that was greater than the size of a deck of cards, and if it had multiple bruises in which case the size of the largest bruise was noted. Scores were then summarized at the lot level.

[3] Multiple is expressed as the proportion of bruised carcasses that had multiple bruises.

[4] Bruising was summarized and analyzed as a binary variable. Therefore, the prevalence of those bruises versus not bruised is reported in this table.

model to determine relationships between the same list of predictor variables of interest (PROC MIXED) using the restricted maximum likelihood method, and diagnostic plots were used to assess model fit. A group analysis was used to account for slaughter lot in the binary logistic regressions, and in the ordinal and linear mixed models, slaughter lot was included as a random effect. Statistical significance was determined at $P < 0.05$. For each primary response variable, separate full models were fitted that included all possible predictor variables of interest. Manual backward elimination was then applied as the variable with the largest P-value was removed from the model during each step and a new model was fit; this process was repeated until all variables in the model had P-values < 0.05. The observational units (n) vary for each model based on the number of lots used. Due to the extensive scope of this observational study and the large number of predictor variables measured, interactions between predictors were not explored in any of the statistical models. This decision was made to balance the potential benefits of including interaction terms with the drawbacks and practical limitations of doing so, such as increased model complexity, reduced interpretability, and the risk of overfitting.

Results

Descriptive Statistics

The majority of cattle (56.4%) were steers, 88.8% of cattle were of *B. taurus* influence, and 57.2% of cattle were slaughtered on the first shift of operation (Table 1). Cattle were transported 155.4 ± 210.2 km (Mean ± SD) and held in lairage for 200.8 ± 195.0 min at a space allowance of 3.1 ± 2.0 m^2/animal (Table 2). Table 2 also reports an average THI value of 60.4 ± 13.6 and wind speeds of 18.1 ± 10.1 km/h. HCWs averaged 396.5 ± 36.91 kg (Table 3). A majority of the cattle in the study had a mobility score of 1 (91.8%), were bruised (69.8%), and were graded as Choice (70.6%; Table 3). Of the plants with DC data, 1.7% of carcasses were classified as DC.

Mobility

Plant, breed, truck waiting time, distance traveled, THI, wind speed, and space allowance in lairage were identified as having significant associations with mobility ($P < 0.05$; Table 4). In comparison to plant 5, plant 1 (odds ratio [OR]:

Table 4. Fed cattle mobility[1] (n = 72,204) ordinal logistic regression analysis. OR[2] associated with the probability of an increased mobility score (increased lameness)

Variable	Estimate	SE	Odds ratio (95% CI)	P value
Plant				
1	−0.9584	0.1292	0.384 (0.298 to 0.494)	<0.0001
2	−0.8389	0.1310	0.432 (0.334 to 0.559)	<0.0001
3	−0.1757	0.1287	0.839 (0.652 to 1.080)	0.1721
4	−0.2203	0.1421	0.802 (0.607 to 1.060)	0.1209
5	*Referent*			
Breed				
B. taurus or <25% *B. indicus* influenced	0.07886	0.2023	1.082 (0.728 to 1.609)	0.6967
Cattle ≥ 25% *B. indicus* influenced	−0.3717	0.2538	0.690 (0.419 to 1.134)	0.1430
Holstein	*Referent*			
Truck waiting time, min	0.002597	0.000963	1.003 (1.001 to 1.004)	0.0070
Distance traveled, 10 km[3]	0.000614	0.000185	1.006 (1.003 to 1.010)	0.0009
THI[4]	−0.00650	0.002923	0.994 (0.988 to 0.999)	0.0262
Wind speed[5], km/h	−0.01156	0.004237	0.989 (0.980 to 0.997)	0.0064
Space allowance, m^2/animal	0.08439	0.02279	1.088 (1.041 to 1.138)	0.0002

[1] Mobility was originally scored as either 1 = normal, walks easily, no apparent lameness; 2 = exhibits minor stiffness, shortness of stride, slight limp, keeps up with normal cattle; 3 = exhibits obvious stiffness, difficulty taking steps, obvious limp, obvious discomfort, lags behind normal cattle; and 4 = extremely reluctant to move even when encouraged by a handler, statue-like (NAMI, 2015).

[2] An OR > 1 indicates that the variable is associated with a multiplicative increase in the odds of an animal showing signs of increased mobility impairment, whereas an OR < 1 indicates that the variable is associated with a multiplicative decrease in the odds of an animal showing signs of increased mobility impairment.

[3] 10 km was used as the unit for distance traveled in this model as a more desirable scale to develop an odds ratio > or < than 1.000.

[4] THI value was calculated using the equation: $\text{THI} = 0.8*T + \text{RH}*(T - 14.4) + 46.4$ (LiveCorp and Meat and Livestock Australia, 2023), where T is the ambient or dry-bulb temperature in °C, and RH is the proportion of relative humidity.

[5] Wind speed was recorded from an online commercial weather service's report (Weather Underground).

95% confidence interval [CI]: 0.384, 0.298 to 0.494) and plant 2 (0.432, 0.334 to 0.559) were associated with reduced odds of animals having worse mobility impairment. An increase in the odds of an animal showing signs of increased impaired mobility was associated with a one-unit increase in truck waiting time (1 min; 1.003, 1.001 to 1.004), distance traveled (10 km; 1.006, 1.003 to 1.010), and space allowance in lairage (1 m^2/animal; 1.088, 1.041 to 1.1138). Conversely, a decrease in the odds of an animal showing signs of increased mobility impairment was associated with a one-unit increase in THI value (0.994, 0.988 to 0.999) and wind speed (1 km/h; 0.989, 0.980 to 0.997).

