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Influence of Beef Carcass Weight on Carcass Chilling, Steak Case Life and Quality Traits

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INFLUENCE OF BEEF CARCASS WEIGHT ON CARCASS CHILLING, STEAK CASE LIFE AND QUALITY TRAITS

By

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This thesis is approved as a creditable and independent investigation by a candidate for the master's degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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ABSTRACT

INFLUENCE OF BEEF CARCASS WEIGHT ON CARCASS CHILLING, STEAK CASE LIFE AND QUALITY TRAITS

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The objective of this thesis was to determine the influence of beef carcass weight on chilling and pH decline of beef carcasses, as well as color, case life and tenderness of steaks from the round, loin, rib and chuck. Twelve carcasses were allotted by hot carcass weight (HCW) into Heavyweight (HW) and Lightweight (LW) groups. Temperature decline, pH decline and thermal image temperature were measured in the round, loin, rib, and chuck for approximately 48 hours. Carcass data including 12th rib fat thickness, ribeye area, and marbling score were collected. The *Semitendinosus* (ST), *Longissimus lumborum* (LL), *Longissimus thoracis* (LT) and the *Serratus ventralis* (SV) were removed, weighed, cut into steaks for assessment of instrumental color, sensory color and Warner-Bratzler Shear Force (WBSF) analysis. HW carcasses had heavier ($P < 0.05$) HCW and muscle weights compared to LW. No HCW × time or HCW main effects ($P > 0.05$) were observed for pH decline. Ribs from HW had increased temperatures ($P < 0.05$) the first 25 h of chilling compared to LW but were similar for remainder of chilling period ($P > 0.05$). Temperature in the round was similar for the first 3 h of chilling ($P > 0.05$), but HW had increased temperatures for remainder of chilling ($P < 0.05$). Steaks from the ST of LW were more tender ($P < 0.05$) than HW at d 5, but were similar at d 10, 14 and 21 ($P > 0.05$). Steaks from the ST of HW were darker ($P < 0.05$) throughout the

display period. On d 1 of retail display, ST steaks from HW carcasses had decreased L* value ($P < 0.05$), whereas the LW increased ($P < 0.05$). Steaks from the ST of HW had lower a* and b* values ($P < 0.05$) than LW. Steaks from the SV of HW had lower subjective color scores ($P < 0.05$) compared to LW. These data suggest the slower temperature decline observed in HW carcasses can result in some negative meat quality traits. However, further research is needed to understand the influence of HCW on chilling time and meat quality outcomes.

CHAPTER I: Review of Literature

Introduction

Over the past 30 years, the beef industry has experienced an increase of 75 kg in average hot carcass weight (USDA-ERS, 2022). Increasing hot carcass weights combined with the continued demand for beef products, means that pounds of product per beef animal slaughtered in packing plants is growing each year. Packing facilities are most efficient from a volume standpoint when cooler and rail space is maximized for carcass density. The larger carcasses processed through the current beef production system are utilizing coolers and chilling systems designed decades prior. These systems were designed for use on carcasses that were over 45 kilograms lighter on average than beef carcasses that are currently harvested. Therefore, if chilling methods have not changed to adapt to increasing carcass weights, larger carcasses may be at risk of improper chilling. Carcass chilling occurs simultaneously with a multitude of biological changes that could affect overall meat quality. This review will discuss factors that could be contributing to the increases in carcass weight, and what influence increased carcass weights could have on meat quality, such as pH decline, meat color and tenderness.

Factors Contributing to Increased Carcass Weight

Increased hot carcass weights have become the new normal within the beef industry for the past several decades. Processing plants desire to become more efficient, reduced discounts given to heavyweight carcasses, along with branded beef programs increasing their carcass weight thresholds have all allowed for this increase to occur

without penalty. Cattle producers have improved genetic selection, nutrition, and implemented growth promotion technologies to increase the efficiency at which they produce beef cattle (Capper, 2011; Maples et al., 2018) contributing to increases in hot carcass weights.

Processing facilities have played a major role in allowing heavier hot carcass weights. Over the years, carcasses receiving heavyweight discounts from packers have decreased (Herrington and Tonsor, 2012). Herrington and Tonsor (2012) reported that between 2003 and 2012, discounts on carcasses weighing between 408 – 431 kg decreased from over $5.00/hundredweight (cwt) to near zero. Branded beef programs such as Certified Angus Beef (CAB, G-1 specification) have increased the weight at which carcasses are eligible to qualify for the program. In 2006, it was reported that CAB was increasing their threshold on carcass weights to include all carcasses up to 454 kg (Marshall, 2006). Recently, CAB has increased that threshold even further by allowing all carcasses under 476 kg to be eligible for CAB premiums (USDA-AMS, 2022). Furthermore, other premium beef branded programs such as, Certified Hereford Beef (G-10 specification) and National Beef Certified Premium Beef (G-20 specification) have increased their carcass weight thresholds to include all carcasses up to 476 kg to adjust for the increasing trend (USDA-AMS, 2022).

For packers, heavier carcasses mean that each trolley or spot on the rail in the chilling cooler is holding more marketable product. Therefore, the amount of marketable product running through a beef processing facility per day is increasing (Herrington and Tonsor, 2012; Bunting, 2015). Over the past 30 years, kg of beef produced in the United States has increased while the number of cattle slaughtered has stayed relatively constant.

Data supplied by the USDA-ERS (2022) showed that in 2019, average monthly federally inspected cattle slaughter was 2.76 million head compared to 2.69 million head slaughtered per month at federally inspected facilities in 1990. However, average monthly federally inspected beef production in 2019 totaled 1013.8 million kg compared to only 837.3 million kg in 1990. Thus, the beef industry within the United States has generated a 17% increase in kg of beef produced with only a 2% increase in number of federally inspected cattle slaughtered over that time period (USDA-ERS, 2022).

Improved management strategies, genetic selection for growth, and nutrition by producers have played a role in making cattle more efficient, and thus larger (Capper, 2011). While it is hard to specifically quantify changes in genetics in the beef industry, there are several factors that indicate weight increases. Ribeye area is one carcass trait that has been shown to be highly correlated with HCW (Powell and Huffman, 1973; Rutherford, 2013; Maples et al., 2018). According to the National Beef Quality Audits (Lorenzen et al., 1993; Boleman et al., 1998; McKenna et al., 2002; Garcia et al., 2008; Gray et al., 2012; Boykin et al., 2017) ribeye areas have steadily increased similarly to HCW over the past decades. Another indicator used to measure genetic improvement in the cattle industry is Estimated Progeny Differences (EPDs), which are the prediction of how future progeny of each animal are expected to perform relative to the progeny of other animals in the database (AMAA, 2022a). Two EPDs used by cattle producers focused on weight include birth weight (BW) and yearling weight (YW). Birth weight is expressed in pounds and is a predictor of a sire's ability to transmit birth weight to his progeny compared to other sires. Yearling weight, also expressed in pounds, is a predictor of a sire's ability to transmit yearling growth to his progeny compared to other

sires (AMAA, 2022a). In 2021, the average BW in the Angus breed was +1.1 compared to 1972 (when EPDs were first recorded in) where the average BW was -3.3. Meanwhile, the average YW for 2021 in the Angus breed was +113, whereas the average in 1972 was -35 (AMAA, 2022b). That translates to a projected increase of 148 pounds or 67 kg in average yearling weight within the Angus breed from 1972 to 2021. Therefore, while BW has stayed low the Angus breed has seen a substantial increase mature weight (AMAA, 2022b).

Advances in nutrition can also be credited with increases in carcass weight. β-adrenergic agonists (BAA) are a common growth promoting feed additive supplemented during the finishing phase. These compounds work by taking dietary nutrients and repartitioning them away from fat deposition and towards lean tissue accretion (Mersmann, 1998; Johnson, 2004; Elam et al., 2009). β-adrenergic agonists bind to the BAA receptors present on the surface of cells leading to a shift in metabolism. Rapid skeletal muscle growth (hypertrophy) is one of the most consistent biological effects observed during the administration of BAA in cattle diets. Muscle hypertrophy can be defined as an increase in the size of existing muscle fibers (Johnson, 2004). Several studies have confirmed that BAA improve live animal performance such as average daily gain, feed efficiency, as well as increase hot carcass weight (Avendaño-Reyes et al., 2006; Bryant et al., 2010; Arp et al., 2014; Johnson et al., 2014).

The beef industry has the means and tools necessary to create heavier cattle through selection of improved genetics and use of growth promoting feed additives. Packers have also shown that they are willing to deal with the heavyweight carcasses by

decreasing discounts and allowing them into branded beef programs. However, the influence of heavier carcasses on beef quality is not well understood.

Factors Affecting Meat Quality

The biological events occurring in the carcass of an animal immediately postmortem play an integral role in the conversion of living muscle into a quality, edible meat product (Matarneh et al., 2017). Postmortem muscle pH decline, loss of muscle contraction, and postmortem proteolysis are biological changes occurring postmortem. A slight change in any of these biological systems can affect meat quality traits, such as tenderness and meat color (Aberle, 2001).

pH decline

Immediately following exsanguination (removal of the blood), normal bodily functions are no longer a viable option to sustain life. The animal is unable to bring oxygen into the body or remove metabolic waste due to loss of the respiratory system. Biological systems within the body must adapt to attempt to maintain homeostasis and continue to produce ATP. This causes the body to switch from oxidative (aerobic) to glycolytic (anaerobic) metabolism (Mayes, 1993; Lawrie, 2006; Huff Lonergan et al., 2010). During glycolytic metabolism, glucose stored in muscle known as glycogen, is converted to ATP and used as an energy source to be sent throughout the body to maintain normal bodily functions. However, glycolytic metabolism is less efficient at producing ATP and ATP quickly diminishes from the body. The most studied explanation for the pH decline phenomena shows that it results from lactic acid buildup within the muscle (Huff Lonergan et al., 2010).

Due to the removal of most of the blood from the animal, the circulatory system is no longer able to efficiently rid the body of the lactic acid. The lactic acid builds up in the muscle of the animal and causes the pH of muscle to decline until it reaches its ultimate pH near 5.6 (Huff Lonergan et al., 2010). The rate and extent of postmortem metabolism significantly influences meat quality. Factors including environmental conditions and pre- and post-slaughter handling can alter metabolism and affect pH decline. These factors can cause an abnormal shift in postmortem metabolism and affect the rate and extent of pH decline in the muscle (Matarneh et al., 2017).

One abnormality is known as Dark, Firm and Dry (DFD) beef, or more commonly referred to in industry as “dark cutting beef”. Dark cutting beef occurs predominantly after chronic exposure to pre-slaughter stress as it depletes stored muscle glycogen and is characterized by its abnormal dark color, firm texture, and dry surface (Wulf et al., 2002; Miller, 2007). Lack of glycogen present in the muscle postmortem reduces production of lactic acid through glycolytic metabolism resulting in a ultimate pH of higher than 5.8 (Miller, 2007; Matarneh et al., 2017). The dark appearance leads to less retail acceptability (Miller, 2007), as well as a higher ultimate pH increases susceptibility to microbial spoilage (Newton and Gill, 1978; Aberle, 2001; Miller, 2007). Wulf et al. (2002) investigated the effect of DFD carcasses on palatability traits of *Longissimus* steaks. They concluded that steaks from DFD carcasses had increased shear force values than those steaks from normal carcasses (Wulf et al., 2002).

Recent research investigating the effect of increased carcass weights on meat quality, have evaluated its effect on pH decline as well. Fevold et al. (2019) reported no differences in pH values at different timepoints between Heavyweight, Middleweight and

Lightweight carcasses in the *Longissimus dorsi* and *Semimembranosus* muscles. Meanwhile, Lancaster et al. (2020) reported a difference in the rate of pH decline in the deep *Semimembranosus,* where overweight carcasses experienced a faster decline in pH values compared to average weight carcasses. Other research has reported similar results where they observed heavy carcasses experienced more rapid pH decline in *Longissimus lumborum* (Agbeniga and Webb, 2018), and the *Longissimus dorsi, Psoas major* and *Semimembranosus* (Djimsa et al., 2018).

The pH value of meat can be measured by directly inserting an electrode into the meat product. However, this can present a multitude of challenges. Many pH electrodes are made of glass, which comes with the risk of breaking inside the carcass. This could be problematic for harvest and processing facilities due to the risk of foreign material in the product (Popp et al., 2018). Direct electrode measurement also can come with the possibility of considerable measurement errors (Bendall and Swatland, 1988). Alternatively, pH can be measured by an indirect method. With this method, samples are collected from the carcass/steak and transferred into an iodoacetate solution. The sample and solution are then homogenized together and the pH electrode may be inserted into the homogenized solution to record a reading (Bendall, 1973). Iodoacetate is used to stop pH decline and fix the pH value of the sample by inhibiting glycolytic intermediates, such as glyceraldehyde-3-phosphate dehydrogenase (Bendall, 1973; Schmidt and Dringen, 2009).

Meat Color

While pH decline can affect the ultimate pH of meat products, the primary selection criteria for meat purchasing decisions is based on visual appearance (Mancini and Hunt,

2005). Even though meat color and quality are not well-correlated (Faustman and Cassens, 1990), meat color drives consumer purchasing decisions more than any other trait due to its association with freshness (Faustman and Cassens, 1990; Mancini and Hunt, 2005). According to Smith et al. (2000), approximately 15% of retail beef products are discounted due to surface discoloration. This corresponds to an annual revenue loss of $1 billion annually (Smith et al., 2000). More recent research by Ramanathan et al. (2022) determined that total annual economic loss within the beef industry caused by discoloration totaled $3.73 billion.

Myoglobin is a sarcoplasmic heme protein that is the primary factor responsible for meat color (Livingston and Brown, 1981). Myoglobin serves a purpose in both the antemortem muscle, as well as meat. In muscle, myoglobin functions as a binder of oxygen and functions to deliver oxygen to the mitochondria, which enables tissues to maintain their physiological functions (Wittenberg and Wittenberg, 2003). In meat, myoglobin serves as the primary pigment and is responsible for up to 80 to 90 percent of total pigmentation in well-exsanguinated animals (Aberle, 2001; Wittenberg and Wittenberg, 2007). Hemoglobin is a protein responsible for the pigment of blood, which could also play a role in meat color. However, with much of an animals blood removed during exsanguination, minimal hemoglobin will remain inside the arteries and veins of muscle tissue, therefore hemoglobin has a minimal role in meat color (Suman and Joseph, 2014).

Myoglobin is a monomeric heme protein with a heme prosthetic group and a globin portion. The globin chain contains eight helical segments forming a coiled structure around the heme. Myoglobin’s ability to bind to oxygen is due to the presence

of the heme in the heme crevice. The globin chain allows the heme group to be water soluble and protects the heme iron from anything that could disrupt its functionality, such as oxidation. The heme group contains double bonds that allows it to absorb visible light and thus serve as a pigment (Mancini and Hunt, 2005). The iron atom of the heme group can exist in one of two states: reduced (ferrous/Fe^{2+}) or oxidized (ferric/Fe^{3+}). This iron atom can accept six electrons into its outer orbit which can form coordinate bonds, with the two most important bonds being the 5^{th} and 6^{th} heme position. The 5^{th} position of the heme bonds with the proximal histidine (position 93 of the globin chain) and connects the heme to the globin chain. Additionally, the distal histidine (position 64 of the globin chain) is in the vicinity of the heme but not bonded. The 6^{th} position of the heme iron is available for binding with oxygen and other molecules, such as carbon monoxide (CO) and nitric oxide (NO) (Mancini and Hunt, 2005; Suman and Joseph, 2014). This 6^{th} position of the heme iron allows for the production of the different pigments of meat color (Mancini and Hunt, 2005).

There are three main pigments associated with the color of fresh meat: Oxymyoglobin, Deoxymyoglobin and Metmyoglobin. Each pigment results in its own color and is dependent on its heme iron state, which can be associated with many factors such as packaging type, exposure time to oxygen, etc. Deoxymyoglobin occurs when there is no ligand present at the 6^{th} position of the heme iron and it exists in the reduced (ferrous; Fe^{2+}) state. As a result, the muscle produces a purplish-red or purplish-pink color (Mancini and Hunt, 2005). Deoxymyoglobin is the primary pigment associated with uncut meat (Aberle, 2001) or meat products stored in a vacuum package (Mancini and

Hunt, 2005). For meat to maintain the deoxygenated state, very low oxygen tension (<1.4 mm Hg) is required (Brooks, 1935).

Oxygenation is the process of converting deoxymyoglobin into oxymyoglobin. Oxymyoglobin forms when oxygen binds to the 6^{th} position of the heme iron but remains in the ferrous state (Fe^{2+}). Once meat is cut and the surface is exposed to air, the formation of oxymyoglobin begins. Oxymyoglobin usually forms within 30 to 45 minutes after exposure to oxygen, in a process known as "bloom" (Aberle, 2001). Upon completion of bloom, oxymyoglobin has developed and is characterized by its distinct bright-cherry red color. While surface oxygenation occurs during bloom, tissue under the surface remains in a deoxygenated state. However, as oxygen exposure increases, oxygen penetrates deeper into the muscle causing oxymyoglobin to form deeper beneath the surface (Mancini and Hunt, 2005).

