Carcass Characteristics and Meat Quality of Dairy-Origin Steers Slaughtered at Eight, Ten and Twelve Months of Age

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Abstract

Approximately 2 million surplus calves are produced annually by the New Zealand dairy industry, which are generally processed at around one week of age as “bobby” calves. Concerns surrounding animal welfare issues, due to the ethics of slaughtering calves at such a young age, pose a threat to the industry’s social licence to farm, consumer acceptability and market access. In addition, the beef sector also faces the challenge of improving production efficiency, whilst minimising environmental impacts. To address these issues, a novel yearling beef production system is proposed, that would utilise dairy-origin calves and implement a slaughter age of between eight and twelve months.

The objective of this study was to compare carcass characteristics and meat quality attributes of Hereford x Friesian-Jersey steers slaughtered at eight, ten and twelve months of age, in order to understand the potential saleable meat yields and type of meat product that could be sourced from yearling dairy-origin cattle. Additionally, the study aimed to determine if postmortem ageing had an effect on meat quality attributes.

Sixty Hereford x Friesian-Jersey weaner steer calves born in spring 2017 were sourced from a commercial calf rearer at three months of age (average 103±1 kg live weight). The calves were managed as a single group; however, they were randomly pre-assigned at eight months of age to one of three slaughter treatments: eight, ten and twelve months of age. Steers were grazed on herb-clover pastures and brassica crops from December 2017 to March 2018, then on ryegrass and white clover pasture until slaughter. Steers were processed in May, July and September 2018 at eight, ten and twelve months of age respectively, at Venison Packers Feilding Ltd.

Growth rates of the three slaughter groups averaged 0.9 kg/day and did not differ between treatments. The final unfasted live weights prior to slaughter at eight, ten and twelve months of age were 252±6 kg, 303±4 kg and 348±5 kg respectively ($P<0.001$), which corresponded to carcass weights of 119±3 kg, 146±3 kg and 174±3 kg ($P<0.001$). Steers slaughtered at twelve months of age achieved a greater dressing-out percentage (50.0±0.2%) than steers slaughtered at eight (47.2±0.2%) and ten (47.4±0.2%) months of age ($P<0.001$). Rib fat depth, P8 fat depth and eye muscle area measured by ultrasound increased at each age (P<0.001). Fat depths at all three ages were below 3 mm, which is the minimum fat depth required for steers to be classified in the ‘P’ fat class designating 3-10 mm of subcutaneous fat, under the current beef carcass classification system. The muscle to bone ratio, intramuscular fat content and yellowness of carcass fat all increased progressively with slaughter age.

Objective meat quality attributes were measured on the *M. longissimus lumborum* (striploin). The caudal half of each striploin muscle was aged for 21 days in vacuum packaging, while the cranial half was frozen immediately after boning, 24 hours postmortem. Shear force values for unaged samples at eight, ten and twelve months of age were 5.1±0.2 kgF, 5.4±0.2 kgF and 5.5±0.2 kgF respectively. Although there was no difference in shear force values, sarcomere length or drip loss between the three slaughter age treatments (P>0.05), ultimate pH and thaw loss increased with age, while cooking loss declined. Meat colour also became darker and redder as animals became older (P<0.001). Proteolytic ageing for 21 days had a positive effect on shear force values and water-holding capacity at all slaughter ages, though differences were minimal (P<0.001).

Overall, the changes in carcass characteristics with age were small, likely due to there being only four months’ difference in age between treatments. However, the greater saleable meat yields and dressing-out percentages at ten and twelve months of age may be advantageous in terms of processing efficiency and profitability. Differences in objective meat quality measures between eight, ten and twelve months of age were also small, indicating that the yearling beef is very tender and of high eating quality. This suggests that the beef obtained from beef-dairy cross cattle slaughtered between eight and twelve months of age and at live weights of 250-300 kg could be processed together under one category, and that the product could justifiably be targeted at markets which offer a premium.

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Table of Contents

List of Tables

List of Figures

Chapter 1. Review of Literature

1.1 Introduction

The red meat sector is a major contributor to New Zealand's economic sustainability, employing 80,000 people and generating NZ$9.5 billion from exports per annum, which represents over 11% of New Zealand's total export earnings (Ministry for Primary Industries, 2019a). Improving productivity and economic returns, whilst minimising environmental impacts and alleviating animal welfare concerns, is a major national challenge (Morris, 2013a; Morris & Kenyon, 2014).

New Zealand's agriculture sector faces potential scrutiny for the practice of slaughtering young surplus calves from the dairy industry, known as 'bobby' calves (Jolly, 2016; Fisher *et al*., 2017; Thomson, 2018). Animal welfare concerns surrounding the slaughter of bobby calves present an increasing threat to the dairy and meat industries' social licence to farm, and to New Zealand's international market reputation and trading capability since animal welfare issues are a potential non-tariff barrier to trade (Jolly, 2016; Thomson, 2018).

Added to bobby calf welfare concerns is the environmental impact of beef cattle production on water quality, soil properties, and greenhouse gas emissions (Morris & Kenyon, 2014; Geenty & Morris, 2017). Many of the environmental issues associated with beef production arise as a consequence of the relatively long production period that is required to achieve current market carcass classification requirements for fat depth, muscling and carcass weight. This is due to older cattle having reduced feed conversion efficiency, increased risk of causing soil damage during winter because of their weight, and potentially greater environmental impacts in terms of nutrient loss to waterways and greenhouse gas emissions (McGee, 2015).

To alleviate these issues, alternative beef production systems need to be considered. There is also an ongoing need for the New Zealand beef sector to position itself at the top-end of the market, with a greater emphasis on product quality and value, rather than volume, to help drive returns given increasing compliance requirements and production costs (Morris, 2013a; Holgate, 2017). An alternative beef cattle finishing system that is used extensively in other countries is accelerated-cycle beef production, where cattle are slaughtered at around eight to twelve months of age

(Domaradzki *et al*., 2017). This system could provide an opportunity to utilise surplus dairy calves, and also help overcome some of the challenges associated with traditional beef production systems in New Zealand.

This review examines the current systems for beef cattle production and carcass classification in New Zealand, and the effects breed and slaughter age have on beef carcass characteristics and meat quality attributes, in order to evaluate the potential for a new accelerated-cycle beef cattle finishing system that has cattle on-farm for a shorter time period of approximately eight to twelve months.

1.2 New Zealand Beef Cattle Industry

1.2.1 Industry Overview

The beef cattle industry is a significant contributor to the New Zealand primary sector, with beef and veal exports for the year ending June 2019 being 453,202 tonnes, valued at NZ$3.37 billion, with co-products accounting for a further NZ$566 million (Meat Industry Association, 2019). As of June 2019, there were 3.92 million beef cattle in New Zealand, of which approximately 1.13 million were beef breeding cows and heifers (Statistics New Zealand, 2019).

In the year ending September 2019, approximately 4.45 million cattle were slaughtered in New Zealand (Ministry for Primary Industries, 2019b). Of these animals, approximately 1.64 million consisted of bulls, steers and heifers finished for export markets, 1.00 million were cull cows from the dairy and beef cattle herds, and the remaining 1.82 million animals were predominantly surplus calves from the dairy industry, commonly known as ‘bobby’ calves (Figure 1.1).

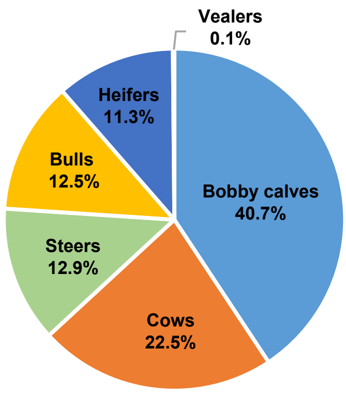

Figure 1.1 Type of cattle slaughtered as a percentage of total number of cattle slaughtered in New Zealand for the year ending September 2019 (Ministry for Primary Industries, 2019b)

Since 2000, growth in dairy cow numbers has meant the dairy industry has become an increasingly important contributor to beef production in New Zealand (Morris, 2013a). It is estimated 69% of all cattle slaughtered in New Zealand (excluding bobby calves) are of dairy origin via bull-beef, cross-bred heifers and steers, and cull cows. Cattle originating from the dairy industry contribute approximately 50-55% of beef product by weight and 45% of total beef product income (Beef + Lamb NZ, 2019a).

1.2.2 Global Beef Consumption

Global beef consumption is currently 69.5 million tonnes per annum, which accounts for 21.4% of total global meat consumption (OECD, 2019). Beef and veal production in New Zealand by volume (bone-in-basis) for the year ending September 2019 was 696,400 tonnes, with 83% of the beef produced being exported offshore (Ministry for Primary Industries, 2019b; Meat Industry Association, 2019). This accounts for 1.0% of global beef production and 6% of traded beef volume (USDA, 2019).

The main export markets for New Zealand beef are North Asia and North America, which account for 52% and 34% of beef exports by value respectively (Figure 1.2) (Meat Industry Association, 2019). Beef exports to China increased by 88% to NZ$1.20 million for the year ending September 2019 compared with the previous year, overtaking the United States as New Zealand's largest beef export market (Beef + Lamb NZ, 2019b). This has been driven by existing strong demand for protein in China, along with increased demand for alternative sources of protein to offset production losses as a result of the African Swine Fever outbreak (Meat Industry Association, 2019).

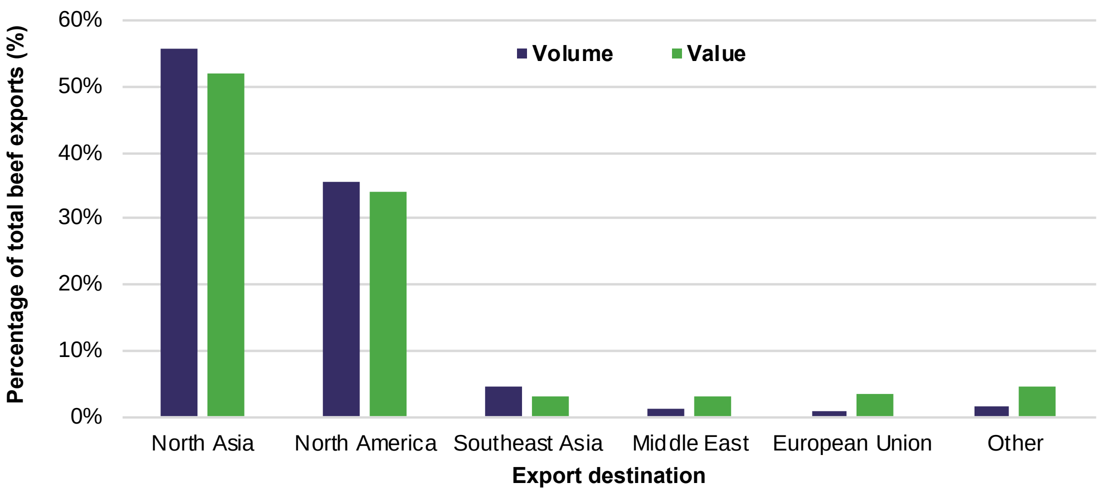

Figure 1.2 New Zealand beef export destinations (by volume and value) for the year ending June 2019 (Adapted from Meat Industry Association, 2019)

1.3 New Zealand Beef Cattle Production Systems

1.3.1 Cattle Breeds Used in New Zealand

The predominant breeds comprising the national beef herd in New Zealand are Angus (37%), mixed breeds (17%), Friesian (14%), Angus x Hereford (12%), Hereford (10%), Friesian x Hereford (4%) and other breeds (6%) including the late maturing European breeds (e.g. Limousin, Simmental and Charolais) (Figure 1.3) (Beef + Lamb NZ, 2019a).

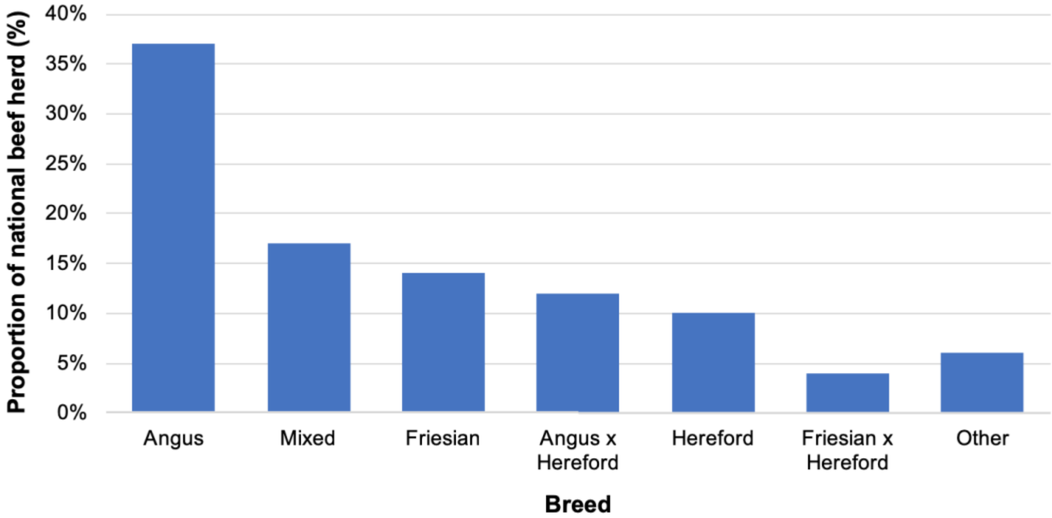

Figure 1.3 Percentage of cattle breeds comprising the national beef cattle herd (including breeding and finishing cattle) for the 2016-17 season (Beef + Lamb NZ, 2019a)

In the New Zealand dairy industry, the predominant dairy breeds are Friesian x Jersey (often termed Kiwi Cross) (48%), Friesian (32%), Jersey (9%), and other breeds (11%) (Beef + Lamb NZ, 2019a). Friesian and beef-cross-Friesian calves are often retained for finishing in beef production systems, while Friesian x Jersey and Jersey calves are considered to have limited use in beef production, due to perceived growth and yield limitations (Jolly, 2016).

1.3.2 Breeding and Finishing Systems

Beef cattle production systems in New Zealand can be broadly divided into breeding cow herds and finishing systems (Morris & Smeaton, 2009). Breeding operations consist of beef breeding cows which are used to generate progeny for finishing as steers and heifers (Geenty & Morris, 2017). Finishing systems utilise cattle sourced from either progeny of beef breeding cows, Friesian or beef-cross-Friesian calves, which are grown to target weights and finished for slaughter (Gleeson, 2003). Beef cattle in New Zealand are predominantly fed low-cost, pasture-based diets with year-round grazing, which offers a comparative advantage internationally due to lower production costs (Morris & Kenyon, 2014). Pasture-raised beef is also considered advantageous for obtaining premiums in some markets (Morris, 2013b).

1.3.3 Types of Beef Derived from Finishing Systems

Finishing systems can be further defined depending on the type of beef and market they supply. The two main types of beef produced are prime and processing beef (Geenty & Morris, 2017). Prime beef, also known as table beef, is usually derived from steers and heifers. When exported as chilled product, this beef generates the highest price per kilogram, with New Zealand's main export markets being Asia, North America and Europe (Meat Industry Association, 2019). Prime beef is also exported as frozen cuts, and a small quantity is exported as frozen quarter carcass beef.

Processing beef, also known as manufacturing or ingredient beef, is sourced from bulls, cull cows and the forequarters of steers and heifers, accounting for around 60% of New Zealand beef exports (Beef + Lamb NZ, 2019b). It is generally boned, boxed and exported frozen as undifferentiated products, as it is typically further processed into products such as minced beef. Most New Zealand processing beef is exported to the United States (Geenty & Morris, 2017).

The proportion of beef carcasses allocated to each beef product class varies depending on the type of animal (Table 1.1). Steers and heifers have the greatest proportion of beef used for prime beef at 54%, with the remaining 46% of the carcass destined for processing beef. In contrast, the majority of bull carcasses are marketed as processing beef, though some cuts can still be used for prime beef, ranging from 0-32% of the carcass depending on the processing company and their market access (Geenty & Morris, 2017).