Bruising

Plant, breed, sex class, shift, distance traveled, THI, wind speed, lairage duration, and space allowance in lairage were identified as having significant associations with bruising ($P < 0.05$; Table 5). In comparison to plant 5, a decrease in the odds of a carcass being bruised was associated with plant 1 (OR: 95% CI: 0.271, 0.252 to 0.292), plant 2 (0.489, 0.457 to 0.524), and plant 4 (0.990, 0.926 to 1.059), whereas plant 3 was associated with an increase in the odds of a carcass being bruised (1.513, 1.404 to 1.631). Compared to slaughter lots of Holstein cattle, cattle lots of *B. taurus* influence or < 25% *B. indicus* influence, and cattle lots ≥ 25% *B. indicus* influenced was associated with a decrease in the odds of a carcass being bruised (0.714, 0.641 to 0.796; 0.715, 0.629 to 0.812, respectively). In comparison to slaughter lots of mixed sex, lots consisting of only steers were associated with an increase in the odds of their carcass being bruised (1.150, 1.081 to 1.225), and lots consisting of only heifers were associated with a decrease in the odds of their carcass being bruised (0.986, 0.923 to 1.052). Cattle that were slaughtered during the first shift of operation per day were associated with a decrease in the odds of their carcass being bruised (0.806, 0.772 to 0.842) compared to cattle slaughtered during the second shift. Additionally, a decrease in the odds of a carcass being bruised was associated with a one-unit increase in distance traveled (10 km; 0.997, 0.996 to 0.998), THI value (0.989, 0.987 to 0.990), wind speed (1 km/h; 0.994, 0.992 to 0.996), and lairage duration (60 min; 0.990, 0.983 to 0.997). However, an increase in the odds of a carcass being bruised was associated with a one-unit increase in space allowance in lairage (1 m^2/animal; 1.035, 1.017 to 1.053).

Dark Cutting

Plant, breed, shift, wind speed, lairage duration, and space allowance in lairage were identified as having significant associations with DC ($P < 0.05$; Table 6). The number of DC carcasses in each lot for Plants 1 and 2 were not obtained and, therefore, were not included in this analysis. In comparison to plant 5, an increase in the odds of a carcass being classified as a DC was associated with plant 3 (OR: 95% CI: 2.875, 1.979 to 4.176) and 4 (4.564, 3.197 to 6.514). Compared to slaughter lots of Holstein cattle, cattle lots of *B. taurus* influence or < 25% *B. indicus* influence was associated with a decrease in the odds of a carcass being classified as a DC (0.714, 0.472 to 1.080), and cattle lots ≥ 25% *B. indicus* influence was associated with an increase in the odds of a carcass being classified as a DC (1.197, 0.748 to 1.916). Cattle slaughtered during the first shift were associated with a decrease in the odds of their carcass being classified as a DC (0.416, 0.336 to 0.514) compared to cattle

Table 5. Fed cattle bruising[1] (n = 68,607) binary logistic regression analysis. OR[2] associated with the probability of a carcass being bruised to some degree

Variable	Estimate	SE	Odds ratio (95% CI)	*P* value
Intercept	1.7381	0.0552	5.687 (5.104 to 6.336)	<0.0001
Plant				
1	−0.9822	0.0205	0.271 (0.252 to 0.292)	<0.0001
2	−0.3921	0.0181	0.489 (0.457 to 0.524)	<0.0001
3	0.7375	0.0231	1.513 (1.404 to 1.631)	<0.0001
4	0.3136	0.0215	0.990 (0.926 to 1.059)	<0.0001
5	*Referent*			
Breed				
B. taurus or < 25% *B. indicus* influenced	−0.1124	0.0221	0.714 (0.641 to 0.796)	<0.0001
Cattle ≥ 25% *B. indicus* influenced	−0.1118	0.0297	0.715 (0.629 to 0.812)	0.0002
Holstein	*Referent*			
Sex class (lots)				
Steer	0.0982	0.0136	1.150 (1.081 to 1.225)	<0.0001
Heifer	−0.0564	0.0147	0.986 (0.923 to 1.052)	0.0001
Mix	*Referent*			
Shift				
1	−0.1079	0.0111	0.806 (0.772 to 0.842)	<0.0001
2	*Referent*			
Distance traveled, 10 km[3]	−0.00027	0.000058	0.997 (0.996 to 0.998)	<0.0001
THI[4]	−0.0115	0.000704	0.989 (0.987 to 0.990)	<0.0001
Wind speed[5] , km/h	−0.00613	0.00112	0.994 (0.992 to 0.996)	<0.0001
Lairage duration[6] , 60 min[3]	−0.00017	0.000056	0.990 (0.983 to 0.997)	0.0027
Space allowance, m²/animal	0.0346	0.00887	1.035 (1.017 to 1.053)	<0.0001

[1] Bruise scoring categories were collapsed into a binary variable for simplicity in analysis (not bruised/bruised).
[2] An OR > 1 indicates that the variable is associated with a multiplicative increase in the odds of a carcass being bruised to some degree, whereas an OR < 1 indicates that the variable is associated with a multiplicative decrease in the odds of a carcass being bruised to some degree.
[3] 10 km was used as the unit for distance traveled in this model as a more desirable scale to develop an odds ratio > or < than 1.000.
[4] THI value was calculated using the equation: $\mathrm{THI} = 0.8*T + \mathrm{RH}*(T - 14.4) + 46.4$ (LiveCorp and Meat and Livestock Australia, 2023), where T is the ambient or dry-bulb temperature in °C, and RH is the proportion of relative humidity.
[5] Wind speed was recorded from an online commercial weather service's report (Weather Underground).
[6] 60 min was used as the unit for lairage duration in this model as a more desirable scale to develop an odds ratio > or < than 1.000.

slaughtered on the second shift. An increase in the odds of a carcass being classified as a DC was associated with a one-unit increase in lairage duration (60 min; 1.034, 1.001 to 1.068) and space allowance in lairage (1 m²/animal; 1.092, 1.049 to 1.136). Conversely, a decrease in the odds of a carcass being classified as a DC was associated with a one-unit increase in wind speed (1 km/h; 0.981, 0.972 to 0.989).

