



## Characterizing Ham and Loin Quality as Hot Carcass Weight Increases to an Average of 119 Kilograms<sup>1,2,3</sup>

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**Abstract:** The objective was to characterize ham and loin quality of carcasses ranging from 78 to 145 kg (average ~119 kg). Hot carcass weight (HCW), back fat depth, and loin depth was measured on 666 carcasses. Loin pH, instrumental and visual color and iodine value of clear plate fat (all 3 layers) was measured on approximately 90% of the population. Quality measurements of the ham, 14 d aged loin and chop, and loin chop shear force (SSF) were evaluated on approximately 30% of the population. Myosin heavy chain fiber type determination was completed on 49 carcasses. Slopes of regression lines and coefficients of determination between HCW and quality traits were calculated using the REG procedure in SAS and considered significantly different from 0 at  $P \leq 0.05$ . As HCW increased, loin depth ( $b_1 = 0.2496$ ,  $P < 0.0001$ ), back fat depth ( $b_1 = 0.1374$ ,  $P < 0.0001$ ), loin weight ( $b_1 = 0.0345$ ,  $P < 0.0001$ ), and ham weight ( $b_1 = 0.1044$ ,  $P < 0.0001$ ) increased. Estimated lean ( $b_1 = -0.0751$ ,  $P < 0.0001$ ) and iodine value ( $b_1 = -0.0922$ ,  $P < 0.0001$ ) decreased as HCW increased, where HCW accounted for 24% ( $R^2 = 0.24$ ) of the variation in estimated lean and 7% ( $R^2 = 0.07$ ) of the variation in iodine value. However, HCW did not explain variation in ham quality traits ( $P > 0.15$ ) and did not explain more than 1% ( $R^2 \leq 0.01$ ) of the variation in 1 d loin color or pH. Loins from heavier carcasses were more tender (decreased SSF;  $b_1 = -0.0674$ ,  $P < 0.0001$ ), although HCW only explained 9% of the variation in SSF. Hot carcass weight did not alter ( $P > 0.22$ ) muscle fiber type percentage or area. These results suggest that increasing HCW to an average of 119 kg did not compromise pork quality.

**Keywords:** color, heavy pigs, hot carcass weight, pork quality, tenderness

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## Introduction

Between 1995 and 2018, average hot carcass weight of U.S. pork carcasses increased from 82 to 96 kg (USDA ERS, 2018), which is an increase of approximately 17%. If current rates of carcass weight increases persist over time, the average pork carcass weight in the United States will be 105 kg by the year 2030 and over 118 kg by 2050. Although this represents an increase in throughput efficiency due

<sup>1</sup>Funding was partially provided by The National Pork Board.

<sup>2</sup>Mention of trade names, proprietary products, or specified equipment does not constitute a guarantee or warranty by the USDA and does not imply approval to the exclusion of other products that may be suitable.

<sup>3</sup>The USDA is an equal opportunity provider and employer.

to increases in economy of scale, projecting continued increases in weights in the future raises some concerns. The average live weight of broilers in the United States has increased by 0.73 kg since 1995, which is an increase of approximately 34% (USDA ERS, 2018). This increase in broiler weight, along with increased growth rate, is often cited as the source of increased adverse muscle conditions such as woody breast syndrome, muscle striping, and pale, soft, and exudative meat (Kuttappan et al., 2016). These conditions resulted in a poor eating experience and reduced consumer confidence of poultry. Therefore, the U.S. pork industry is concerned that increasing carcass weight of pigs will lead to similar issues of pork quality.

Slower chilled loins were paler in color, had less perceived marbling, but were more tender compared with loins that chilled more rapidly (Shackelford et al., 2012). Additionally, Arkfeld et al. (2016) reported that ham temperature decline lags behind loin temperature decline continuously throughout the chilling process and even at the time of fabrication at 22 h postmortem. Furthermore, loins and hams from carcasses weighing 105 kg chilled slower than loins and hams from carcasses weighing 85 kg (Overholt et al., 2019). Therefore, the ability to chill carcasses appropriately may become compromised as carcass weight increases, ultimately compromising pork quality, eating experience, and resulting in a reduction in consumer confidence.

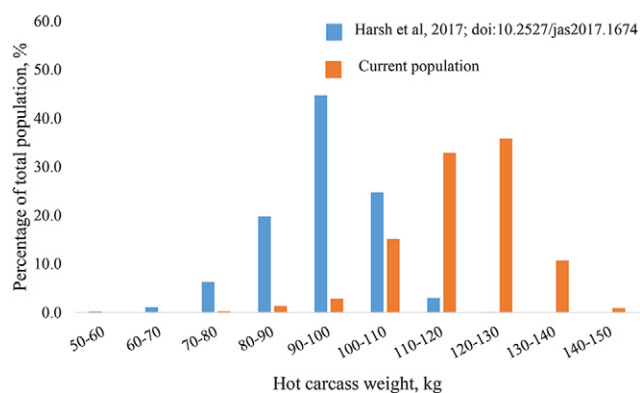
Harsh et al. (2017) characterized the influence of carcass weight on pork quality (Fig. 1). However, the average HCW in that study was 96 kg, which may not be representative of carcass weights in the near and distant future. Therefore, the objective was to characterize ham and loin quality of carcasses with weights ranging from 78 to 145 kg, with a mean HCW of 119 kg.

## Materials and Methods

The Kansas State University Institutional Animal Care and Use Committee approved protocols used in the live phase portion of the experiment. Pigs were slaughtered in a federally-inspected facility. Meat purchased from that facility was transported to the U.S. Meat Animal Research Center (Clay Center, NE) and then to the University of Illinois Meat Science Laboratory (Urbana, IL).

### *Pigs and experimental design*

Commercial pigs evaluated in this study were described in detail by Lerner et al. (2018) and used



**Figure 1.** Frequency of observations of carcass weights from Harsh et al. (2017) with a mean HCW of 95 kg and from the current study with a mean HCW of 119 kg.

typical U.S. production practices to evaluate differences in space allowance and marketing strategy on growth performance in pigs heavier than the current average weight of 96 kg (USDA ERS, 2018). A total of 976 pigs (resulting from the matting of 327 boars to a Camborough female, PIC, Hendersonville, TN) were used in a 160 d growth study. Pigs were allotted into 6 different treatment groups based on space allowance and marketing strategy. The first 4 treatments reduced space allowance per pig via initial pen stocking density and had only 1 final marketing event. The fifth and sixth treatments consisted of different pig removal strategies. When pigs were removed due to illness or death, pen gates were adjusted. Pigs were provided ad libitum access to feed and water throughout the study. Diets were corn- and soybean meal-based and included 30 to 40% corn dried distiller's grains with solubles until the final dietary phase. Data were collected on 666 carcasses at the production facility. This represents the number of carcasses which at least 1 observation was recorded. Complete data collection was not achieved for any specific trait, leading to the discrepancy in total number of observations for each quality trait (Table 1). This population of pigs had a mean HCW of 119 kg and were used to assess the effect of increasing carcass weights on pork quality.

### *Abattoir data collection*

Upon completion of the live phase portion of the experiment (Lerner et al., 2018), pigs were loaded on trucks and transported approximately 565 km to a USDA federally-inspected abattoir. Pigs were provided ad libitum access to water but no access to feed during lairage. Time in lairage followed normal operating procedures of the abattoir. Pigs were slaugh-

**Table 1.** Population summary statistics of carcass characteristics

Variable	No.	Mean	Minimum	Maximum	SD	CV
Hot carcass weight, kg	666	118.80	78.46	145.12	10.47	8.81
Fat depth, mm <sup>1</sup>	612	16.18	7.60	27.60	3.12	19.26
Loin depth, mm <sup>1</sup>	612	67.64	45.20	89.60	7.25	10.71
Estimated lean, % <sup>2</sup>	612	53.19	48.41	58.30	1.61	3.02
Iodine value <sup>3</sup>	591	69.51	58.74	81.93	3.74	5.38
Ham, kg	203	13.98	10.93	16.96	1.29	9.25
% of HCW <sup>4</sup>	203	23.38	20.08	27.14	1.20	5.13
Boneless loin, kg	613	4.67	3.19	6.60	0.54	11.56
% of HCW <sup>4</sup>	613	7.85	5.56	11.21	0.69	8.74

<sup>1</sup>Measured using a Fat-O-Meater probe (SFK Technology A/S, Herlev, Denmark).

<sup>2</sup>Estimated lean was calculated using the equation: % Lean =  $\{15.31 - [31.277 \times (\text{BF, mm}/25.4)] + [3.813 \times (\text{LD, mm}/25.4)] + (0.51 \times \text{HCW, lb})\} / \text{HCW} \times 100$ .

<sup>3</sup>Iodine values were measured using the Bruker Method.