Table 1.1 Proportion of prime and processing beef obtained from different types of cattle (Geenty & Morris, 2017)

Production Type	Prime Beef	Processing Beef
Steer (beef breeds or beef x dairy crosses)	54%	46%
Heifer (beef breeds or beef x dairy crosses)	54%	46%
Bull (usually Friesian or Friesian cross with some beef breeds)	0-32%	68-100%
Cow (dairy and beef)	0%	100%

1.4 Importance of the Dairy Industry to Beef Production

1.4.1 Sources of Animals from the Dairy Industry

In New Zealand, the number of dairy cattle reached 6.4 million in June 2018 (Statistics New Zealand, 2019). The dairy sector contributes directly to beef production through the slaughter of cull cows and bobby calves, and indirectly through the supply of Friesian bull calves and cross-bred steers or heifers to beef cattle farmers (Morris & Kenyon, 2014; Bown *et al*., 2016). Approximately 700,000-800,000 cull dairy cows and heifers are slaughtered per annum, equivalent to 70-75% of the adult cow kill (Beef + Lamb NZ, 2019a).

An increasing proportion of cattle finished in the beef industry is composed of calves retained from the dairy industry. Approximately 440,000 to 500,000 calves are retained from the dairy industry for beef production per annum, which represents 35-40% of the total calves entering the beef herd (Table 1.2) (Morris, 2013b; Geenty & Morris, 2017). The advantages of finishing calves from the dairy industry rather than beef cattle are improved efficiency (since more feed goes directly into production than towards maintenance of breeding cattle) and that there is no capital tied up in a breeding herd (Morris & Smeaton, 2009). The most common finishing system which utilises dairy-origin cattle, is the bull beef production system (and similar systems utilising beef-dairy cross calves raised as steers or heifers) where Friesian or Friesian-cross calves are bought from a calf rearer at approximately 100 kg live weight and slaughtered between 18 and 30 months of age (Gleeson, 2003; Geenty & Morris, 2017).

Table 1.2 Source and number of calves entering the National Beef Herd per annum (Geenty & Morris, 2017)

Production Type	Number	Percentage
Number of beef cows	1,019,000	
Beef cow calving percentage	80%	
Number of beef calves	812,000	65%
Dairy beef retentions	440,000	35%
Total calf input	**1,252,000**	**100%**

Approximately 1.82 million surplus calves generated by the dairy industry are slaughtered per annum within 4 to 14 days of birth, for production of veal and other co-products (Beef + Lamb NZ, 2019a). It is further estimated that approximately 400,000 calves are also euthanised on-farm as a means of disposal, as they are considered to have no value for beef production (Archer *et al*., 2014). Bobby calves are born by the necessity for dairy cows to become pregnant in order to produce milk that is saleable, and are typically bull and heifer calves born to low-genetic merit parents or heifers, that are not required as dairy replacements, or from unwanted breed crosses such as Jersey (Jolly, 2016). Compared with Friesian cattle, animals with Jersey-based genetics tend to be slower growing (Barton *et al*., 1994; Cook, 2014). There is also widespread belief amongst beef farmers that Jersey-based cattle yield less saleable meat (Cook, 2014; Bown *et al*., 2016).

1.4.2 Challenges Associated with Slaughter of Bobby Calves

Bobby calves have the potential to present an animal welfare and market access issue for New Zealand agriculture (Ministry for Primary Industries, 2016). The very young slaughter age of these calves may be perceived negatively by consumers, affecting New Zealand's reputation in international markets and creating a non-tariff barrier for entry into markets (Ministry for Primary Industries, 2016; Thomson, 2018). Furthermore, the practice of slaughtering bobby calves could have adverse implications on the agriculture sector's social licence to operate in New Zealand (Edwards & Trafford, 2016). A "zero-bobby" policy would require alternative end points for surplus dairy calves. Friesian-Jersey and Jersey calves currently have limited use in beef production and feature heavily in the bobby calf kill. Various methods are needed to reduce the number of calves slaughtered at these young ages, and to consider their potential for meat production (Jolly, 2016; Fisher *et al*., 2017). Given that most land suitable for finishing is already allocated in New Zealand, there is insufficient capacity to significantly increase the number of bobby calves retained for beef production when using current beef production systems, which slaughter cattle between 18 and 36 months of age (Thomson, 2018).

Bobby calves provide a potential source of animals for a newly proposed beef production system in which cattle are slaughtered at approximately one year of age. An accelerated-cycle beef production system where cattle are slaughtered at around one year of age would allow greater turnover of animals and therefore potential for increased utilisation of bobby calves.

1.5 Carcass Classification in New Zealand

Carcass classification provides signals to the farmer regarding desirable composition and conformation for maximising saleable meat yields; hence it is the basis of the payment schedule for beef producers (Schreurs, 2012). The value of a beef carcass to a processor is primarily determined by the quantity of saleable meat, and secondarily by the quality of that beef (Purchas, 2003). Feedback is signalled to farmers through variation in schedule prices based on carcass weight, fat depth and muscling, which in turn form the basis of beef carcass classification in New Zealand, as shown in Table 1.3 (Schreurs, 2012).

Table 1.3 Grading criteria for beef carcass classification in New Zealand (New Zealand Meat Classification Authority, 2004)

Grading Criteria	Sex	Bobby Calf	Steer or Heifer	Bull	Prime Cow	Manufacturing Cow
	Criteria	Milk fed calves, generally under two weeks old	Male cattle castrated young or female cattle having no more than six permanent incisors	Entire cattle with masculine characteristics	Female cattle having more than six permanent incisors	Female cattle having more than six permanent incisors
	Weight Classes	No classes	Yes	Yes	Yes	Yes
	Fat Classes		5	2	3	No classes
	Muscling Classes		3	3	3	No classes

Beef carcasses are firstly classified based on sex class and age. Castrated male cattle are classified as Steer, and entire male cattle are classified as Bull. Female cattle are classified as Heifer if they have no more than six permanent incisors, while females with more than six permanent incisors are classified as either Prime Cow or M (manufacturing) Cow. Steers and Heifers are grouped together under the same classification class, as differences in carcass composition between steers and heifers tend to be small when slaughtered at relatively young ages, and hence both steers and heifers contribute to the prime beef market (Kirton, 1989).

Milk-fed calves, generally younger than two weeks of age, are classified as ‘bobby calves’. In New Zealand, bobby carcasses are not classified into fat classes or muscling classes (New Zealand Meat Classification Authority, 2004). Farmers are paid on a cents/kg carcass weight basis, which may vary depending on what weight range the carcass falls into (Jolly, 2016).

Bulls, steers and heifers are classified into fat classes (New Zealand Meat Classification Authority, 2004). Fat class is assessed by measuring the subcutaneous fat depth over the eye muscle at the 12th rib, but consideration is also given to the fat content of the whole carcass. This is largely because subcutaneous fat depth is used as an indirect indicator of carcass fat percentage and saleable meat yield (Purchas, 2003). As subcutaneous fat depth increases, carcass fat percentage tends to increase and saleable meat yield may decrease if it exceeds the allowable fat level of 10 mm (Schreurs, 2012). Carcasses with high fat depths are penalised by a reduction in price per kilogram (Schreurs, 2012). Heifer and Prime Cow carcasses with fat depths of between 3 and 10 mm are allocated a ‘P’ grade, which generates the highest price per kilogram as it is within the allowable fat range. Steer and Heifer carcasses with low fat depths are allocated either ‘A’ (nil fat) or ‘L’ (<3 mm) grades, while Steer, Heifer and Prime Cow carcasses with excessive fat depths are allocated ‘T’ (11-16 mm) or ‘F’ (≥17 mm) grades. Bulls are graded on only two fat classes, either ‘M’ (<3 mm) or ‘TM’ (≥3 mm) grades.

One of three muscling classes is also assigned to all Bull, Steer, Heifer and Prime Cow carcasses, based on the degree of muscling over the carcass (New Zealand Meat Classification Authority, 2004). Carcasses with greater muscling are rewarded with higher schedule prices per kilogram of carcass, as increased muscling is associated with higher muscle to bone ratios, and therefore greater lean and saleable meat yield.

1.6 Slaughter Ages of Cattle in New Zealand

Cattle are slaughtered at a variety of different ages in New Zealand, depending on the production system from which the animal originates. Differences in slaughter ages between different production systems are an important consideration, due to effects that slaughter age can have on production efficiency, carcass characteristics and meat quality attributes.

Factors that may determine the age at which cattle are slaughtered include:

- feed availability and live weight gain
- ability to winter cattle depending on soil type and feed availability
- sex class of the animal
- growth potential of the breed
- seasonal variation in schedule prices
- target slaughter weights – likely to be dictated by schedule prices
- market requirements for cut sizes or meat quality attributes, as indicated by carcass classification (Purchas, 2003)

1.6.1 Veal Production

Veal is a class of meat produced from calves slaughtered before eight months of age or young cattle slaughtered between eight and twelve months of age (Sans & de Fontguyon, 2009; Domaradzki *et al*., 2017). Depending on the respective slaughter age and feeding regime, veal can be categorised into bobby, rosé or white veal. Bobby veal, produced from surplus calves generated by the dairy industry, is the only type of veal produced on a large scale in New Zealand (Jolly, 2016).

1.6.2 Steer and Heifer Finishing

Bull calves generated from beef breeding cow herds are generally castrated and raised as steers for slaughter to supply the prime beef market, predominantly exported to Europe, Asia and North America (Geenty & Morris, 2017). Unless the finishing farm also has a breeding operation, steers are purchased at weaning at 6 to 8 months of age in autumn, at live weights of over 250 kg, and finished to target carcass weights of 300-400 kg (Geenty & Morris, 2017). Ideally, the steers are slaughtered at 18 to 22 months of age before their second winter, but they can be kept on for a second winter and slaughtered at 27 to 36 months of age (Purchas, 2003). As the carcass grading system of steers is more complex than for bulls due to having a range of fat classes, it is important steers are slaughtered at optimal weights and level of finishing (≥3 mm subcutaneous fat) (Purchas, 2003; Beef + Lamb NZ, 2010).

Non-replacement beef and beef-dairy cross heifers are generally finished at around 18 months of age, with target carcass weights of around 240-300 kg (Purchas, 2003). To meet carcass classification requirements, heifers must be slaughtered before no more than six permanent incisors have erupted, which usually occurs at 30 to 36 months of age (Keeling *et al*., 1991).

Heifer calves are also utilised for beef production in once-bred heifer systems (Geenty & Morris, 2017). These cattle are slaughtered after weaning their first calf at 30 months of age to ensure they are classified as heifers rather than cows in order to receive higher schedule prices, as well as producing off-spring for meat production (Keeling *et al*., 1991).

1.6.3 Bull Beef Finishing

Bull beef production systems utilise entire male calves from the dairy industry, and account for 19% of the adult cattle slaughter in New Zealand (Ministry for Primary Industries, 2019b). Typically, Friesian or beef-cross-Friesian calves are purchased from calf rearers in October and November as three to four-month-old weaned calves, at approximately 100 kg live weight (Geenty & Morris, 2017). These bulls are then either slaughtered between December and June before their second winter at 18 to 22 months of age, or before their third winter at 27 to 30 months of age. Carcass weights are typically in the range of 280-310 kg (Purchas, 2003).

Only two fat classes are used for grading bull carcasses: ‘M’ (<3 mm subcutaneous fat) or ‘TM’ (≥3 mm subcutaneous fat) (New Zealand Meat Classification Authority, 2004). The limited number of fat classes for bulls under carcass classification means there is greater flexibility for slaughter age and weight of bulls than for steers. This is largely due to bulls producing predominantly lean growth, with little fat deposition compared to steers and heifers (Purchas, 2003). The majority of meat from bulls is destined for processing beef, mainly exported as frozen product to the United States (Geenty & Morris, 2017).

1.7 Yearling Beef Production Systems Used Globally

1.7.1 Yearling Beef Production Systems

Yearling beef production is practised in Argentina, Belgium, Poland, Spain and the United Kingdom, where cattle are regularly slaughtered at or prior to one year of age (Domaradzki *et al*., 2017). There is strong demand in Argentina and Europe for young beef and veal, due to this meat being considered a healthy, low-fat, high-quality product with desirable flavour (Domaradzki *et al*., 2017). In Europe, these animals are raised on milk, concentrates and grains rather than pasture, and slaughter generally occurs between six and twelve months of age (Domaradzki *et al*., 2017).

White veal and rosé veal production systems are common in Europe and the United States. White veal is obtained from calves that were fed a milk-only diet. To prevent muscle reddening of white veal, calves are usually penned to restrict movement (Sans & de Fontguyon, 2009). Rosé veal is produced from calves that have a milk and grass diet, and are typically slaughtered at around six to eight months of age (Sans & de Fontguyon, 2009). The calves are allowed greater freedom to move and often remain unweaned from their mother from birth until slaughter (Vea Sous La Mere, 2019).

Grass-fed yearling beef production has become increasingly common in Argentina, allowing farmers to intensify beef production per hectare, and capitalise on faster growth rates associated with younger cattle (Cid *et al*., 2011; Arelovich *et al*., 2011). Approximately 5 million calves are raised for yearling beef production annually, mainly consisting of Angus and Hereford breeds. These cattle are slaughtered at around 10 to 14 months of age, once they reach live weights of around 400-440 kg (200-230 kg carcass weight) for steers or 320-340 kg (160-170 kg carcass weight) for heifers (Cid *et al*., 2011; Agrositio, 2018). Smaller, finished animals are also favoured by the Argentine market as consumers perceive meat from the younger cattle to be more tender (Agrositio, 2018).

1.7.2 Potential Yearling Beef Production in New Zealand

In New Zealand, a pasture-based yearling beef production system could provide an alternative use for surplus dairy-origin calves to help mitigate welfare issues associated with bobby calves. Growing calves in an accelerated-cycle production system would allow for a greater turnover of animals than beef production systems with slaughter ages of 18 to 36 months, helping to reduce the number of calves slaughtered as bobby calves. If cattle could be slaughtered at or just prior to one year of age, this could also improve production efficiency (Cid *et al*., 2011). The growth curve for cattle follows a sigmoid curve (Figure 1.4).

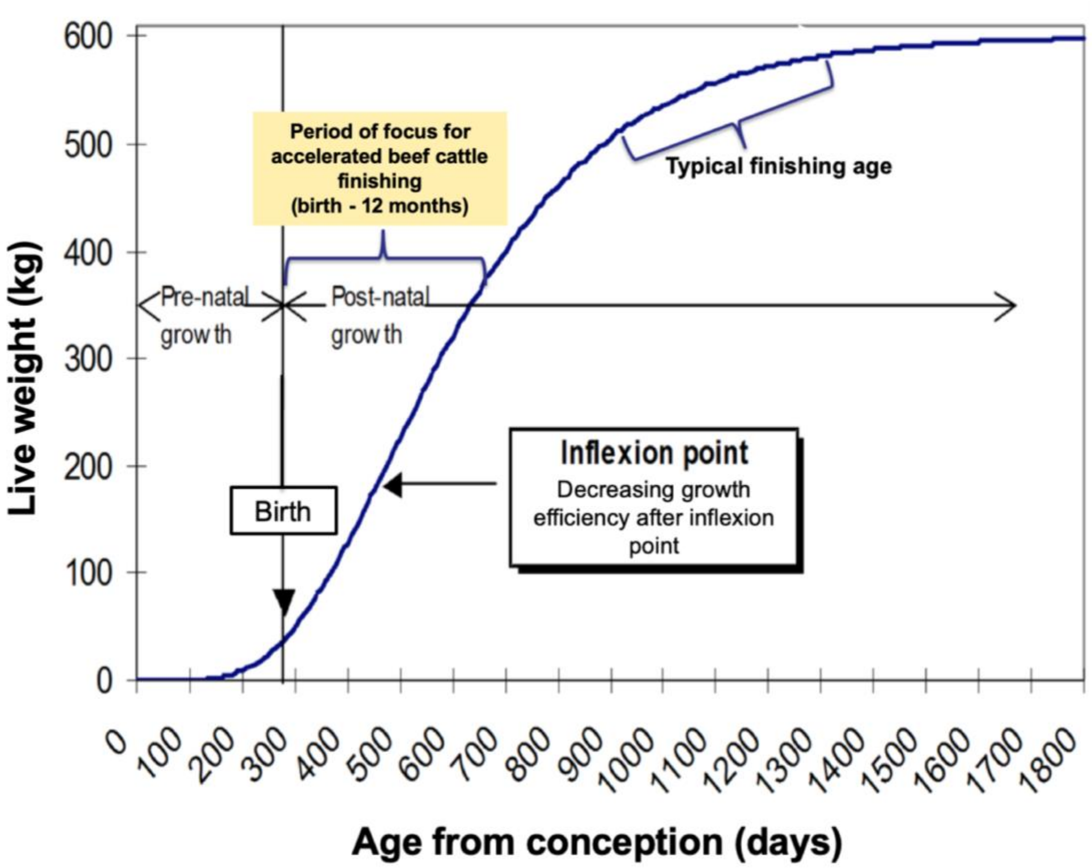

Figure 1.4 General growth pattern of cattle with increasing age (Adapted from Fitzhugh, 1976)

During the first year after birth, the physiology of cattle allows for accelerating growth rates under optimal conditions, up until inflexion is reached at around one year of age (Fitzhugh, 1976). This initial period of accelerating growth is the most efficient in terms of conversion of feed into growth (Amer *et al*., 1994; Marti *et al*., 2013; Vickers & Stewart, 2016). This has been demonstrated with Hereford steers, where feed conversion efficiency decreased from 0.14 kgLWG/kgDMI for steers slaughtered at

12 months of age to 0.05 kgLWG/kgDMI for steers slaughtered at 30 months of age (Marti *et al*., 2013). Similarly, for Holstein bulls, feed conversion efficiency reduced from 0.23 for bulls slaughtered at 10 months of age to 0.19 at 14 months of age (Marti *et al*., 2013).