Quality Grades

Plant, breed, sex class, shift, truck waiting time, and THI were identified as having significant associations with QG ($P < 0.05$; Table 7). Compared to plant 5, an increase in the odds of a carcass having a poorer QG was associated with plant 2 (OR: 95% CI: 4.185, 3.277 to 5.344), and plant 4 (4.894, 3.819 to 6.273). In comparison to slaughter lots of Holstein cattle, cattle lots of *B. taurus* influence or < 25% *B. indicus* influence and cattle lots ≥ 25% *B. indicus* influence was associated with a decrease in the odds of a carcass having a poorer QG (0.530, 0.358 to 0.784; 0.583, 0.364 to 0.934, respectively). Compared to slaughter lots of mixed sex, lots consisting of only steers were associated with an increase in the odds of their carcass having a poorer QG (1.301, 1.038 to 1.630), and lots consisting of only heifers were associated with a decrease in the odds of their carcass having a poorer QG (0.729, 0.573 to 0.928). Cattle slaughtered during the first shift were associated with a decrease in the odds of their carcass having a poorer QG (0.777, 0.657 to 0.920) compared to cattle slaughtered during the second shift. A decrease in the odds of a carcass having a poorer QG was associated with a one-unit increase in truck waiting time (1 min; 0.997, 0.995 to 0.999), whereas an increase in the odds of a carcass having a poorer QG was associated with a one-unit increase in THI value (1.012, 1.006 to 1.017).

Hot Carcass Weight

Plant, breed, sex class, THI, and lairage duration were identified as having significant associations with HCW ($P < 0.05$; Table 8). In comparison to plant 5, HCW was lighter in plants 1 through 4 ($P < 0.0001$). HCWs were heavier in slaughter lots of cattle of *B. taurus* influence or < 25% *B. indicus* influence (estimate = 31.2117, $P < 0.0001$) and cattle lots ≥ 25% *B. indicus* influence (estimate = 23.8301, $P = 0.0043$) compared to Holstein cattle. Slaughter lots consisting only of steers (estimate = 28.3222, $P < 0.0001$) had heavier HCW, and slaughter lots consisting only of heifers (estimate = -10.1478, $P = 0.0176$) had lighter HCW compared to lots of mixed sex. HCWs were also lighter in environmental conditions with increased THI (estimate = -0.3810, $P < 0.0001$).

Table 6. Fed cattle DC (n = 44,568) binary logistic regression analysis. OR[1] associated with the probability of a carcass being classified as a dark cutter.

Variable	Estimate	SE	Odds ratio (95% CI)	*P* value
Intercept	−4.1292	0.1398	0.016 (0.012 to 0.021)	<0.0001
Plant[2]				
3	0.1979	0.0905	2.875 (1.979 to 4.176)	0.0286
4	0.6601	0.0841	4.564 (3.197 to 6.514)	<0.0001
5	*Referent*			
Breed				
B. taurus or < 25% *B. indicus* influenced	−0.2843	0.0805	0.714 (0.472 to 1.080)	0.0004
Cattle ≥ 25% *B. indicus* influenced	0.2321	0.1042	1.197 (0.748 to 1.916)	0.0259
Holstein	*Referent*			
Shift				
1	−0.4389	0.0541	0.416 (0.336 to 0.514)	<0.0001
2	*Referent*			
Wind speed[3], km/h	−0.0197	0.00462	0.981 (0.972 to 0.989)	<0.0001
Lairage duration, 60 min[4]	0.000559	0.000274	1.034 (1.001 to 1.068)	0.0415
Space allowance, m^2/animal	0.0878	0.0203	1.092 (1.049 to 1.136)	<0.0001

[1] An OR > 1 indicates that the variable is associated with a multiplicative increase in the odds of a carcass being classified as a dark cutter, whereas an OR < 1 indicates that the variable is associated with a multiplicative decrease in the odds of a carcass being classified as a dark cutter.
[2] DC data was not available from Plants 1 and 2 and, therefore, were not included in the analysis.
[3] Wind speed was recorded from an online commercial weather service's report (Weather Underground).
[4] 60 min was used as the unit for lairage duration in this model as a more desirable scale to develop an odds ratio > or < than 1.000.

Discussion

Study and Plant Characteristics

The results of this study provide a holistic view of the effects of preslaughter management factors on specific animal welfare and meat quality outcomes. This dataset combines aggregate data from multiple plants in various regions of the United States and is representative of current fed cattle slaughter statistics. Additionally, many of the variables in this dataset reflect current trends in the industry (i.e., cattle characteristics, mobility, and carcass characteristics; Boykin et al., 2017; Eastwood et al., 2017), making it highly representative of the preslaughter sector of the current fed beef cattle industry.

A common theme in the results from this study was differences between plants and shift for many of the outcome variables: mobility scores, the prevalence of bruising, and DC, QG, and HCW differed by plant. These differences could be due to company differences in management and protocols and regional differences (e.g., environmental conditions, breed type, and proximity of plant to feedlot) that may have impacted these welfare and meat quality outcomes. Additionally, the current study's results reflect differences between shifts at the plant. Differences in employees and management from the first to second shift, as well as truck arrival and wait times to unload at shift change could influence these outcomes.