<sup>4</sup>Calculated by multiplying each primal weight by 2 (to account for both carcass sides). % of HCW =  $[2(\text{primal weight})/\text{HCW}] \times 100$ .

tered on 2 separate days using CO<sub>2</sub> immobilization and terminated via exsanguination. Immediately after evisceration, a sequential identification number was written on the shoulder of each carcass and the respective pen number (indicative of live animal space treatment) tattoo was recorded. Carcasses were measured for HCW, back fat depth, and loin depth. Back fat depth and loin depth were evaluated using the Fat-O-Meater probe (FOM; SFK Technology A/S, Herlev, Denmark) perpendicular to the muscle by starting at the most posterior rib and counting approximately 3 or 4 ribs toward the anterior end. The FOM is an optical probe that measures the difference in light reflectance as it passes through fat and muscle tissue. Carcasses were held in the blast-chiller for approximately 120 min and then in equilibration bays until fabrication at 17 h postmortem. During temperature equilibration, one-third of the carcasses were randomly identified for loin and ham quality evaluation. The vertebral column and the medial side of the ham were labeled with corresponding sequence numbers that matched the shoulder sequence for identification during fabrication. At approximately 17 h postmortem, carcasses were fabricated into whole leg/fresh ham (NAMP number 401; NAMI, 2014) and bone-in loins (NAMP number 410; NAMI, 2014).

### Iodine values

As carcasses exited the blast chiller, approximately 3.81-cm diameter adipose tissue cores (consisting of all 3 adipose layers) were collected from the clear

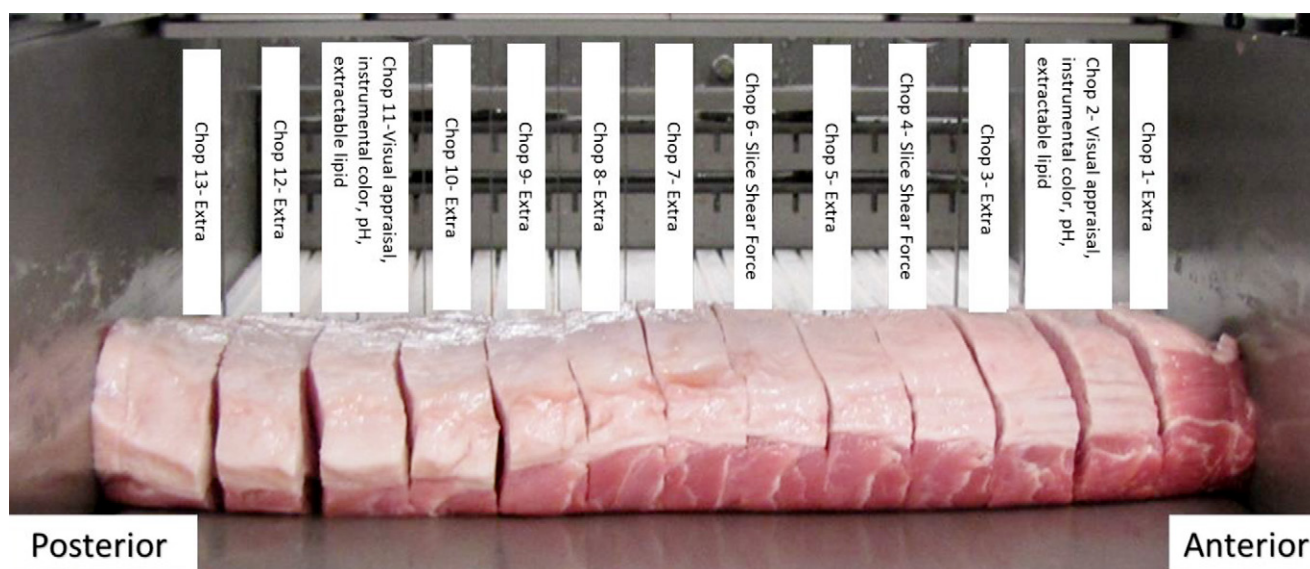
plate (adipose tissue located over the scapula and cervical vertebra) near the dorsal midline of the left side of every carcass. Iodine values were measured using the near-infrared technology (Bruker, Billerica, MA).

### Hams

Legs (fresh hams, NAMP number 401; NAMI, 2014) with sequence numbers were collected and placed in combos to be weighed and evaluated for ham quality traits. Leg primal weight was recorded, and instrumental color (L\*, a\*, and b\*) was measured with a Konica Minolta CR-400 colorimeter (Minolta Camera Company, Osaka, Japan) using D65 illuminant, 2° observer angle, and an 8-mm aperture on the *gluteus medius* of the ham face on 203 hams in the population. Additionally, pH was measured by penetrating the surface of the *gluteus medius* of the ham with a REED SD-230 pH meter (Reed Instruments, Wilmington, NC) fitted with a PHE-2385 glass combo electrode (Omega Engineering, Inc., Stamford, CT).

### Loins

During loin fabrication, loins were cut into boneless Canadian back loins (NAMP number 414; NAMI, 2014). An identifier button was placed in the ventral side of each loin. Visual muscle color (6-point visual scale; NPPC, 1999), marbling (10-point visual scale; NPPC, 1999), and subjective firmness (5-point subjective scale; NPPC, 1991) were evaluated on the ventral surface of the boneless loin on the boning and trimming line. An industry professional with over 10 yr of pork quality research experience conducted evaluations. Color, marbling, and firmness scores were evaluated at the same location along the loin, the area of the 10th rib, to allow for consistent oxygenation of the loin muscle. Instrumental color (L\*, a\*, and b\*) of the *longissimus* muscle (LM) was measured on the ventral side at approximately 25 and 75% the length of the loin using a Hunter Miniscan XE Plus colorimeter (Hunter Associates Laboratory, Inc., Reston, VA) with illuminant D65, 10° observer angle, and 25-mm port. Ultimate (>17 h postmortem) pH was measured by penetrating the surface on the ventral side at approximately the area between the fourth and sixth rib with a REED SD-230 m fitted with a FC 200 B series electrode (Hanna Instruments; Woonsocket, RI). After 1 d postmortem evaluations on a single day of slaughter, a 2-cm-thick cross-section sample from 60 loins was cut from the posterior end of the *longissimus lumborum*, packaged in whirl pack bags, and transported



**Figure 2.** Illustration of the standardized loin used to assign chops to various meat quality measurements.

in coolers to the University of Illinois for preparation for fiber type determination.

A total of 278 boneless loins, 170 from d 1 and 108 from d 2, were vacuum-packaged, boxed, and transported to the U.S. Meat Animal Research Center (USMARC). Upon arrival at USMARC, loins were immediately placed on carts in a single-layer and ventral side up. Loins were weighed (scale was tarred to account for vacuum packaging bag) to record initial loin weight and were stored at 4°C until 14 d postmortem. At 14 d postmortem, loins were removed from the packaging and weighed to determine aged weight. Purge loss was calculated:  $[(\text{initial weight, g} - \text{aged weight, g}) / \text{initial weight, g}] \times 100$ . At 14 d postmortem, loins were prepared for slicing with a Grasselli NSL 400 portion meat slicer (Grasselli SPA, Albinea, Italy; Fig. 2). The posterior end of each loin (approx. 4-cm long) was removed by a straight cut perpendicular to the length of the loin at a point 5-cm posterior to the anterior tip of *gluteus accessorius*. The anterior end of the loin was removed by a second cut made 396-mm anterior to the first cut leaving a 396-mm long center-cut loin section that fits the width of the Grasselli NSL 400 portion meat slicer. This approach maximized yield of chops with the greatest proportion of their mass/cross-sectional area comprised of *longissimus lombo-rum* and excluded chops with a high proportion of their mass/cross-sectional area comprised of other muscles (*spinalis dorsi*, *multifidus dorsi*, *gluteus medius*, and *gluteus accessorius*). Additionally, this approach standardized anatomical location of chop assignment across loins. Chops were numbered starting from the

anterior end with chop 1, proceeding to the posterior end with chop 13 and designated to either slice shear force (SSF) or quality measurements (Fig. 2).

### **Slice shear force**

Chops 4 and 6 were used for determination of SSF. Immediately after cutting, fresh (never frozen) chops were weighed to record initial weight. The following day (15 d postmortem), chops were cooked using a belt grill (Magigrill, model TBG60; MagiKitch'n Inc., Quakertown, PA) to a desired internal temperature of 71°C. Cooked chops were weighed and cooking loss was calculated:  $[(\text{initial weight, g} - \text{cooked weight, g}) / \text{initial weight, g}] \times 100$ . Slice shear force was measured using the procedures of Shackelford et al. (2004) on both chops. Immediately after cooking, a 1-cm thick  $\times$  5-cm long slice was removed from each chop parallel to the muscle fibers. Each sample was sheared once with a flat, blunt-end blade using an electronic machine (TMS-PRO Texture Measurement System; Food Technology Corporation; Sterling VA). The SSF values from the 2 chops were then averaged, providing 1 SSF value for chops cooked to 71°C and used for all analyses (Table 2).