Beyond the inflexion point, cattle enter a decelerating growth phase as they approach maturity (Figure 1.4) due to increased fat deposition and maintenance requirements (Agastin *et al*., 2013; Park *et al*., 2018). Cattle which are slaughtered at traditional ages of 18 months to 36 months, therefore undergo a period of naturally slowed growth rates (Figure 1.4) and, hence, become less efficient (Vickers & Stewart, 2016). To counteract the environmental issues of finishing cattle over multiple winters to reach a slaughter age of 24 to 36 months (McGee, 2015), cattle could be processed for meat production within one year of age. Nutrient losses from the farm system could be reduced if cattle do not need to be carried through their first winter, which is typically the period of greatest risk in terms of nutrient loss (McGee, 2015). Also, because animals are lighter, there is less chance of pugging or damage to fragile soils (Morris & Kenyon, 2014).

An accelerated-cycle, yearling beef production system would allow for greater turnover of animals, compared with existing New Zealand beef production systems which have cattle on-farm for up to three years. Accelerated-cycle beef production could potentially increase the number of dairy-origin calves utilised for beef production. This could, therefore, reduce the number of animals being slaughtered as bobby calves.

In addition, a yearling beef production system could also aid farmers with feed budgeting over winter when pasture growth is typically slow (Morris, 2017). If slaughter could occur during or prior to the cattle’s first winter, the number of stock units carried through winter could be reduced, and feed reallocated to other stock classes or deferred to a later time. Because of these potential benefits that could be attained from a pasture-based accelerated-cycle beef production system, consideration must first be given to the effect breed and age may have on carcass and meat quality attributes, since slaughtering cattle as yearlings is a novel concept in New Zealand.

1.8 Effect of Age and Breed on Carcass Characteristics

1.8.1 Importance of Carcass Characteristics

Variation in carcass characteristics can have a significant influence on carcass value for both producers and processors (Purchas, 2003). Understanding the implications of different slaughter ages on carcass characteristics is important when considering a new beef production system with a novel slaughter age, to ensure it is profitable for stakeholders across the supply chain. Consideration must also be given to the effect of breed on carcass characteristics, since a yearling beef production system could utilise dairy-origin calves rather than beef breeds.

The carcass characteristics of most importance for beef production are carcass weight, dressing-out percentage, saleable meat yield, subcutaneous fat depth and muscling (Purchas, 2003; New Zealand Meat Classification Authority, 2004). These characteristics influence the value of the carcass and identify the fit of the carcass within the current classification system. Saleable meat yield, also known as retail meat yield or retail beef yield, is the main determinant of carcass value, and is measured indirectly using carcass weight, subcutaneous fat depth and muscling in cattle. Fat depth is used as a proxy for estimating the carcass fat percentage, because saleable meat yield will be reduced if fat depths exceed the level of allowable fat (10 mm) (Schreurs, 2012).

Carcass characteristics and composition are greatly affected by the age and degree of maturity of cattle at slaughter (McGee, 2015). In cattle, lean tissue growth slows and fat deposition increases with age, resulting in a change in the percentage of carcass weight represented by each component from birth to maturity (Keane, 2011; Beermann, 2014; McGee 2015). Growth rates of carcass tissues are defined by allometric growth coefficients. Changes over time are due to differences in the priority use of nutrients by these tissues as animals become older (Beermann, 2014).

This review will consider the effect of slaughter age and breed on carcass characteristics: specifically, dressing-out percentage, lean and saleable meat yield, subcutaneous fat, intramuscular fat and eye muscle area.

1.8.2 Dressing-out Percentage

Effect of age on dressing-out percentage

Dressing-out percentage is the carcass weight expressed as a percentage of live weight (Purchas, 2003; Schreurs, 2012). Dressing-out percentage values generally increase as animals become older and carcass weight increases, as shown in Table 1.4 (Morris *et al*., 1990; Warren *et al*., 2008). When animals are younger and smaller, non-carcass components such as the gut make up a greater proportion of live weight than when the animal is older and heavier. With increasing age and slaughter weight, non-carcass components such as organs grow relatively more slowly than the animal overall, and so decline as a percentage of live weight over time (Keane, 2011). In contrast, carcass tissues, specifically muscle and fat, grow more rapidly than non-carcass tissues as the animal gets older causing dressing-out percent values to increase (Morris *et al*., 1992; Beermann, 2014).

The tendency for the dressing-out percentages to increase with age does not hold true when considering young, milk-fed ruminants. Young ruminants often have similar or greater dressing-out percent values compared with older animals (Table 1.4), due to having less developed non-carcass tissues, especially the fore-gut (Specht *et al*., 1994). Non-carcass components therefore represent a smaller portion of the animal by weight.

Table 1.4 Dressing-out percentages (DO%) of cattle slaughtered from various production systems at different ages, averaged for age categories of 0-8 months, 9-20 months and 21-36 months

Slaughter age	Production type	Breed	Live weight (kg)	Carcass weight (kg)	DO %	Author	Age group DO%
0-8 months							
4 days	Bobby Veal	F	44	26	58.3	Brekke & Wellington, 1969	
4 days	Bobby Veal	F	39	22	55.1	Specht *et al*., 1994	
9 days	Bobby Veal	J x F	30	16	54.3	Kirton *et al*., 1971	
2 months	White Veal	F	90	55	60.9	Brekke & Wellington, 1969	**58.6**
3 months	White Veal	F	131	83	63.2	Brekke & Wellington, 1969	
4 months	White Veal	F	181	107	59.1	Specht *et al*., 1994	
6 months	White Veal	F	229	136	59.6	Domaradzki *et al*., 2017	
9-20 months							
14 months	Steer[c]	A	390	193	49.6	Warren *et al*., 2008	
14 months	Steer[c]	H x F	377	184	48.8	Warren *et al*., 2008	
18 months	Steer	F x F	409	231	55.8	Morris *et al*., 1992	
18 months	Steer	A	451	226	50.1	Muir *et al*., 2001	
18 months	Bull	F	281	142	50.5	Dalton & Everett, 1972	**50.8**
18 months	Bull	F	350	178	50.8	Dalton & Everett, 1972	
19 months	Bull	F	456	235	51.3	Pečiulaitienė *et al*., 2015	
19 months	Steer[c]	A	519	268	51.7	Warren *et al*., 2008	
19 months	Steer[c]	H x F	511	256	50.1	Warren *et al*., 2008	
20 months	Heifer	H x F	462	232	50.1	Pečiulaitienė *et al*., 2015	
21-36 months							
23 months	Steer	F	463	241	52.1	Barton *et al*., 1994	
23 months	Steer	J	354	181	51.2	Barton *et al*., 1994	
23 months	Steer	F x J	432	226	52.2	Barton *et al*., 1994	
24 months	Steer[c]	A	659	348	52.8	Warren *et al*., 2008	
24 months	Steer[c]	H x F	377	323	54.4	Warren *et al*., 2008	
24 months	Steer	H x A	595	302	50.6	Coleman *et al*., 2016	
24 months	Steer	H x AF	624	312	50.1	Coleman *et al*., 2016	
24 months	Steer	H x AFJ	589	293	49.7	Coleman *et al*., 2016	
24 months	Steer	H x AJ	587	289	49.3	Coleman *et al*., 2016	
27 months	Steer	H	610	318	52.1	Muir *et al*., 2000	**51.8**
27 months	Steer	H x F	601	310	52.6	Muir *et al*., 2000	
27 months	Steer	F	609	306	50.2	Muir *et al*., 2000	
27 months	Heifer	H x F	468	240	51.3	Khadem *et al*., 1995	
29 months	Bull	F	559	290	51.9	Muir *et al*., 2001	
29 months	Bull	J x F	522	271	51.9	Muir *et al*., 2001	
29 months	Steer	H x F	629	329	52.3	Muir *et al*., 2000	
29 months	Steer	S x J	505	281	55.6	Purchas *et al*., 1992	
29 months	Steer	H x J	511	265	52.1	Purchas *et al*., 1992	
35 months	Steer	F	753	367	48.7	Muir *et al*., 2000	

[c] Diet: Concentrate and silage. All other animals were fed pasture.
Breed: Angus (A), Brahman (B) Friesian (F), Hereford (H), Jersey (J), Simmental (S)

Effect of breed on dressing-out percentage

Dairy breeds generally have lower dressing-out percentages than traditional New Zealand beef breeds when compared within the same sex and live weight (Table 1.5) (Taylor, 1982; Barton & Pleasants, 1997; Muir *et al*., 2000; Purchas & Morris, 2007; Keane, 2011; Irshad *et al*., 2013). This is a result of dairy breeds typically having higher proportions of non-carcass tissues, notably gut and liver tissue, and mesenteric and omental fat (Barton & Pleasants, 1997; Bown *et al*., 2016). It is possible that beef breeds also deposit more muscle and fat into the carcass earlier than dairy breeds (Bown *et al*., 2016). Beef-dairy crosses tend to have intermediate dressing-out percentages between that of dairy and beef breeds (Table 1.5) (Muir *et al*., 2000; Purchas & Morris, 2007).

Table 1.5 Effect of breed on dressing-out percentages of beef, beef-dairy cross and dairy breed steers

`	Beef Breeds		Cross	Dairy Breeds			Author
	Angus	Hereford	H x F	Friesian	F x J	Jersey	
15 months		54.5_b		50.4_a			Taylor, 1982
27 months	53.5_b		52.9_b	51.5_a			Muir *et al*., 2000
27 months		51.7_b		51.4_b	50.2_a		Purchas & Morris, 2007
30 months	53.9_b	54.1_b		54.1_b		50.9_a	Barton & Pleasants, 1997

$_{a,b}$ Within a row, means with different superscript letters differ significantly (P<0.05)
Breed: Friesian (F), Hereford (H), Jersey (J)

1.8.3 Muscle to Bone Ratio

Effect of age on muscle to bone ratio

A higher muscle to bone (M:B) ratio equates to greater lean meat yield and saleable meat yield, when all other factors remain equal (Irshad *et al*., 2013). As cattle age, the muscle to bone ratio increases because the relative growth rate of muscle is higher than for bone (Table 1.6) (Davies, 1989). It should be noted that the methods used to measure muscle to bone ratios in Table 1.6 may differ between studies.

Table 1.6 Average muscle to bone (M:B) ratios of calves, bulls, steers and heifers slaughtered at different ages, averaged for age categories of 0-12 months, 13-20 months and 21-36 months

Slaughter age	Production type	Breed	Carcass weight (kg)	M:B Ratio	Author	Average M:B ratio for age group
0-12 months						
4 days	Bobby Veal	F	22	1.9	Specht *et al*., 1994	
10 months	Steer	F	210	2.5	Marti *et al*., 2013	**2.3**
12 months	Steer	F	252	2.6	Marti *et al*., 2013	
13-20 months						
14 months	Steer	F	293	2.6	Marti *et al*., 2013	
15 months	Steer[c]	H x F	259	2.8	Nogalski *et al*., 2018	
15 months	Bull[c]	H x F	275	2.6	Pogorzelska *et al*., 2018	
18 months	Steer[c]	H x F	317	3.2	Nogalski *et al*., 2018	
18 months	Bull[c]	H x F	346	2.8	Pogorzelska *et al*., 2018	
18 months	Steer	F x F	231	3.3	Morris *et al*., 1992	**3.1**
18 months	Steer	B x F	231	3.6	Morris *et al*., 1992	
18 months	Bull	A	142	2.9	Dalton & Everett, 1972	
18 months	Bull	F	178	2.7	Dalton & Everett, 1972	
20 months	Steer	F	241	3.4	Bass *et al*., 1981	
20 months	Steer	A	204	3.6	Bass *et al*., 1981	
21-36 months						
30 months	Steer & Heifer	F		3.0	Purchas *et al*., 2002a	
30 months	Steer & Heifer	H		4.4	Purchas *et al*., 2002a	
30 months	Steer & Heifer	H x F		4.2	Purchas *et al*., 2002a	**4.0**
30 months	Steer & Heifer	J		4.4	Purchas *et al*., 2002a	

[c] Diet: Concentrate and silage. All other animals were fed pasture.
Breed: Angus (A), Brahman (B) Friesian (F), Hereford (H), Jersey (J)

Effect of breed on muscle to bone ratio

Friesian cattle have consistently been found to have lower muscle to bone ratios than other breeds, while Angus cattle have higher muscle to bone ratios relative to other breeds (Dalton & Everett, 1972; Bass *et al*., 1981; Barton & Pleasants, 1997; Purchas *et al*., 2002a; Keane, 2011). Jersey cattle have greater muscle to bone ratios than other dairy breeds, but similar ratios to those of beef breeds, due to having finer bones and smaller skeletal frame (Bass *et al*., 1981; Purchas *et al*., 2002a).

1.8.4 Lean and Saleable Meat Yield

Effect of age on lean and saleable meat yield

Lean and saleable meat yields (LMY and SMY) generally increase with age when animals are young, due to minimal fat deposition and increasing muscle to bone ratios (Purchas, 2003). However, beyond the inflexion point at around one year of age, LMY tends to decrease as animals get older and carcass weights become heavier (Table 1.7). Although muscle to bone ratios continue to increase with age, fat deposition increases at a much greater rate (Purchas, 2003; Marti *et al*., 2013). SMY will also decrease with age once the 10 mm fat depth allowance is exceeded (Purchas, 2003). Gender can also have a significant influence on LMY and SMY, due to differences in the rate of muscle and fat deposition between bulls, steers and heifers (Purchas, 2003). Methodologies used to measure carcass composition may have differed between studies in Table 1.7.