Mobility

Increased concern for cattle mobility began approximately a decade ago when cattle arriving at packing plants were reported to have elevated mobility impairment issues (Huffstutter and Polansek, 2013). In response to this issue, a tool was created by industry experts to monitor fed cattle mobility known as the NAMI Mobility Scoring System (NAMI, 2015). This scoring tool is still widely used today (NAMI, 2015; NCBA, 2023). With the heightened industry awareness around mobility as a welfare challenge in cattle, the scoring of mobility has been included in recent industry benchmarking efforts. The 2016 NBQA (Eastwood et al., 2017) and the current study report high percentages of cattle with normal mobility (i.e., a score of 1; 96.8% and 91.8%, respectively). However, there is still much to learn about the risk factors associated with the preslaughter period that influence mobility impairment of cattle. Cattle are transported a wide range of distances from feedlots to processing plants. Many of these distances have been reported in previous benchmarking studies (12.9 to 1,400.1 km, Eastwood et al., 2017; 2.7 to 1,332.5 km in the current study). The continual consolidation of both feedlot operations and processing plants has increased the distances that animals are transported to reach these facilities (Speer et al., 2001). Additionally, economic drivers (i.e., better prices in distance markets) may also increase transportation distance (Schwartzkopf-Genswein et al., 2012). In the present study, increased distance traveled was associated with increased odds of mobility impairment in cattle, which is similar to findings from González et al. (2012a) and Mijares et al. (2021) who reported longer durations and distances that cattle spent on the truck, the greater the likelihood of them developing mobility impairment, or becoming non-ambulatory. The magnitude of this result, however, is slight (OR: 95% CI: 1.006, 1.003 to 1.010) and, therefore, further exploration of this relationship is warranted. It is important to note that transportation distances reported in the current study do not necessarily translate directly to estimating transportation duration that may include delays or road conditions that have added impacts on animal welfare and meat quality (Schwartzkopf-Genswein et al., 2012; Miranda-de la Lama et al., 2014).

Similarly, in the current study, longer truck wait times to unload cattle at the plant were also associated, albeit with slight magnitude (OR: 95% CI: 1.003, 1.001 to 1.004), with increased odds of cattle experiencing increased mobility impairment. Wait times to unload cattle from trucks at the plant have not been extensively researched. Previous studies (Mounier et al., 2006; Warren et al., 2010; González et al.,

Table 7. Fed cattle quality grade (*n* = 75,083) ordinal logistic regression analysis. OR[1] associated with the probability of a carcass having a poorer quality grade

Variable	Estimate	SE	Odds ratio (95% CI)	*P* value
Plant				
1	−0.04101	0.1269	0.960 (0.748 to 1.231)	0.7466
2	1.4314	0.1248	4.185 (3.277 to 5.344)	<0.0001
3	0.2792	0.1450	1.322 (0.995 to 1.757)	0.0542
4	1.5881	0.1266	4.894 (3.819 to 6.273)	<0.0001
5	*Referent*			
Breed				
B. taurus or < 25% *B. indicus* influenced	−0.6350	0.1998	0.530 (0.358 to 0.784)	0.0015
Cattle ≥ 25% *B. indicus* influenced	−0.5403	0.2406	0.583 (0.364 to 0.934)	0.0247
Holstein	*Referent*			
Sex class (lots)				
Steer	0.2628	0.1152	1.301 (1.038 to 1.630)	0.0225
Heifer	−0.3164	0.1231	0.729 (0.573 to 0.928)	0.0102
Mix	*Referent*			
Shift				
1	−0.2517	0.08582	0.777 (0.657 to 0.920)	0.0034
2	*Referent*			
Truck waiting time, min	−0.00313	0.000956	0.997 (0.995 to 0.999)	0.0010
THI[2]	0.01157	0.002720	1.012 (1.006 to 1.017)	<0.0001

[1] An OR > 1 indicates that the variable is associated with a multiplicative increase in the odds of a carcass having a poorer quality grade, whereas an OR < 1 indicates that the variable is associated with a multiplicative decrease in the odds of a carcass having a poorer quality grade.

[2] THI value was calculated using the following equation: $THI = 0.8*T + RH*(T - 14.4) + 46.4$ (LiveCorp and Meat and Livestock Australia, 2023), where T is the ambient or dry-bulb temperature in °C, and RH is the proportion of RH.

Table 8. Multivariable linear mixed-effects regression model for associations with preslaughter management factors and HCW in fed beef cattle slaughter lots (*n* = 548)

Variable	Estimate	SE	*P* value
Intercept	415.5700	8.1136	<0.0001
Plant			
1	−39.6153	3.6652	<0.0001
2	−57.6965	3.6716	<0.0001
3	−32.5246	3.6076	<0.0001
4	−47.4243	3.7033	<0.0001
5	*Referent*		
Breed			
B. taurus or < 25% *B. indicus* influenced	30.3114	6.2163	<0.0001
Cattle ≥ 25% *B. indicus* influenced	23.5411	7.4948	0.0018
Holstein	*Referent*		
Sex class, lots			
Steer	28.3327	3.6249	<0.0001
Heifer	−9.3469	3.8685	0.0160
Mix	*Referent*		
THI[1]	−0.3810	0.09622	<0.0001

[1] THI value was calculated using the following equation: $THI = 0.8*T + RH*(T - 14.4) + 46.4$ (LiveCorp and Meat and Livestock Australia, 2023) where T is the ambient or dry-bulb temperature in °C, and RH is the proportion of relative humidity.

2012b) have documented average wait times to unload at 15.4, 30, and 25 min, respectively. Mounier et al. (2006) used truck wait times to unload in an analysis of unloading score; however, they found no evidence of an association between the 2 variables. The follow-up study to the benchmarking efforts by González et al. (2012b) reported that wait times to unload are one reason for extended transportation journey time (González et al., 2012a). The results in the present study align with previous literature indicating that general increases in time on the truck are associated with impaired mobility in cattle (González et al., 2012a). Previous research and the results from the current study suggest the need for route optimization and streamlined protocols for efficient and timely delivery of cattle to the processing plants. Additionally, specific research on the change in mobility scores throughout the preslaughter period (before transport, after transport, and after lairage) may provide some added insight into what specific factors impact cattle mobility the most. In future studies, it would be valuable to include a measurement of mobility at unloading in addition to immediately prior to slaughter to understand how the condition of cattle upon arrival can impact both the response to management procedures and how mobility changes over time.