### **Aged quality**

Chops 2 (anterior) and 11 (posterior) were used to measure muscle color (6-point visual scale; NPPC, 1999), marbling (10-point visual scale; NPPC, 1999), and firmness (5-point subjective scale; NPPC, 1991) after 2 h of oxygenation and values were averaged

**Table 2.** Population summary statistics of ham and loin quality

Variable	No.	Mean	Minimum	Maximum	SD	CV
Ham quality						
Instrumental color <sup>1</sup>						
Lightness, L*	203	44.83	36.95	58.50	3.12	6.96
Redness, a*	203	10.05	6.37	14.43	1.56	15.51
Yellowness, b*	203	1.84	-2.18	5.82	1.52	82.78
Gluteus medius pH	202	5.67	5.25	6.13	0.13	2.29
Loin quality						
1-d pH	613	5.69	5.49	6.66	0.11	2.00
1-d Instrumental color <sup>1</sup>						
Ventral lightness, L*	613	54.20	47.11	63.47	2.27	4.18
Ventral redness, a*	613	8.32	5.35	12.06	1.02	12.21
Ventral yellowness, b*	613	13.43	10.37	15.93	0.85	6.33
1-d NPPC visual quality <sup>2</sup>						
Ventral color	613	3.32	2.0	5.0	0.61	18.31
Ventral marbling	613	2.15	1.0	6.0	0.90	41.99
Ventral firmness	613	2.39	1.0	4.0	0.77	32.11
Average chop wt, g	276	240.79	161.25	304.68	26.36	10.95
Chop quality						
14-d pH	276	5.51	5.18	6.35	0.15	2.66
14-d NPPC visual quality <sup>2</sup>						
Color	276	3.02	1.5	5.0	0.43	14.35
Marbling	276	1.54	1.0	3.0	0.32	20.67
Firmness	276	2.90	2.0	3.0	0.21	7.25
Slice shear force, kg <sup>3</sup>	276	10.95	6.92	20.67	2.46	22.50
Cook loss, %	276	18.09	13.30	23.94	1.43	7.89
Moisture, %	277	73.92	70.79	76.61	0.70	0.95
Extractable lipid, %	277	2.12	0.47	5.78	0.81	38.27

<sup>1</sup>L\* measures darkness to lightness (greater L\* value indicates a lighter color). a\* measures redness (greater a\* value indicates a redder color). b\* measures yellowness (greater b\* value indicates a more yellow color).

<sup>2</sup>NPPC color using the 1999 standards, half point scale where 1 = visually palest and 6 = visually darkest. NPPC marbling using the 1999 standards where 1 = visually the least marbling and 6 = visually the most marbling. NPPC firmness using the 1991 standard where 1 = softest and 6 = firmest.

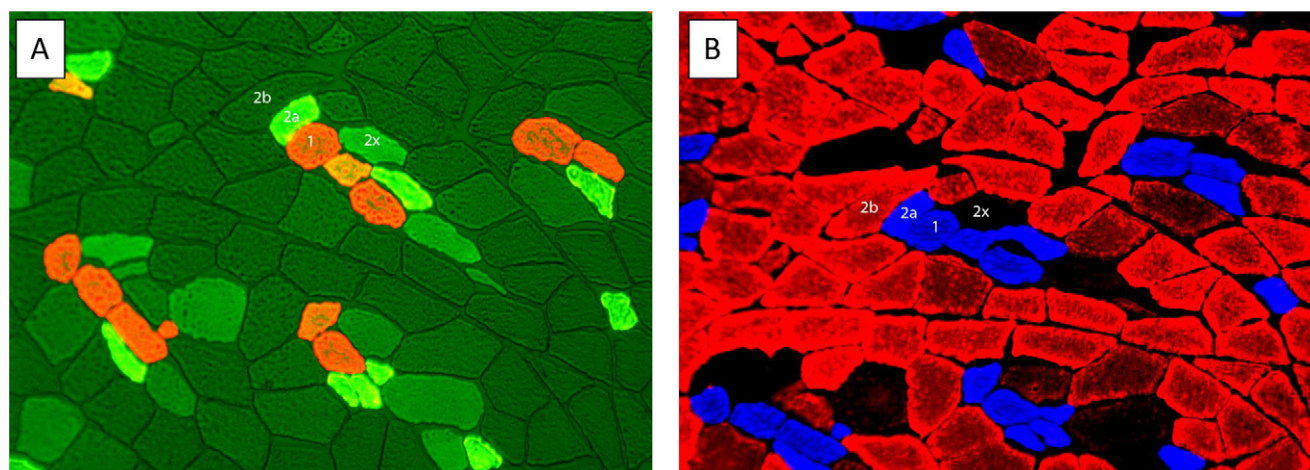
<sup>3</sup>Value represents the average from chop 4 and 6.

for the 2 chops. Instrumental color (L\*, a\*, and b\*) was measured on both chops using a Hunter Miniscan XE Plus colorimeter (Hunter Associates Laboratory, Inc., Reston, VA) with illuminant D65, 10° observer angle, and 25-mm port. Ultimate pH was measured by penetrating the surface of each chop with a REED SD-230 m (Wilmington, NC) fitted with a FC 200 B series electrode (Hanna Instruments). Measurements from both chops were averaged and average values are reported. Following this, chops 2 and 11 were vacuum packaged, frozen, and transported to the University of Illinois Meat Science Laboratory for intramuscular extractable lipid determination (Table 2).

### Proximate composition

Chops used for analysis of moisture and extractable lipid were allowed to partially thaw at 22°C, taking care to prevent exudation. This was done by not

allowing the chops to reach ambient temperature and all purge was included in the blender during homogenization. Chops were trimmed of all subcutaneous fat and secondary muscles before homogenization in a Cuisinart (East Windsor, NJ) food processor. The homogenate was used to determine moisture and extractable lipid content. Briefly, 10-g samples were weighed in duplicate and placed in a drying oven at 110°C for at least 24 h. After drying, samples were weighed to quantify moisture loss and lipid was extracted using an azeotropic mixture of chloroform and methanol (87:13) as described by Novakofski et al. (1989). Samples were returned to the drying oven for at least an additional 24 h before collecting a lipid extracted weight. Moisture and extractable lipid percentages were determined by the differences between initial weight, dried weight, and extracted weight (Table 2).



**Figure 3.** Representative images of cross-section immunofluorescent analysis of loin muscle fibers. Both images were used as references to each other to determine fiber type. Fibers that appeared red in (A) and blue in (B) were considered type 1, fibers that appeared light green in (A) and blue in (B) were considered type 2a, fibers that appeared unstained in (A) and red in (B) were considered type 2b, and fibers that appeared unstained in both (A) and (B) were considered type 2x.

### ***Myosin heavy chain fiber type determination***

As described above, samples were collected from loins from a single slaughter day (d 1). Loins for myosin heavy chain fiber type determination represented carcasses with HCW ranging from 97 to 133 kg. Upon arrival at the University of Illinois, samples were excised from the loin with muscle fiber orientation running parallel to each other, frozen in liquid nitrogen-cooled isopentane and stored at  $-80^{\circ}\text{C}$  until further analysis. Samples were cut to no more than 30- $\mu\text{m}$  thick sections on a cryostat (Reichert-Jung Cryocut 1800, Leica Microsystems Inc., Buffalo Grove, IL); thickness was adjusted for each individual sample to optimize image quality. A total of 2 consecutive sections for each sample were placed on separate glass slides. Immunofluorescence was used to distinguish skeletal muscle fiber types. Slides were first blocked with a 10% normal goat serum for 60 min at approximately  $24^{\circ}\text{C}$ . Primary antibodies (Developmental Hybridoma Bank, Iowa City, IA) of unique antibody isoform structure targeted myosin heavy chain (MHC) isoforms 1 (BA-F8, IgGb2, 1/50) and 2a/X (SC-71, IgG1, 1/100) were used on slide A and 1/2a (BF-35, IgG1, 1/100) and 2b (BF-F3, IgM, 1/10) were used on slide B. Secondary antibodies conjugated to 3 distinct Alexa Fluor (Thermo Fisher, Waltham, MA) dyes differentiated fiber types (A-21145, Alexa Fluor 594, 1/100; A-21121, Alexa Fluor 488, 1/100; A-21426, Alexa Fluor 555, 1/100) were used between both slides with slide A having Alexa Fluor 594 and 488 and slide B having Alexa Fluor 488 and 555 (Fig. 3). Slides were rinsed in three 1X PBS (Phosphate Buffered Saline 10X; BioWittaker Lonza, Switzerland) washes after each incubation step.