Table 1.7 Lean meat yield (LMY), bone and fat percentage of cattle from various production types slaughtered at different ages

Slaughter age	Production type	Breed	LMY%	Bone%	Fat%	Author
4 days	Bobby Veal	F	58.8			Specht *et al*., 1994
10 months	Steer[c]	F	56.9	22.9	19.6	Marti *et al*., 2013
12 months	Steer[c]	F	53.0	20.2	26.3	Marti *et al*., 2013
14 months	Steer[c]	F	52.8	20.1	27.0	Marti *et al*., 2013
15 months	Steer[c]	H x F	54.2	19.5	26.3	Nogalski *et al*., 2018
15 months	Bull[c]	H x F	60.7	23.4	15.9	Pogorzelska *et al*., 2018
18 months	Steer[c]	H x F	48.1	15.2	35.4	Nogalski *et al*., 2018
18 months	Bull[c]	H x F	61.0	21.5	18.3	Pogorzelska *et al*., 2018
18 months	Steer	F x F	64.8[1]	19.4	16.0[2]	Morris *et al*., 1992
18 months	Steer	B x F	64.8[1]	17.9	17.3[2]	Morris *et al*., 1992
18 months	Bull	A	71.6[1]	24.5	3.9[2]	Dalton & Everett, 1972
18 months	Bull	F	70.1[1]	25.9	4.0[2]	Dalton & Everett, 1972
20 months	Steer	F	61	19	20	Bass *et al*., 1981
20 months	Steer	A	62	17	21	Bass *et al*., 1981
23 months	Steer	F	69.0[1]	22.7	8.3[2]	Barton *et al*., 1994
23 months	Steer	J	68.0[1]	22.6	9.4[2]	Barton *et al*., 1994
23 months	Steer	F x J	68.8[1]	22.3	8.9[2]	Barton *et al*., 1994
30 months	Steer	A	63.2[1]	21.6	15.2[2]	Barton & Pleasants, 1997
30 months	Steer	H	62.6[1]	25.3	12.0[2]	Barton & Pleasants, 1997
30 months	Steer	F	60.7[1]	22.7	16.5[2]	Barton & Pleasants, 1997

[1] Saleable meat yield (SMY) – trimmed to 90% visual lean
[2] Refers to excess (trimmed) fat
[c] Diet: Concentrate and silage. All other animals were fed pasture.
Breed: Angus (A), Brahman (B) Friesian (F), Hereford (H), Jersey (J)

Effect of breed on lean and saleable meat yield

Differences in LMY and SMY between breeds are variable, often depending on the age of slaughter and level of fatness. LMY did not differ between dairy (Friesian and Jersey) or British beef breeds (Angus and Hereford), although these breed types had a lower LMY than late maturing European breeds (Charolais and Simmental) (Bass *et al*., 1981). Maternal beef breeds with a high carcass fat percentage may have lower LMY than dairy breeds or terminal beef breeds which have a lower fat percentage (Purchas, 2003). Limousin have been found to have a greater SMY (72.5%) than Friesian (63.2%) and Angus (52.0%) steers due to having a lower fat percentage and greater muscle to bone ratio. Despite Angus having a higher muscle to bone ratio than Friesian, the higher fat percentage resulted in Angus having the lowest SMY (Purchas, 2003).

1.8.5 Subcutaneous and Intramuscular Fat

Subcutaneous fat depth is used to grade carcasses as it is an indirect measure of carcass fat percentage (Schreurs, 2012). Intramuscular fat (IMF) or marbling is also important as it is associated with improved flavour, juiciness and tenderness in beef (Purchas, 1989; Nishimura *et al*., 1999; Thompson, 2004; Moletta *et al*., 2014).

Effect of age on fat deposition

In cattle, the rate of fat deposition increases as animals get closer to maturity, as shown by increasing fat depths in Table 1.8 (Pálsson, 1955; Irshad *et al*., 2013). Due to intramuscular fat being a late-developing fat depot, higher proportions of intramuscular fat are generally found in older animals nearing maturity (Irshad *et al*., 2013; Yim & Hur, 2019). Figure 1.5 illustrates increasing fat deposition with age, and indicates greater variation in carcass fat depths at older ages. Variation in breed, diet, gender and methodologies should be considered when interpreting Table 1.8 and Figure 1.5.

Table 1.8 Subcutaneous rib fat depth and intramuscular fat (IMF) percentage of the *Longissimus thoracis* muscle of bulls, steers and heifers at different ages measured on the carcass at slaughter

Slaughter age	Production type	Breed	Subcutaneous fat (mm)[1]	IMF (%)	Author
4 days	Bobby Veal	F	< 1.0		Specht *et al*., 1994
5 months	Rosé veal	F		0.57	Yim & Hur, 2019
7 months	Rosé veal	F		0.65	Yim & Hur, 2019
10 months	Steer & Bull	F		1.6	Marti *et al*., 2013
12 months	Steer	H x AF	3.1[2]	2.7[2]	Coleman *et al*., 2016
12 months	Steer & Bull	F		2.2	Marti *et al*., 2013
14 months	Steer & Bull	F		3.0	Marti *et al*., 2013
18 months	Steer	H x AFJ	3.8[2]	4.8[2]	Coleman *et al*., 2016
18 months	Steer	F x HF	6.0		Morris *et al*., 1992
18 months	Steer	B x HF	5.5		Morris *et al*., 1992
18 months	Steer	A	2.9		Muir *et al*., 2001
19 months	Heifer	C x A	3.3	1.71	Coleman, 2016
20 months	Steer & Bull	F	4.0		Morris *et al*., 1990
20 months	Steer & Bull	A	4.8		Morris *et al*., 1990
20 months	Steer & Bull	H	6.0		Morris *et al*., 1990
20 months	Steer & Bull	J	4.5		Morris *et al*., 1990
24 months	Steer	H x AF	4.8[2]	5.2[2]	Coleman *et al*., 2016
25 months	Steer	C x A	5.1	2.36	Coleman, 2016
27 months	Steer	H	9.1		Muir *et al*., 2000
27 months	Steer	H x F	7.9		Muir *et al*., 2000
27 months	Steer	F	3.9		Muir *et al*., 2000
27 months	Heifer	H x F	6.2	4.07	Khadem *et al*., 1995
29 months	Steer	H x F	4.8		Muir *et al*., 2000
30 months	Steer	A	12		Barton & Pleasants, 1997
30 months	Steer	H	11.4		Barton & Pleasants, 1997
30 months	Steer	F	5.0		Barton & Pleasants, 1997
31 months	Steer & Bull	F	7.0		Morris *et al*., 1990
31 months	Steer & Bull	A	8.4		Morris *et al*., 1990
31 months	Steer & Bull	H	10.2		Morris *et al*., 1990
31 months	Steer & Bull	J	8.8		Morris *et al*., 1990
35 months	Steer	F	7.2		Muir *et al*., 2000

[1] Fat depths measured using a ruler on the quartered, chilled carcass at the 10/11th rib over the *M. longissimus*
[2] Measured on live animal using ultrasound
Breed: Angus (A), Brahman (B), Charolais (C), Friesian (F), Hereford (H), Jersey (J)

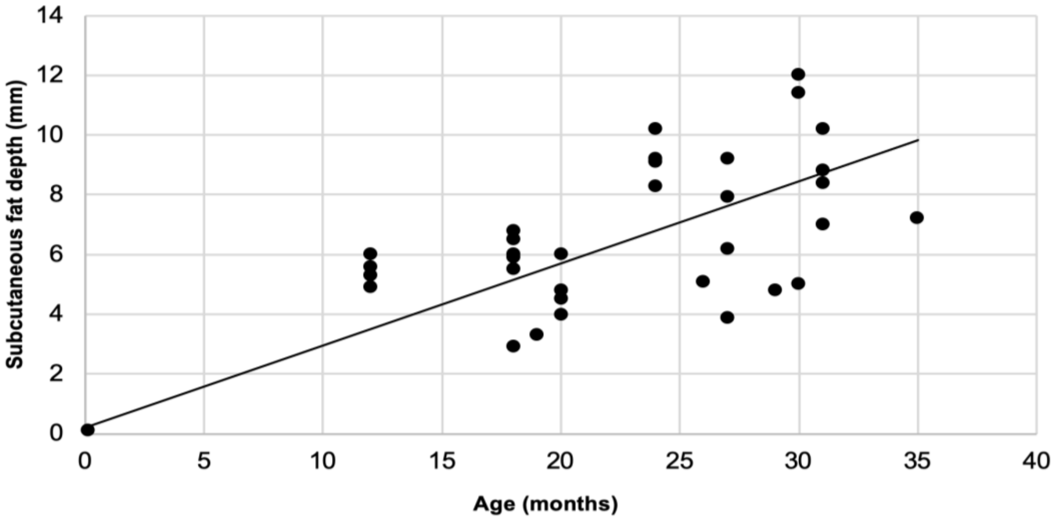

Figure 1.5 Relationship between age and subcutaneous fat depth measured over the *Longissimus thoracis* muscle of calves, bulls, steers and heifers using data from Table 1.8. Line shown is a best fit linear regression (y = 0.275x + 0.2)

Effect of breed on fat deposition

When compared at the same slaughter weight, dairy breeds typically have less subcutaneous fat cover than beef breeds (Table 1.9) (Schaefer *et al*., 1986; Irshad *et al*., 2013). Dairy breeds are therefore less likely to require trimming, but are at greater risk of falling into low fat grades compared with beef breeds, particularly if slaughtered at low weights (Bown *et al*., 2016).

When comparing different dairy breeds, the earlier maturing Jersey breed tends to have more fat than Friesian at any set weight (Morris *et al*., 1990; Barton *et al*., 1994; Barton & Pleasants, 1997; Purchas & Morris, 2007). British beef breeds (Angus and Hereford) have similar fat depths at the same age, but greater fat depths than European breeds (Charolais, Simmental and Limousin) (Barton & Pleasants, 1997; Purchas & Morris, 2007). Subcutaneous fat depths of Hereford-sired steers with 25% dairy genetics were similar for all cross-breeds (Coleman *et al*., 2016).

Table 1.9 Effect of breed on subcutaneous fat depth measured over the *Longissimus thoracis* muscle for beef, beef-dairy cross and dairy breed steers

`	Beef Breeds		Cross	Dairy Breeds			Author
	Angus	Hereford	H x F	Friesian	F x J	Jersey	
15 months	6.5_b			3.0_a			Taylor, 1982
21 months	4.4_b	5.7_d		3.2_a		3.9_b	Morris *et al*., 1990
27 months		9.2_c	7.9_b	3.9_a			Muir *et al*., 2000
30 months	11.5_c	11.6_c		4.6_a		5.9_b	Barton & Pleasants, 1997
31 months	8.4_b	10.2_c		6.8_a		8.8_b	Morris *et al*., 1990

Breed: Friesian (F), Hereford (H), Jersey (J)

$_{a,b,c}$ Within a row, means with differing superscript letters are significantly different (*P*<0.05)

Breeds differ in their ability to deposit intramuscular fat, primarily depending on whether they are early or late maturing breeds (Irshad *et al*., 2013). Early maturing breeds such as Jersey, Hereford and Angus tend to have more intramuscular fat than later maturing breeds such as Friesian (Purchas & Zou, 2008; Irshad *et al*., 2013). Jersey cattle have been found to have higher levels of intramuscular fat than Angus, Hereford and Friesian cattle (Purchas & Barton, 1976), although other studies have found no differences between Angus, Hereford, Hereford x Friesian, and Jersey steers (Muir *et al*., 2000; Barton & Pleasants, 1997). Some breeds are also genetically predisposed to depositing high levels of intramuscular fat, such as the Wagyu breed (Nishimura *et al*., 1999; Ueda *et al*., 2007).

1.8.6 Eye Muscle Area

The transverse surface area of the *Longissimus thoracis et lumborum* muscle (eye muscle (EMA) or rib-eye area) is used to indirectly consider the lean muscle component of carcasses. A larger eye muscle area is associated with a higher proportion of lean meat in the carcass (Johnson *et al*., 1992; Wolcott *et al*., 2001; Purchas, 2003).

Effect of age on eye muscle area

As an animal gets older, eye muscle area increases in response to growth (Table 1.10) (Wolcott *et al*., 2001; Coleman *et al*., 2016). However, the rate of muscle deposition slows as animals get older (Figure 1.6).

Table 1.10 Eye muscle area (EMA) of calves, bulls, steers and heifers at different ages

Slaughter age	Sex class	Breed	EMA (cm_2)	Author
4 days	Bobby Veal	F	13	Specht *et al*., 1994
8 months	Heifer & Steer	A,H,M,S	41	Wolcott *et al*., 2001
12 months	Heifer & Steer	A,H,M,S	50	Wolcott *et al*., 2001
12 months	Steer	H x AF	60	Coleman *et al*., 2016
18 months	Heifer & Steer	A,H,M,S	64	Wolcott *et al*., 2001
18 months	Steer	H x AF	64	Coleman *et al*., 2016
18 months	Steer	F x F	61	Morris *et al*., 1992
18 months	Steer	B x HF	55	Morris *et al*., 1992
21 months	Steer & Bull	F	76	Morris *et al*., 1990
21 months	Steer & Bull	A	79	Morris *et al*., 1990
21 months	Steer & Bull	H	73	Morris *et al*., 1990
21 months	Steer & Bull	J	75	Morris *et al*., 1990
23 months	Steer	F	59	Barton *et al*., 1994
23 months	Steer	J	51	Barton *et al*., 1994
23 months	Steer	F x J	58	Barton *et al*., 1994
24 months	Steer	H x AF	73	Coleman *et al*., 2016
27 months	Heifer	H x F	63	Khadem *et al*., 1995
29 months	Steer	S x J	71	Purchas *et al*., 1992
29 months	Steer	H x J	66	Purchas *et al*., 1992
31 months	Heifer	F	59	Burke *et al*., 1998
31 months	Heifer	J	60	Burke *et al*., 1998
31 months	Steer & Bull	F	91	Morris *et al*., 1990
31 months	Steer & Bull	A	97	Morris *et al*., 1990
31 months	Steer & Bull	H	93	Morris *et al*., 1990
31 months	Steer & Bull	J	92	Morris *et al*., 1990

Breed: Angus (A), Brahman (B), Friesian (F), Hereford (H), Jersey (J), Murray Grey (M), Simmental (S)

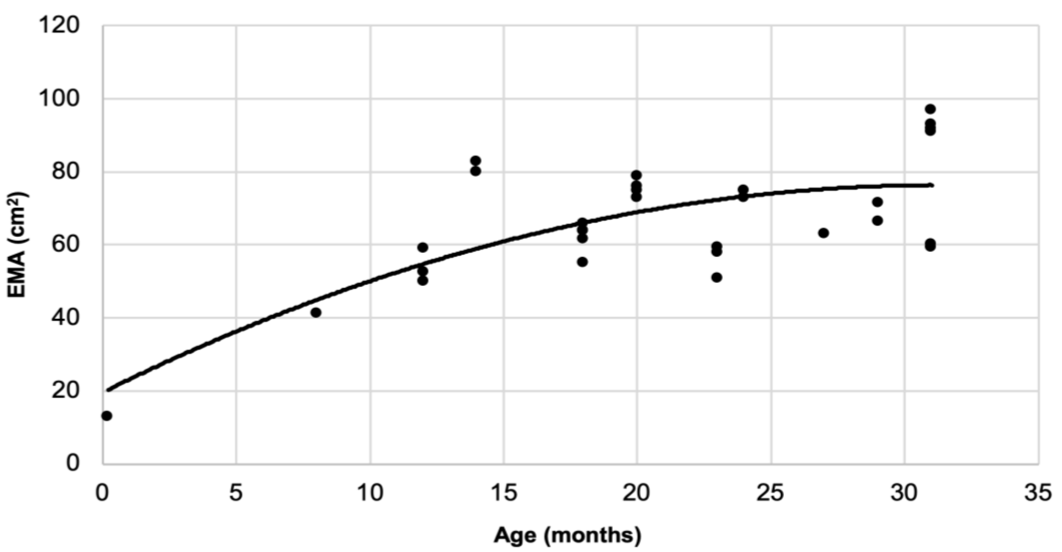

Figure 1.6 Relationship between age and eye muscle area (EMA) of calves, bulls, steers and heifers using data from Table 1.10. Line shown is a best fit polynomial regression ($y = -0.058x^2 + 3.618x + 19.663$)

Effect of breed on eye muscle area

When slaughtered at the same age, Friesian and Jersey cattle have smaller eye muscle areas than Hereford cattle, with Angus and cross-breeds being intermediate (Morris *et al*., 1990; Barton & Pleasants, 1997). However, differences in eye muscle area between dairy and beef breeds tend to be small when adjusted for carcass weight, since the area is primarily determined by slaughter age and weight (Morris *et al*., 1990; Barton & Pleasants, 1997; Keane, 2011).