Metmyoglobin is the result of oxidation of the heme iron of myoglobin from the reduced (ferrous, Fe^{2+}) to the oxidized (ferric, Fe^{3+}) state (Livingston and Brown, 1981; Mancini and Hunt, 2005). During this process, the oxygen is still bound to 6^{th} position of the heme iron. The result of this process is accompanied by the production of a brown color (Suman and Joseph, 2014). Metmyoglobin formation plays the primary role in surface discoloration, which results in reduced consumer appeal of meat products. This is the result of metmyoglobin formation beneath the surface (located beneath the superficial oxymyoglobin and interior deoxymyoglobin) that gradually thickens and moves towards the surface. Metmyoglobin formation can depend on many factors such as temperature, pH, microbial growth, and others (Mancini and Hunt, 2005).

Research has been conducted on the effect of beef carcass weight on temperature decline and its effect on meat color in steaks. Egolf (2021) reported that *Semitendinosus* steaks from heavyweight carcasses with increased temperature in the round had lighter colored steaks compared to steaks from lightweight carcasses that experienced lower temperatures. Similar results from Fevold et al. (2019) showed that steaks from the *Longissimus dorsi* and *Semimembranosus* of lightweight carcasses (experienced lower temperatures during chilling) were less red and less yellow than similar steaks coming from heavyweight carcasses. Other research determined that heavyweight carcasses with elevated temperatures early in the chilling period resulted in lower oxygenated lean scores, and more surface discoloration than average weight carcasses (Lancaster et al., 2020).

Tenderness

While meat color is very important to consumer purchasing decisions, tenderness of beef cuts is one of the most important quality attributes in terms of consumer preference and acceptance (Savell et al., 1987; Casas et al., 2006). Tenderness of steaks is also the driving factor in economic terms for consumers (Boleman et al., 1997). Over many years of conducting the National Beef Quality Audit, retailers and restauranteurs rated tenderness as one of their top-quality concerns (Lorenzen et al., 1993; Boleman et al., 1998; McKenna et al., 2002).

Tenderness can be measured both objectively and subjectively. Objective measurement entails a set scale or standard being used to rank or score multiple samples against each other. Subjective measurement utilizes panelists/people, either trained or

untrained (consumer), to assign scores to samples along a scale designated by the researcher. Warner Bratzler shear force (WBSF) is the most common objective tenderness measurement method and is widely accepted and utilized throughout the industry (AMSA, 2015) as it provides an unbiased result to compare tenderness between samples. For WBSF, steaks are cooked to a consistent temperature before allowing each steak to cool. A minimum of six uniform 1.27-cm cores are then removed from each steak to obtain a shear force measurement. The cores should be removed from each steak at a point parallel to the muscle fiber direction and sheared perpendicular to the orientation of the fibers. Cores are sheared using a V-shaped blade to determine the kilograms of force (kgf) required to shear through each sample (AMSA, 2015).

The ability to translate WBSF values into data that the average consumer can interpret has been an area of focus for the industry. Therefore, several studies have been conducted to determine tenderness thresholds. Belew et al. (2003) and Shackelford et al. (1991) developed tenderness categories based on WBSF values. The tenderness categories included “Very tender” (WBSF < 3.2 kg), “Tender” (3.2 kg < WBSF < 3.9 kg), “Intermediate” (3.9 kg < WBSF < 4.6 kg), and “Tough” (4.6 kg < WBSF). These standards were used to classify the percentage of cuts into each category (Shackelford et al., 1991; Belew et al., 2003) For a muscle to be labeled as tender, it must have a WBSF value of 3.9 kg or less. The standards established by this research have been used to categorize tenderness of steaks and other researchers (Voges et al. (2007), Martinez et al. (2017), and Guelker et al. (2013)) have utilized these standards to determine the percentage of steaks classified into each tenderness category for US retail and foodservice institutions for the national beef tenderness survey.

Understanding the make-up and structure of muscle cells is very important to fully grasp the tenderization process. Muscle cells are highly organized, multi-nucleated cells (Huff Lonergan et al., 2010). When evaluated under a microscope, they appear as striated (Hopkins, 2006; Huff Lonergan et al., 2010) due to the presence of highly specialized organelles known as myofibrils. Myofibrils are composed of structures known as sarcomeres (Huff Lonergan et al., 2010). Sarcomeres are the basic or "functional" unit of the cell (Fraterman et al., 2007; Huff Lonergan et al., 2010) and contain the structural components needed to perform muscle contraction (Huff Lonergan et al., 2010).

Each individual sarcomere is located between two Z – lines / disks (Hopkins, 2006; Huff Lonergan et al., 2010). Within the sarcomere is the thick filament, mostly made up of the protein myosin, and the thin filament, predominately made up of the protein actin. Actin and myosin are primarily responsible for muscle contraction within the sarcomere (Aberle, 2001; Hopkins, 2006; Huff Lonergan et al., 2010). Myosin consists of a "rod" region making up the backbone of the thick filament with globular heads that extend from it. The thin filament contains myosin binding sites that interact with the globular heads of myosin during muscle contraction. The I – band consists of the thin filaments. The A – band consists of the thick filaments; however, it can contain portions of the thin filaments depending on the state of contraction (Aberle, 2001; Huff Lonergan et al., 2010).

After harvest, meat can be allowed to age (a period where the carcass or cut is stored at a refrigerated temperature of approximately 4° C). The primary goal of meat aging is to improve the tenderness of the product. Postmortem storage of muscle has been

shown to increase tenderness, through both objective and subjective measurement (Koohmaraie et al., 1991). Increased tenderness during postmortem storage has been credited to proteolysis caused by the calpain enzyme system (Goll et al., 1983; Mohrhauser et al., 2014).

Proteolysis is the degradation of proteins into smaller peptides or amino acids. The calpain/calpastatin system is thought to be a main contributor to postmortem proteolysis in meat (Goll et al., 2003). Calpain is an endogenous enzyme responsible for the breakdown of myofibrillar proteins, such as troponin-t and desmin, in the antemortem and postmortem systems (Koohmaraie et al., 1991; Koohmaraie, 1996). This process results in the initial breakdown of the sarcomere, or the functional unit of the muscle. However, calpain is regulated by calpastatin. Calpastatin blocks calpain and restricts its activity within the postmortem system (Koohmaraie, 1996; Huff Lonergan et al., 2010). Increased levels of calpastatin within the muscle tissue can result in decreased tenderness throughout the aging process (Geesink and Koohmaraie, 1999).

Temperature variation during the chilling process of meat can have major impacts on meat quality characteristics, especially tenderness. Both heat and cold extremes can influence the end product and consumer acceptability. The temperature at which the muscle of carcasses reach rigor mortis can greatly affect multiple meat quality characteristics (Devine et al., 2002). Heat-shortening, cold-shortening, and thaw rigor are all examples of temperature changes associated with tenderness issues.

Heat shortening, also referred to as heat-toughened or high rigor temperature meat, is caused when muscle enters rigor mortis above 20° C (Locker and Hagyard, 1963; Devine et al., 1999). The increased temperatures up to 50° C leads to a rapid

depletion of ATP, which creates severe shortening and an early onset of rigor (Aberle, 2001). On the other end of the spectrum, cold shortening is a process that occurs when muscle has not reached rigor mortis and is chilled below 15° C. Chilling below 15° C prior to the completion of rigor allows for calcium ions to continue to leak out of the sarcoplasmic reticulum and allow the muscle to contract. This continued contraction prevents the aging process from functioning properly and keeps the sarcomere shortened, inducing toughness (Aberle, 2001; Savell et al., 2005). Thaw rigor is a more severe version of cold shortening. Thaw rigor occurs when muscle is frozen before the completion of rigor (Aberle, 2001). When the muscle is frozen, glycogen is still present and available to be used in the muscle. During freezing, ice crystals puncture into the sarcoplasmic reticulum creating holes. Once the muscle is thawed calcium is able to flow out of these holes and into the muscle inducing severe contraction. This causes the muscle to shorten very quickly and results in increased toughness (Marsh and Leet, 1966; Aberle, 2001; Savell et al., 2005)

Recent research has been conducted on the effect of carcass weight on temperature decline in beef carcasses and its effect on tenderness. Other research has observed that heavyweight carcasses with increased temperatures throughout the chilling period resulted in lower shear force values in the *Longissimus lumborum* (Egolf, 2021) and the *Semimembranosus, Psoas major and Longissimus dorsi* compared to lighter weight carcasses that experienced lower temperatures (Djimsa et al., 2018). In contrast, Lancaster et al. (2020) and Fevold et al. (2019) both observed that heavier carcass weights with increased temperatures, resulted in no differences in shear force values compared to lighter weight carcasses.

Summary

There are many factors that can be credited with the increase in carcass weight observed within the beef industry in the United States. Packers and processors have reduced the discounts for heavyweight carcasses to allow heavier carcasses to qualify for branded beef programs. Furthermore, allowing heavier carcasses helps the packing plants desire to be more efficient by maximizing cooler and rail space to maximize daily production. Additionally, improvements in genetics through EPDs and nutrition through the use of feed additives have also played a crucial role in increased weights throughout the beef industry.

Immediately after slaughter, many biological systems throughout the body are experiencing changes. The carcass attempts to maintain homeostasis; however, it is forced to switch away from using oxygen to relying on glycolytic metabolism. Glycolytic metabolism increases the production of lactic acid that causes the pH of muscle to drop, which can affect meat color. At the same time, postmortem proteolysis through the endogenous enzyme calpain, is breaking down proteins within the sarcomere to cause tenderization. All of these biological changes occur during the early postmortem period and play an integral role in the development of meat quality. Research has shown that changes in temperature can have negative impacts on each of these biological systems. However, research investigating the effect of beef hot carcass weight on temperature decline and its effect on meat quality traits is limited. Therefore, the objective of this thesis is to determine the influence of beef carcass weight on carcass chilling, pH decline, color, case life and tenderness of steaks from the round, loin, rib and chuck.

LITERATURE CITED

Aberle, E. D. 2001. Principles of meat science. 4th ed. ed. Kendall/Hunt, Dubuque, Iowa.

Agbeniga, B., and E. C. Webb. 2018. Influence of carcass weight on meat quality of commercial feedlot steers with similar feedlot, slaughter and post-mortem management. Food Res. Int. 105:793-800. (Article) doi: 10.1016/j.foodres.2017.10.073

AMAA. 2022a. American Angus Association. EPD and $Value Definitions. (Accessed May, 5, 2022.

AMAA. 2022b. American Angus Association. Genetic Trend EPD/$Value by Birth Year. (Accessed May 5, 2022.

AMSA. 2015. Research guidelines for cookery, sensory evaluation, and instrumental tenderness measurements of meat. . American Meat Science Association, Champaign, Illinois USA

Arp, T. S., S. T. Howard, D. R. Woerner, J. A. Scanga, D. R. McKenna, W. H. Kolath, P. L. Chapman, J. D. Tatum, and K. E. Belk. 2014. Effects of dietary ractopamine hydrochloride and zilpaterol hydrochloride supplementation on performance, carcass traits, and carcass cutability in beef steers. J Anim Sci 92(2):836-843. doi: 10.2527/jas.2013-7122

Avendaño-Reyes, L., V. Torres-Rodríguez, F. J. Meraz-Murillo, C. Pérez-Linares, F. Figueroa-Saavedra, and P. H. Robinson. 2006. Effects of two beta-adrenergic agonists on finishing performance, carcass characteristics, and meat quality of feedlot steers. J Anim Sci 84(12):3259-3265. doi: 10.2527/jas.2006-173

Belew, J. B., J. C. Brooks, D. R. McKenna, and J. W. Savell. 2003. Warner–Bratzler shear evaluations of 40 bovine muscles. Meat Sci. 64(4):507-512. doi: https://doi.org/10.1016/S0309-1740(02)00242-5

Bendall, J. R. 1973. 5 - Postmortem changes in muscle. In: G. H. Bourne, editor, The Structure and Function of Muscle (Second Edition). Academic Press. p. 243-309.

Bendall, J. R., and H. J. Swatland. 1988. A Review of the Relationships of pH with Physical Aspects of Pork Quality. Meat Sci. 24(2):85-126. (Review) doi: 10.1016/0309-1740(88)90052-6

Boleman, S. J., S. L. Boleman, R. K. Miller, J. F. Taylor, H. R. Cross, T. L. Wheeler, M. Koohmaraie, S. D. Shackelford, M. F. Miller, R. L. West, D. D. Johnson, and J. W. Savell. 1997. Consumer evaluation of beef of known categories of tenderness. J. Anim. Sci. 75(6):1521-1524. doi: 10.2527/1997.7561521x

Boleman, S. L., S. J. Boleman, W. W. Morgan, D. S. Hale, D. B. Griffin, J. W. Savell, R. P. Ames, M. T. Smith, J. D. Tatum, T. G. Field, G. C. Smith, B. A. Gardner, J. B. Morgan, S. L. Northcutt, H. G. Dolezal, D. R. Gill, and F. K. Ray. 1998. National Beef Quality Audit 1995: Survey of producer-related defects and carcass quality and quantity attributes. J. Anim. Sci. 76(1):96-103. (Article)

Boykin, C. A., L. C. Eastwood, M. K. Harris, D. S. Hale, C. R. Kerth, D. B. Griffin, A. N. Arnold, J. D. Hasty, K. E. Belk, D. R. Woerner, R. J. Delmore, J. N. Martin, D. L. VanOverbeke, G. G. Mafi, M. M. Pfeiffer, T. E. Lawrence, T. J. McEvers, T. B. Schmidt, R. J. Maddock, D. D. Johnson, C. C. Carr, J. M. Scheffler, T. D. Pringle, A. M. Stelzleni, J. Gottlieb, and J. W. Savell. 2017. National Beef Quality Audit-2016: In-plant survey of carcass characteristics related to quality, quantity, and

value of fed steers and heifers. J. Anim. Sci. 95(7):2993-3002. (Article) doi: 10.2527/jas.2017.1543

Brooks, J. 1935. The oxidation of haemoglobin to methaemoglobin by oxygen-II—The relation between the rate of oxidation and the partial pressure of oxygen. Proceedings of the Royal Society of London. Series B-Biological Sciences 118(811):560-577.

Bryant, T. C., T. E. Engle, M. L. Galyean, J. J. Wagner, J. D. Tatum, R. V. Anthony, and S. B. Laudert. 2010. Effects of ractopamine and trenbolone acetate implants with or without estradiol on growth performance, carcass characteristics, adipogenic enzyme activity, and blood metabolites in feedlot steers and heifers. J. Anim. Sci. 88(12):4102-4119. (Article) doi: 10.2527/jas.2010-2901

Bunting, S. 2015. Heavier carcasses are the trend; is it sustainable? Progressive Cattlemen, Jerome, ID doi: https://www.progressivecattle.com/topics/management/heavier-carcasses-are-the-trend-is-it-sustainable

Capper, J. L. 2011. The environmental impact of beef production in the United States: 1977 compared with 2007. J. Anim. Sci. 89(12):4249-4261. doi: 10.2527/jas.2010-3784

Casas, E., S. N. White, T. L. Wheeler, S. D. Shackelford, M. Koohmaraie, D. G. Riley, C. C. Chase, D. D. Johnson, and T. P. L. Smith. 2006. Effects of calpastatin and mu-calpain markers in beef cattle on tenderness traits. J. Anim. Sci. 84(3):520-525. (Article)

Devine, C. E., S. R. Payne, and R. W. Wells. 2002. Effect of muscle restraint on sheep meat tenderness with rigor mortis at 18 degrees C. Meat Sci. 60(2):155-159. (Article) doi: 10.1016/s0309-1740(01)00117-6

Devine, C. E., N. M. Wahlgren, and E. Tornberg. 1999. Effect of rigor temperature on muscle shortening and tenderisation of restrained and unrestrained beef m-longissimus thoracicus et lumborum. Meat Sci. 51(1):61-72. (Article) doi: 10.1016/s0309-1740(98)00098-9

Djimsa, B., D. Woerner, M. Nair, J. Martin, R. Delmore, and K. Belk. 2018. Effects of electrical stimulation, chilling rate, and carcass size on rates of temperature decline and pH decline, and beef quality. Meat and Muscle Biology 2:87-87. doi: 10.22175/rmc2018.077

Egolf, S. R. 2021. The influence of carcass weight on beef primal temperature, tenderness, and palatability, South Dakota State University.