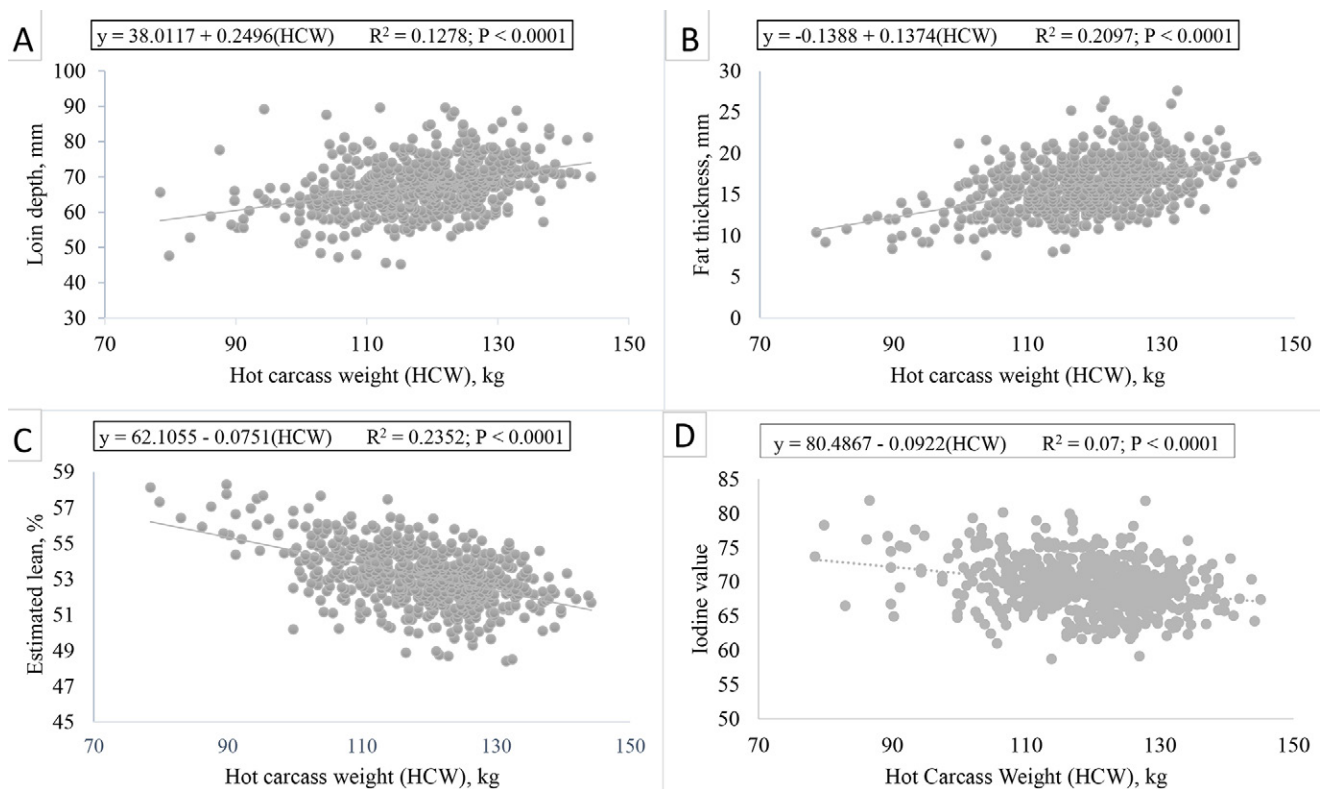
An Advanced Microscopy Group Evos Florescent Microscope (model AMF-4306-US; Life Technologies) with total magnification of  $295\times$  was used to visualize florescence and capture 2 representative images from each section that were used to determine fiber type composition and fiber type cross-sectional area (CSA; Fig. 3). On 1 image a scale equal to 400 nm was placed using the microscope. Prior to computer analysis, this scale was traced in Adobe Photoshop (Adobe Systems Inc., San Jose, CA) to determine the ratio of pixels to actual distance (400 nm). This was done 3 times and the average of the 3 ratios generated was used in the analysis of every slide to convert pixels to nm. Cells were traced in Photoshop to determine average CSA for each fiber type.

### ***Statistical analysis***

Summary statistics were calculated using the MEANS procedure of SAS. Predictive ability of HCW was calculated for each dependent variable using the REG procedure of SAS (version 9.4; SAS Inst. Inc., Cary, NC). Coefficients of determination ( $R^2$ ) and the slope of each regression line were calculated as a means to predict trends in quality attributes and were considered significantly different from 0 at  $P \leq 0.05$ .

## **Results**

Carcass weights in the current study represent the projected HCW among commercial pigs in the U.S. pork supply in 2050. The population represented a 67 kg range in HCW, from 78.46 to 145.12 kg and a



**Figure 4.** Effect of carcass weight (HCW) on carcass characteristics. The traits evaluated include (A) loin depth, (B) back fat depth, (C) estimated lean, and (D) iodine values. Data are depicted as the linear regression of the trait using carcass weight as the independent variable. Coefficients of determination included on figures where the slope of linear regression lines were different from zero ( $P < 0.05$ ).

mean weight of 118.80 kg (Table 1). Evaluated quality parameters exhibited commercially relevant ranges with a *gluteus medius* lightness range of 36.95 to 58.50, ventral loin pH range of 5.49 to 6.66, ventral loin visual color score range of 2.0 to 5.0, and SSF range of 6.92 to 20.67 kg (Table 2).

### Carcass characteristics

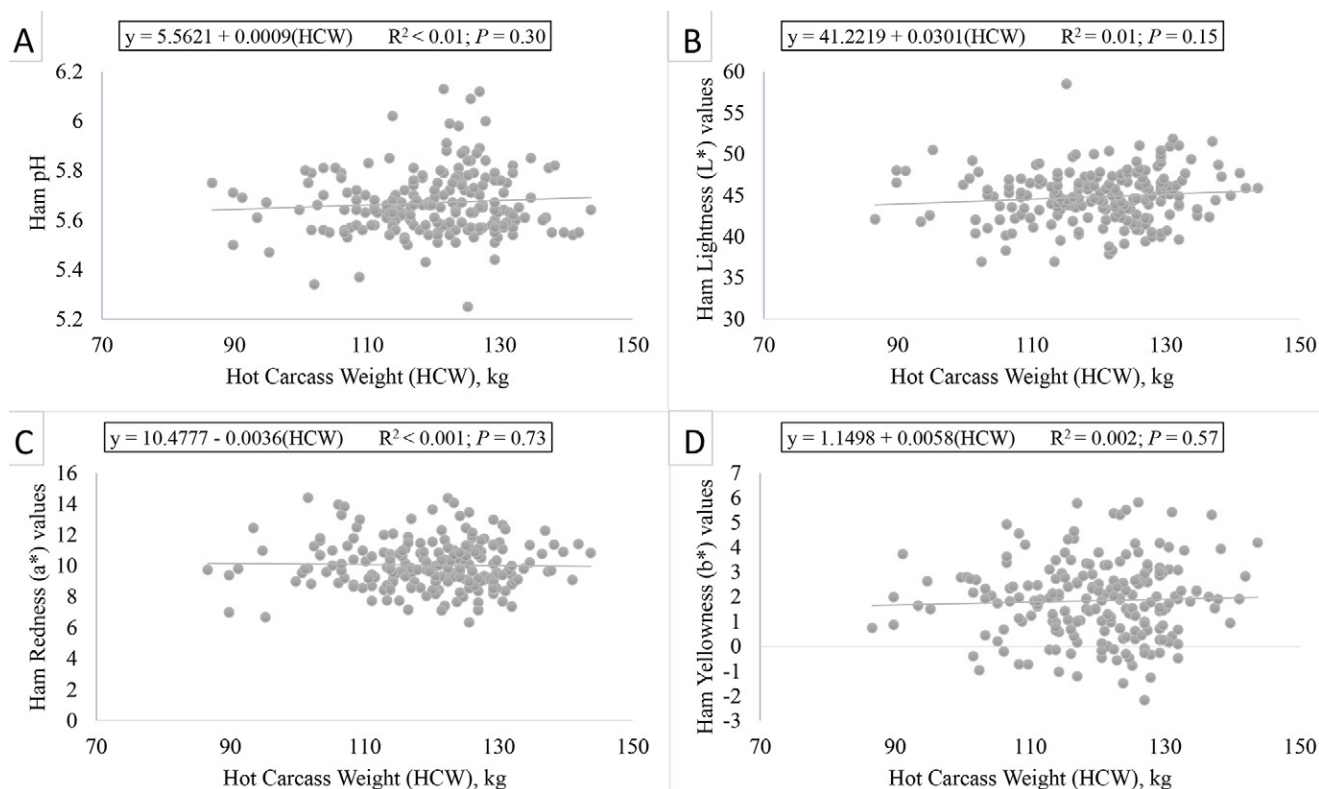
Heavier carcasses had increased loin depth ( $b_1 = 0.2496$ ,  $P < 0.0001$ ; Fig. 4A) and back fat depth ( $b_1 = 0.1374$ ,  $P < 0.0001$ ; Fig. 4B), where HCW accounted for 13% ( $R^2 = 0.13$ ) of the variation of loin depth and 21% ( $R^2 = 0.21$ ) of back fat depth. With these increases in back fat depth and loin depth, there was a decrease in estimated lean as HCW increased ( $b_1 = -0.0751$ ,  $P < 0.0001$ ; Fig. 4C), which accounted for 24% ( $R^2 = 0.24$ ) of the variation. Additionally, there was a decrease in iodine value as carcass weight increased ( $b_1 = -0.0922$ ,  $P < 0.0001$ ; Fig. 4D), however, HCW only accounted for 7% ( $R^2 = 0.07$ ) of the variation in iodine value.