1.9 Meat Quality Attributes

Meat quality can be defined as the degree to which a product satisfies the needs and expectations of a consumer (Purchas, 1989). The main characteristics of importance to meat quality for the consumer are appearance and palatability, which are influenced by factors such as ultimate pH, lean meat and fat colour, tenderness, juiciness and flavour of the meat (Purchas & Zou, 2008; Coleman *et al*., 2016). Meat quality attributes are mostly not accounted for by the New Zealand carcass classification system and are only considered indirectly, with the primary focus being the identification of carcasses that yield more saleable meat (Schreurs, 2012).

However, meat quality is important for beef production as it influences the value of carcasses for processors and marketers by determining consumer demand for the product and therefore market share (Purchas, 2003). Consumers' eating experience and subsequent repurchasing decisions are both influenced by meat quality (Purchas, 2003). Therefore, meat quality influences which markets beef is suitable for and the price consumers are willing to pay (Geenty & Morris, 2017).

1.9.1 Ultimate pH

The ultimate pH of beef can affect both palatability and appearance characteristics of the product (Purchas, 1989). Ultimate pH for beef under normal conditions is in the range of 5.4-5.6 (Purchas, 2003; Oliete *et al*., 2005). A quadratic relationship exists between ultimate pH and tenderness in beef, with intermediate pH values of 5.8-6.2 generally producing less tender meat than beef with a low or high ultimate pH (Purchas, 1990; Purchas & Aungsupakorn, 1993). Dark coloured ("dark cutting") meat is also associated with an elevated ultimate pH (Sheath & McCall, 2003).

Effect of slaughter age on ultimate pH

Ultimate pH is generally not influenced by age at slaughter. Some studies indicate that ultimate pH increases with age, although differences in pH were small and potentially due to differences in pre-slaughter factors that occur with cattle of different ages (Bouton *et al*., 1978; Du Plessis & Hoffman, 2007; Bureš & Bartoň, 2012). Many other studies have reported no differences in ultimate pH between slaughter ages (Biss *et al*., 1993; Purchas & Grant, 1995; Czyżak-Runowska *et al*., 2017; Pogorzelska-Przybyłek *et al*., 2018; Marenčić *et al*., 2018).

Effect of breed on ultimate pH

Differences in ultimate pH between breeds are uncommon. A comparison of Angus, Hereford x Friesian and Jersey x Friesian steers slaughtered at 33 months of age found no significant difference in ultimate pH (Purchas & Morris, 2007). Ultimate pH of beef from Hereford-sired steers born to beef and beef-dairy cross cows also did not differ between breeds (Coleman *et al*., 2016).

1.9.2 Tenderness

Tenderness is considered one of the most important quality attributes of beef, as it is often the characteristic consumers are most dissatisfied with (Purchas, 2003; Lucero-Borja *et al*., 2014). Factors affecting tenderness in beef include collagen content and solubility, intramuscular fat and ultimate pH (Purchas, 1989; Li *et al*., 2006). Warner-Bratzler shear-force is the most commonly used method to assess tenderness objectively, while subjective tenderness can be measured using sensory panels (Purchas & Morris, 2007).

Effect of slaughter age on tenderness

It is common for tenderness to decrease as cattle get older, when animals are compared over a wide range of ages, as indicated by increasing shear force values in Table 1.11 and Figure 1.7 (Bouton *et al*., 1978; Purchas, 1989; Schönfeldt & Strydom, 2011; Purchas & Grant, 1995; Li *et al*., 2011; Yim & Hur, 2019). Muscle tends to become less tender with increased animal age, as decreased collagen solubility reduces beef tenderness (Hunsley *et al*., 1971; Li *et al*., 2011; Yim & Hur, 2019). Collagen is a structural protein found in connective tissue in which muscle fibres are embedded (Weston *et al*., 2002). Molecules within collagen fibres are held together by intermolecular cross-link bonds (Goll *et al*., 1964). Initially, these are reducible with heat, but become replaced with mature, heat-stable cross-links as an animal ages (Goll *et al*., 1964; Nishimura *et al*., 1999; Weston *et al*., 2002; Mashele *et al*., 2017). This age effect is more observable in muscles with a higher connective tissue content (Bouton *et al*., 1978; Mashele *et al*., 2017). The relationship between age and tenderness, however, is less consistent when cattle of a narrow age range are compared (Bureš & Bartoň, 2012; Marti *et al*., 2013; Pogorzelska-Przybyłek *et al*., 2018; Nogalski *et al*., 2018). Figure 1.7 demonstrates that beef from cattle slaughtered at typical New Zealand finishing ages of 18 to 36 months often produce beef with reduced and less consistent tenderness. In contrast, beef from younger cattle (<18 months) tends to have lower shear force values with less variability in tenderness.

Greater intramuscular fat levels are also associated with improved tenderness (Li *et al*., 2006). Intramuscular fat dilutes the muscle fibres in meat, causing a lower resistance to shearing (Purchas & Barton, 1976; Nishimura *et al*., 1999; Muir *et al*., 2000). The lubrication effect created by stimulation of saliva production from intramuscular fat can also improve subjective tenderness scores (Purchas, 1989; Li *et al*., 2006). Since fat deposition increases with age, older animals may have improved tenderness, however, this effect is generally only observed with very high intramuscular fat levels (Purchas, 1989; Nishimura *et al*., 1999; Li *et al*., 2006).

Table 1.11 Tenderness of *Longissimus* muscle of bulls, steers and heifers slaughtered at different ages measured using Warner-Bratzler shear-force and trained sensory panels

Slaughter age	Production type	Breed	Work done (kg F)	Peak force (kg F)	Sensory score[1]	Days aged	Author
0-12 months							
2 months	White veal	H x A		3.64	78	0	Bouton *et al*., 1978
3 months	White Veal	F		2.85	57	0	Johnson *et al*., 1988
3 months	Veal	Q		2.94		0	Li *et al*., 2011
4 months	White Veal	F		2.46	69	6	Lensink *et al*., 2001
5 months	White Veal	F		2.40		7	Gottardo *et al*., 2005
6 months	White Veal	L		6.44		12	Domaradzki *et al*., 2017
7 months	White Veal	L		5.66		12	Domaradzki *et al*., 2017
9 months	Rosé Veal	A		4.75	60	0	Bouton *et al*., 1978
9 months	Steer	Q		3.53		0	Li *et al*., 2011
10 months	Steer & Bull	F		4.8		7	Marti *et al*., 2013
11 months	White Veal	L		2.40		10	Domaradzki *et al*., 2017
12 months	Steer	Q		4.21		0	Li *et al*., 2011
12 months	Steer & Bull	F		5.3		7	Marti *et al*., 2013
13-18 months							
14 months	Steer & Bull	F		5.3		7	Marti *et al*., 2013
14 months	Bull[c]	C x S		4.55	50	0	Bureš & Bartoň, 2012
14 months	Heifer[c]	C x S		3.52	60	0	Bureš & Bartoň, 2012
15 months	Steer[c]	H x F		3.85	70	0	Nogalski *et al*., 2018
15 months	Steer	Q		5.34		0	Li *et al*., 2011
16 months	Steer	A	3.23	4.52	55	0	Bouton *et al*., 1978
18 months	Steer[c]	H x F		3.78	76	0	Nogalski *et al*., 2018
18 months	Heifer[c]	A		4.98	55	7	Ahnström *et al*., 2012
18 months	Bull[c]	C x S		4.32	54	0	Bureš & Bartoň, 2012
18 months	Heifer[c]	C x S		3.23	34	0	Bureš & Bartoň, 2012
19-36 months							
19 months	Heifer	C x A	2.65	8.33		7	Coleman, 2016
20 months	Steer & Bull	H x F	2.95	9.85		7	Purchas & Grant, 1995
20 months	Steer & Bull	H x F	3.53	12.14		0	Purchas *et al*., 1997
22-25 months	Steer	H x A	2.63	9.42		7	Coleman *et al*., 2016
26 months	Steer	C x A	2.64	9.41		7	Coleman, 2016
27 months	Steer	H		5.89	29	6	Muir *et al*., 2000
27 months	Steer	H x F		5.83	32	6	Muir *et al*., 2000
27 months	Steer	F		6.23	64	6	Muir *et al*., 2000
27 months	Steer	A	2.99	12.13	52	6	Purchas & Morris, 2007
27 months	Steer	H x F	3.36	11.78	49	6	Purchas & Morris, 2007
27 months	Steer	J x F	3.69	13.80	45	6	Purchas & Morris, 2007
28 months	Steer & Bull	H x F	3.78	14.52		0	Purchas *et al*., 1997
28 months	Steer & Bull	H x F	3.88	13.80		7	Purchas & Grant, 1995
31 months	Heifer	H x F	2.99	10.27		7	Burke *et al*., 1998
31 months	Heifer	H x J	3.24	9.47		7	Burke *et al*., 1998

[c] Diet: Concentrate and silage. All other animals were fed pasture.
[1] Assessed on a scale of 1 (least tender) to 100 (most tender) by trained sensory panel
Breed: Angus (A), Charolais (C), Friesian (F), Hereford (H), Jersey (J), Limousin (L), Simmental (S), Qinchuan (Q)

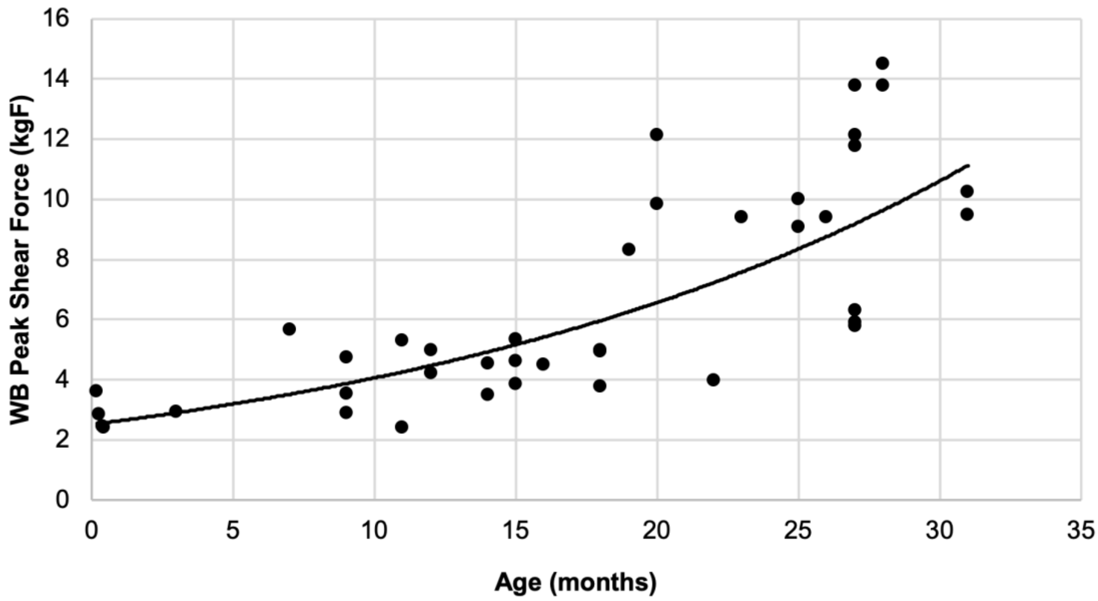

Figure 1.7 Relationship between age and Warner-Bratzler peak shear force values for *Longissimus* samples from bulls, steers and heifers using data from Table 1.11. Line shown is a best fit exponential regression ($y = 2.519e^{0.048x}$)

Effect of breed on tenderness

Tenderness of meat from beef and dairy breeds does not differ when compared at the same slaughter age (Table 1.12) (Beanaman *et al*., 1962; Taylor, 1982; Purchas & Barton, 1976; Schaefer *et al*., 1986; Purchas & Morris, 2007; Coleman *et al*., 2016). Jersey cattle have also sometimes been found to have more tender meat than other dairy breeds, likely due to the effect of greater intramuscular fat (Purchas & Barton, 1976; Purchas, 1989; Purchas, 2003). However, no difference was observed in studies involving Friesian x Jersey steers and steers with only 25% Jersey genetics, indicating improved tenderness may only be noticeable with cattle with a high proportion of Jersey genetics (Purchas & Morris, 2007; Coleman *et al*., 2016).

Table 1.12 Effect of breed on tenderness for unaged *Longissimus* samples from beef, beef-dairy cross and dairy breed steers measured using Warner-Bratzler shear force

`	Beef breeds		Cross	Dairy breeds			Author
	Angus	Hereford	H x F	Friesian	F x J	Jersey	
18 months	5.6	5.1		5.2			Beanaman *et al*., 1962
18 months	5.6	5.1		5.2			Beanaman *et al*., 1962
27 months		5.9	5.8	6.2			Muir *et al*., 2000
27 months	12.1		11.8		13.8		Purchas & Morris, 2007
30 months	8.9^{a}			10.1^{b}		9.0^{a}	Purchas & Barton, 1976

^{a,b} Within a row, means with different superscript letters differ significantly (P<0.05)
Breed: Friesian (F), Hereford (H), Jersey (J)

1.9.3 Effect of Proteolytic Ageing on Tenderness

Postmortem ageing of beef is a technique commonly used to improve meat quality, having consistently been shown to enhance beef tenderness, with longer storage times associated with increasing tenderness (Table 1.13) (Jones *et al*., 1991; Aalhus *et al*., 1992; Mandell *et al*., 2001; Wu *et al*., 2014; Yim & Hur, 2019). Beef is aged by chilling meat at a constant temperature between 0-2ºC, typically using vacuum packaging (Beef + Lamb NZ, 2010). This improves beef tenderness through the process of proteolysis, where muscle fibres are slowly broken down by naturally occurring proteolytic enzymes within the muscle (Jones *et al*., 1991; Purchas, 2004). Slaughter age generally does not affect proteolytic enzyme activity, with the key determinant of tenderness with ageing being the number of days aged (Table 1.13) (Yim & Hur, 2019).

However, breed can influence the effectiveness of postmortem ageing on tenderness. *Bos taurus* breeds, such as Angus, Hereford, and Friesian, tend to produce more tender meat than *Bos indicus* cattle, such as Brahman and Nellore, due to differences in the calpain system (Wheeler *et al.,* 1990). Calpains are major proteases involved in the ageing process, which are inhibited by calpastatin. *Bos indicus* cattle have higher concentrations of calpastatin in the muscle, resulting in less muscle degradation during ageing and therefore less tender meat (Wheeler *et al.,* 1990; Aroeira *et al*., 2016).

Table 1.13 Effect of vacuum packed ageing on Warner-Bratzler shear force values for beef *Longissimus* samples

Slaughter age	Sex	Breed	Number of days aged					Author
			0	7	14	21	28	
5 months	Veal/Bull	Holstein	12.4^{a}	9.3^{b}		7.2^{c}	4.5^{d}	Yim & Hur, 2019
8 months	Veal Bull	Holstein	14.1^{a}	13.0^{b}		10.2^{c}	8.9^{d}	Yim & Hur, 2019
10-12 months[C]	Veal/Bull	Holstein	4.8^{a}	3.6^{b}				Mandell *et al*., 2001
18 months[C]	Steer/Heifer	Friesian	7.3^{a}	6.5^{b}				Aalhus *et al*., 1992
18-24 months	Bull	Angus	9.7^{a}	8.5^{b}	6.5^{c}	5.6^{d}	5.1^{e}	Wu *et al*., 2014
24-36 months	Steer/Heifer	Mixed	11.9^{a}			9.9^{b}		Purchas, 2004

^{a,b,c,d,e} Within a row, means with different superscript letters differ significantly (P<0.05)
[C] Diet: Concentrate and grain. All other animals were fed pasture.

1.9.4 Lean Meat and Fat Colour

Lean meat and fat colour are appearance characteristics that have an important influence on consumers' purchasing decisions as they are some of the few characteristics that can be assessed at the point of sale (Young & West, 2001). Bright, light red coloured meat represents freshness to consumers (Faustman, 2014).