Elam, N. A., J. T. Vasconcelos, G. Hilton, D. L. VanOverbeke, T. E. Lawrence, T. H. Montgomery, W. T. Nichols, M. N. Streeter, J. P. Hutcheson, D. A. Yates, and M. L. Galyean. 2009. Effect of zilpaterol hydrochloride duration of feeding on performance and carcass characteristics of feedlot cattle. J. Anim. Sci. 87(6):2133-2141. (Article) doi: 10.2527/jas.2008-1563

Faustman, C., and R. G. Cassens. 1990. The Biochemical Basis for Discoloration in Fresh Meat: A Review. J. Muscle Foods 1(3):217-243. doi: https://doi.org/10.1111/j.1745-4573.1990.tb00366.x

Fevold, M., L. Grube, W. L. Keller, K. R. Maddock-Carlin, and R. J. Maddock. 2019. Tenderness and juiciness of beef steaks from varying hot carcass weights. Meat and Muscle Biology

Fraterman, S., U. Zeiger, T. S. Khurana, M. Wilm, and N. A. Rubinstein. 2007. Quantitative proteomics profiling of sarcomere associated proteins in limb and

extraocular muscle allotypes. Mol Cell Proteomics 6(4):728-737. doi: 10.1074/mcp.M600345-MCP200

Garcia, L. G., K. L. Nicholson, T. W. Hoffman, T. E. Lawrence, D. S. Hale, D. B. Griffin, J. W. Savell, D. L. VanOverbeke, J. B. Morgan, K. E. Belk, T. G. Field, J. A. Scanga, J. D. Tatum, and G. C. Smith. 2008. National Beef Quality Audit-2005: Survey of targeted cattle and carcass characteristics related to quality, quantity, and value of fed steers and heifers. J. Anim. Sci. 86(12):3533-3543. (Article) doi: 10.2527/jas.2007-0782

Geesink, G. H., and M. Koohmaraie. 1999. Effect of calpastatin on degradation of myofibrillar proteins by mu-calpain under postmortem conditions. J Anim Sci 77(10):2685-2692. doi: 10.2527/1999.77102685x

Goll, D. E., Y. Otsuka, P. A. Nagainis, J. D. Shannon, S. K. Sathe, and M. Muguruma. 1983. Role of Muscle Proteinases in Maintenance of Muscle Integrity and Mass. J. Food Biochem. 7(3):137-177. (Article) doi: 10.1111/j.1745-4514.1983.tb00795.x

Goll, D. E., V. F. Thompson, H. Li, W. Wei, and J. Cong. 2003. The calpain system. Physiol Rev 83(3):731-801. doi: 10.1152/physrev.00029.2002

Gray, G. D., M. C. Moore, D. S. Hale, C. R. Kerth, D. B. Griffi, J. W. Savell, C. R. Raines, T. E. Lawrence, K. E. Belk, D. R. Woerner, J. D. Tatum, D. L. VanOverbeke, G. G. Mafi, R. J. Delmore, S. D. Shackelford, D. A. King, T. L. Wheeler, L. R. Meadows, and M. E. O'Connor. 2012. National Beef Quality Audit-2011: Survey of instrument grading assessments of beef carcass characteristics. J. Anim. Sci. 90(13):5152-5158. (Article) doi: 10.2527/jas.2012-5551

Guelker, M. R., A. N. Haneklaus, J. C. Brooks, C. C. Carr, R. J. Delmore, Jr., D. B. Griffin, D. S. Hale, K. B. Harris, G. G. Mafi, D. D. Johnson, C. L. Lorenzen, R. J. Maddock, J. N. Martin, R. K. Miller, C. R. Raines, D. L. VanOverbeke, L. L. Vedral, B. E. Wasser, and J. W. Savell. 2013. National Beef Tenderness Survey–2010: Warner-Bratzler shear force values and sensory panel ratings for beef steaks from United States retail and food service establishments1. J. Anim. Sci. 91(2):1005-1014. doi: 10.2527/jas.2012-5785

Herrington, M. A., and G. T. Tonsor. 2012. Beef premiums and discounts: An update of 5-area cattle and beef quality premiums and discounts. Kansas State University: Department of Agricultural Economics doi: https://www.agmanager.info/sites/default/files/PremiumsAndDiscounts.pdf

Hopkins, P. M. 2006. Skeletal muscle physiology. Continuing Education in Anaesthesia Critical Care & Pain 6(1):1-6. doi: 10.1093/bjaceaccp/mki062

Huff Lonergan, E., W. Zhang, and S. M. Lonergan. 2010. Biochemistry of postmortem muscle — Lessons on mechanisms of meat tenderization. Meat Sci. 86(1):184-195. doi: https://doi.org/10.1016/j.meatsci.2010.05.004

Johnson, B. J. 2004. B-adrenergic agonists: Efficacy and potential mode of action in cattle. 2004 Plains Nutrition Council Proceedings doi: https://theplainsnutritioncouncil.com/web/wp-content/uploads/2019/10/2004-Plains-Nutrition-Council-proceedings.pdf

Johnson, B. J., S. B. Smith, and K. Y. Chung. 2014. Historical Overview of the Effect of β-Adrenergic Agonists on Beef Cattle Production. Asian-Australas J Anim Sci 27(5):757-766. doi: 10.5713/ajas.2012.12524

Koohmaraie, M. 1996. Biochemical factors regulating the toughening and tenderization processes of meat. Meat Sci 43s1:193-201. doi: 10.1016/0309-1740(96)00065-4

Koohmaraie, M., G. Whipple, D. H. Kretchmar, J. D. Crouse, and H. J. Mersmann. 1991. Postmortem Proteolysis in Longissimus Muscle from Beef, Lamb and Pork Carcasses. J. Anim. Sci. 69(2):617-624. (Article)

Lancaster, J. M., B. J. Buseman, T. M. Weber, J. A. Nasados, R. P. Richard, G. K. Murdoch, W. J. Price, M. J. Colle, and P. D. Bass. 2020. Impact of beef carcass size on chilling rate, pH decline, display color, and tenderness of top round subprimals. Transl. Anim. Sci. 4(4):12. (Article) doi: 10.1093/tas/txaa199

Lawrie, R. A. 2006. Chapter 5 - The conversion of muscle to meat. In: R. A. Lawrie, editor, Lawrie's Meat Science (Seventh Edition). Woodhead Publishing. p. 128-156.

Livingston, D., and W. Brown. 1981. The chemistry of myoglobin and its reactions. Food Technology (RESEARCH)

Locker, R. H., and C. J. Hagyard. 1963. A cold shortening effect in beef muscles. Journal of the Science of Food and Agriculture 14(11):787-793. doi: https://doi.org/10.1002/jsfa.2740141103

Lorenzen, C. L., D. S. Hale, D. B. Griffin, J. W. Savell, K. E. Belk, T. L. Frederick, M. F. Miller, T. H. Montgomery, and G. C. Smith. 1993. National Beef Quality Audit - Survey of Producer-Related Defects and Carcass Quality and Quality Attributes. J. Anim. Sci. 71(6):1495-1502. (Article) doi: 10.2527/1993.7161495x

Mancini, R. A., and M. C. Hunt. 2005. Current research in meat color. Meat Sci. 71(1):100-121. (Article; Proceedings Paper) doi: 10.1016/j.meatsci.2005.03.003

Maples, J. G., J. L. Lusk, and D. S. Peel. 2018. Unintended consequences of the quest for increased efficiency in beef cattle: When bigger isn't better. Food Policy 74:65-73. doi: https://doi.org/10.1016/j.foodpol.2017.11.005

Marsh, B. B., and N. G. Leet. 1966. Studies in Meat Tenderness. III. The Effects of Cold Shortening on Tenderness. J. Food Sci. 31(3):450-459. doi: https://doi.org/10.1111/j.1365-2621.1966.tb00520.x

Marshall, T. 2006. CAB changes some carcass specifications. Beef Magazine doi: https://www.beefmagazine.com/Carcass_Specifications

Martinez, H., A. Arnold, J. Brooks, C. C. Carr, K. Gehring, D. Griffin, D. Hale, G. Mafi, D. Johnson, C. Lorenzen, R. Maddock, R. Miller, D. VanOverbeke, B. Wasser, and J. Savell. 2017. National Beef Tenderness Survey–2015: Palatability and Shear Force Assessments of Retail and Foodservice Beef. Meat and Muscle Biology 1:138. doi: 10.22175/mmb2017.05.0028

Matarneh, S. K., E. M. England, T. L. Scheffler, and D. E. Gerrard. 2017. Chapter 5 - The Conversion of Muscle to Meat. In: F. Toldra´, editor, Lawrie´s Meat Science (Eighth Edition). Woodhead Publishing. p. 159-185.

Mayes, P. A. 1993. Metabolsim of glycogen, Harper's biochemistry Appleton and Lange Pblishing Division of Prentice Hall, New Jersey. p. 50-400.

McKenna, D. R., D. L. Roeber, P. K. Bates, T. B. Schmidt, D. S. Hale, D. B. Griffin, J. W. Savell, J. C. Brooks, J. B. Morgan, T. H. Montgomery, K. E. Belk, and G. C. Smith. 2002. National Beef Quality Audit-2000: Survey of targeted cattle and carcass characteristics related to quality, quantity, and value of fed steers and heifers. J. Anim. Sci. 80(5):1212-1222. (Article)

Mersmann, H. J. 1998. Overview of the effects of beta-adrenergic receptor agonists on animal growth including mechanisms of action. J Anim Sci 76(1):160-172. doi: 10.2527/1998.761160x

Miller, M. F. 2007. Dark firm and dry beef. Beef Facts. Product Enhancement. doi: https://fyi.extension.wisc.edu/wbic/files/2011/04/Dark-Firm-and-Dry-Beef.pdf

Mohrhauser, D. A., S. M. Lonergan, E. Huff-Lonergan, K. R. Underwood, and A. D. Weaver. 2014. Calpain-1 activity in bovine muscle is primarily influenced by temperature, not pH decline. J. Anim. Sci. 92(3):1261-1270. (Article) doi: 10.2527/jas.2013-7270

Newton, K. G., and C. O. Gill. 1978. Storage quality of dark, firm, dry meat. Appl Environ Microbiol 36(2):375-376. doi: 10.1128/aem.36.2.375-376.1978

Popp, J., A. R. Sharifi, S. Janisch, and C. Krischek. 2018. Two Frequently Used pH Determination Methods Showed Clearly Different pH Slopes During Early Post Mortem Ageing of Pork. Food Anal. Meth. 11(6):1773-1779. (Article) doi: 10.1007/s12161-018-1163-8

Powell, W. E., and D. L. Huffman. 1973. Predicting Chemical Composition of Beef Carcasses from Easily Obtainable Carcass Variables. J. Anim. Sci. 36(6):1069-1076. doi: 10.2527/jas1973.3661069x

Rutherford, B. 2013. Bigger cattle; smaller steaks. Beef Magazine doi: https://www.beefmagazine.com/retail/bigger-cattle-smaller-steaks

Savell, J. W., R. E. Branson, H. R. Cross, D. M. Stiffler, J. W. Wise, D. B. Griffin, and G. C. Smith. 1987. National Consumer Retail Beef Study: Palatability Evaluations of Beef Loin Steaks that Differed in Marbling. J. Food Sci. 52:517-519.

Savell, J. W., S. L. Mueller, and B. E. Baird. 2005. The chilling of carcasses. Meat Sci. 70(3):449-459. (Article; Proceedings Paper) doi: 10.1016/j.meatsci.2004.06.027

Schmidt, M. M., and R. Dringen. 2009. Iodoacetate and iodoacetamide strongly compromise the glutathione metabolism of astrocytes. J. Neurochem. 110:78-78. (Meeting Abstract)

Shackelford, S. D., J. B. Morgan, H. R. Cross, and J. W. Savell. 1991. Identification of Threshold Levels for Warner-Bratzler Shear Force in Beef Top Loin Steaks. J. Muscle Foods 2(4):289-296. doi: https://doi.org/10.1111/j.1745-4573.1991.tb00461.x

Smith, G., K. Belk, J. Sofos, J. Tatum, and S. Williams. 2000. Economic implications of improved color stability in beef. Antioxidants in muscle foods: Nutritional strategies to improve quality:397-426.

Suman, S. P., and P. Joseph. 2014. Chemical and Physical Characteristics of Meat | Color and Pigment

USDA-AMS. 2022. Certified Beef Programs. Grades and Standards doi: https://www.ams.usda.gov/grades-standards/certified-beef-programs

USDA-ERS. 2022. Historical livestock and poultry live and dressed weights. Livestock Meat Domestic Data. doi: https://www.ers.usda.gov/data-products/

Voges, K. L., C. L. Mason, J. C. Brooks, R. J. Delmore, D. B. Griffin, D. S. Hale, W. R. Henning, D. D. Johnson, C. L. Lorenzen, R. J. Maddock, R. K. Miller, J. B. Morgan, B. E. Baird, B. L. Gwartney, and J. W. Savell. 2007. National beef tenderness survey – 2006: Assessment of Warner–Bratzler shear and sensory panel ratings for

beef from US retail and foodservice establishments. Meat Sci. 77(3):357-364. doi: https://doi.org/10.1016/j.meatsci.2007.03.024

Wittenberg, J. B., and B. A. Wittenberg. 2003. Myoglobin function reassessed. J. Exp. Biol. 206(12):2011-2020. doi: 10.1242/jeb.00243

Wittenberg, J. B., and B. A. Wittenberg. 2007. Myoglobin-enhanced oxygen delivery to isolated cardiac mitochondria. J. Exp. Biol. 210(Pt 12):2082-2090. doi: 10.1242/jeb.003947

Wulf, D. M., R. S. Emnett, J. M. Leheska, and S. J. Moeller. 2002. Relationships among glycolytic potential, dark cutting (dark, firm, and dry) beef, and cooked beef palatability. J. Anim. Sci. 80(7):1895-1903. (Article)

CHAPTER II: Influence of beef carcass weight on carcass chilling, steak case life and quality traits

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ABSTRACT

The objective of this study was to determine the influence of beef carcass weight on chilling and pH decline, color, case life and tenderness of steaks from the round, loin, rib and chuck. Twelve carcasses were allotted by hot carcass weight (HCW) into Heavyweight (HW; HCW = 450 $\pm$ 19 kg) and Lightweight (LW; HCW = 349 $\pm$ 34 kg) groups. Data logging thermometers were placed in the left side of carcasses in the round, loin, rib and chuck to track temperature decline. Thermal images were captured of the round, loin, rib and chuck to determine surface temperature at five timepoints over the first 24 h. pH decline was measured in the *Semitendinosus* (ST), *Longissimus lumborum* (LL), *Longissimus thoracis* (LT) and the *Serratus ventralis* (SV) at eight timepoints over the first 48 h. 12th rib fat thickness, ribeye area and marbling score were collected. The ST, LL, LT and SV were removed around 48 h postmortem, weighed and cut into steaks. One steak from each muscle was used for a 10 d retail display and evaluated for instrumental and sensory color and discoloration each day. Steaks were aged 5, 10, 14 or 21 d for Warner-Bratzler Shear Force (WBSF) analysis. HW carcasses had heavier ($P <$

0.05) HCW and muscle weights compared to LW. No HCW × time or HCW effects (P > 0.05) were observed for pH decline. No HCW × time interaction or HCW effects (P > 0.05) was observed for deep temperature decline in the chuck and loin. A HCW × time interaction was noted for deep temperature decline (P < 0.05) in the rib and round. Ribs from HW had increased temperatures (P < 0.05) the first 25 h of chilling compared to LW but were similar for remainder of chilling period (P > 0.05). Temperature in the round was similar for the first 3 h of chilling (P > 0.05), but HW had increased temperatures for the rest of chilling (P < 0.05). A HCW × time interaction was detected for WBSF (P < 0.05) and L* values (P < 0.05) in the ST. Steaks from the ST of LW were more tender (P < 0.05) than HW at d 5, but were similar at d 10, 14 and 21 (P > 0.05). Steaks from ST HW were darker (P < 0.05) throughout the display period. On d 1 of retail display, ST steaks from HW had decreased L* value (P < 0.05), whereas the LW increased (P < 0.05) compared to d 0. Steaks from the ST of HW had lower a* and b* values (P < 0.05) than LW. Steaks from the SV of HW had darker subjective color scores (P < 0.05) compared to LW. These data suggest the slower temperature decline observed in HW carcasses can result in differences in meat quality. However, further research is needed to better understand the influence of HCW on chilling time and meat quality.

INTRODUCTION

Over the past 30 years, the average beef carcass weight has increased over 75 kilograms (Figure 2.1, (USDA-ERS, 2022)). However, these increases in hot carcass weight have come with minimal changes to cooling systems and protocols involved with chilling beef carcasses. Many packers are still utilizing chilling systems that were

designed decades ago. These systems were designed for use on carcasses that were a much lighter weight, on average, than the beef carcasses that have been harvested in industry recently (Savell, 2012). Therefore, it stands to reason that if chilling methods have not changed to adapt to increasing carcass weights, heavy weight carcasses are at risk of ineffective chilling.

Previous research has shown that temperature changes in carcasses can affect meat quality traits such as pH decline, steak tenderness, and beef color. Mohrhauser et al. (2014) reported that beef carcass sides subjected to delayed chilling had a more rapid pH decline compared to sides subjected to normal chilling. Another study evaluated the effect of delayed chilling of young steer carcasses at several different timepoints on tenderness of steaks, reporting that carcasses subjected to a delayed chill of 20 hr had more tender steaks than those subjected to normal chilling (Fields et al., 1976). Kim et al. (2012) investigated heat toughening of strip loins and concluded that increased antemortem temperatures decreased postmortem resulting in tougher loin steaks. However, research investigating the direct influence of carcass weight on postmortem chilling and its effect on meat quality traits is limited. Egolf (2021) observed that heavyweight carcasses do not chill as quickly as lightweight carcasses in a large commercial plant, which resulted in increased tenderness in *Longissimus lumborum* (LL) steaks from Heavyweight carcasses when compared to similar steaks from Lightweight carcasses. The same study also concluded that *Serratus ventralis* (SV) and *Semitendinosus* (ST) steaks from Heavyweight carcasses had increased L* (lighter) and b* (more yellow) values when compared to SV and ST steaks from Lightweight carcasses. The same study also reported SV, LL and ST steaks from Heavyweight

carcasses had increased a* (more red) values than steaks from Lightweight carcasses (Egolf, 2021). Lancaster et al. (2020) observed that deep muscle temperature decline in the *Semimembranosus* (SM) of overweight carcasses (>432 kg) was slower than temperature decline in average weight carcasses (341 – 397 kg). Steaks from the SM of overweight carcasses had increased L* and b* values compared to top round steaks from average weight carcasses (Lancaster et al., 2020).