### Hot carcass weight and ham quality

Heavier carcasses produced heavier pork leg (fresh ham) primals ( $b_1 = 0.1044$ ,  $P < 0.0001$ ; data not shown in tabular form), where HCW explained 73% ( $R^2 = 0.73$ ) of variation in ham weight. There were no significant differences observed in *gluteus medius* pH ( $b_1 = 0.0009$ ,  $P = 0.30$ ; Fig. 5A) or instrumental lightness ( $b_1 = 0.0301$ ,  $P = 0.15$ ; Fig. 5B), redness ( $b_1 = -0.0036$ ,  $P = 0.73$ ; Fig. 5C) or yellowness ( $b_1 = 0.0058$ ,  $P = 0.57$ ; Fig. 5D) as carcass weight increased.

### Hot carcass weight and early postmortem loin quality

Similar to hams, heavier carcasses resulted in heavier boneless Canadian back loins ( $b_1 = 0.0345$ ,  $P < 0.0001$ ; data not shown in tabular form), where carcass weight explained 45% ( $R^2 = 0.45$ ) of the variation in loin weight. However, there were no significant differences in early aged ventral loin pH ( $b_1 = -0.0003$ ,  $P = 0.52$ ; Fig. 6A) as carcass weight increased. As carcass weight increased, 1 d loin instrumental yellowness ( $b^*$ ) increased ( $b_1 = 0.0092$ ,  $P < 0.01$ ; Fig. 6D), however HCW only explained 1% ( $R^2 = 0.01$ ) of



**Figure 5.** Effect of carcass weight (HCW) on 1 d postmortem ham quality. The traits evaluated include (A) *gluteus medius* pH, (B) *gluteus medius* lightness  $L^*$ , (C) *gluteus medius* redness  $a^*$ , and (D) *gluteus medius* yellowness  $b^*$ . Data are depicted as the linear regression of the trait using carcass weight as the independent variable. Coefficients of determination included on figures where the slope of linear regression lines were different from zero ( $P < 0.05$ ).

the variation in  $b^*$ . Moreover, no differences were observed in any other instrumental color parameter: lightness ( $b_1 = 0.0084$ ,  $P = 0.34$ ; Fig. 6B) or redness ( $b_1 = 0.0029$ ,  $P = 0.47$ ; Fig. 6C). There were also no differences in visual appraisals: color ( $b_1 = -0.0024$ ,  $P = 0.32$ ; Fig. 7A), marbling ( $b_1 = -0.0005$ ,  $P = 0.88$ ; Fig. 7B), or firmness ( $b_1 = 0.0044$ ,  $P = 0.13$ ; Fig. 7C) as carcass weight increased.

### Hot carcass weight and chop quality

Heavier carcasses resulted in heavier chops, [4 and 6, ( $b_1 = 1.6626$ ,  $P < 0.0001$ ; Fig. 8A)], explaining 46% ( $R^2 = 0.46$ ) of variation in chop weight. As HCW increased, chops became more tender, indicated by reduced SSF ( $b_1 = -0.0674$ ,  $P < 0.0001$ ; Fig. 8B). Carcass weight also predicted less cook loss ( $b_1 = -0.0512$ ,  $P < 0.0001$ ; Fig. 8C), with heavier carcasses compared with lighter carcasses. However, HCW only explained 9% ( $R^2 = 0.09$ ) of the variation in SSF values and 15% ( $R^2 = 0.15$ ) of the variation in cook loss percentage. As carcass weight increased there were no significant differences in any chop quality parameters such as, 14 d pH ( $b_1 = -0.0008$ ,  $P = 0.35$ ; Fig. 9A),

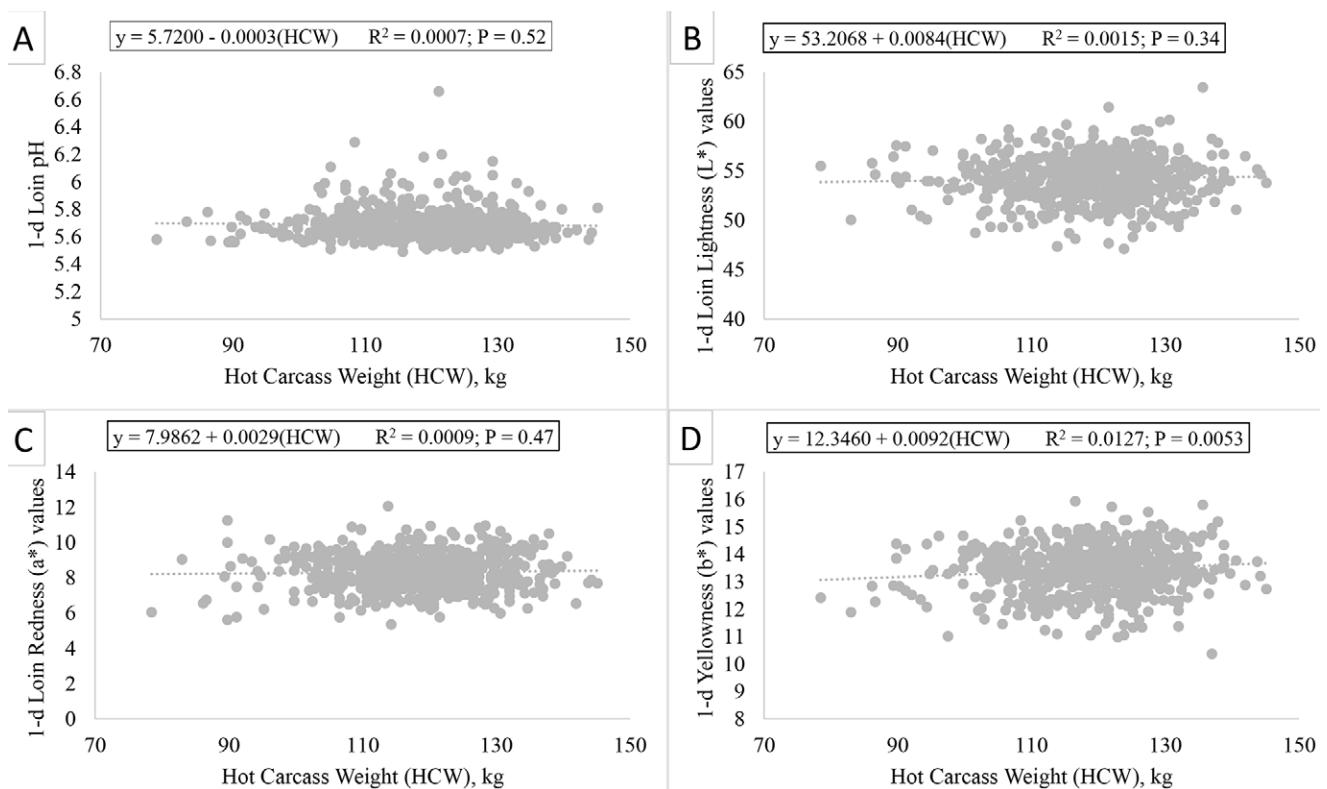
visual color ( $b_1 = 0.0035$ ,  $P = 0.15$ ; Fig. 9B), marbling ( $b_1 = 0.0015$ ,  $P = 0.40$ ; Fig. 9C), or firmness ( $b_1 = 0.0010$ ,  $P = 0.40$ ; Fig. 9D). As carcass weight increased, there were no significant differences in chop moisture percentage ( $b_1 = -0.0030$ ,  $P = 0.44$ ) and chop lipid percentage ( $b_1 = 0.0026$ ,  $P = 0.56$ ; data not shown in tabular form).

### Hot carcass weight and muscle fiber type

Loins used for fiber type determination had a mean carcass weight of 119 kg with a range from 97.51 to 133.33 kg (Table 3). There were no significant differences in the percentage of fiber type 1 ( $b_1 = -0.0170$ ,  $P = 0.81$ ; Fig. 10A), 2a ( $b_1 = -0.0786$ ,  $P = 0.23$ ; Fig. 10B), 2x ( $b_1 = -0.0201$ ,  $P = 0.80$ ; Fig. 10C), or 2b ( $b_1 = 0.1224$ ,  $P = 0.37$ ; Fig. 10D) as carcass weight increased.