Interestingly, in the present study, increased space allowance was associated with increased signs of impaired mobility in cattle. Space allowance for animals in holding pens is one area typically included in plant audits. Federal regulations state that animals must have access to water and have sufficient space to lie down when held overnight (Code of Federal Regulations. Humane Slaughter of Livestock., 1979), but do not provide strict stocking density or space allowance guidelines while in lairage. The Meat Institute (formerly NAMI) guidelines have recommendations for stocking densities for cattle in lairage pens based on average pen weight; however, verification of recommended stocking density is not included in the scored portion of this tool and is considered a secondary item that asks if the holding pens "appear to be overcrowded" (NAMI, 2021). Understanding how cattle behave during lairage could provide insight into why this relationship between space allowance and mobility was seen (i.e., do they spend more time lying down, do they have more space to move throughout the entire period causing fatigue?). There is limited additional research on the effects of space allowance in lairage on cattle mobility, to begin with, and this should be explored further to provide additional evidence, such as the increased risk of injury or increases in stress that would impact cattle welfare and meat quality. Specific research focusing on the changes in cattle mobility throughout the preslaughter process, or analyzing cattle behavior during lairage (e.g., lying down or drinking) may provide insight into factors affecting cattle mobility preslaughter.

In contrast to other literature, the present study reports decreased odds of an animal showing signs of increased mobility impairment with increased THI values; however, the magnitude of the results are minor (OR: 95% CI: 0.994, 0.988 to 0.999) and, therefore, should be interpreted with caution. Increased THI values (i.e., increased temperature and humidity) have traditionally been found to impact cattle mobility negatively (González et al., 2012a; Lee et al., 2018; Mijares et al., 2021). Conversely, increased wind speeds were associated with decreased odds of an animal showing signs of mobility impairment, suggesting that increased airflow may be alleviating heat stress (Marchesini et al., 2018; FASS, 2020) and, therefore, may be decreasing the odds of cattle showing signs of heat exhaustion and, therefore, mobility impairment as well. Wind speed during the preslaughter period is not typically measured, but results such as decreased mobility impairment may provide some additional evidence for the necessity of additional heat abatement technologies to be used during lairage. It should be noted that the windspeed measurement taken was not on-site and, therefore, future studies should explore plant-specific microclimate impact on mobility and other relevant outcomes.

There was no evidence of an association between sex class and mobility in the current study. Information regarding the impact of sex class and breed type on mobility is limited, however, one study found that heifers had a 43.86% increase in the percentage of mobility scores ≥ 2 compared to steers (Mijares et al., 2021). Conversely, a study by González et al. (2012a) reported that steers or bulls were more likely to be lame and non-ambulatory during the preslaughter phase compared with heifers or cows. To the author's knowledge, there is currently no published research on differences in mobility scores at the plant by breed. However, breed is often confounded by sex class (i.e., at a fed cattle plant, Holstein cattle are steers), yet additional research in this space may provide further insight on handling and managing cattle breeds differently. In the current study, although breed was a signifiant model factor, comparisons between breed types did not provide evidence of a statisical difference in mobility between breed types. Recognizing cattle that are unfit for transportation, minimizing standing time, providing cattle enough time to rest and recuperate, and investigating methods for improving cattle mobility in lairage (e.g., the addition of rubber mats) should all be considered by processing facilities and transporters alike to improve cattle welfare.

Bruising

Several potential risk factors for bruising during the preslaughter period have been identified, including transportation factors, animal handling, animal characteristics, and stocking density (McNally and Warriss, 1996; Strappini et al., 2009; Hoffman and Luehl, 2012; Mendonca et al., 2018). Bruise prevalence in the industry remains high (38.9%, Eastwood et al., 2017; 69.8%, in the current study), warranting continued research on the potential causes of bruising and methods to mitigate the occurrence. There are several ways to evaluate and score bruising (e.g., a 10-point size and weight-based scale used by the NBQA; Eastwood et al., 2017; a 4-point scale based on bruise depth and severity; Strappini et al., 2010). The authors decided to simplify carcass bruising using a binary variable (Bruised/Not Bruised) for the current study to aid in interpretation (i.e., applicability) and comparison to other studies irrespective of the bruise scoring systems used in each.

In the present study, breed type was associated with the odds of a carcass being bruised; specifically, Holstein cattle were associated with increased odds of being bruised. Similarly, previous studies by Lee et al. (2017) and Kline et al. (2020) reported a greater bruising prevalence in Holstein cattle than in beef breeds. Larger frame sizes in Holstein cattle compared to their beef breed counterparts (Long et al., 1979; Tatum et al., 1986) can lead to more traumatic events (i.e., injury to the topline) during transportation from both decreased space allowance and clearance when entering or exiting the trailers likely increasing the prevalence of subsequent carcass bruising (Lee et al., 2017). Another cattle characteristic, sex class, was also found to be associated with carcass bruising in the present study. Slaughter lots consisting of only steers were associated with increased odds of being bruised and slaughter lots of only heifers were associated with decreased odds of being bruised in comparison to slaughter lots of mixed sex. The impact of sex class on bruising prevalence is variable across studies. The findings in the current study are similar to previous literature by Romero et al. (2013) that reported increased bruise prevalence in male cattle compared to females. The findings of increased bruising in steers may be due to their larger body mass compared to heifers, or additional agnostic behaviors occurring between cattle that result in injury and/or damage to cattle that should be researched further, particularly in lairage. Conversely, other studies have reported increases in bruising in female cattle compared to steers and bulls (Yeh et al., 1978; Hoffman and Luehl, 2012), however, these female cattle were classified as cows rather than heifers, which may account for some of the differences observed.