The objective of this study was to determine the influence of beef carcass weight on carcass chilling, pH decline, color, case life and tenderness of steaks from the round, loin, rib, and chuck. It was hypothesized that heavyweight carcasses would experience a slower temperature and a faster pH decline leading to lighter colored steaks, decreased case life, and tougher steaks when compared to lightweight carcasses.

MATERIALS AND METHODS

Carcass Chilling

Twelve finished beef cattle from a single feedlot were harvested at the South Dakota State University (SDSU) Meat Laboratory over two slaughter dates two weeks apart. These cattle were selected to fit within one of two weight ranges based on live weight: 500 – 614 kg or 659 – 727 kg. After slaughter, carcasses were allotted to one of two weight groups based on hot carcass weight (HCW): Heavyweight (HW; HCW = 450 ± 7.6 kg) or Lightweight (LW, HCW = 349 ± 7.6 kg). Upon final inspection, approximately 60 minutes after exsanguination, data logging thermometers (ThermaData stainless steel USB temp data logger; ThermoWorks, American Fork, UT) were placed in the left side of each carcass in the round, loin, rib, and chuck. A 20-cm data logger was

placed in the round approximately 15 cm below the Achilles tendon. In the loin, a 10-cm temperature logger was placed opposite the third lumbar vertebrae. In the rib, a 10-cm logger was placed opposite the eighth rib. Also, a 20-cm data logger was placed in the pocket between the chuck and the brisket so that the tip of the temperature logger would rest near the scapula. All 10-cm and 20-cm temperature data will be referred to as deep muscle temperature. To track sub-surface temperature of each carcass, a second temperature logger (Multitrip multiuse temperature recorder; Temprecord International Ltd, Auckland, New Zealand) was placed in each of the primals beneath the surface of the subcutaneous fat; except in the round, where the logger was placed beneath the surface of the ST, due to lack of subcutaneous fat at that location. Approximately 75 minutes after exsanguination, carcasses were moved into a chilling cooler where they were exposed to an average air temperature of 3.3 ± 0.7°C. A spray chill system was used to intermittently spray carcasses with water chilled to an average of 5.5°C. The system was controlled with a Model K2000 programmed timer (Scott's Sales; McCallsburg, Iowa) to allow for regularly scheduled spraying. The timer would spray for one hundred and sixty seconds alternating between the left and right side of the carcass. After spraying, the timer would be off for thirty-two minutes and repeat for 24 h.

Thermal Imaging

Thermal images were taken to measure surface temperature of each carcass. Thermal imaging could be used as a quick, non-invasive method to determine surface temperature of carcasses while in the cooler. Images were captured using a forward-looking infrared camera (FLIR C3, FLIR Systems, Wilsonville, OR) at eight locations on the carcass. Emissivity setting of the camera was 0.95. Images of the round, loin, rib, and

chuck were recorded on both the fat and split side of the carcass at five timepoints after cooler entry throughout the chilling period: Cooler entry (CE; 0 hr), 3, 6, 12, and 24 hr post CE. These images were analyzed using FLIR Tools (FLIR Systems, Wilsonville, OR) to determine average surface temperature of each carcass at the round, loin, rib and chuck.

pH Decline

Postmortem pH was measured at eight time points (CE, 2, 4, 6, 8, 12, 24, and 48 hr postmortem) throughout the chilling period. Approximately 10 grams of the ST, LL, *Longissimus thoracis* (LT), and SV were removed for pH analysis at each time point. Immediately following sample removal, each sample was diced into small pieces and 5 grams of muscle tissue was homogenized in a 50 mL solution containing 5 mMol of sodium iodoacetate and 150 mMol of potassium chloride (Bendall, 1973). An Orion 370 benchtop pH meter (Thermo Scientific, Beverly, MA) and a Flat Surface Combo probe (model 476286; SI Analytics, Weilheim, Germany) were used to measure pH.

Carcass Evaluation and Sample Collection

Approximately 48hr postmortem, carcass measurements were recorded including: ribeye area (REA), 12th rib fat thickness (FT) and marbling score. The ST (IMPS #171C), LL (IMPS #180), LT (IMPS #112A), SV (IMPS #116G), and kidney, pelvic and heart (KPH) fat were collected from the left side of each carcass during fabrication, and individual weights recorded. Each muscle was portioned into 2.54-cm steaks for various analyses. The most anterior steak of each muscle was designated for use in a 10-d trained color panel immediately following fabrication. The next four sequential steaks were aged

for either 5, 10, 14, or 21 d postmortem for evaluation of Warner-Bratzler shear force (WBSF). All WBSF steaks were vacuum packaged and frozen at approximately -20°C and stored for approximately three months until analysis could be completed.

Warner-Bratzler Shear Force

Steaks designated for WBSF were thawed for 24 hr at 3°C before being cooked on an electric clamshell grill to an internal peak temperature of 71°C. A thermometer (Model 35140, Cooper-Atkins Corporation, Middlefield, CT) was used to record peak internal temperature. After cooking, steaks were cooled for 12 hr at 3°C before six cores (1.27-cm diameter) were removed parallel to the muscle fiber orientation (AMSA, 2015). A single peak shear force measurement was measured from each core using a texture analyzer (Shimadzu Scientific Instruments Inc., Lenexa, KS, Model EZ-SX) with a Warner-Bratzler attachment. All cores were averaged to determine the shear force value for each steak.

Objective and Subjective Color Panel

Steaks designated for the trained color panel were tray-overwrapped with a high oxygen permeable wrap and placed under a simulated retail display (2.5°C ± 0.9°C) for 10 days. Light intensity was between 1612.5 and 2152 lux according to AMSA (2012) guidelines and monitored daily. Steaks were rotated throughout the display area each day to ensure even distribution of light exposure among samples. Objective color measurements (L*, a* and b*) were measured using a colorimeter (Chroma Meter CR 410; Konica Minolta, Inc., Tokyo, Japan) on each day of the color panel. Additionally, a set of seven to twelve trained panelists evaluated steaks each day according to standards

set forth by AMSA (2012). Steaks from the four sampled muscles were evaluated for color score (1 = Extremely bright cherry-red, 8 = Extremely dark red), and surface discoloration (1 = No discoloration or 0%, 6 = Extreme discoloration or 81 to 100%).

Statistical Analysis

Statistical analysis was conducted using the MIXED procedure of SAS (SAS Inst. Inc., Cary, NC) for the effects of weight group, time (chilling, aging and display), and their interaction. Carcass data and muscle weights were analyzed as a completely randomized design. Temperature and pH decline, objective and subjective color, and WBSF were analyzed as repeated measures. Slaughter date was used as a random variable. Covariance structure was determined by the lowest AIC value. Peak temperature was used as a covariate for WBSF values. Significance was considered $P < 0.05$. Trends were reported at $0.05 \geq P \leq 0.10$. Statistical analysis for thermal images was conducted using CORR procedure of SAS (SAS Inst. Inc., Cary, NC) for their Pearson correlation to deep muscle and sub-surface temperature. Positive correlations were determined by $r > 0$. Significance was determined $P < 0.05$.

RESULTS AND DISCUSSION

Carcass Characteristics

As expected, HW carcasses had increased ($P < 0.0001$) HCW compared to LW carcasses (Table 2.1). HW carcasses tended to have larger ($P = 0.069$) REA compared to LW carcasses (Table 2.1). No effect of weight group was observed for FT ($P = 0.197$), dressing percent ($P = 0.268$), marbling score ($P = 0.465$), or Yield grade ($P = 0.162$;

Table 2.1). HW carcasses had increased weights of the ST ($P = 0.0027$), LL ($P = 0.0031$), LT ($P = 0.0001$), SV ($P = 0.0026$) and KPH fat ($P = 0.0008$) compared to LW carcasses (Table 2.2). Weights of the ST, LL and SV from HW carcasses increased by approximately 34% compared to similar muscles from LW carcasses. Weight of the LT from HW carcasses increased by 48% compared to LW carcasses.

Carcass Chilling

No effect of HCW or HCW × chilling time interaction ($P = 0.9977$) was observed for deep muscle temperature decline in the chuck (Figure 2.2). A HCW × chilling time interaction ($P < 0.0001$) was detected for deep muscle temperature decline in the rib. Rib primals from HW carcasses had increased ($P < 0.05$) temperatures for the first 25 h of chilling compared to LW carcasses but were similar ($P > 0.05$) for the remainder of the chilling period (Figure 2.3). No effect of HCW or HCW × chilling time interaction ($P = 0.1373$) was observed for deep muscle temperature decline in the loin (Figure 2.4). A HCW × chilling time interaction ($P = 0.0092$) was detected for deep muscle temperature decline in the round. Temperature in the round was not different ($P > 0.05$) between weight groups for the first 3 h of chilling, but HW carcasses had increased ($P < 0.05$) temperatures for the remainder of chilling (Figure 2.5). No effect of HCW or HCW × chilling time interaction ($P > 0.05$) was observed for sub-surface temperature decline in the chuck ($P = 0.9897$; Figure 2.6), rib ($P = 0.9996$; Figure 2.7), loin ($P = 0.9995$; Figure 2.8) or round ($P = 0.9973$; Figure 2.9). Similar to the current study, Lancaster et al. (2020) reported that the deep SM of overweight carcasses chilled at a slower rate than average weight carcasses. However, there was no difference in temperature observed between the two weight groups after 48 h (Lancaster et al., 2020).Other research by

Fevold et al. (2019) also determined that SM temperature was similar between HW and LW carcasses at 0 and 4 h of chilling; however, internal temperature was higher in the SM of HW carcasses after 24 h of chilling. Fevold et al. (2019) also described that LL temperature was lower in LW after 4 h of chilling, but no differences in temperature were found between HW and LW carcasses after 24 h. Djimsa et al. (2022) reported that LW carcasses had a faster temperature decline within the LL compared to HW carcasses; however, no differences were observed after 12 h of chilling. Lightweight carcasses exhibited a more rapid temperature decline within the SM even though they started at higher temperatures (Djimsa et al., 2022). Further research by Egolf (2021) noted that heavier carcass weights resulted in increased temperatures throughout chilling in the round, loin and chuck. The current study found no differences in temperature within the loin and chuck. Results from Egolf (2021) could differ from this due to that study being conducted at a commercial packing facility, while the current study was collected at the SDSU Meat Laboratory.

Thermal Imaging

Thermal imaging data is presented in Tables 2.3-2.6. In the round, no significant correlations ($P > 0.05$) were detected between the fat or split side temperature and deep muscle temperature at 0, 3, 6 and 12 h of chilling. No significant correlations ($P > 0.05$) were detected between the fat side temperature and sub-surface temperature at 0 and 3 h of chilling. Also, no significant correlations ($P > 0.05$) were observed between split side temperature and sub-surface temperature at 0, 3, 6, 12 and 24 h. However, a positive correlation was detected for fat side temperature ($r = 0.5875$, $P = 0.0446$) and split side temperature ($r = 0.7492$, $P = 0.0050$) with deep muscle temperature at 24 h. Fat side

temperature was positively correlated with sub-surface temperature at 6 h (r = 0.6344, *P* = 0.0488), 12 h (r = 0.6833, *P* = 0.0294), and 24 h (r = 0.6837, *P* = 0.0293).

For the loin, no significant correlations (*P* > 0.05) were detected between the fat side temperature and deep muscle temperature at 0 and 3 h of chilling. Also, no significant correlations (*P* > 0.05) were observed between the split side temperature and deep muscle temperature at 0, 3 and 6 h of chilling. Furthermore, no significant correlations (*P* > 0.05) were detected between fat or split side temperature and sub-surface temperature at 0, 3 and 6 h of chilling. However, fat side temperature was positively correlated with deep muscle temperature at 6 h (r = 0.6877, *P* = 0.0133), 12 h (r = 0.7658, *P* = 0.0037), and 24 h (r = 0.9003, *P* = <0.0001). Split side temperature was positively correlated with deep muscle temperature at 12 h (r = 0.9053, *P* = <0.0001) and 24 h (r = 0.8311, *P* = 0.0008). Fat side temperature was positively correlated with sub-surface temperature at 12 h (r = 0.7316, *P* = 0.0105) and 24 h (r = 0.9382, *P* = <0.0001). Split side temperature was positively correlated with sub-surface temperature at 12 h (r = 0.7820, *P* = 0.0045) and 24 h (r = 0.8111, *P* = 0.0024).

For the rib, no significant correlations (*P* > 0.05) were detected between the fat or split side temperature and deep muscle temperature at 0, 3, and 6 h of chilling. No significant correlations (*P* > 0.05) were detected between the fat side temperature and sub-surface temperature at 0 h of chilling. Also, no significant correlations (*P* > 0.05) were observed between split side temperature and sub-surface temperature at 0, 3 and 6 h of chilling. However, fat side temperature was positively correlated with deep muscle temperature at 12 h (r = 0.8180, *P* = 0.0011) and 24 h (r = 0.8228, *P* = 0.0010). Split side temperature was positively correlated with deep muscle temperature at 12 h (r = 0.7082,

P = 0.0100) and 24 h (r = 0.6915, *P* = 0.0127). Fat side temperature was positively correlated with sub-surface temperature at 3 h (r = 0.6459, *P* = 0.0233), 6 h (r = 0.7956, *P* = 0.0020), 12 h (r = 0.8347, *P* = 0.0007), and 24 h (r = 0.9020, *P* = <0.0001). Split side temperature was positively correlated with sub-surface temperature at 12 h (r = 0.8417, *P* = 0.0006) and 24 h (r = 0.7465, *P* = 0.0053).

For the chuck, no significant correlations (*P* > 0.05) were detected between the fat side temperature and deep muscle temperature at 0, 3, 6, 12 and 24 h of chilling. Also, no significant correlations (*P* > 0.05) were detected between split side temperature and deep muscle temperature at 0, 3 and 24 h of chilling. No significant correlations (*P* > 0.05) were detected between the fat side temperature and sub-surface temperature at 0, 3 and 6 h of chilling. Furthermore, no significant correlations (*P* > 0.05) were observed between split side temperature and sub-surface temperature at 0, 3, 6 and 12 h. However, split side temperature was negatively correlated with deep muscle temperature at 6 h (r = -0.7847, *P* = 0.0025) and 12 h (r = -0.6331, *P* = 0.0271). Fat side temperature was positively correlated with sub-surface temperature at 12 h (r = 0.6392, *P* = 0.0342) and 24 h (r = 0.7354, *P* = 0.0099). Split side was positively correlated (r = 0.6533, *P* = 0.0293) with sub-surface temperature at 24 h (Table 2.6).

Published data on the use of thermal imaging within the meat industry is minimal. Hite et al. (2020) reported that thermal images of beef carcasses are positively correlated to internal muscle temperature and concluded that thermal images could be utilized as a quick, non-invasive method to help predict chilling rate once in the blast chiller (Hite et al., 2020). In contrast, the current study concluded that significant correlations were inconsistent between primals and timepoints on both the fat and split sides of the carcass.

Although, the loin and rib were always significantly positively correlated with deep and sub-surface temperature on the fat and split side at 12 and 24 h. This could suggest that there is potential for thermal images to be an effective means for predicting carcass temperature. However, this data suggests that further research is needed to determine the overall effectiveness of thermal imaging as a means for quickly and non-invasively predicting internal carcass temperature.

pH Decline

No HCW × chilling time interaction or HCW main effect ($P > 0.05$) was detected for pH decline in the ST, LL, LT and SV. Fevold et al. (2019) reported similar findings as they showed no differences in pH values at different timepoints between hot carcass weight groups in the *Longissimus dorsi* and SM muscles. In contrast, other research has reported a difference in the rate of pH decline in the deep SM, where HW carcasses experienced a more rapid decline in pH values compared to LW carcasses (Agbeniga and Webb, 2018; Lancaster et al., 2020; Djimsa et al., 2022). Results of these studies could be related to incubation of muscle at a high temperature favoring a fast rate of pH decline due to its effect on enzyme activity and the rate of glycolysis (Newbold and Scopes, 1967). Furthermore, high temperature interacting with low pH has been shown to cause denaturation and loss of functionality of proteins that affect meat quality (Offer et al., 1989; Jacob and Hopkins, 2014). Thus, more rapid pH decline within HW carcasses could negatively affect meat quality. These results could differ from the current study due to muscle selection within the round. The SM is a much larger muscle allowing for increased postmortem temperature, whereas the ST is much smaller and closer to the surface and the spray chill system. In the current study, as expected, pH values declined

in each of the four muscles throughout the chilling process to an ultimate pH between 5.5 – 5.7 (Figures 2.10 – 2.13). Previous literature has concluded that under normal, unstressed slaughter conditions, the ultimate pH of muscle should reside between 5.3 – 5.7 (Bate-Smith and Bendall, 1949; Newton and Gill, 1978; Aberle, 2001).

In the current study, no differences were observed in temperature within the loin and the chuck throughout the chilling period. Even though differences in temperature were detected between weight groups in the rib early in the chilling period, no differences were seen after 25 h of chilling. This lack of difference in temperature could help explain why no differences were observed in pH within these three primals. In the round, differences in temperature between the weight groups was seen throughout most of the chilling period. This increased temperature in HW carcasses could point to the possibility of faster pH decline according to previous research (Agbeniga and Webb, 2018; Lancaster et al., 2020). However, one possible explanation could be that deep muscle temperature was measured 20 cm beneath the surface of the round and pH was measured in the ST which is near the surface of the carcass. Sub-surface temperature in the round was measured beneath the surface of the ST and no differences were observed for temperature between the weight groups. This lack of difference in temperature in the ST could explain why no differences in pH were seen in the current study.