Although, fiber type 2a area tended to decrease as carcass weight increased ( $b_1 = -40.7257$ ,  $P = 0.07$ ; Fig. 11B), there were no significant differences in total fiber area ( $b_1 = -26.1387$ ,  $P = 0.33$ ; data not shown in tabular form), type 1 area ( $b_1 = -26.6331$ ,  $P = 0.22$ ; Fig. 11A), type 2x ( $b_1 = -46.9459$ ,  $P = 0.25$ ; Fig. 11C),





**Figure 6.** Effect of carcass weight (HCW) on early aged (1 d postmortem) loin quality. The traits evaluated include (A) loin ventral pH, (B) loin ventral lightness  $L^*$ , (C) loin ventral redness  $a^*$ , and (D) loin ventral yellowness  $b^*$ . Data are depicted as the linear regression of the trait using carcass weight as the independent variable. Coefficients of determination included on figures where the slope of linear regression lines were different from zero ( $P < 0.05$ ).

or type 2b ( $b_1 = -26.2537$ ,  $P = 0.38$ ; Fig. 11D) as carcass weight increased.

## Discussion

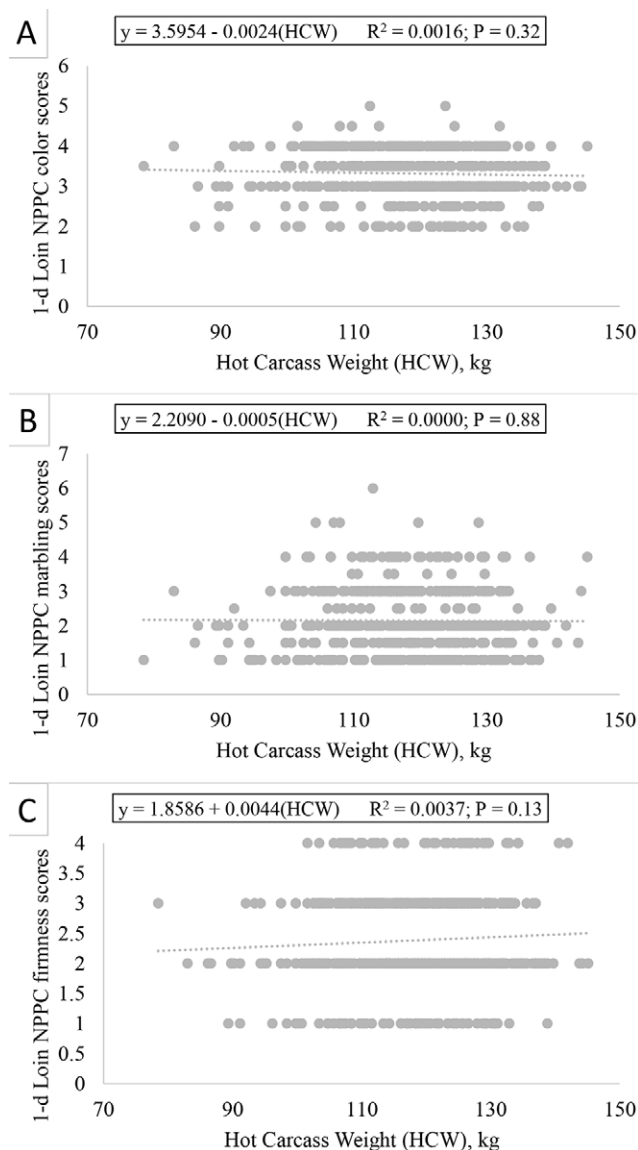
With the current historical and upward trend in pork carcass weights, the objective of this study was to characterize pork quality of carcasses with a mean weight of 119 kg. Harsh et al. (2017) attributed little variation in pork quality to increasing HCW. However, the average carcass weight of pigs evaluated in this study were much heavier than was used in the 2017 study by Harsh et al. (119 vs. 96 kg).

It is important to acknowledge the lack of variation in ham and loin quality attributed to HCW, regardless of the slope of linear regression lines demonstrated between HCW and quality attributes. Coefficients of determination ( $R^2$ ) provide more information regarding the usefulness of a linear regression line and act as a calculation for the percentage of variation in a dependent variable that can be explained by the independent variable (HCW for this study; Taylor, 1990). Therefore,  $R^2$  values were used in this study to in-

terpret the observed relationships more thoroughly. The original hypothesis was that increasing carcass weights would create differences in chilling rates and overall size (weight) would cause variation in muscle fiber types, which could have a negative impact on muscle quality and potentially reduce muscle quality or even introduce myopathies. However, with the increase in HCW there were anticipated increases in primal weights but also slight improvement in loin chop tenderness and cook loss.

Wu et al. (2017) reported that for every 10 kg increase in live weight, back fat depth increased by 1.8 mm and fat free lean decreased by 0.78 units. Similarly, in this study, there was approximately a 1.38 mm increase in back fat and a 0.75 unit decrease in estimated lean for every 10 kg increase in carcass weight. However, it is important to note that Wu et al. (2017) reported live weight, while the present study reported carcass weight. As carcass weight increases, we would expect an increase in primal and sub primal weights, which was observed in the present study.

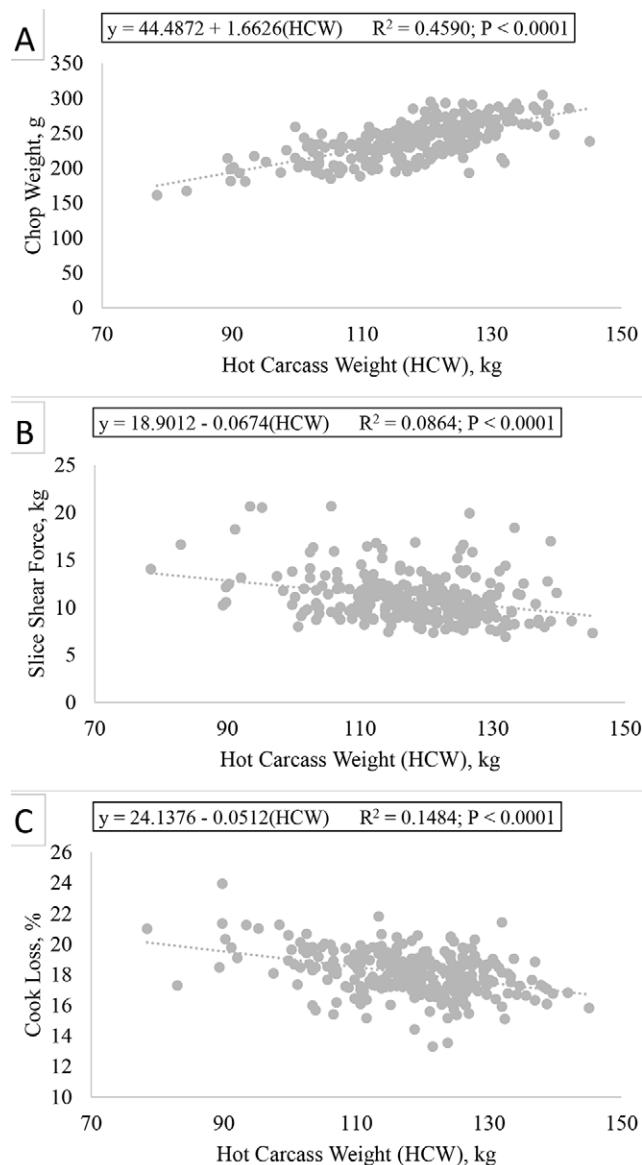
Harsh et al. (2017) reported that heavier carcasses resulted in darker and redder ham face color, however carcass weight was not predictive of pH or instrumen-



**Figure 7.** Effect of carcass weight (HCW) on early aged (1 d postmortem) loin quality. The traits evaluated include (A) loin visual color scores, (B) loin visual marbling scores, and (C) loin subjective firmness scores. Data are depicted as the linear regression of the trait using carcass weight as the independent variable. Coefficients of determination included on figures where the slope of linear regression lines were different from zero ( $P < 0.05$ ).