Additional factors that were found to be associated with carcass bruising in the current study included space allowance in lairage, lairage duration, and distance traveled, all of which resulted in relatively low magnitudes of change, so conclusions should be made cautiously. More specifically, increases in space allowance per animal were found to be associated with increased odds of carcass bruising. There is limited research on the effects of space allowance in lairage on the prevalence of carcass bruising in beef cattle, however, review papers on road transport of cattle have identified that there is substantial research on the effects of stocking density (i.e., space allowance) during transport on bruise prevalence (Knowles, 1999; Strappini et al., 2009). It may be possible that cattle with too much space are more likely to move around more or come in contact with objects that would cause bruising more frequently. Research focusing on the optimum space allowance in lairage is needed to explore this theory further.

In the current study, the decreased odds of carcass bruising in cattle that experienced increased lairage durations are congruent with findings from a similar study by Strappini et al., (2010). However, other studies have found contrasting results of increased prevalence and risk of bruising in cattle that spent longer durations in lairage (McNally and Warriss, 1996; Romero et al., 2013). Lairage durations are inevitably difficult to compare across studies as “short” and “long” lairage durations and lairage conditions vary from plant to plant and, therefore, across studies; to demonstrate differences in studies, Romero et al. (2013) reported lairages greater than 18 h which is significantly longer than what was found in both the current study and McNally and Warriss (1996). Additional studies across varying lairage conditions with consistent lairage durations may aid in a greater understanding of its effects. As mentioned previously, additional research focusing on cattle behavior during lairage may also aid in a better understanding of the relationships between lairage factors and welfare and meat quality outcomes.

Interestingly, increased distances traveled in the present study were associated with decreased odds of carcass bruising, contrasting previous literature that has reported increases in bruise prevalence with extended distances traveled (Marshall, 1977; Hoffman et al., 1998; Bethancourt-Garcia et al., 2019). However, one study by Mendonça et al. (2019) reported that short journeys (<120 km) resulted in greater rates of bruising to the hip and round, and the greatest number of front bruises occurred in the shortest (<120 km) and greatest (>240 km) distances. In the current study, transportation distances ranged from 2.7 to 1,332.5 km and averaged 155.4 km. Previous studies and the current study likely differ in additional transport conditions such as road conditions, delays during transport, or environmental conditions that could also influence bruising. Animals transported for long durations are more likely to have compromised welfare from exposure to extreme temperatures, deprivation of food, water, rest, and increased risk of injury exacerbated by length of exposure compared to animals transported for shorter distances (Nielsen et al., 2011; Mendonça et al., 2019). However, it is important to note that the associated negative aspects accompanying transportation may be the consequence of many factors, not just distance traveled such as trailer stocking density, trailer design, road conditions, or driver behavior/skill (Tarrant, 1990; Strappini et al., 2009; Hoffman and Luehl, 2012).

There was no evidence of associations in the present study with bruise prevalence and truck waiting time and there is no additional research measuring this relationship. Much like lairage duration, further research across varying transport conditions and research on the effects of truck waiting time in varying conditions may aid in a greater understanding of its effects.

In the present study, increases in THI values were associated with decreased odds of bruising, contrasting the results of increased bruise prevalence when daily minimum temperatures increased, as reported by Hoffman and Luehl (2012). However, the study by Hoffman and Luehl (2012) also reported that maximum temperatures did not affect bruise levels. The authors speculate that increases in temperature and humidity may decrease cattle levels of movement to decrease heat load, resulting in fewer interactions with their surroundings that may inflict injury. To the authors’ knowledge, there is currently no published data on the associations between wind speed and carcass bruising, yet the present study reports decreased odds of bruising, albeit slight, with increased wind speeds. It could be possible that much like improved airflow in trailers during transportation in warmer temperatures improves animal welfare in the preslaughter period (Miranda-de la Lama et al., 2014; Schuetze et al., 2017), increased wind speeds throughout the entirety of the preslaughter period may also improve animal welfare in regards to decreased risk of injury and/or bruising as well. The need for further research measuring the relationship between airflow, wind speed, and other environmental conditions and animal welfare outcomes such as injury has been outlined before by Schwartzkopf-Genswein et al. (2016), and this research is still warranted today. Processing plants and transporters need to pay special attention to specific risk factors for bruising in cattle and ways to mitigate them.

Dark Cutting

In cattle that are under high metabolic demand, such as from preslaughter stress, activation of the sympathetic nervous system breaks down muscle glycogen, decreasing the glycogen stores, which in turn limits the pH decline postmortem and thus disrupting the muscle’s normal postmortem metabolism and pH decline (Scanga et al., 1998; Ponnampalam et al., 2017; Sullivan et al., 2022). This higher ultimate muscle pH results in a darker, purplish-red colored lean with reduced shelf-life commonly referred to as DC beef or DFD meat (Ponnampalam et al., 2017; Terlouw et al., 2021). Several factors during the preslaughter phase such as transportation (Wythes et al., 1988; Marenčić et al., 2012), lairage (Wythes et al., 1988; Teke et al., 2014; Loredo-Osti et al., 2019), environmental conditions (Scanga et al., 1998; Steel et al., 2022a), and specific animal characteristics such as breed type and sex class (Scanga et al., 1998; Page et al., 2001) have previously been reported to influence DC in beef.