Warner-Bratzler shear force and Cook loss

No main effect of HCW or HCW × aging day interaction ($P > 0.05$) was observed for WBSF values in steaks from the LL, LT and SV. As expected, WBSF values improved for the LL ($P < 0.0001$), LT ($P = 0.0005$), and SV ($P = 0.0008$) steaks over the

aging period (Table 2.7). Steaks from the LL were more tender ($P < 0.0001$) on d 10 and 14 compared to d 5. Meanwhile, LL steaks were the most tender ($P \leq 0.0001$) after 21 d of aging. Steaks from the LT were more tender ($P = 0.0184$) on d 10 than d 5 and were the most tender ($P \leq 0.0257$) on d 14 and 21 compared to other aging days. Steaks from the SV improved in tenderness ($P = 0.0245$) from d 5 to d 14 of aging. SV steaks were found to be the most tender ($P \leq 0.015$) after d 21 of aging.

A HCW × aging day interaction ($P = 0.0149$) was detected for WBSF values in ST steaks. Steaks from the ST from LW carcasses were more tender ($P = 0.0002$) than HW steaks at d 5 of aging but were not different at d 10 ($P = 0.1162$), d 14 ($P = 0.1785$) or d 21 ($P = 0.2749$) of aging (Figure 2.14). Lancaster et al. (2020) reported no differences in WBSF values of top round steaks aged 14 d from overweight and average weight carcasses. Similarly, Fevold et al. (2019) reported no differences between different weight groups in WBSF values of steaks taken from the *Longissimus dorsi* and SM muscles aged 14 d. These studies show similar results to the current study, as all four muscles had no differences in WBSF values between weight groups at 14 d of aging. However, other research has shown that heavier weight carcasses have improved WBSF values in steaks from the LL (Egolf, 2021).

The current study saw very few differences in WBSF values between weight groups. However, changes in WBSF between aging days were seen in each muscle. To help consumers better understand differences in tenderness values between muscles, categories were created. Belew et al. (2003) and Shackelford et al. (1991) developed tenderness categories based on WBSF values. The tenderness categories included “Very tender” (WBSF < 3.2 kg), “Tender” (3.2 kg < WBSF < 3.9 kg), “Intermediate” (3.9 kg <

WBSF < 4.6 kg), and “Tough” (4.6 kg < WBSF). In the current study, the ST would be described as “Tough” at the early aging periods of 5 and 10 d postmortem. However, even after the ST was aged for 14 and 21 d, it would still fall into the “Intermediate” category. The LL would be classified as “Tough” after 5 d of aging, before dropping down to “Intermediate” at d 10 and d 14 of aging. After 21 d of aging, the LL would be classified as “Tender.” The LT would be described as “Tough” after 5 and 10 d of aging. After 14 d of aging the LT would enter the “Intermediate” category, before being classified as “Tender” after 21 d of aging. The SV began in the “Intermediate” category at 5 and 10 d postmortem and then after 14 d and 21 d of aging the SV would be classified as “Tender.”

No HCW main effect or HCW × aging day interaction was observed for percent cook loss in steaks from the ST ($P = 0.630$), LL ($P = 0.880$), LT ($P = 0.414$), or SV ($P = 0.467$; Table 2.8).

Objective and Subjective Color

No main effect of HCW or HCW × day of retail display interaction ($P > 0.05$) was observed for L*, a* or b* in LL, LT, or SV steaks (Table 2.9). A HCW × day of retail display interaction ($P = 0.0001$) was detected for L* values in steaks from the ST. *Semitendinosus* steaks from HW carcasses were darker (lower L* value; $P = 0.0004$) throughout the display period. Between d 0 and d 1 of retail display, HW ST steaks L* values decreased ($P = 0.003$), whereas the LW ST steaks increased ($P = 0.0209$; Figure 2.15). A tendency ($P = 0.0980$) was observed for L* values in the LT, where HW steaks tended to have decreased L* values compared to LW steaks. *Semitendinosus* steaks from

HW carcasses had decreased a* (P = 0.005) and b* (P = 0.001) values compared to ST steaks from LW carcasses (Table 2.9). Contrary to our findings, Egolf (2021) reported ST steaks from HW carcasses had increased L values compared to steaks from LW carcasses. They also observed that steaks from the SV, LL and ST in HW carcasses had increased a and b values compared to similar steaks from LW carcasses. Similar to Egolf (2021), results from Fevold et al. (2019) showed that steaks from the *Longissimus dorsi* and SM in HW carcasses had increased L*, a* and b* values than similar steaks coming from LW carcasses. Djimsa et al. (2022) concluded similar findings where they observed the *Psoas major* from HW carcasses had increased a* and b* values compared to LW carcasses. However, Lancaster et al. (2020) reported no differences in L*, a* and b* between overweight and average weight SM steaks. Multiple factors could be influencing the difference in results between the current study and previous literature. Length of time that steaks were displayed, and intensity of the retail lights the steaks were exposed too both could be playing a role. The current study and Fevold et al. (2019) both evaluated color over a 10 d retail display. Meanwhile, Lancaster et al. (2020) used a 4 d retail display to evaluate color and Egolf (2021) and Djimsa et al. (2022) both only evaluated objective color at one time point. The current study displayed steaks under lights measuring between 1612.5 and 2152 lux. Meanwhile, Lancaster et al. (2020) had an average light intensity of 401 lux during their display period. Fevold et al. (2019) did not report a light intensity measurement. These differences in display time and display conditions both could be contributing to differences in results seen throughout these studies.

Hot carcass weight did not influence ($P > 0.05$) subjective color scores in the ST, LL, or LT (Table 2.10). However, SV steaks from HW carcasses had increased (darker; $P = 0.007$) subjective color scores compared to steaks from LW carcasses (Table 2.10). A tendency ($P = 0.0668$) was observed for subjective color scores in the ST, where HW steaks tended to have increased (darker) color scores compared to LW steaks. No HCW or HCW × day of retail display interaction ($P > 0.05$) was observed for subjective discoloration scores in the SV, LT, LL or ST steaks throughout the 10-day display period (Table 2.10). Lancaster et al. (2020) reported SM steaks from overweight carcasses had decreased (lighter) subjective color scores than steaks from average weight carcasses. They also observed that top round steaks from overweight carcasses had a greater discoloration percentage compared to similar steaks from average weight carcasses. These results could be accredited to the carcasses experiencing a more rapid pH decline along with delayed chilling (Lancaster et al., 2020). Previous research has indicated that a more rapid pH decline at periods of high temperatures can result in increased protein denaturation, which can be attributed to lighter colored muscle (Hector et al., 1992; Lancaster et al., 2020). Therefore, this rapid pH decline while muscle temperature is still high could result in pale, soft and exudative conditions in beef muscle (Nair et al., 2016).

IMPLICATIONS

Results from this study suggest that beef carcass weight does impact carcass chilling rate during the first 48 hours postmortem. Heavier carcasses have prolonged temperature decline in the round, resulting in increased temperature at the time of fabrication, when compared to lighter weight beef carcasses. This, combined with

increased toughness of eye of round steaks from heavyweight carcasses at early aging periods, could suggest a negative effect on meat quality due to increased carcass weights. Since the round holds a large percentage of the carcass' muscle weight, this could lead to a substantial amount of product being affected.

Additionally, thermal imaging shows promise as a new and innovative tool for determining chilling rate of beef carcasses. Data from this research project indicates that most fat side and split side thermal imaging surface temperatures were positively correlated to deep internal and sub-surface temperatures after 12hr of chilling. However, further research will be needed to determine the overall effectiveness of using thermal imaging to predict internal temperature of carcasses.

LITERATURE CITED

Aberle, E. D. 2001. Principles of meat science. 4th ed. ed. Kendall/Hunt, Dubuque, Iowa.

Agbeniga, B., and E. C. Webb. 2018. Influence of carcass weight on meat quality of commercial feedlot steers with similar feedlot, slaughter and post-mortem management. Food Res. Int. 105:793-800. (Article) doi: 10.1016/j.foodres.2017.10.073

AMSA. 2012. AMSA meat color measurement guidelines. American Meat Science Association, Champaign, Illinois USA:1-135.

AMSA. 2015. Research guidelines for cookery, sensory evaluation, and instrumental tenderness measurements of meat. . American Meat Science Association, Champaign, Illinois USA

Bate-Smith, E. C., and J. R. Bendall. 1949. Factors determining the time course of rigor mortis. J Physiol 110(1-2):47-65. doi: 10.1113/jphysiol.1949.sp004420

Bendall, J. R. 1973. 5 - Postmortem changes in muscle. In: G. H. Bourne, editor, The Structure and Function of Muscle (Second Edition). Academic Press. p. 243-309.

Boykin, C. A., L. C. Eastwood, M. K. Harris, D. S. Hale, C. R. Kerth, D. B. Griffin, A. N. Arnold, J. D. Hasty, K. E. Belk, D. R. Woerner, R. J. Delmore, J. N. Martin, D. L. VanOverbeke, G. G. Mafi, M. M. Pfeiffer, T. E. Lawrence, T. J. McEvers, T. B. Schmidt, R. J. Maddock, D. D. Johnson, C. C. Carr, J. M. Scheffler, T. D. Pringle, A. M. Stelzleni, J. Gottlieb, and J. W. Savell. 2017. National Beef Quality Audit-2016: In-plant survey of carcass characteristics related to quality, quantity, and value of fed steers and heifers. J. Anim. Sci. 95(7):2993-3002. (Article) doi: 10.2527/jas.2017.1543

Djimsa, B., D. Woerner, M. Nair, J. Martin, R. Delmore, and K. Belk. 2018. Effects of electrical stimulation, chilling rate, and carcass size on rates of temperature decline and pH decline, and beef quality. Meat and Muscle Biology 2:87-87. doi: 10.22175/rmc2018.077

Djimsa, B. A., M. N. Nair, A. M. Hess, K. E. Belk, and D. R. Woerner. 2022. The Impact of Carcass Size, Chilling Conditions, and Electrical Stimulation on Beef Postmortem Temperature and pH Decline. Meat and Muscle Biology 6(1):1-16. doi: https://doi.org/10.22175/mmb.13893

Egolf, S. R. 2021. The influence of carcass weight on beef primal temperature, tenderness, and palatability, South Dakota State University.

Fevold, M., L. Grube, W. L. Keller, K. R. Maddock-Carlin, and R. J. Maddock. 2019. Tenderness and juiciness of beef steaks from varying hot carcass weights. Meat and Muscle Biology

Fields, P. A., Z. L. Carpenter, and G. C. Smith. 1976. Effects of Elevated Temperature Conditioning on Youthful and Mature Beef Carcasses. J. Anim. Sci. 42(1):72-83. doi: 10.2527/jas1976.42172x

Hector, D. A., C. Brew-Graves, N. Hassen, and D. A. Ledward. 1992. Relationship between myosin denaturation and the colour of low-voltage-electrically-stimulated beef. Meat Sci 31(3):299-307. doi: 10.1016/0309-1740(92)90060-h

Hite, L. M., A. D. Blair, K. R. Underwood, and J. K. Grubbs. 2020. Investgation on the use of FLIR (Forward Looking Infrared) camera to detect relationships between internal and surface temperatures of beef carcasses during chilling. SDSU Beef Day 2020 Summary Publication:162-163. doi:

https://openprairie.sdstate.edu/cgi/viewcontent.cgi?article=1036&context=sd_beefday_2020

Jacob, R. H., and D. L. Hopkins. 2014. Techniques to reduce the temperature of beef muscle early in the post mortem period – a review. Anim. Prod. Sci. 54(4):482-493. doi: https://doi.org/10.1071/AN12338

Kim, Y. H., A. Stuart, G. Nygaard, and K. Rosenvold. 2012. High pre rigor temperature limits the ageing potential of beef that is not completely overcome by electrical stimulation and muscle restraining. Meat Sci 91(1):62-68. doi: 10.1016/j.meatsci.2011.12.007

Lancaster, J. M., B. J. Buseman, T. M. Weber, J. A. Nasados, R. P. Richard, G. K. Murdoch, W. J. Price, M. J. Colle, and P. D. Bass. 2020. Impact of beef carcass size on chilling rate, pH decline, display color, and tenderness of top round subprimals. Transl. Anim. Sci. 4(4):12. (Article) doi: 10.1093/tas/txaa199

Nair, M. N., S. P. Suman, M. K. Chatli, S. Li, P. Joseph, C. M. Beach, and G. Rentfrow. 2016. Proteome basis for intramuscular variation in color stability of beef semimembranosus. Meat Sci. 113:9-16. doi: https://doi.org/10.1016/j.meatsci.2015.11.003

Newbold, R. P., and R. K. Scopes. 1967. Post-mortem glycolysis in ox skeletal muscle. Effect of temperature on the concentrations of glycolytic intermediates and cofactors. Biochem J 105(1):127-136. doi: 10.1042/bj1050127

Newton, K. G., and C. O. Gill. 1978. Storage quality of dark, firm, dry meat. Appl Environ Microbiol 36(2):375-376. doi: 10.1128/aem.36.2.375-376.1978

Offer, G., P. J. Knight, R. E. Jeacocke, R. Almond, T. Cousins, J. Elsey, N. Parsons, A. Sharp, R. Starr, and P. P. Purslow. 1989. The Structural Basis of the Water-Holding, Appearance and Toughness of Meat and Meat Products. Food Structure 8:17.

Ramanathan, R., L. H. Lambert, M. N. Nair, B. Morgan, R. Feuz, G. Mafi, and M. Pfeiffer. 2022. Economic loss, amount of beef discarded, natural resources wastage, and environmental impact due to beef discoloration. Meat and Muscle Biology 6(1)

Savell, J. W. 2012. Beef carcass chilling: Current understanding, future challenges. National Cattlemen's Beef Association, Centennial, CO

USDA-ERS. 2022. Historical livestock and poultry live and dressed weights. Livestock Meat Domestic Data. doi: https://www.ers.usda.gov/data-products/

Table 2.1. Least squares means of carcass characteristics for Heavyweight and Lightweight cattle

	Weight Group[1]			
Trait	**Lightweight**	**Heavyweight**	**SEM[2]**	***P*-value[3]**
Hot carcass weight, kg	349	450	7.60	**<0.001**
Ribeye area, cm^2	89.6	102.1	4.36	0.069
12th rib fat thickness, cm	1.04	1.38	0.17	0.197
Dressing percent, %	63.2	64.7	0.88	0.268
Yield grade	2.5	3.1	0.32	0.162
Marbling score[4]	445	480	32.5	0.465

[1]Carcasses separated based on hot carcass weight measured after slaughter before entering the chilling cooler

[2]Standard error of the mean

[3]Probability of difference among least square means

[4]Marbling score: 200=Traces^0, 300=Slight^0, 400=Small^0, 500=Modest^0

Table 2.2. Least squares means of individual muscle and fat weights for Heavyweight and Lightweight carcasses

	Weight Group[1]			
Muscle	**Lightweight**	**Heavyweight**	**SEM[2]**	***P*-value[3]**
***Semitendinosus*, kg**	2.07	2.78	0.13	**0.0027**
***Longissimus lumborum*, kg**	4.83	6.56	0.32	**0.0031**
***Longissimus thoracis*, kg**	5.09	7.56	0.29	**0.0001**
***Serratus ventralis*, kg**	1.73	2.40	0.12	**0.0026**
Kidney, pelvic and heart fat, kg	4.81	7.97	0.48	**0.0008**

[1]Carcasses separated based on hot carcass weight measured after slaughter before entering the chilling cooler
[2]Standard error of the mean
[3]Probability of difference among least square means

Table 2.3. Pearson correlation coefficients between deep muscle (10 or 20 centimeters) temperature and average thermal image temperature of fat side of carcass at each timepoint

		Time After Cooler Entry[1]				
Primal	**Statistical Value[2]**	**0 h**	**3 h**	**6 h**	**12 h**	**24 h**
Round	**r value**	-0.0007	0.0807	0.0492	0.4399	**0.5875**
	***P*-value**	0.9982	0.8030	0.8792	0.1524	**0.0446**
Loin	**r value**	-0.0164	0.3953	**0.6887**	**0.7658**	**0.9003**
	***P*-value**	0.9598	0.2035	**0.0133**	**0.0037**	**<0.0001**
Rib	**r value**	-0.3947	0.3594	0.5117	**0.8180**	**0.8228**
	***P*-value**	0.2042	0.2512	0.0890	**0.0011**	**0.0010**
Chuck	**r value**	0.0620	-0.1704	-0.4165	-0.4825	-0.0038
	***P*-value**	0.8481	0.5965	0.1781	0.1121	0.9906

[1]Time temperature was measured after carcass entered chilling cooler.

[2]**r-value:** Correlations were considered lowly correlated at $r \leq 0.35$, moderately at $0.36 \leq r \leq 0.67$, and highly if $r \geq 0.68$. ***P*-value**: Probability there is a relationship.