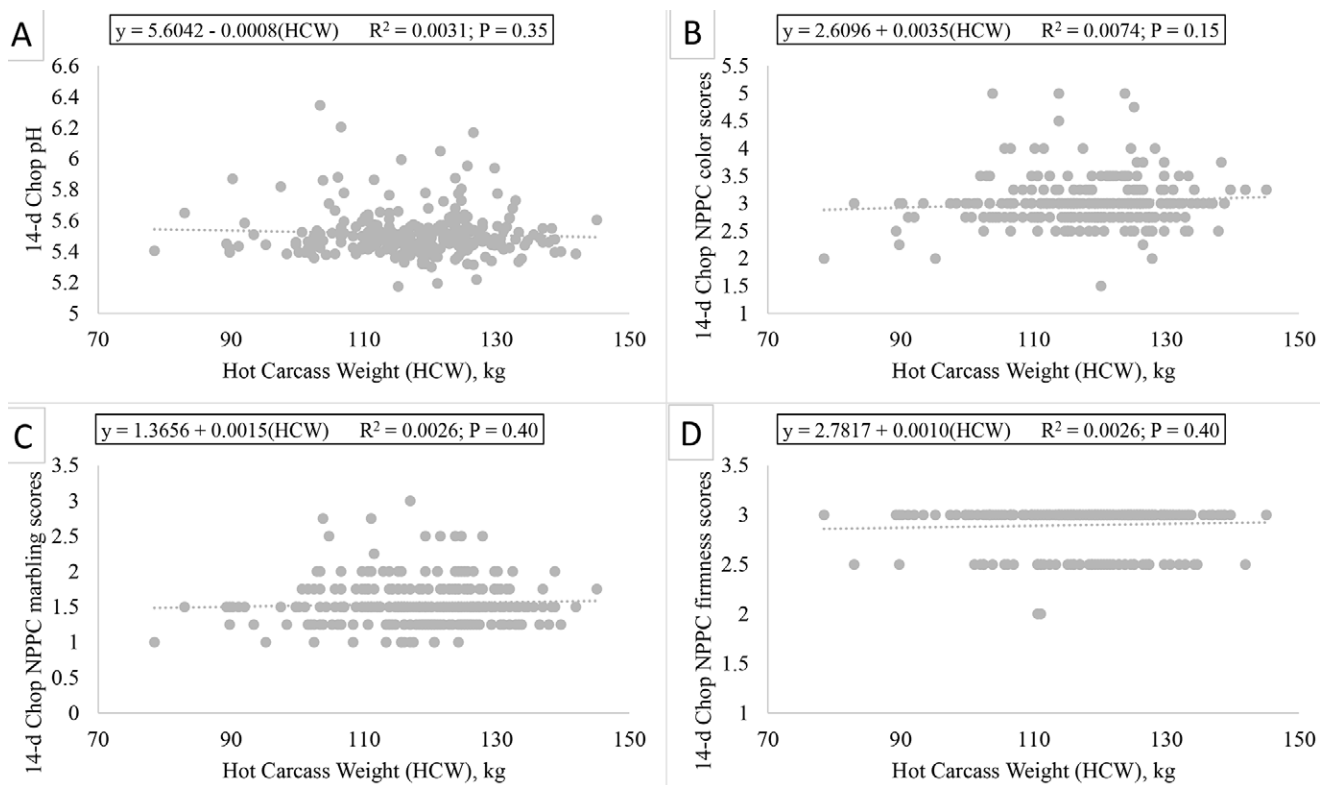
tal color of the *gluteus medius* in this population of pigs. Although, statistical differences were reported by Harsh et al. (2017), HCW only accounted for 0.47% of the variation in *gluteus medius*  $L^*$  values and  $\leq 0.39\%$  of the variation in  $a^*$  values. Similarly, in the present study, HCW only accounted for less than 1.0% ( $R^2 < 0.01$ ) of the variation in the *gluteus medius*  $L^*$  values and  $a^*$  values.

In the present study, there was no significant difference in pH due to increasing carcass weights. This is in contrast with the majority of published litera-



**Figure 8.** Effect of carcass weight (HCW) on aged (14 d postmortem) chop quality. The traits evaluated include (A) chop weight, (B) slice shear force (SSF), (C) 71°C cook loss. Data are depicted as the linear regression of the trait using carcass weight as the independent variable. Coefficients of determination included on figures where the slope of linear regression lines were different from zero ( $P < 0.05$ ).

ture, which has observed a decrease in pH as carcass weight increases (Harsh et al., 2017; Wu et al., 2017). Additionally, in the present study, there were no significant differences in either instrumental lightness or redness, as well as, visual color measurements as carcass weight increased. This agrees with Durkin et al. (2012) who reported a slaughter weight range of 120 to 170 kg and Park and Lee (2011) who reported a slaughter weight range of 110 to 140 kg, where neither reported differences in instrumental lightness ( $L^*$ ) when comparing lighter carcasses to heavier car-



**Figure 9.** Effect of carcass weight (HCW) on aged (14 d postmortem) chop quality. The traits evaluated include (A) chop 14-d pH, (B) chop 14-d visual color scores, (C) chop 14-d visual marbling scores, and (D) chop 14-d subjective firmness scores. Data are depicted as the linear regression of the trait using carcass weight as the independent variable. Coefficients of determination included on figures where the slope of linear regression lines were different from zero ( $P < 0.05$ ).

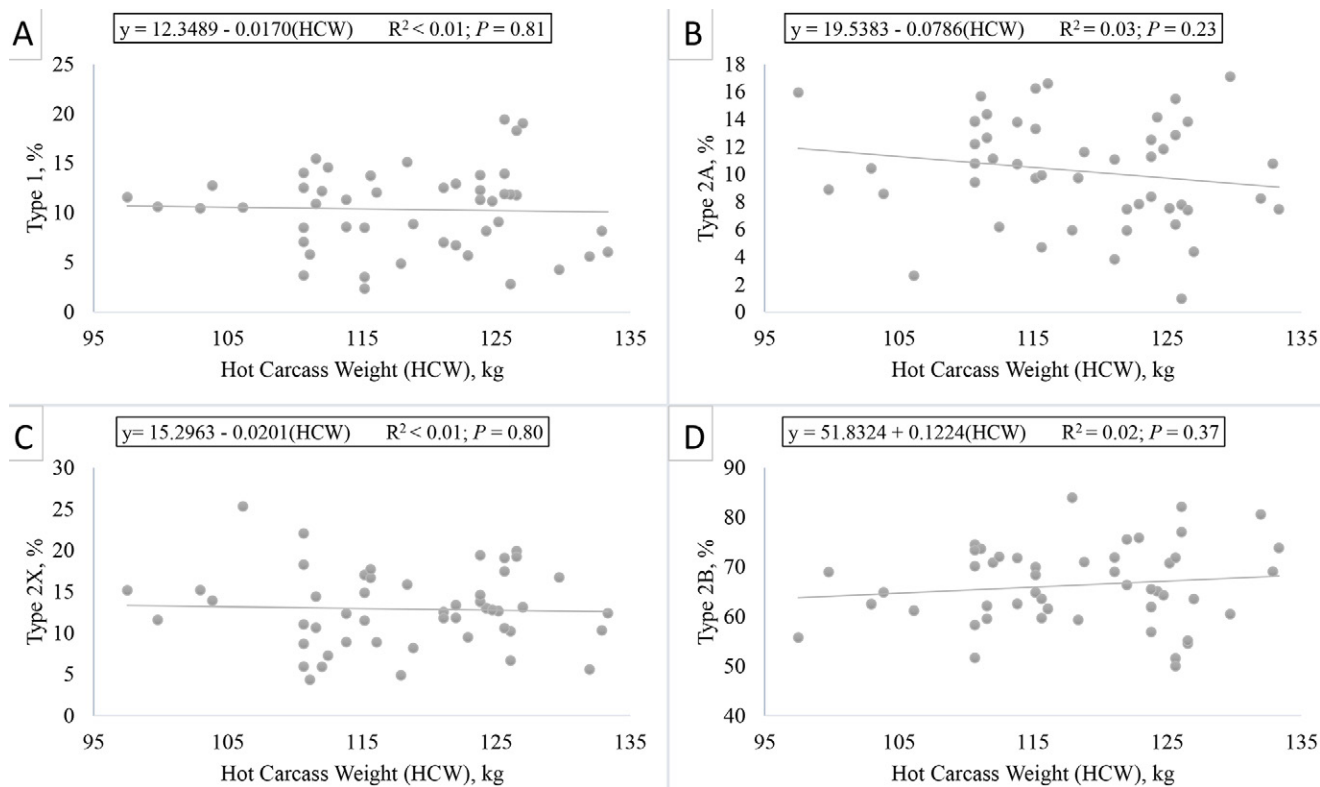
casses. In contrast, Harsh et al. (2017) reported a 1.9 unit decrease in  $L^*$  over the 80-kg range from 53 to 129 kg of hot carcass weight. Still, this is less than a full NPPC visual color score change. Park and Lee (2011) and Virgili et al. (2003) reported no significant difference in redness values ( $a^*$ ) with increasing carcass weight, which is in agreement with findings in the present study. However, it is important to note that Virgili et al. (2003) fabricated carcasses while they were still warm and then chilled the primal cuts at  $-2^{\circ}\text{C}$  for 24 h. In the present study, instrumental yellowness ( $b^*$ ) increased as carcass weight increased, where HCW only accounted for  $<2\%$  of the variation in loin instrumental yellowness values. In agreement, Durkin et al. (2012) reported an increase of 0.1 unit in yellowness values ( $b^*$ ) per 10 kg live weight increase. Though no differences with visual color were detected in the present study, Harsh et al. (2017) reported darker loins, indicated by an increase in visual color score, as carcass weight increased. In contrast, Correa et al. (2006) demonstrated that slaughter weight had no impact on visual color scores (Japanese color standards), although the weight range in this study was