Effect of slaughter age on lean meat colour

Lean meat colour tends to become darker and redder as cattle get older, due to greater myoglobin concentrations in the animal, as shown in Table 1.14, and Figures 1.8 and 1.9 (Purchas, 2003; Li *et al*., 2011; Marenčić *et al*., 2018). Myoglobin is the pigment largely responsible for the red colour of meat (Purchas, 1989). Veal, in particular white veal, tends to be lighter and pinker in colour, while beef from older animals is darker and redder (Purchas, 1989). Differences in meat colour due to slaughter age are often only observed when animals with a large difference in age are compared (Purchas, 1989; Ahnström *et al*., 2012; Bureš & Bartoň, 2012; Pogorzelska-Przybyłek *et al*., 2018). However, meat from older animals with a high level of intramuscular fat may have a lighter appearance (Purchas, 2003).

Table 1.14 Lean meat colour of *Longissimus* muscle of bulls, steers and heifers slaughtered at different ages measured using chromameter

Slaughter age	Production type	Breed	L* (lightness)	a* (redness)	b* (yellowness)	Author
0-12 months						
1 day	Bobby Veal	J	51.5	6.6	9.5	Biss *et al*., 1993
5 days	Bobby Veal	J	50.4	7.2	8.9	Biss *et al*., 1993
14 days	Bobby Veal	J	48.5	7.5	8.3	Biss *et al*., 1993
21 days	Bobby Veal	J	50.0	8.3	10.0	Biss *et al*., 1993
4 months	White Veal	F	58.7	11.2	8.5	Lensink *et al*., 2001
4 months	White Veal	F	58.5			Tarantola *et al*., 2003
5 months	White Veal	F	54.1	12.6	8.9	Gottardo *et al*., 2005
5 months	Rosé Veal	F	50.4	11.8	8.7	Yim & Hur, 2019
5 months	White Veal	F	61.0			Tarantola *et al*., 2003
6 months	White Veal	L	40.3			Domaradzki *et al*., 2017
6 months	Rosé Veal	F	42.8	11.3	6.6	Yim & Hur, 2019
6 months	White Veal	F	58.8	11.3		Tarantola *et al*., 2003
7 months	White Veal	L	38.6			Domaradzki *et al*., 2017
7 months	Rosé Veal	F	42.8	7.8	6.6	Yim & Hur, 2019
8 months	White Veal	L	36.6			Domaradzki *et al*., 2017
8 months	Rosé Veal	F	44.8		3.1	Yim & Hur, 2019
9 months	White Veal	L x S	40.1	8.7	7.5	Domaradzki *et al*., 2017
11 months	White Veal	L	43.2	9.4	8.8	Domaradzki *et al*., 2017
13-18 months						
13 months	Heifer	S	43.8	28.6	11.7	Marenčić *et al*., 2018
14 months	Bull	S	42.6	29.2	11.4	Marenčić *et al*., 2018
14 months	Bull[c]	C x S	43.2	13.7	13.9	Bureš & Bartoň, 2012
14 months	Heifer[c]	C x S	44.6	12.7	13.8	Bureš & Bartoň, 2012
14-15 months	Heifer	S	43.7	28.8	11.7	Marenčić *et al*., 2018
15-16 months	Bull	S	42.1	29.4	11.5	Marenčić *et al*., 2018
15 months	Steer[c]	H x F	35.7	18.4	13.7	Nogalski *et al*., 2018
16-17 months	Heifer	S	43.6	28.9	11.8	Marenčić *et al*., 2018
17-18 months	Bull	S	41.6	29.4	11.5	Marenčić *et al*., 2018
18 months	Steer[c]	H x F	36.8	18.9	14.6	Nogalski *et al*., 2018
18 months	Heifer[c]	A	35.2	17.8	3.6	Ahnström *et al*., 2012
18 months	Bull[c]	C x S	45.4	13.1	13.9	Bureš & Bartoň, 2012
18 months	Heifer[c]	C x S	42.2	13.7	13.0	Bureš & Bartoň, 2012
19-36 months						
19 months	Heifer	C x A	37.9	13.7	4.0	Coleman, 2016
20 months	Bull & Steer	H x F	34.1	18.5	8.2	Purchas & Grant, 1995
22 months	Heifer[c]	A	35.3	20.8	6.2	Ahnström *et al*., 2012
22-25 months	Steer	H x A	38.9	14.2	4.2	Coleman *et al*., 2016
26 months	Steer	C x A	38.2	15.5	4.4	Coleman, 2016
27 months	Steer	H	35.2	21.9	11.9	Muir *et al*., 2000
27 months	Steer	H x F	33.2	21.4	10.9	Muir *et al*., 2000
27 months	Steer	F	33.3	21.1	10.9	Muir *et al*., 2000
27 months	Steer	A	37.0	16.7	5.6	Purchas & Morris, 2007
27 months	Steer	H x F	35.1	14.3	4.8	Purchas & Morris, 2007
27 months	Steer	J x F	35.0	15.4	5.6	Purchas & Morris, 2007
28 months	Bull & Steer	H x F	32.1	18.2	7.7	Purchas & Grant, 1995
31 months	Heifer	H x F	34.6	23.5	10.8	Burke *et al*., 1998
31 months	Heifer	H x J	34.5	24.7	12.4	Burke *et al*., 1998

[c] Diet: Concentrate and silage. All other animals were fed pasture.
Breed: Angus (A), Charolais (C), Friesian (F), Hereford (H), Jersey (J), Limousin (L), Simmental (S)

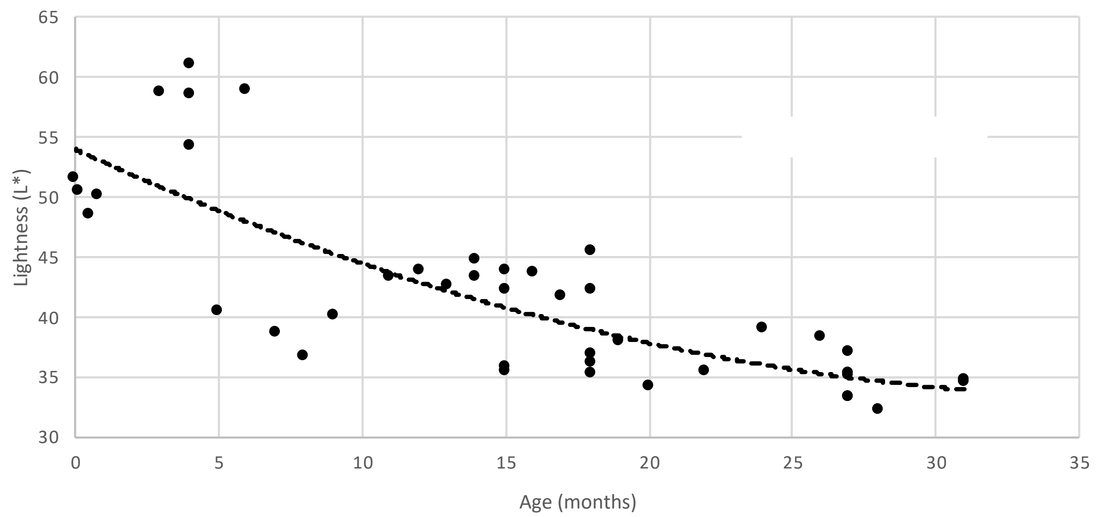

Figure 1.8 Relationship between age and lean meat colour (lightness) of lean meat from bulls, steers and heifers collated using data from Table 1.14. Line shown is a best fit polynomial regression ($y = 0.011x^2 - 0.978x + 53.35$)

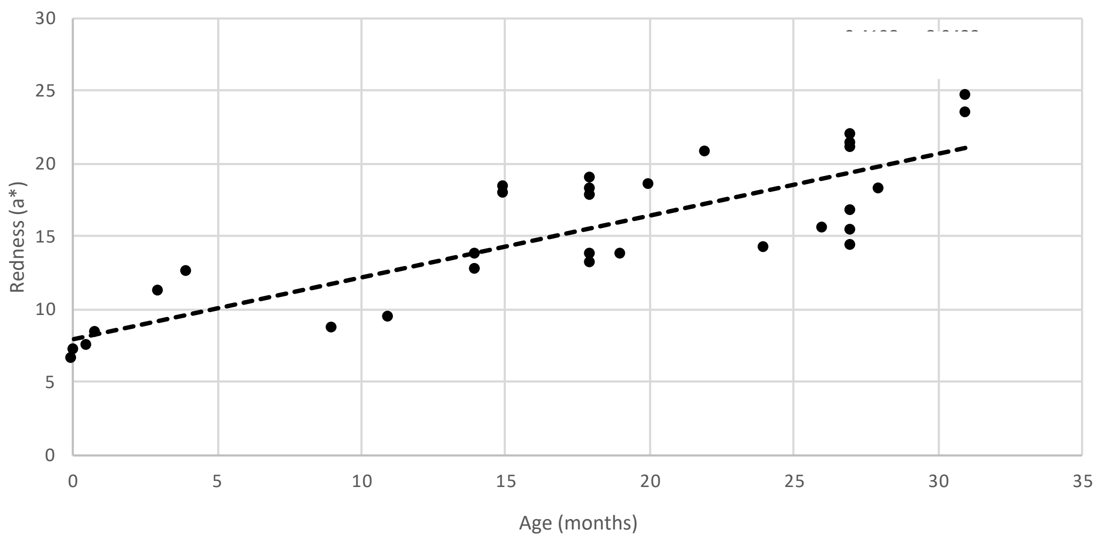

Figure 1.9 Relationship between age and lean meat colour (redness) of lean meat from bulls, steers and heifers collated using data from Table 1.14. Line shown is a best fit linear regression $y = 0.420x + 8.043$)

Effect of breed age on lean meat colour

When comparing beef and dairy breeds slaughtered at the same age, generally no differences in lean meat colour in terms of lightness, redness or yellowness have been observed (Muir *et al*., 2000). Angus steers have been found to have significantly greater values for lightness, redness and yellowness than Hereford x Friesian and Jersey x Friesian steers (Table 1.15) (Purchas & Morris, 2007).

Table 1.15 Lean meat colour (lightness, redness, yellowness) of *Longissimus* muscle from beef, beef-dairy cross and dairy breed steers measured using chromameter

Breed	L* (lightness)	a* (redness)	b* (yellowness)	Author
Hereford	35.2	21.9	11.9	Muir *et al*., 2000
Hereford x Friesian	33.2	21.4	10.9	
Friesian	33.3	21.1	10.9	
Angus	37.0[b]	16.7[b]	6.80[b]	Purchas & Morris, 2007
Hereford x Friesian	35.1[a]	14.3[a]	4.83[a]	
Jersey x Friesian	35.0[a]	15.4[ab]	5.55[ab]	
Hereford x Angus	38.9	14.2	4.2	Coleman *et al*., 2016
Hereford x Angus-Friesian	38.7	13.5	3.8	
Hereford x Angus-Kiwi	38.1	12.9	3.4	
Hereford x Angus-Jersey	38.3	14.5	4.4	

[a,b,c,] Within a column and author, means with different superscript letters are significantly different ($P<0.05$)

Effect of slaughter age on fat colour

Fat colour is important since yellow fat is regarded as an undesirable characteristic; since some consumers perceive it to be an indication of meat from older, inferior cattle (Dunne *et al*., 2009). Although the degree of yellow fat acceptance varies between markets, white fat is considered preferable (Dunne *et al*., 2009). Yellow fat arises from the presence of yellow fat-soluble pigments, including carotenoid pigments found in plant chlorophyll (Dunne *et al*., 2009). Yellow fat is particularly problematic for New Zealand meat since pasture diets of cattle contain high concentrations of carotenoid pigments (Purchas, 1989; Nozière *et al*., 2006).

Older animals are associated with increased likelihood of yellow fat due to accumulation of carotenoid pigments over an animal's lifetime, as indicated by higher values for yellowness in Table 1.16 (Purchas, 2003).

Table 1.16 Subcutaneous fat colour of *Longissimus* muscle of bulls, steers and heifers slaughtered at different ages measured using chromameter

Slaughter age	Production type	Breed	L* (lightness)	a* (redness)	b* (yellowness)	Author
19 months	Heifer	C x A	67.9	4.5	11.5	Coleman, 2016
24 months	Steer	H x A	69.8	5.0	6.5	Coleman *et al*., 2016
26 months	Steer	C x A	62.4	8.8	13.2	Coleman, 2016
27 months	Steer	H	78.2	1.8	14.2	Muir *et al*., 2000
27 months	Steer	H x F	77.1	1.6	15.9	Muir *et al*., 2000
27 months	Steer	F	73.5	2.0	16.9	Muir *et al*., 2000
27 months	Steer	A	56.7	6.0	14.5	Purchas & Morris, 2007
27 months	Steer	H x F	55.8	5.0	15.6	Purchas & Morris, 2007
27 months	Steer	J x F	54.4	5.5	19.1	Purchas & Morris, 2007
31 months	Heifer	H x F	70.4	2.6	23.8	Burke *et al*., 1998
31 months	Heifer	H x J	69.0	2.2	26.0	Burke *et al*., 1998

Breed: Angus (A), Charolais (C), Friesian (F), Hereford (H), Jersey (J)

Effect of breed on fat colour

Fat colour is more strongly affected by breed than lean meat colour. Dairy breeds tend to have a greater incidence of yellow fat than beef breeds when fed a pasture-based diet, as shown below in Table 1.17 (Burke *et al*., 1998; Muir *et al*., 2000; Purchas & Morris, 2007). For example, Friesian cattle have been shown to have significantly yellower fat than Hereford and Hereford x Friesian cattle slaughtered at the same age and same level of maturity (Muir *et al*., 2000).

Table 1.17 Fat colour (lightness, redness, yellowness) of *Longissimus* muscle from beef, beef-dairy cross and dairy breed steers measured using chromameter

Breed	L* (lightness)	a* (redness)	b* (yellowness)	Author
Hereford	78.2^{b}	1.81^{b}	14.2^{a}	
Hereford x Friesian	75.7^{b}	1.33^{b}	16.0^{a}	Muir *et al*., 2000
Friesian	59.7^{a}	0.73^{a}	22.3^{b}	
Angus	56.7^{b}	6.01	14.5^{a}	
Hereford x Friesian	55.8^{b}	5.03	15.6^{a}	Purchas & Morris, 2007
Jersey x Friesian	54.4^{a}	5.52	19.1^{b}	

^{a,b} Within a row, means with different superscript letters differ significantly (P<0.05)

Jersey cattle have long been recognised as a breed with a high incidence of yellow fat (Burke *et al*., 1998; Muir *et al*., 2000; Purchas & Morris, 2007). The enzyme needed to chemically modify carotenoid pigments in the diet to colourless compounds is found in relatively low concentrations in Jersey cattle, so more of the yellow pigments accumulate in the adipose tissue of cattle of that breed (Nozière *et al*., 2006). However, breed composites with only a small proportion of Jersey genetics may not be affected by increased incidence of yellow fat (Coleman *et al*., 2016). A comparison of 20- to 24-month-old beef-dairy steers and heifers found that although the yellowness values were highest for the breed with one quarter Jersey, there was no significant difference in fat colour between beef and dairy-beef crossbreeds (Coleman *et al*., 2016).

1.9.5 Flavour

Flavour, which includes the taste and aroma of meat, is an important component of meat palatability and influences a consumer's repurchasing decisions (Purchas, 1989). Flavour is a result of hundreds of different compounds found in meat, which are also altered during cooking and storage (Purchas, 2003). Beef flavour is most commonly assessed subjectively using sensory panels (Wood *et al*., 2004). Chemical analysis can also be used to a limited extent to measure flavour compounds present in meat (Wood *et al*., 2004).

Effect of slaughter age on flavour

Meat flavour tends to intensify as age increases, primarily due to greater concentrations of intramuscular fat (Table 1.18) (Purchas, 1989; Purchas, 2003; Marti *et al*., 2013). Fat has a positive effect on flavour due to flavour compounds stored in the adipose tissue that are released during cooking (Rodbotten *et al*., 2004). Clear differences exist between veal and beef from cattle older than twelve months of age, with veal having a lower flavour intensity and less gamey notes (Rodbotten *et al*., 2004). Diet and sex class can also affect beef flavour, which may explain the variation between studies in Table 1.18 (Young & West, 2001).