In the current study, several of these same factors (i.e., breed type, environmental conditions, and lairage) were found to be associated with DC. For example, compared to slaughter lots of Holstein cattle, *B. taurus* cattle were associated with decreased odds of DC, whereas *B. indicus* cattle were associated with increased odds of DC. Congruent with these results, Cook (1998) and Viljoen (2007) reported that *B. indicus* or Brahman-influenced cattle had significantly darker meat. Holstein cattle, much like *B. indicus* cattle, are more heat tolerant than *B. taurus* cattle (Forbes et al., 1998; Santana et al., 2017), making them more susceptible to colder temperatures or temperature fluctuations than *B. taurus* cattle. This susceptibility to weather changes may be another reason *B. taurus* cattle were associated with decreased odds of DC in the current study. However, it is important to note that there was no evidence of THI being associated with DC in the current study, but temperature and THI have been identified in a previous study (Scanga et al., 1998) to have an association with DC. The absence of an association between THI and DC in the current study could be due, in part, to the average THI value being 60.4, well within the range where cattle should be comfortable and exhibiting no signs of heat stress (LiveCorp and Meat and Livestock Australia, 2023). An additional environmental factor, wind speed, was identified in the current study to have a negative association with DC. In previous literature, intermediate wind speeds (10 to 15 km/h) at the abattoir have resulted in lower incidences of dark beef (Murray, 1989), and increased wind speeds within 7 d of departure from the feedlot to the processing facility was also associated with lower risk of DC beef (Steel et al., 2022b). These findings are congruent with associations with DC in the current study. These results may be due, in part, to an increase in air movement aiding in evaporative cooling from the skin (Vermunt and Tranter, 2011) and serve as additional evidence for the implementation of heat mitigation methods such as fans to decrease this occurrence of DC.

None of the transportation factors measured in this study were associated with DC. Past research has reported that transportation duration and rest stops during transportation affect final meat pH. However, cattle were transported by various means in previous literature (e.g., by rail or road) and for various durations that may have significantly differed from the journeys of cattle in the present study (Wythes et al., 1988; Brown et al., 1990; Marenčić et al., 2012). In the current study, increased space allowance was also associated with increased odds of DC. Romero et al. (2017) reported contradicting findings, stating that a higher prevalence of DFD meat was associated with higher stocking densities in lairage. It is unclear as to why increased space allowances for cattle in the current study were associated with increased odds of DC; however, further research on cattle behavior while in lairage and risk factors for DC, as mentioned previously, may help explain this. Lairage durations have also been shown to be related to increased incidence of DC beef in previous literature, and in the current study, longer lairage durations were associated with increased odds of DC. Other studies have reported greater incidence of DC in cattle that were held for longer lairage duration (Puolanne and Aalto, 1981; Fabiansson et al., 1984; Bartoš et al., 1993; Steel et al., 2021b), and a study by Loredo-Osti et al. (2019) found reduced probability of DC (7.21% to 0.02%) with a reduction from 14.9 to 3 h in lairage. However, Brown et al. (1990) reported a greater incidence of DC in cattle that were slaughtered on the day of arrival (5.5%) to the slaughter plant compared to holding them in lairage overnight before slaughter (3.1%). Other authors suggest that 3 h in lairage is an appropriate amount of time for rest for many species and that longer lairage duration may be counterproductive (Gallo et al., 2003; Diaz et al., 2014). The mean lairage duration in the current study was 200.8 min, or approximately 3.5 h. However, lairage durations ranged from 4.0 to 1,072.0 min. Lairage durations and environments also differ substantially from plant to plant, which may also play a role in the varying results. Further research evaluating specific risk factors during the preslaughter period in DC can help improve animal welfare and meat quality, and ultimately reduce economic loss. Additionally, this growing body of research emphasizes the need for slaughter plants to focus on reducing extended lairage durations and focusing on cattle comfort while in lairage.

Quality Grades

Quality grading (QG) beef carcasses is based on 2 characteristics: the degree of marbling (i.e., the primary determination of quality grade), and the degree of maturity (Hale et al., 2013). Literature exploring the associations of preslaughter factors with QG is limited; current literature is more focused on meat quality (i.e., pH) or overall eating quality. However, QG encompasses factors that affect meat palatability (i.e., tenderness, flavor, and juiciness), and the QG is only given if color, texture, and firmness of the lean are normal (i.e., if the carcass has not already been given a discounted grade; USDA Market News Service, 2023). Thus, a deviation in normal lean color (i.e., DC beef) results in a discounted carcass grade classified as a DC (currently averaging a $36.67/cwt discount from the base price as of October 2, 2023; USDA Market News Service, 2023).

Several preslaughter factors are associated with QG, such as breed type, sex class, transportation, and environmental factors. Compared to slaughter lots of Holstein cattle, cattle lots of *B. taurus* and *B. indicus* influence was associated with decreased odds of a carcass having a lower QG. These results contradict the findings of the 2016 NBQA (Boykin et al., 2017), where dairy breed carcasses on average had better QG (717 ± 1.7; least square means ± SEM) indicative of a higher quality grade than native and *B. indicus* breeds (705 ± 0.9, and 667 ± 4.7, respectively). In contrast, a Bertrand et al. (1983) reported higher QG in Angus cattle compared to Hereford, Holstein, and Brown Swiss cattle breeds. A sample population encompassing more U.S. regions and slaughter plants may find results congruent with the 2016 NBQA. Another animal characteristic, sex class, was found to be associated with QG in the current study. Compared to slaughter lots of mixed sex, steer slaughter lots were associated with an increase in the odds of a carcass having a poorer QG, and heifer lots were associated with a decrease in the odds of a carcass having a poorer QG, contrary to the 2016 NBQA that reported slightly higher QGs in steers than heifers (708 ± 0.9, and 704 ± 1.5, respectively).