**Table 3.** Population summary statistics of fiber type determination

Variable	No.	Mean	Minimum	Maximum	SD	CV
Hot carcass weight, $\text{kg}^1$	49	119.05	97.51	133.33	8.93	7.50
Fiber type <sup>2</sup>						
MHC1, %	49	10.34	2.36	19.41	4.11	39.72
MHC2A, %	49	10.26	0.96	17.08	3.84	37.49
MHC2X, %	49	12.92	4.35	25.33	4.64	35.88
MHC2B, %	49	66.29	50.00	83.97	7.99	12.05
Fiber area <sup>2</sup>						
Total, $\text{nm}^2$	49	7,298	4,577	11,433	1,572.8	21.6
MHC1, $\text{nm}^2$	49	4,141	2,087	7,614	1,272.1	30.7
MHC2A, $\text{nm}^2$	49	4,559	2,476	8,141	1,331.4	29.2
MHC2X, $\text{nm}^2$	49	8,152	4,674	15,369	2,377.3	29.2
MHC2B, $\text{nm}^2$	49	8,081	5,332	12,164	1,740.6	21.5

<sup>1</sup>Range of carcass weight represented by loins selected for fiber type determination.

<sup>2</sup>MHC1 = myosin heavy chain isoform 1; MHC2A = myosin heavy chain isoform 2a; MHC2X = myosin heavy chain isoform 2x; MHC2B = myosin heavy chain isoform 2b.



**Figure 10.** Effect of carcass weight (HCW) on fiber type determination. The traits evaluated include (A) type 1%, (B) type 2a percentage, (C) type 2x percentage, and (D) type 2b percentage. Data are depicted as the linear regression of the trait using carcass weight as the independent variable. Coefficients of determination included on figures where the slope of linear regression lines were different from zero ( $P < 0.05$ ).

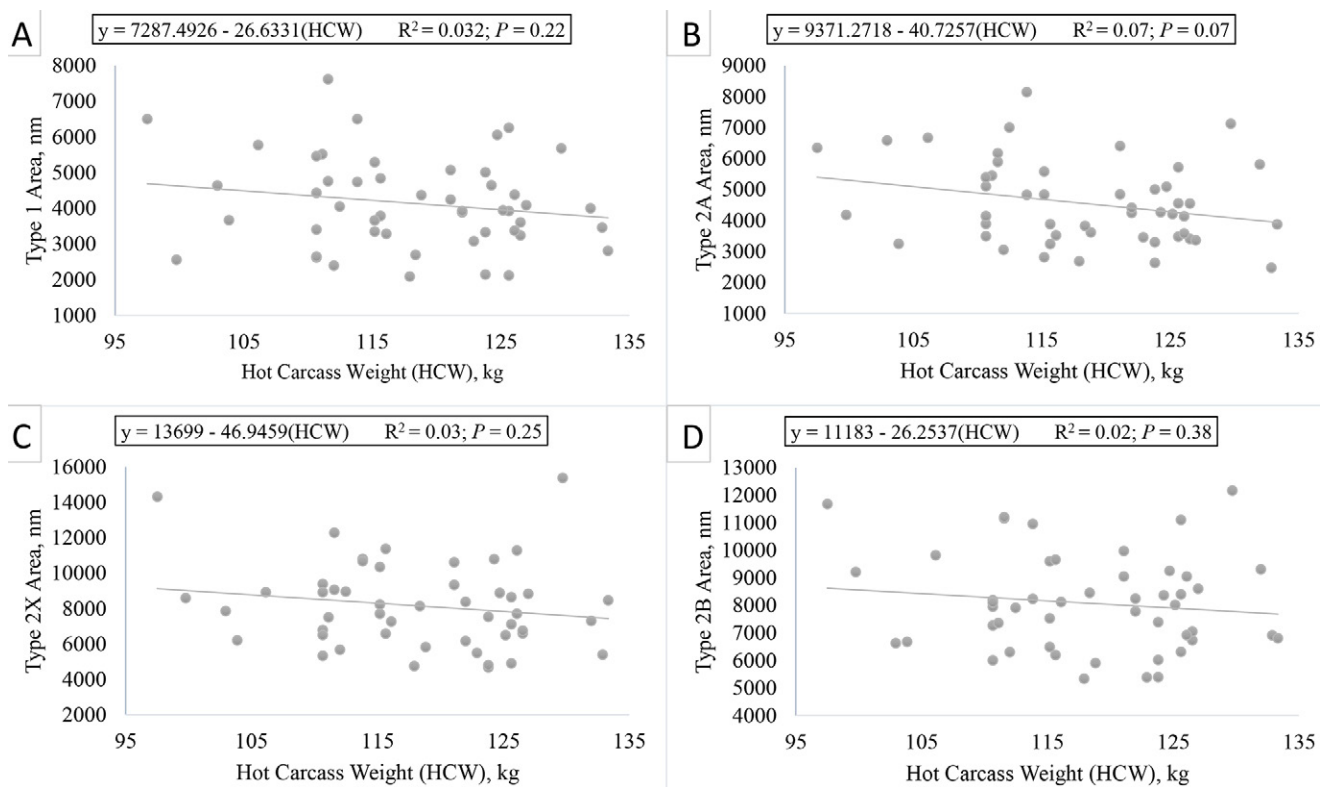
107 to 125 kg for live weight. Overall, with increased carcass weights, there were no detrimental effects on loin pH, instrumental or visual color observed where HCW only explained approximately 1% of this variation in the present study.

In agreement with Harsh et al. (2017), tenderness of loin chops in the current population improved as carcass weight increased. There was a 0.67 kg decrease in SSF for every 10 kg increase in HCW. Wu et al. (2017) reported the effect of HCW on Warner-Bratzler shear force was inconclusive because of directionality differences among studies reviewed. Previously, Shackelford et al. (2012) reported that slower chilled loins were more tender compared with loins that chilled more rapidly. Additionally, Overholt et al. (2019) reported that loins from heavier carcasses chilled slower than loins from lighter carcasses. Therefore, it is interesting to speculate that loins from heavier carcasses in the present study chilled more slowly and this contributed to the improvement in tenderness observed. However, other factors such as sarcomere length, connective tissue content or solubility, or postmortem proteolysis may also contribute to differences in tenderness; those factors were not measured in the present study.

Overall, HCW only accounted for approximately 9% of the variation reported in tenderness values meaning there are several other factors that also contribute to tenderness in pork loins.

Water holding capacity is affected by both pH and chilling method, therefore heavier carcasses present potential issues with reduced chilling rates. However, water-holding capacity of loins and chops appeared to be unaffected and even improved in this study. Both Durkin et al. (2012) and Harsh et al. (2017) observed a reduction in cook loss of LM chops from heavier pigs. Likewise, Wu et al. (2017), who included studies with live weights ranging from 92 to 182 kg, reported that heavier carcasses had LM chops with less drip loss. The average effect was small with only a 0.1% unit reduction in drip loss for every 10-kg increase in slaughter weight. In the present study, a reduction of 0.51% units in cook loss was observed for every 10-kg of increase in carcass weight, where HCW explained 15% of this variation.

In the present study, there were no significant differences noted between either percentages of fiber types or fiber type areas within the LM as carcass weight increased. Total fiber number and fiber type composition of skeletal muscle are important to car-



**Figure 11.** Effect of carcass weight (HCW) on fiber type determination. The traits evaluated include (A) type 1 area, (B) type 2a area, (C) type 2x area, and (D) type 2b area. Data are depicted as the linear regression of the trait using carcass weight as the independent variable. Coefficients of determination included on figures where the slope of linear regression lines were different from zero ( $P < 0.05$ ).

cass characteristics and meat quality in pigs (Rehfeldt et al., 2000). Previous reports have correlated muscle fiber area of different fiber types to pork quality attributes like pH and color (Kim et al., 2018). However, in the present study, the lack of differences in muscle fiber types of the loin supports the lack of loin quality differences. Although there were no differences observed in muscle fiber size of the current study, total fiber number of the LM was not measured. Miller et al. (1975) reported that porcine muscle mass and growth rate are associated more with muscle fiber number than fiber size. Therefore, the increased loin weight at heavier hot carcass weight may be a result of increased muscle fiber number more than muscle hypertrophy.

## Conclusion

Hot carcass weight has been trending upward for several years causing concern in the U.S. pork industry that these increased weights may result in poorer quality pork. The results of the current study suggest those concerns are unfounded as increasing hot carcass weight had no or limited impact on pork quality

traits such as pH, instrumental or visual color, water-holding capacity, or tenderness. Although the current study observed slope estimates that differed from 0 for some traits, the predicted change would not have practical implications for quality traits.

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