Table 2.4. Pearson correlation coefficients between deep muscle (10 or 20 centimeters) temperature and average thermal image temperature of split side of carcass at each timepoint

		Time After Cooler Entry[1]				
Primal	**Statistical Value[2]**	**0 h**	**3 h**	**6 h**	**12 h**	**24 h**
Round	**r value**	-0.0876	-0.3311	-0.2754	0.4463	**0.7492**
	***P*-value**	0.7866	0.2931	0.3864	0.1458	**0.0050**
Loin	**r value**	-0.0906	0.2074	0.5371	**0.9053**	**0.8311**
	***P*-value**	0.7796	0.5178	0.0717	**<0.0001**	**0.0008**
Rib	**r value**	-0.4735	0.1450	0.3548	**0.7082**	**0.6915**
	***P*-value**	0.1199	0.6529	0.2581	**0.0100**	**0.0127**
Chuck	**r value**	-0.1442	-0.5357	**-0.7847**	**-0.6331**	0.0228
	***P*-value**	0.6547	0.0727	**0.0025**	**0.0271**	0.9440

[1]Time temperature was measured after carcass entered chilling cooler.

[2]**r-value:** Correlations were considered lowly correlated at $r \leq 0.35$, moderately at $0.36 \leq r \leq 0.67$, and highly if $r \geq 0.68$. ***P*-value**: Probability there is a relationship.

Table 2.5. Pearson correlation coefficients between sub-surface (5 centimeters) temperature and average thermal image temperature of fat side of carcass at each timepoint

		Time After Cooler Entry[1]				
Primal	**Statistical Value[2]**	**0 h**	**3 h**	**6 h**	**12 h**	**24 h**
Round	**r value**	-0.0786	0.4264	**0.6344**	**0.6833**	**0.6837**
	***P*-value**	0.8290	0.2191	**0.0488**	**0.0294**	**0.0293**
Loin	**r value**	-0.1259	0.4641	0.4527	**0.7316**	**0.9382**
	***P*-value**	0.7123	0.1504	0.1620	**0.0105**	**<0.0001**
Rib	**r value**	0.3054	**0.6459**	**0.7956**	**0.8347**	**0.9020**
	***P*-value**	0.3344	**0.0233**	**0.0020**	**0.0007**	**<0.0001**
Chuck	**r value**	0.3579	0.2989	0.5749	**0.6392**	**0.7354**
	***P*-value**	0.2799	0.3719	0.0643	**0.0342**	**0.0099**

[1]Time temperature was measured after carcass entered chilling cooler.

[2]**r-value:** Correlations were considered lowly correlated at $r \leq 0.35$, moderately at $0.36 \leq r \leq 0.67$, and highly if $r \geq 0.68$. ***P*-value**: Probability there is a relationship.

Table 2.6. Pearson correlation coefficients between sub-surface (5 centimeters) temperature and average thermal image temperature of split side of carcass at each timepoint

		Time After Cooler Entry[1]				
Primal	**Statistical Value[2]**	**0 h**	**3 h**	**6 h**	**12 h**	**24 h**
Round	**r value**	-0.1443	-0.0981	0.3291	0.4703	0.6294
	***P*-value**	0.6908	0.7874	0.3532	0.1701	0.0512
Loin	**r value**	-0.2368	0.1165	0.2535	**0.7820**	**0.8111**
	***P*-value**	0.4833	0.7330	0.4519	**0.0045**	**0.0024**
Rib	**r value**	0.1647	0.2113	0.5215	**0.8417**	**0.7465**
	***P*-value**	0.6090	0.5097	0.0821	**0.0006**	**0.0053**
Chuck	**r value**	0.0067	0.0451	0.2221	0.5761	**0.6533**
	***P*-value**	0.9844	0.8952	0.5115	0.0636	**0.0293**

[1]Time temperature was measured after carcass entered chilling cooler.

[2]**r-value:** Correlations were considered lowly correlated at $r \leq 0.35$, moderately at $0.36 \leq r \leq 0.67$, and highly if $r \geq 0.68$. ***P*-value**: Probability there is a relationship.

Table 2.7. Least squares means of Warner-Braztler shear force values for steaks from various muscles for multiple aging days

	Aging day					
Muscle	**5**	**10**	**14**	**21**	**SEM[1]**	***P*-value[2]**
***Longissimus lumborum*, kg**	5.76[a]	4.42[b]	4.16[b]	3.28[c]	0.31	**<0.0001**
***Longissimus thoracis*, kg**	5.51[a]	4.71[b]	3.98[c]	3.75[c]	0.27	**0.0005**
***Serratus ventralis*, kg**	4.21[a]	3.91[ab]	3.71[b]	3.22[c]	0.15	**0.0008**

[1]Standard error of the mean

[2]Probability of difference among least square means

[a,b,c] Superscripts depict differences between aging days within muscle, $P < 0.05$.

Table 2.8. Least squares means of percent cook loss for steaks from various muscles for Heavyweight and Lightweight carcasses

	Weight Group[1]			
Muscle	**Lightweight**	**Heavyweight**	**SEM[2]**	***P*-value[3]**
***Semitendinosus*, %**	27.68	28.15	0.68	0.630
***Longissimus lumborum*, %**	17.15	17.38	1.04	0.880
***Longissimus thoracis*, %**	19.46	18.41	0.88	0.414
***Serratus ventralis*, %**	25.09	25.85	0.75	0.467

[1]Carcasses separated based on hot carcass weight measured after slaughter before entering the chilling cooler.
[2]Standard error of the mean
[3]Probability of difference among least square means

Table 2.9. Least squares means of objective color measurements (L*, a*, b*) values for steaks from various muscles over a 10-day color panel for Heavyweight and Lightweight carcasses

		Weight Group[1]			
Muscle	**Objective color value[2]**	**Lightweight**	**Heavyweight**	**SEM[3]**	***P*-value[4]**
Semitendinosus	**L***	49.33	46.13	0.48	<**0.001**
	a*	17.39	16.13	0.40	**0.005**
	b*	10.34	8.95	0.21	**0.001**
Longissimus lumborum	**L***	46.30	45.98	0.76	0.773
	a*	15.18	13.96	0.57	0.106
	b*	6.63	6.17	0.25	0.216
Longissimus thoracis	**L***	47.22	45.99	0.61	0.181
	a*	15.46	14.03	0.78	0.241
	b*	6.94	6.05	0.34	0.098
Serratus ventralis	**L***	45.74	46.46	0.98	0.600
	a*	13.07	12.63	0.36	0.354
	b*	6.06	6.29	0.43	0.701

[1]Carcasses separated based on hot carcass weight measured after slaughter before entering the chilling cooler.
[2]**L***: 0 = Black, 100 = White; **a***: Negative values = green; Positive values = red; **b***: Negative values = blue; Positive values = yellow
[3]Standard error of the mean
[4]Probability of difference among least square means

Table 2.10. Least squares means of subjective color measurements (color score, percent discoloration) for steaks from various muscles over a 10-day trained color panel for Heavyweight and Lightweight carcasses

		Weight Group[1]			
Muscle	**Subjective color value[2]**	**Lightweight**	**Heavyweight**	**SEM[3]**	***P*-value[4]**
Semitendinosus	**Color score**	4.25	4.46	0.19	0.067
Longissimus lumborum	**Color score**	5.37	5.62	0.20	0.319
Longissimus thoracis	**Color score**	5.08	5.45	0.20	0.102
Serratus ventralis	**Color score**	5.98	6.35	0.09	**0.007**
Semitendinosus	**Surface discoloration**	3.25	3.29	0.17	0.348
Longissimus lumborum	**Surface discoloration**	2.87	2.87	0.24	0.954
Longissimus thoracis	**Surface discoloration**	2.75	2.77	0.22	0.633
Serratus ventralis	**Surface discoloration**	3.28	3.37	0.20	0.193

[1]Carcasses separated based on hot carcass weight measured after slaughter before entering the chilling cooler.

[2]**Color Score**: 1 = Extremely bright cherry red, 2 = Bright cherry red, 3 = Moderately bright cherry red, 4 = Slightly bright cherry red, 5 = Slightly dark cherry red, 6 = Moderately dark red, 7 = Dark red, 8 = Extremely dark red. **Surface Discoloration**: 1 = No discoloration; 0%, 2 = Slight discoloration; 1-21%, 3 = Small discoloration; 21-40%, 4 = Modest discoloration; 41-60%, 5 = Moderate discoloration; 61-80%, 6 = Extreme discoloration; 81-100%

[3]Standard error of the mean

[4]Probability of difference among least square means

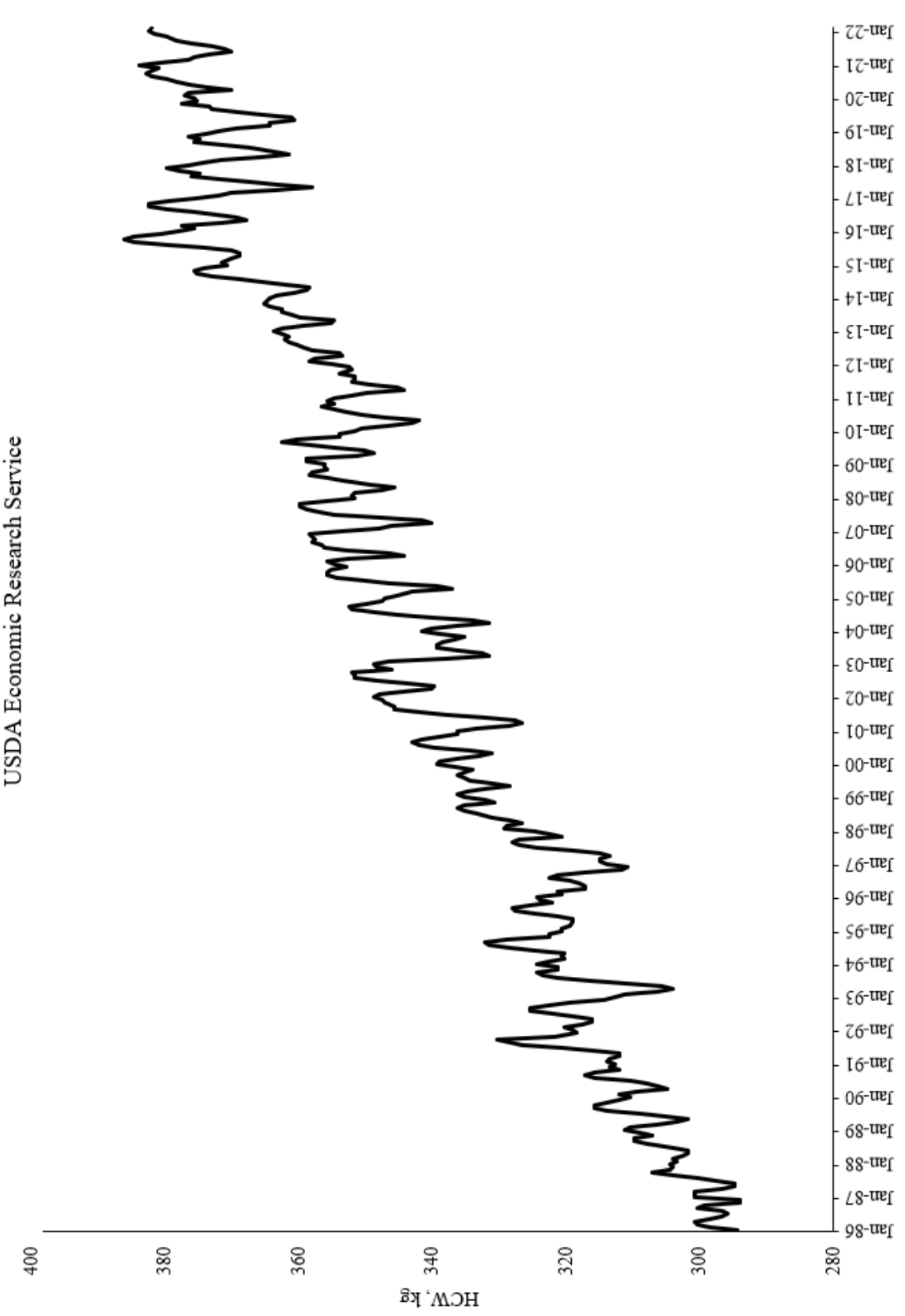


Figure 2.1 - Average beef hot carcass weights in the United States from January 1986 thru February 2022 according to the USDA Economic Research Service

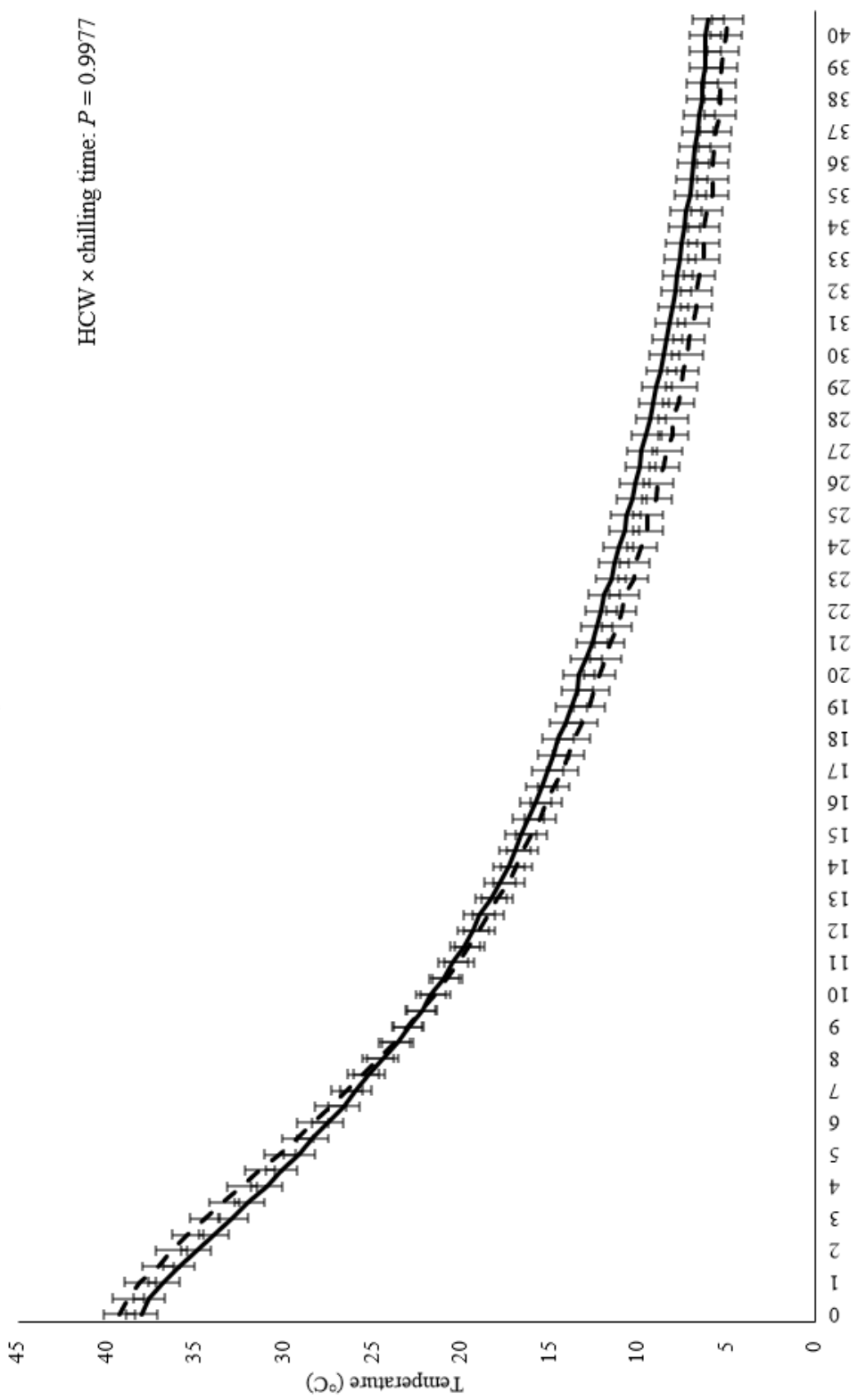


Figure 2.2 - The influence of Heavyweight and Lightweight carcasses and chilling time on deep temperature decline (20 cm) in the chuck