While not all environmental factors were found to have an association with QG in the present study, an increase in the odds of a carcass having a poorer QG was associated with an increase in THI value. Increased THI values generally indicate warmer seasonal temperatures that may cause heat stress in cattle, resulting in decreased feed intake, animal growth, and production efficiency (Brown-Brandl, 2018). This decrease in production efficiency may lead to poorer QG and may not be strictly related to THI values during the preslaughter period. For example, more feedlot heifers in shaded pens graded USDA Choice than those in unshaded pens, which resulted primarily from the prevalence of DC being decreased by approximately half in carcasses from shaded heifers compared to unshaded (Mitlöhner et al., 2002). This data supports the concept that the associations between increased temperatures and THI values and increased prevalence in DC in previous studies (Scanga et al., 1998; Steel et al., 2022a) may be contributing to the decreases in meat quality in the present study. One transportation factor was found to be associated with QG in the current study; a decrease in the odds of a carcass having a poorer QG was associated with an increase in truck waiting time. However, the magnitude of this result was slight (OR: 95% CI: 0.997, 0.995 to 0.999). To the author's knowledge, truck waiting time and QG associations have not been previously researched in cattle. Additional research on this topic is warranted to fully understand this relationship and determine if these results are expected. In general, truck waiting time to unload should be minimized to alleviate its adverse effects on cattle welfare, especially in the warmer months.

Hot Carcass Weight

Hot carcass weight (HCW) is the hot (pre-chilled) weight of the carcass postslaughter and after removal of the head, hide, intestinal tract, and additional internal organs (UGA Extension, 2017), and is used to determine yield grade and dressing percentage (i.e., the percentage of the live animal that ends up as a carcass and is calculated using the formula: [HCW ÷ live weight] × 100%). Much like QG, there are price discounts that are associated with carcass size (i.e., weighing less than 600 pounds and more than 900 pounds; USDA Market News Service, 2023). Preslaughter challenges expose cattle to risks of fear, dehydration, and hunger, increased physical activity, and fatigue (Carrasco-García et al., 2020), many of which have the potential to affect HCW postmortem. For example, long periods without feed and water (i.e., during transportation) may result in what is called "tissue shrink" caused by extra-cellular and intra-cellular fluid loss that will decrease the final carcass weight (Barnes et al., 2017).

In the present study, HCWs were heavier in cattle of *B. taurus* influence or < 25% *B. indicus* influence and cattle lots of ≥ 25% *B. indicus* influence compared to Holstein cattle. These results are similar to those reported in other studies that have concluded that even at the same live weight, dairy breeds will typically have lower dressing out percentages and thus lower carcass weights, compared to beef breeds due to higher proportions of non-carcass tissues (i.e., intestines or organs) removed from the carcass (Kempster et al., 1982; Preston and Willis, 1982). Not surprisingly, slaughter lots of steers had heavier HCW, and slaughter lots of heifers had lighter HCW compared to lots of mixed sex in the current study. Previous studies have reported that steers generally weigh more than heifers in live weight and HCW, attributed to differences in growth rates between the sexes, which is lower in heifers (Boykin et al., 2017; Augusto et al., 2019).

Impacts on HCW were also associated with higher THI values. A decrease in HCWs during periods of increased THI values could be due to heat stress conditions that cattle may be enduring in the time leading up to slaughter that would cause decreased feed intake and thus limit animal growth (Brown-Brandl, 2018), however, that was not measured in the current study. Associations between decreased HCW and increased fasting durations have been previously reported (Clariget et al., 2021), and thus, it is surprising that HCW in the current study was not significantly associated with longer lairage durations. Cattle lose live weight rapidly within the first 24 h without access to feed and water, and this fasting duration can have detrimental effects on carcass shrinkage and muscle quality (Jones et al., 1990). There was no evidence of additional preslaughter factors in the current study (e.g., operation shift, transportation factors, space allowance in lairage, and wind speed) having an association with HCW. On average, transportation distance and truck waiting times were short (155.4 km and 30.3 min, respectively; Table 2) and, therefore, a majority of the journeys may not have resulted in enough time to make a significant difference in final carcass weights in the current study. In general, minimizing the amount of time that cattle are without food and water and focusing on heat mitigation strategies throughout the preslaughter period may help alleviate losses in carcass weight.

Conclusions

There have been substantial efforts made within the beef industry to promote and manage animal welfare and subsequent meat quality. However, there continues to be room for improvement in this ever-changing industry. Results from the current study have identified areas where further research is needed to fill knowledge gaps and fully understand the impacts of preslaughter management factors on welfare and meat quality outcomes. More specifically, knowledge of cattle behavior in lairage and changes in cattle mobility throughout the preslaughter phase warrant further exploration. Additionally, welfare and meat quality outcomes from truck waiting time at the plant to unload cattle and preslaughter factors' impacts on QG are deficient in the current literature. Outcomes of the preslaughter phase are multifactorial and identifying specific risk factors continues to be a challenge, however, continued research to identify these risk factors is imperative for improving beef cattle welfare and meat quality. The results of this study will also aid in informed decision-making regarding cattle management during the preslaughter phase. The outcomes of a project of this magnitude have the potential for industry stakeholders to question further and evaluate current management practices and make significant and positive changes in the preslaughter sector of the industry. Continued multidisciplinary research, recommended management practices put into practice, and education of industry stakeholders, plant employees, and truck drivers are imperative to the development and implementation of preslaughter management practices that are sustainable.

Acknowledgments

This project was funded by the Agriculture and Food Research Initiative Competitive Grant no. 2019-67015-29578 from the USDA National Institute of Food and Agriculture. Thank you to everyone who has supported and aided with this project including the processing companies, multitude of plant employees, and several undergraduate and graduate students.

Conflict of interest statement

The authors have no disclosures to declare.

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