Effect of breed on flavour

No differences in flavour have been observed between beef, beef-dairy and dairy breeds (Table 1.18) (Beanaman *et al*., 1962; Purchas & Barton, 1976; Schaefer *et al*., 1986; Muir *et al*., 2000; Purchas & Morris, 2007).

Table 1.18 Flavour and aroma intensity of *Longissimus* muscle of different breeds of bulls, steers and heifers slaughtered at different ages measured using sensory panels

Slaughter age	Production type	Breed	Flavour intensity[1]	Ageing (days)	Author
3 months	White Veal	F	42	0	Johnson *et al*., 1988
4 months	Rosé Veal	F	50	2	Mandell *et al*., 2001
5 months	White Veal	F	54	0	Lensink *et al*., 2001
10 months	Steer & Bull	F	48	7	Marti *et al*., 2013
12 months	Steer & Bull	F	50	7	Marti *et al*., 2013
14 months	Steer & Bull	F	52	7	Marti *et al*., 2013
14 months	Bull[c]	C x S	59	4	Bureš & Bartoň, 2012
14 months	Heifer[c]	C x S	62	4	Bureš & Bartoň, 2012
15 months	Steer	H	65	0	Taylor, 1982
15 months	Steer	F	70	0	Taylor, 1982
18 months	Heifer[c],	A	54	14	Ahnström *et al*., 2012
18 months	Bull[c]	C x S	66	4	Bureš & Bartoň, 2012
18 months	Heifer[c]	C x S	62	4	Bureš & Bartoň, 2012
22 months	Heifer[c]	A	56	14	Ahnström *et al*., 2012
27 months	Steer	H	62	28	Muir *et al*., 2000
27 months	Steer	H x F	65	28	Muir *et al*., 2000
27 months	Steer	F	64	28	Muir *et al*., 2000
27 months	Steer	A	52	0	Purchas & Morris, 2007
27 months	Steer	H x F	55	0	Purchas & Morris, 2007
27 months	Steer	J x F	54	0	Purchas & Morris, 2007

[c] Diet: Concentrate and silage. All other animals were fed pasture.
[1] Assessed on a scale of 1 (minimum beef flavour intensity) to 100 (maximum beef flavour intensity) by trained sensory panel
Breed: Angus (A), Charolais (C), Friesian (F), Hereford (H), Jersey (J), Limousin (L), Simmental (S)

1.9.6 Juiciness and Water-holding Capacity

Juiciness is related to the water-holding capacity of the meat and its ability to stimulate salivation (Purchas, 1989). Juiciness influences the palatability of beef depending on the amount of water released from the meat or the presence of intramuscular fat which stimulates salivation (Purchas, 1989; Schönfeldt & Strydom, 2011).

Effect of slaughter age on juiciness and water-holding capacity

Drip loss is the weight loss from a sample of meat over a set time. Less drip loss occurs in meat from younger animals (Table 1.19) (Schönfeldt & Strydom, 2011). Protein has a greater ability to retain water than fat (Bureš & Bartoň, 2012). Therefore, drip loss is generally greater in older animals (Johnson *et al*., 1988; Bureš & Bartoň, 2012). However, a higher level of intramuscular fat in older animals means subjective juiciness scores tend to increase with age due to the lubrication effect caused by salivation (Schönfeldt & Strydom, 2011). Reduced cooking losses may be associated with improved juiciness due to more water and meat juices being retained in the consumed meat (Bouton *et al*., 1978; Schönfeldt & Strydom, 2011; Purchas & Grant, 1995).

Table 1.19 Cooking loss, drip loss, expressed water and subjective juiciness scores for *Longissimus* muscle of bulls, steers and heifers slaughtered at different ages

Slaughter age	Production type	Breed	Cooking loss (%)	Drip loss 48 hr (%)	Expressed water (cm_2/g)	Sensory Score[1]	Author
1 day	Bobby Veal	J	38.3		42.2		Biss *et al*., 1993
5 days	Bobby Veal	J	39.1		42.6		Biss *et al*., 1993
14 days	Bobby Veal	J	37.0		43.3		Biss *et al*., 1993
21 days	Bobby Veal	J	38.5		44.6		Biss *et al*., 1993
4 months	Rosé Veal	F	21.1	4.9		68	Mandell *et al*., 2001
4 months	White Veal	F	33.8		2.9		Lensink *et al*., 2001
5 months	White Veal	F	27.8	2.7			Tarantola *et al*., 2003
5 months	White Veal	F	29.3				Gottardo *et al*., 2005
5 months	White Veal	F	29.1	3.1			Tarantola *et al*., 2003
6 months	White Veal	L	30.3	1.7			Domaradzki *et al*., 2017
6 months	White Veal	F	27.2	2.4			Tarantola *et al*., 2003
7 months	White Veal	L	29.9	1.6			Domaradzki *et al*., 2017
8 months	White Veal	L	34.6	1.5			Domaradzki *et al*., 2017
9 months	White Veal	L x S	31.2	1.5			Domaradzki *et al*., 2017
11 months	White Veal	L	30.9	1.8			Domaradzki *et al*., 2017
14 months	Bull[C]	C x S		16.9		54	Bureš & Bartoň, 2012
14 months	Heifer[C]	C x S		13.0		53	Bureš & Bartoň, 2012
18 months	Heifer[C]	A	22.9			58	Ahnström *et al*., 2012
18 months	Bull[C]	C x S		12.1		58	Bureš & Bartoň, 2012
18 months	Heifer[C]	C x S		17.2		58	Bureš & Bartoň, 2012
19 months	Heifer	C x A	26.2	8.6	30.6		Coleman, 2016
20 months	Bull & Steer	H x F	26.9				Purchas & Grant, 1995
22 months	Heifer[C]	A	20.7			59	Ahnström *et al*., 2012
24 months	Steer	H x A	24.3	8.1	31.7		Coleman *et al*., 2016
26 months	Steer	A	26.9	8.0	31.2		Coleman, 2016
27 months	Steer	H				57	Muir *et al*., 2000
27 months	Steer	H x F				61	Muir *et al*., 2000
27 months	Steer	F				61	Muir *et al*., 2000
27 months	Steer	A	30.0	10.2	42.9	46	Purchas & Morris, 2007
27 months	Steer	H x F	27.6	9.1	42.2	49	Purchas & Morris, 2007
27 months	Steer	J x F	28.9	9.6	42.8	45	Purchas & Morris, 2007
28 months	Bull & Steer	H x F	25.6				Purchas & Grant, 1995
31 months	Heifer	H x F	26.6				Burke *et al*., 1998
31 months	Heifer	H x J	26.3				Burke *et al*., 1998

[C] Fed concentrate and silage diet. All other studies fed pasture-based diet.
[1] Assessed on a scale of 1 (minimum juiciness) to 100 (maximum juiciness) by trained sensory panel
Breed: Angus (A), Charolais (C), Friesian (F), Hereford (H), Jersey (J), Limousin (L), Simmental (S)

Effect of breed on juiciness and water-holding capacity

Tests of juiciness and water-holding capacity do not differ between dairy and beef breeds (Taylor, 1982; Muir *et al*., 2000; Purchas & Morris, 2007; Purchas & Zou, 2008; Coleman *et al*., 2016).

1.10 Relationship Between Age, Carcass Weight and Maturity

The effect of slaughter age on carcass characteristics and meat quality is closely related to carcass weight and degree of maturity at slaughter, and therefore is indirectly related to growth rate (Purchas, 1989). Changes in carcass characteristics primarily occur as the animal grows, increases in live weight and becomes close to reaching maturity, rather than solely because the animal is getting older. However, because finishing animals are generally constantly growing in commercial production systems, age is a suitable measure for comparing changes in carcass characteristics since age and carcass weight usually increase simultaneously (Purchas, 1989).

While clear differences exist between cattle slaughtered at different ages that are also of different live weights, this relationship may vary if comparing cattle slaughtered at the same live weight but different ages or different degrees of maturity, as a result of different growth rates (Purchas, 2003). This is because if cattle with different growth rates are slaughtered at the same live weight, a faster growing animal will be younger at slaughter, compared with a slower growing animal which will take longer to reach the same set live weight.

Two studies that compared Hereford x Friesian and Friesian bulls slaughtered in two groups at 20 and 28 months old, but at the same live weight of 500 kg, demonstrated age primarily has an effect on beef tenderness, as shown in Table 1.20 (Purchas & Grant, 1995; Purchas *et al*., 1997). Despite no difference in carcass weights, the younger bulls had lower peak shear force values than the older bulls, which was attributed to greater collagen solubility in the younger cattle (Purchas & Grant, 1995; Purchas *et al*., 1997). There was no difference in lean meat colour or cooking loss between the two age groups in Purchas *et al*. (1997), though meat was slightly redder in the older cattle than the younger cattle when compared by Purchas & Grant (1995).

Other meat quality attributes that were not assessed but are likely to differ as a result of growth rate and carcass composition, are flavour and juiciness. Animals that have grown faster and been slaughtered at a younger age would be expected to have greater fat deposition and more intramuscular fat than older, slower-growing animals slaughtered at the same live weight, which would be reflected in improved juiciness and flavour (Purchas, 2003). However, this can depend on the stage of maturity. In both studies, subcutaneous and intramuscular fat was higher in the younger cattle (Purchas & Grant, 1995; Purchas *et al*., 1997).

Table 1.20 Comparison of meat quality attributes of unaged *Longissimus thoracis* muscle from Hereford x Friesian and Friesian bulls slaughtered at 500 kg at two different ages (Purchas *et al*., 1997; Purchas & Grant, 1995)

	Purchas & Grant, 1995			**Purchas *et al*., 1997**		
Slaughter Age	**20 months**	**28 months**	**Sig[1]**	**20 months**	**28 months**	**Sig[1]**
Ultimate pH	5.85	6.07	**	6.26	6.39	*
Shear force (kgF)	9.85	13.0	***	12.14	14.52	**
*L** (meat lightness)	33.5	33.0	NS	31.4	30.7	NS
*a** (meat redness)	17.7	19.4	**	16.1	16.2	NS
*b** (meat yellowness)	7.7	8.5	*	6.5	6.2	NS
Cooking loss (%)	26.4	25.8	NS	23.51	23.20	NS

[1] Significance within study: NS = Not significant ($P > 0.05$); * = $P < 0.05$; ** = $P < 0.01$; *** = $P < 0.001$.

Chapter 2. Research Questions and Objectives

In New Zealand, there is an imperative need to investigate alternative uses for surplus dairy-origin calves, whilst also improving the efficiency of pasture-based beef production systems and minimising their environmental impacts. Cattle finished for prime beef production in New Zealand are generally processed between 18 and 36 months of age. However, international research indicates high-quality beef can be obtained from cattle slaughtered at approximately one year of age.

There is potential for pasture-based yearling beef production to be implemented in New Zealand, which could utilise surplus calves from the dairy industry. The feasibility of pasture-based yearling beef production (8 to 12 months of age) using dairy-origin cattle has not yet been studied, and the quantity and quality of product obtained is not understood.

Growth, carcass and meat quality attributes of steers slaughtered at the traditional New Zealand ages of 18 to 36 months have been extensively researched and characterised. However, there has been little consideration of cattle slaughtered at intermediate ages of between eight and twelve months, particularly when using calves of dairy origin for beef production. International studies that have considered a yearling slaughter age for cattle have limited applicability in a New Zealand context, due to different breeds and diets.

Previous studies indicate that dressing-out percentage and carcass fat tend to increase as animals exceed 24 months of age, but lean and saleable meat yield generally decline due to increasing proportions of fat in live weight gain as animals progress towards maturity. Tenderness generally declines with age due to reduced collagen solubility, but this can be alleviated if intramuscular fat is deposited. Slaughtering animals at younger ages may be beneficial for meat quality without the additional feed and time required to deposit intramuscular fat.

Dairy breeds tend to have lower dressing-out percentages, lower M:B ratios, less subcutaneous fat, and smaller eye muscle areas than beef breeds, although lean meat yields are often similar. Few differences in meat quality characteristics between beef and dairy breeds have been observed, the only exception being cattle with a high proportion of Jersey genetics, which are associated with a greater incidence of yellow fat. These findings largely dismiss the traditional perception that dairy breeds produce inferior quality meat, indicating there is potential to utilise dairy-origin cattle for high-value beef production.

Therefore, the research questions include:

- What are the growth rates of dairy-origin steers finished in a forage-based system?
- What are the yields and meat quality of yearling beef produced under New Zealand pastoral systems?

And the objectives of the study were to:

- Characterise and compare the growth, carcass characteristics and objective meat quality attributes of dairy-origin steers slaughtered at eight, ten and twelve months of age, in a New Zealand forage-based system.
- Determine if there is an optimal slaughter age for yearling beef of dairy origin, in respect to carcass and meat quality attributes.
- Compare the effect of ageing (proteolytic activity) on objective meat quality attributes for yearling beef of dairy origin, in particular tenderness.

It is hypothesised that steers slaughtered at twelve months of age will have carcasses that are more valuable in terms of meat yield; however, steers slaughtered at eight months of age will have superior meat quality attributes. Carcass weights, carcass lengths, dressing-out percentages, fat depths, eye muscle areas, muscle to bone ratios and muscularity, are expected to increase with slaughter age, due to ongoing muscle and fat deposition as cattle get older. The yellowness of carcass fat and redness of meat are expected to increase with slaughter age. It is also hypothesised that aged beef will have lower shear force values, but other meat quality attributes will remain similar to unaged beef.

Chapter 3. Materials and Methods

3.1 Animals and Their Management

Sixty Hereford x Friesian-Jersey weaner steer calves born in spring 2017 were sourced from a commercial calf rearer at an average of three months of age (103±1 kg). Castration occurred before six weeks of age using rubber castration rings. Sires and their Estimated Breeding Values (EBVs) were unknown as the calves were sourced directly from a commercial calf rearer, and bulls were unrecorded.

From late November 2017 until mid-May 2018, the steers were grazed at Massey University's Keebles Farm (latitude 40.40°S, longitude 175.60ºE), 7 km south-east of Palmerston North. They were then transferred to Massey University's Haurongo Farm (latitude 40.39°S, longitude 175.63° E), 5 km south of Palmerston North, for the remainder of the experiment. All steers were managed as a single group but were preassigned via random allocation at eight months of age to the treatment groups of eight, ten and twelve-month slaughter ages. There were 20 steers in each group and the groups were balanced for live weight.

Feeding levels were maintained to achieve a target live weight gain of 1 kg/day. Steers were grazed on a herb-clover forage crop consisting of plantain (*Plantago lanceolata*), chicory (*Cichorium intybus*), white clover (*Trifolium repens*) and red clover (*Trifolium pratense*) between December and January, and supplemented with Sharpes Earlywean Calf Pellets (16% crude protein) until the end of January at approximately 0.5 kg/head/day. During February, the steers were grazed on Hunter Brassica (*Brassica campestris*) before returning to the herb-clover forage crop in early March. From late March until slaughter, steers were grazed on mature ryegrass and white clover pasture, and were break-fed during June and July. All steers were managed under commercial conditions and were treated monthly with an oral anthelmintic (Coopers Alliance) from weaning until 12 months of age.

Steers were weighed 1-2 hours off feed, every two weeks from arrival on-farm until slaughter. Prior to being transported to the abattoir, the steers were weighed on-farm, 1-2 hours off feed, to obtain a final pre-slaughter live weight. Height at the withers was also measured using a height stick for all steers on-farm at eight, ten and twelve months of age prior to slaughter.

3.2 Slaughter and Carcass Measurements

Steers allocated to the eight-month-old slaughter group were transported to the abattoir on May 16th, the ten-month-old group were transported on July 17th, and the twelve-month-old group were transported on September 4th, 2018. Steers were transported approximately 25 km to the abattoir, a journey of approximately 30 minutes. All steers were slaughtered the following morning, approximately 24 hours after transport. Steers in the eight, ten, and twelve-month slaughter treatment groups were slaughtered and processed at Feilding Venison Packers Limited, following standard commercial dressing procedures for beef cattle. The dressed carcasses were hung in a chiller overnight at 4ºC and boned the following day into commercial cuts.