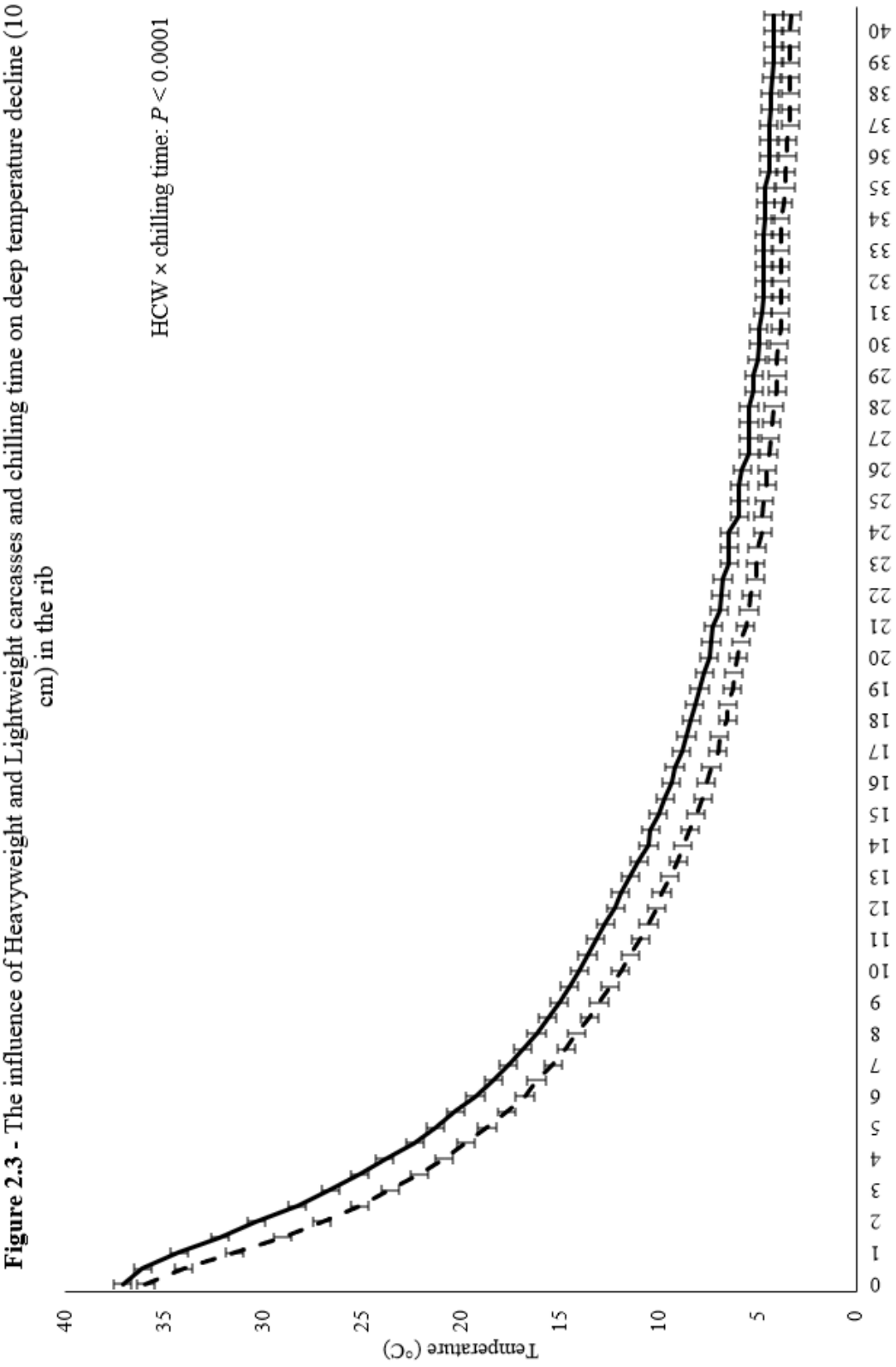
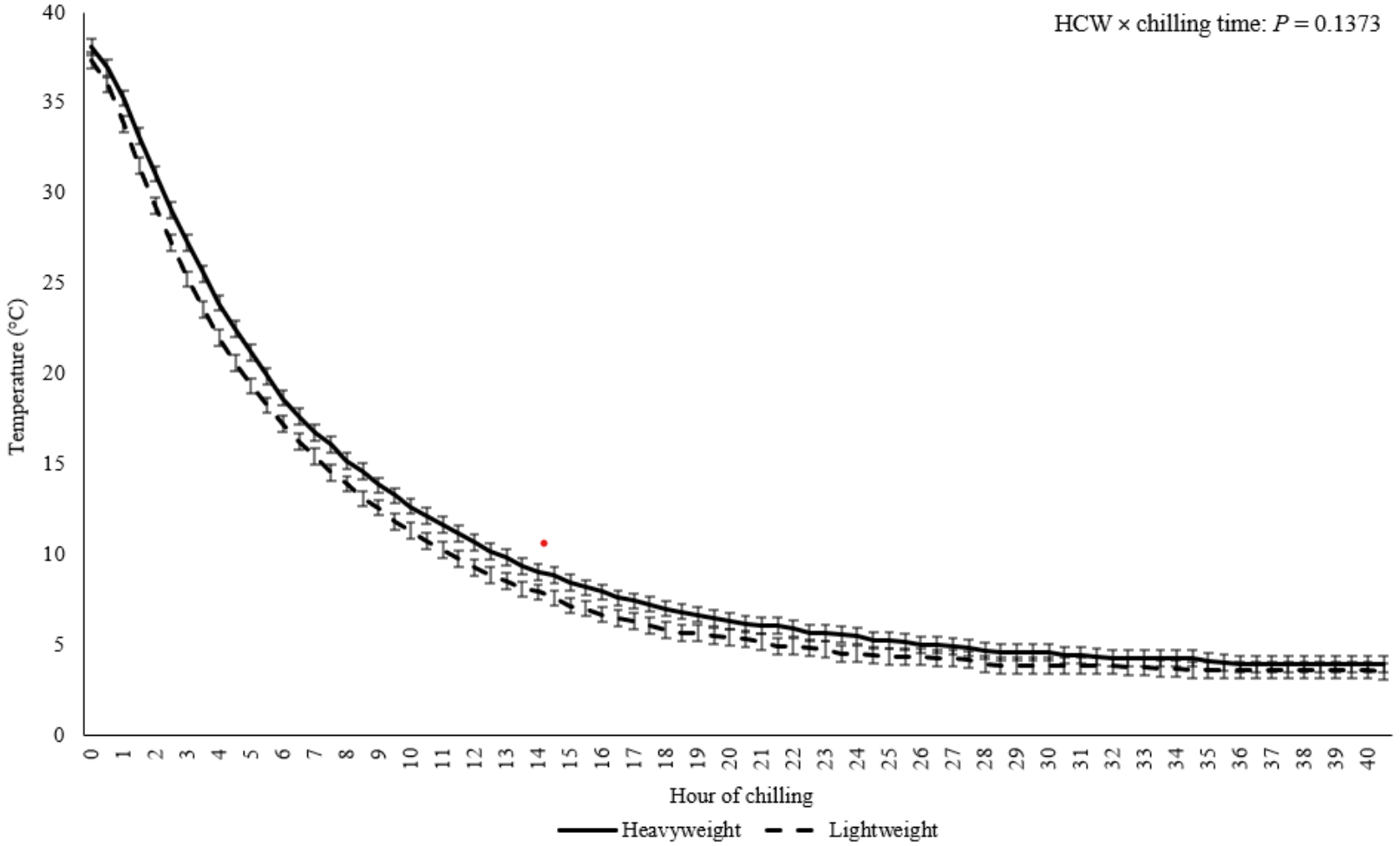


Figure 2.3 - The influence of Heavyweight and Lightweight carcasses and chilling time on deep temperature decline (10 cm) in the rib

Figure 2.4 - The influence of Heavyweight and Lightweight carcasses and chilling time on deep temperature decline (10 cm) in the loin



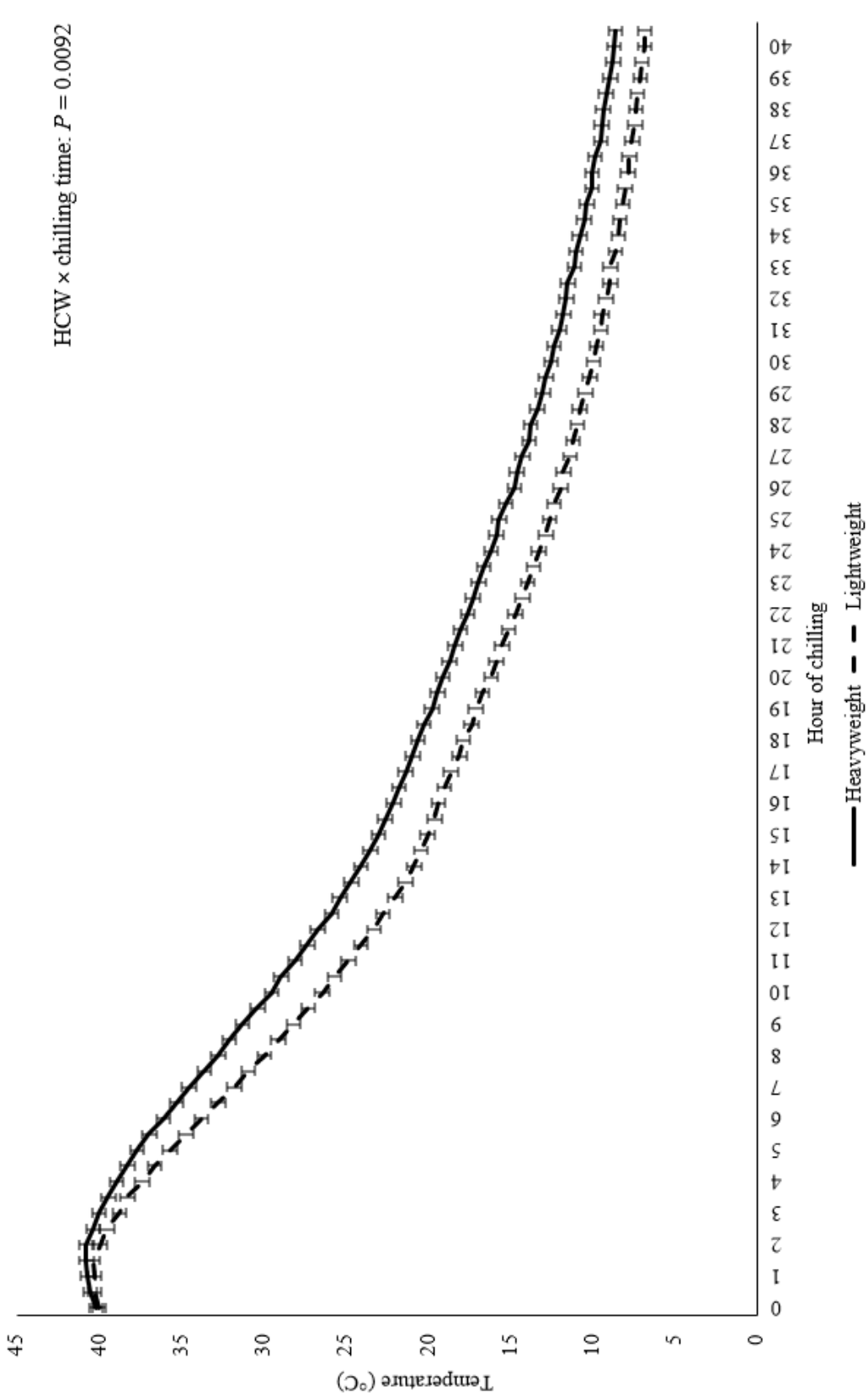


Figure 2.5 - The influence of Heavyweight and Lightweight carcasses and chilling time on deep temperature decline (20 cm) in the round

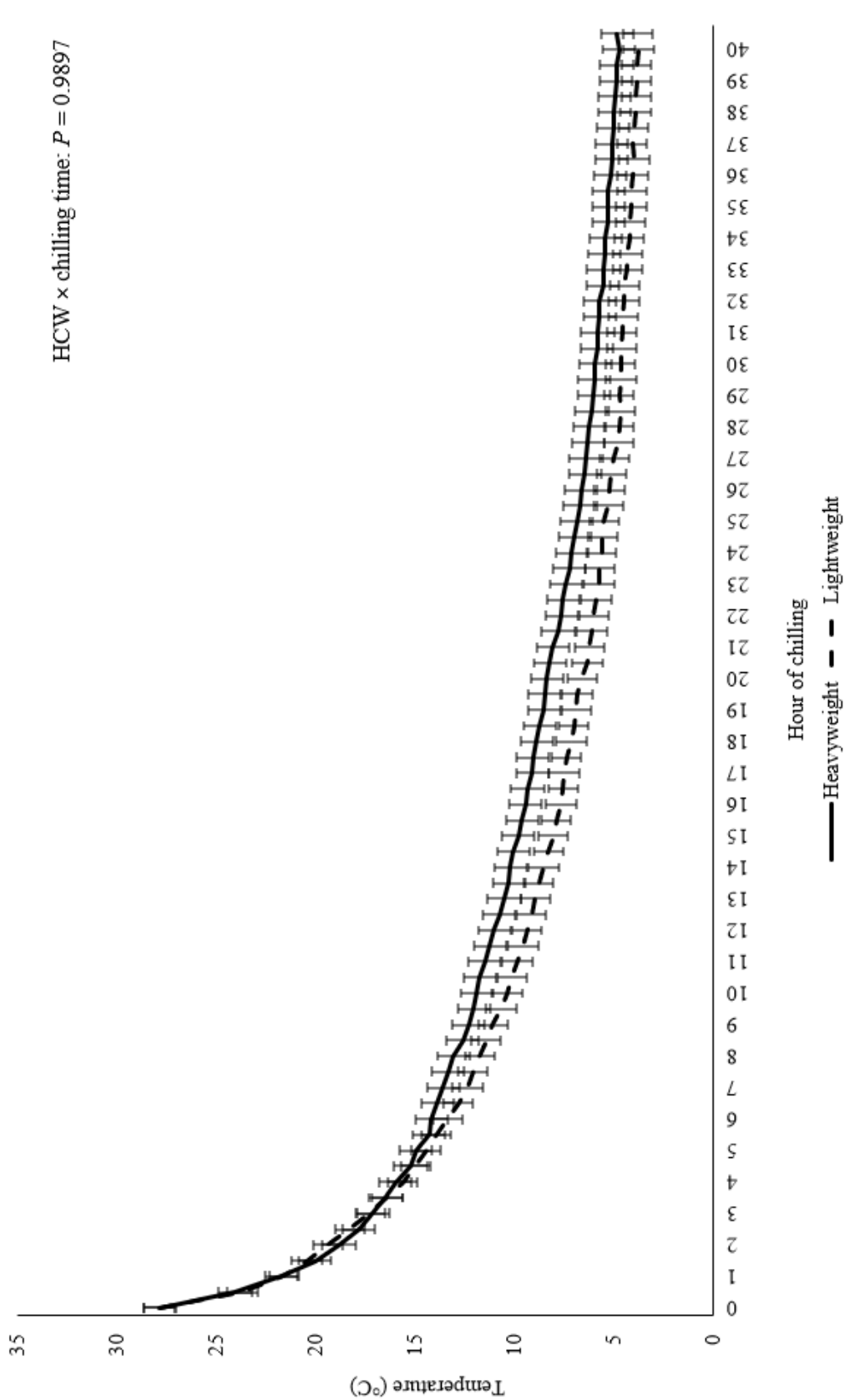


Figure 2.6 - The influence of Heavyweight and Lightweight carcasses and chilling time on sub-surface temperature decline in the chuck

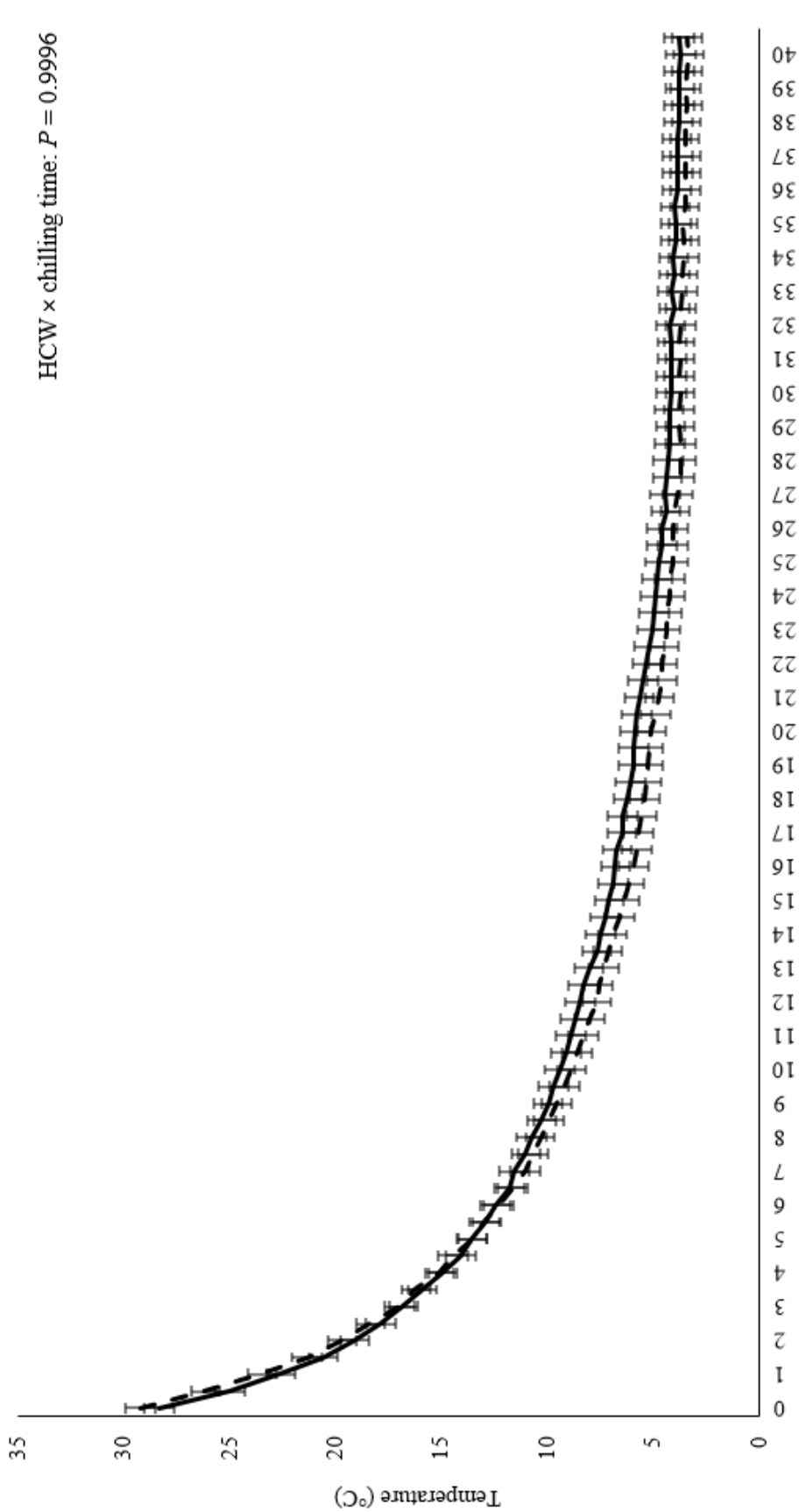
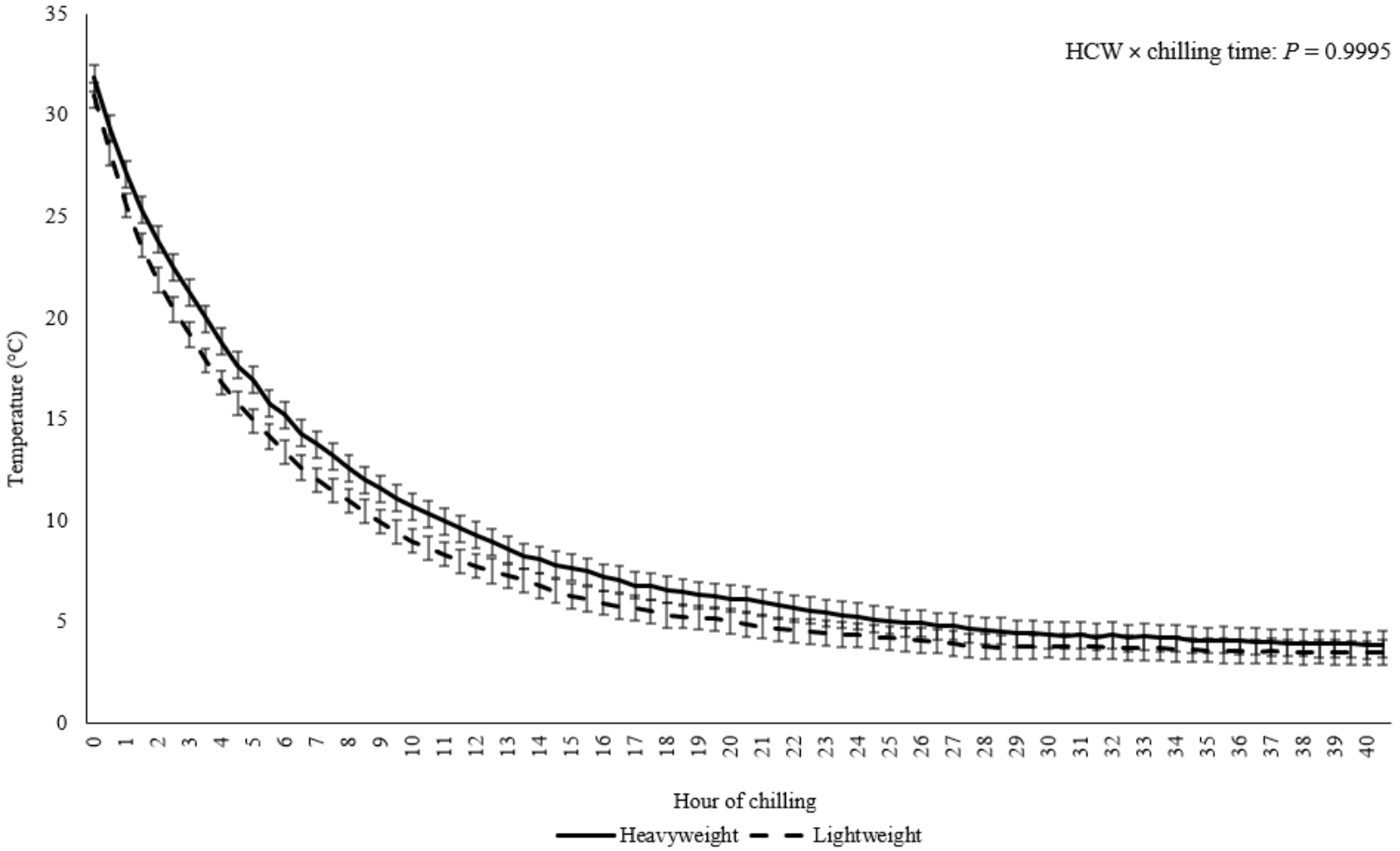


Figure 2.7 - The influence of Heavyweight and Lightweight carcasses and chilling time on sub-surface temperature decline in the rib

Figure 2.8 - The influence of Heavyweight and Lightweight carcasses and chilling time on sub-surface temperature decline in the loin



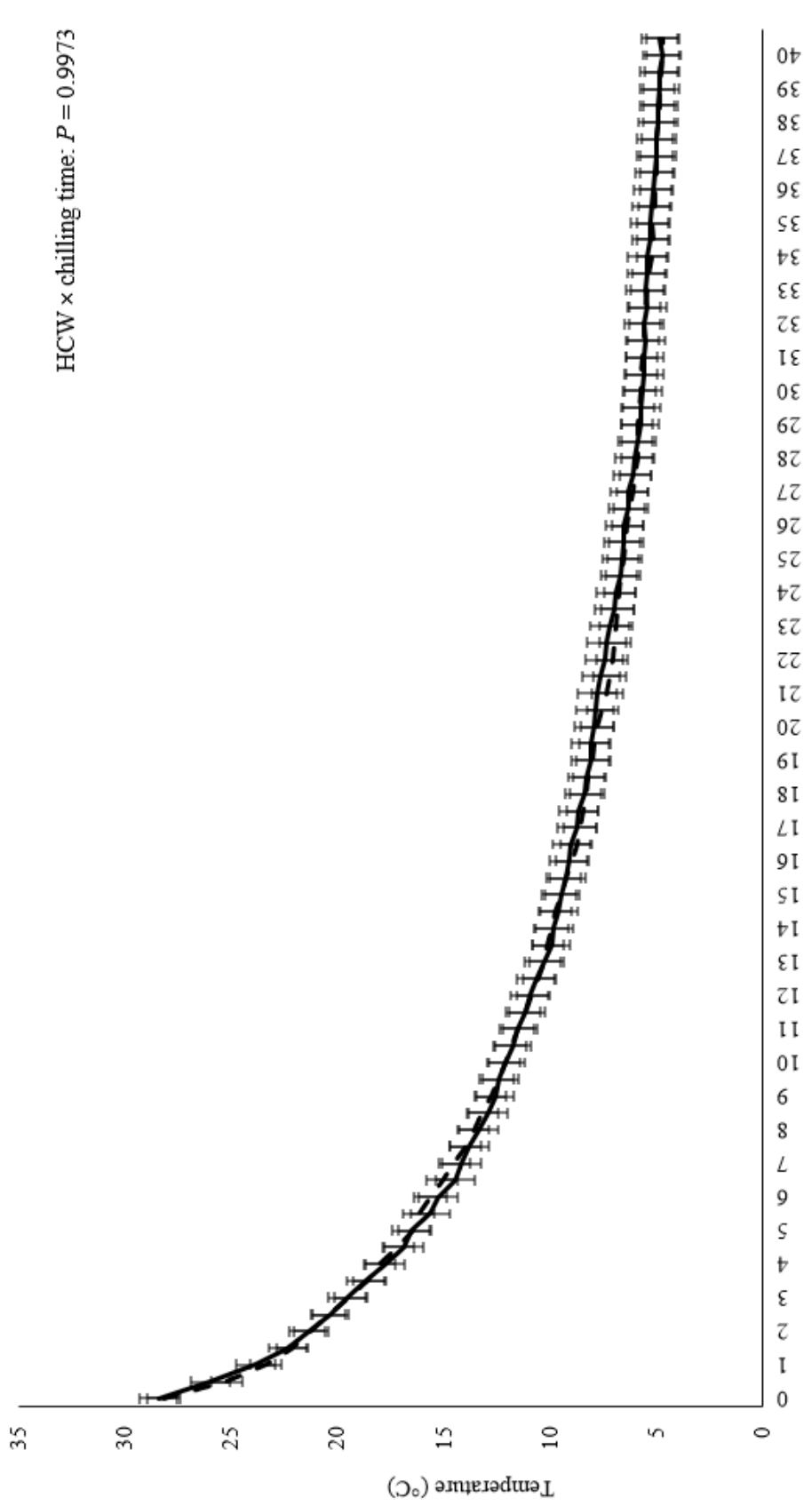


Figure 2.9 - The influence of Heavyweight and Lightweight carcasses and chilling time on sub-surface temperature decline in the round

Figure 2.10 - The influence of time on pH decline of postmortem samples from the *Serratus ventralis*

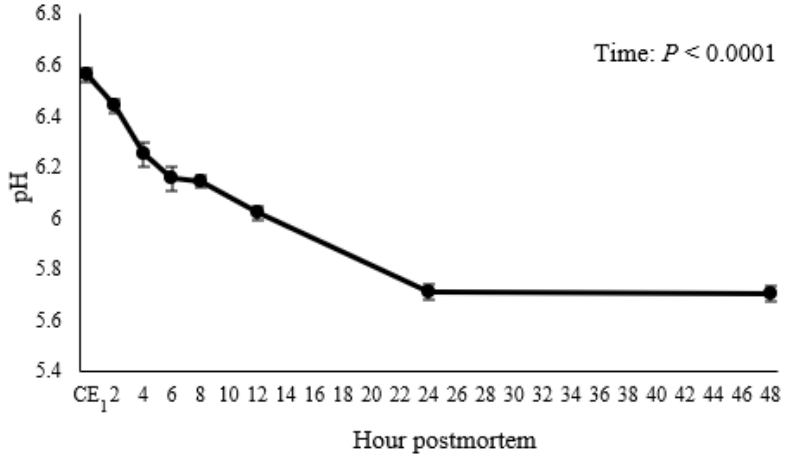


Figure 2.11 - The influence of time on pH decline of postmortem samples from the *Longissimus thoracis*

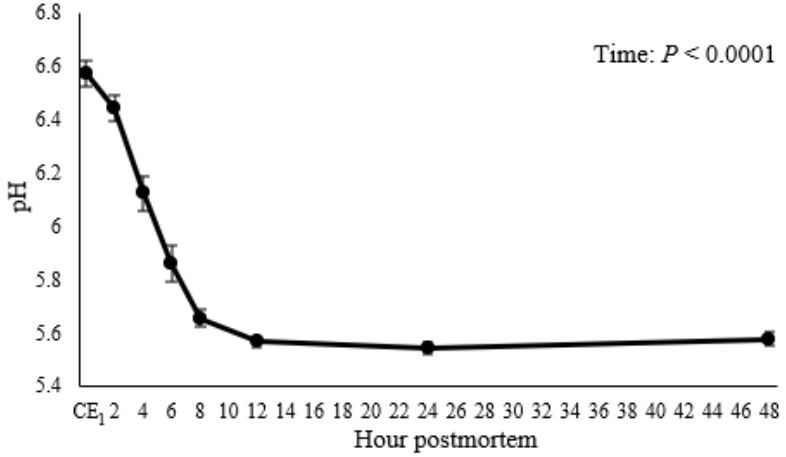


Figure 2.12 - The influence of time on pH decline of postmortem samples from the *longissimus lumborum*

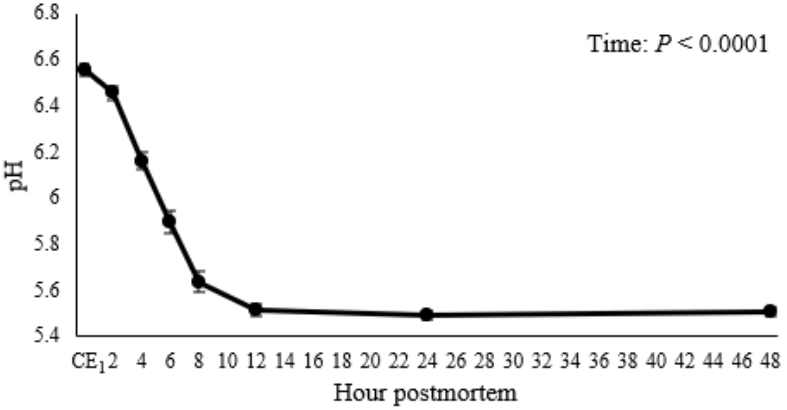
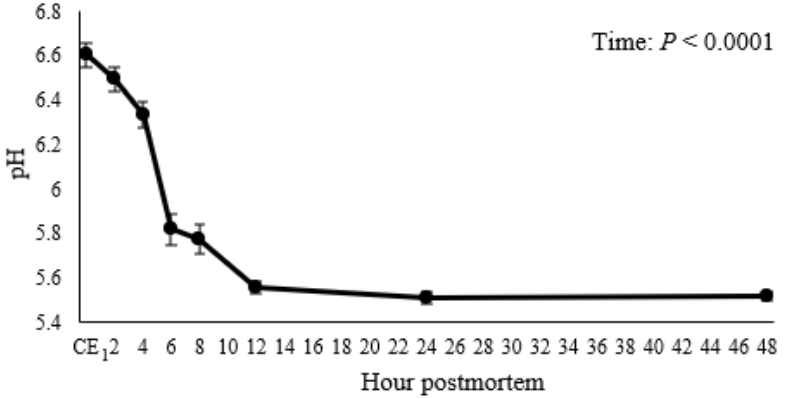


Figure 2.13 - The influence of time on pH decline of postmortem samples from the *Semitendinosus*



[1]CE = Cooler entry

Figure 2.14 – The influence of Heavyweight and Lightweight carcasses and aging time on Warner-Bratzler shear force (WBSF) values of eye of round steaks (*Semitendinosus*)

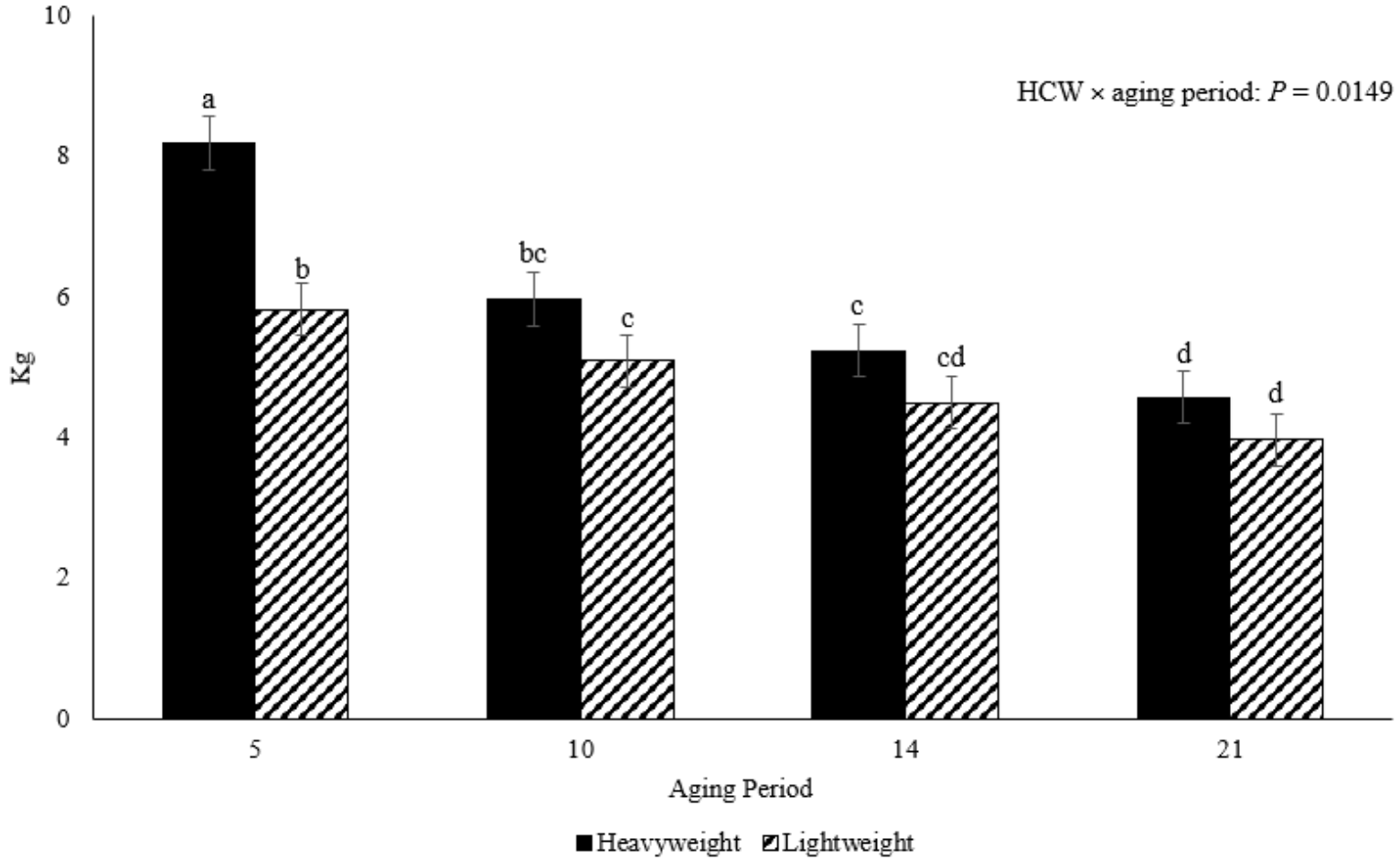


Figure 2.15 - The influence of Heavyweight and Lightweight carcasses and day of retail display on L* values of eye of round steaks (*Semitendinosus*)