At boning, 24 hours after slaughter, the outside (*M. biceps femoris, M. semitendinosus*), topside (*M. semimembranosus, M. adductor femoris*), knuckle (*M. quadriceps femoris*) and cube roll (*M. longissimus thoracis*) cuts were obtained from the left side of each carcass for carcass measurements (Figure 3.1). The femur bone was also collected so that the femur length and weight could be measured.

The striploin (*M. longissimus lumborum)* from the left side of each carcass was also collected and vacuum packed during boning for meat quality analysis (Figure 3.1). The caudal half of the striploin from each carcass was aged at 1ºC for 21 days and then frozen at -20ºC for seven days. The cranial half of the striploin was frozen at -20ºC immediately after boning for 28 days.

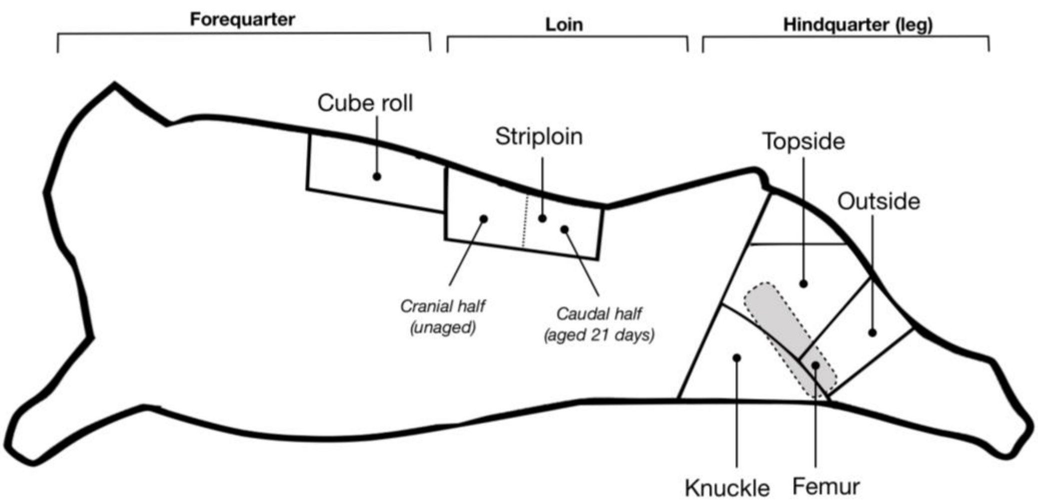

Figure 3.1 Location of beef cuts and bone collected from the left side of the carcass at boning

3.3 Ultrasound

Three weeks prior to the eight- and ten-month slaughter dates, and one week prior to the twelve-month slaughter date, carcass composition was assessed using ultrasound by a commercial operator (Austins Ultrasound Limited). Measurements included: the transverse area of the *Longissimus thoracis* muscle of the cube roll cut (eye muscle area; EMA) between the 12th and 13th rib, fat depth measured at a point over the *Longissimus thoracis* between the 12th and 13th rib where the muscle was deepest (rib fat), and fat depth over the *Gluteus medius* muscle at the P8 site on the rump (P8 fat depth). The P8 rump site is located at the point of intersection between a horizontal line from the dorsal tuberosity of the *Tripartite tuber ischii* (pin bone) parallel to the backbone, and a vertical line from the crest on the spinous process of the third sacral vertebra (Hopkins, 1989).

3.4 Carcass Measurements

Hot carcass weight was measured at the abattoir after the carcasses were halved. The weight of the left and right sides of the carcass were added together to obtain the carcass weight for each steer. Dressing-out percentages were calculated as the hot carcass weight as a percentage of the on-farm pre-slaughter live weight. The length of each carcass side was measured as they hung in the chiller after carcasses had been chilled at 4ºC overnight (24 hours postmortem). Carcass length was measured from the distal end of the tarsal bones to the mid-point of the cranial edge of the first rib (Purchas *et al*., 2002a). The carcass length for each animal was determined from the mean length of the two carcass sides. In the chiller, subcutaneous fat colour was visually assessed against a colour standard, using a score where one is the whitest and eight is the yellowest (Burke *et al*., 1998; Collier *et al*., 2015).

Muscularity index, which expresses muscularity as the ratio of muscle depth to the length of an adjacent bone, was calculated using the sum of weight of the five main muscles surrounding the femur (those in the outside, topside and knuckle) and femur length (Purchas *et al*., 1991; Purchas *et al*., 2002b). Muscularity was calculated for each animal using the formula developed by Purchas *et al*. (1991):

$$Muscularity = \frac{\left[\sqrt{\frac{(Five\ muscle\ weight\ (g)}{Femur\ length\ (cm)}}\right]}{Femur\ length\ (cm)}$$

Muscle to bone (M:B) ratio was calculated from the weight of the same five muscles within the outside, topside and knuckle cuts surrounding the femur, divided by femur weight (Purchas *et al*., 2002b):

$$M{:}B = \frac{Five\ muscle\ weight\ (g)}{Femur\ weight\ (g)}$$

After chilling at 1ºC for 21 days, a tracing of the transverse area of the *Longissimus thoracis* muscle of the cube roll cut (eye muscle area; EMA) between the 12th and 13th rib was made. A planimeter (Placom KP-90N, Tokyo, Japan) was then used to measure the traced area.

3.5 Meat Quality

Four weeks after slaughter, samples were thawed at 1ºC for 24 hours in preparation for meat quality analysis (Figure 3.2). After thawing, the vacuum-packed striploin was dried with tissue paper and weighed. The striploin was then removed from the packaging. Both the striploin and packaging were blotted dry and weighed.

Two 20 mm steaks were cut for the measurement of pH and then myofibrillar fragmentation on the first steak, and meat colour and sarcomere length on the second steak (Figure 3.2). Two 25 mm steaks cut from the central part of the striploin were weighed and then placed into a plastic bag to be cooked for the measurement of Warner-Bratzler shear force and cooking loss. A 40 mm steak was used to assess drip loss. The remaining lean muscle from the 20 mm and 40 mm steaks after the respective meat quality tests were completed, was trimmed of external connective tissues, minced and then frozen for analysis of intramuscular fat (IMF) content. The remainder of the striploin was vacuum packed and refrozen as a reserve.

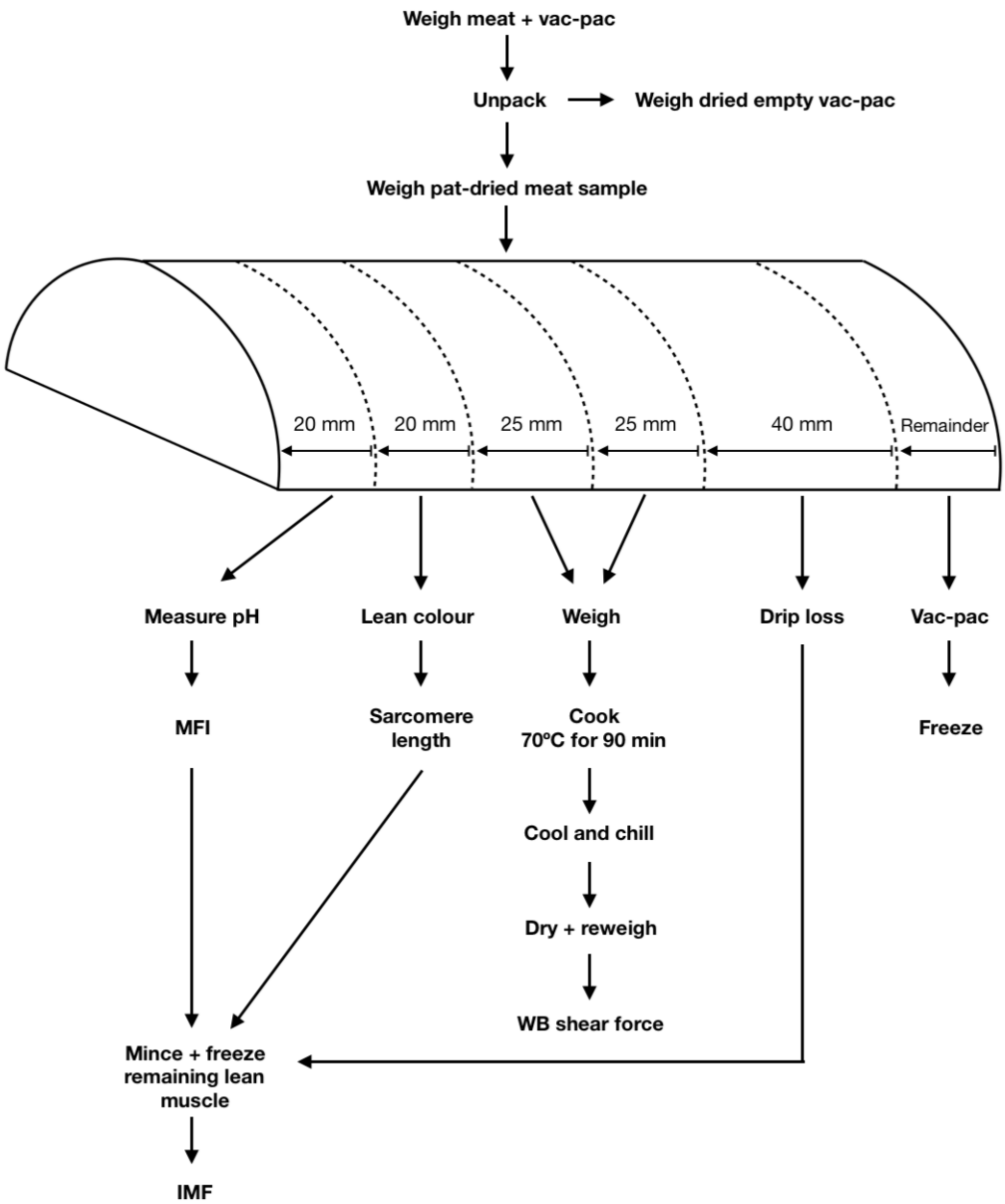

Figure 3.2 Schematic of beef striploin (*Longissimus lumborum)* partitioning for meat quality analysis.

3.5.1 Ultimate pH

Ultimate pH was measured at three points, medial to distal across the transverse internal cut of the striploin using a pH spear (Eutech Instruments, Singapore). Standard buffers of pH 4.01, 7.0 and 10.01 were used to calibrate the pH spear. The three measurements were averaged to obtain the ultimate pH for each striploin sample.

3.5.2 Lean Meat Colour

The transverse cut surface of a 20 mm striploin steak was exposed to air for 30 minutes. Subsequently, lean meat colour was measured using a Minolta Chroma Meter (CR-200; Konica Minolta, Mahwah, NJ, USA) calibrated using a standard white tile supplied by the manufacturer. The CIE *L** (lightness), *a** (redness) and *b** (yellowness) values were measured (Illuminant D65, 8 mm diameter aperture, 0° viewing angle) through a polycarbonate petri dish at three points from medial to distal across the loin.

3.5.3 Tenderness

Two 25 mm steaks from each striploin sample were used for assessment of Warner-Bratzler shear force. The samples were cooked individually in a plastic bag immersed in a water bath at 70°C for 90 minutes, then chilled at 1ºC for at least four hours (Purchas & Aungsupakorn, 1993). The two steaks were weighed before and after cooking so cooking loss could be calculated. Warner-Bratzler shear force with a V-shaped blade (TMS-Pilot, Food Technology Corporation, Virginia, USA) was measured on cylindrical cores of 13 mm diameter which were cut using a cork borer. An initial cut was made to identify the muscle fibre direction of the steaks. The cores were then cut parallel to the fibre direction so that shears were made across muscle fibres (Purchas & Aungsupakorn, 1993). Six replicates were measured per sample for peak force, peak area and average area. Peak force was measured as the maximum measured load required to shear through the core of meat (kgF), average force was measured as the mean load throughout the duration of the test (kgF), and peak area being the area under the load curve measured in $kgF.s^{-1}$ (Food Technology Corporation, 2019).

Sarcomere length was measured by laser diffraction on unaged striploin samples. A segment of lean muscle 8-10 mm long with a 1 mm^2 cross section was dissected along the length of the muscle fibres from each unaged striploin sample. The segment was then teased-out with a scalpel blade and compressed between two glass microscope slides after adding 2-3 drops of distilled water. A He-Ne laser (2 mW, 632.8 nm wavelength, 0.8 mm beam diameter, Melles Griot, California, USA) was passed through the sample to create a diffraction pattern on a screen set at a distance of 100 mm from the microscope slide. The sample on the microscope stage was shifted horizontally in the laser beam until 3 bands were clearly visible. The distance between the first order diffraction bands was measured in millimetres, and ten measurements per sample were used to calculate the mean distance (mm). The following formula was used to convert the distance to the sarcomere length in microns, as detailed by Bouton *et al*. (1973):

$$Sarcomere\ length\ (\mu m) = 0.6328 * \left[\sqrt{\left\{\left(\frac{x}{20}\right)^2 + 100\right\}}\right] / \left(\frac{x}{20}\right)$$

Myofibrillar fragmentation index (MFI) was measured by assessing the proportion of muscle fragments from a sample of *Longissimus lumborum* muscle that passed through 231 µm mesh by filtration following a standard homogenisation procedure (Purchas *et al*., 1997). Approximately 5 g (±0.1 g) of finely diced lean muscle from the striploin was added to 50 mL of physiological saline (0.85% NaCl) and 5 drops of antifoam, which was then homogenised (Ultra-Turrax, 18 mm diameter shaft, one-third speed) for two 30-second periods. The homogenised mixture was rapidly poured through pre-weighed stainless-steel mesh filters and left to drip-dry for three hours. The filters were then dried at 30ºC for 40 hours and subsequently reweighed. Myofibrillar fragmentation index values normally range from 78% when no fragments pass through the filter, up to 100% when all fragments pass through (Purchas *et al*., 1997). Myofibrillar fragmentation index was calculated as:

$$MFI\% = 100\ - \frac{weight\ of\ dried\ sample\ retained\ on\ filter\ (g)}{weight\ of\ muscle\ sample\ (g)}$$

3.5.4 Water-holding Capacity

Thaw loss (water loss from freezing and then thawing) was measured using the weight of the thawed meat and packaging before unpacking, and the weight of the dried meat sample and dried packaging individually. Thaw loss was calculated as:

$$Thaw\ loss\ (\%) = \frac{whole\ weight\ -\ (package\ weight\ +\ meat\ weight\ after\ drying)}{whole\ weight\ -\ package\ weight}\ x\ 100$$

Cooking loss was calculated as the difference in weight of the 25 mm steak before and after cooking, expressed as a percentage of the weight before cooking. Drip loss was assessed by cutting a 40 mm^3 cube of raw meat from the 40 mm steak, which was weighed and suspended on a meat hook in a plastic bag without touching the sides of the bag (Coleman *et al*., 2016). The bag was then placed in a chiller at 1°C. After 24 and 48 hours of suspension, the cube was blotted dry and reweighed. Drip loss was calculated as the original weight minus the weight at 24 or 48 hours, and the value was expressed as a percentage of the original weight.

3.5.5 Intramuscular Fat

An internal sample of the striploin, trimmed of subcutaneous fat and visual connective tissue, was finely minced (Kenwood MG450 with 3 mm hole-plate), vacuum packed and frozen to measure the intramuscular fat (IMF) content of the loin using a Soxhlet extraction procedure (AOAC 911.36), performed by the Nutrition Laboratory at Massey University.

3.6 Statistical Analysis

Data was analysed using SAS 9.4 (SAS Institute Inc., Cary, NC, USA). Mixed models allowing for repeat measures were used to analyse all live weight and ultrasound measurements, with age at measurement and treatment group included as a fixed effect, and steer as a random effect. General linear models were used to analyse carcass and meat quality attributes. These models included slaughter age and treatment group as fixed effects. Models for meat quality attributes also included slaughter age, treatment group, ageing treatment and the interaction of slaughter age and ageing as fixed effects, and animals were included as a random effect. Ultimate pH was included as a linear covariate for the meat quality measurements of shear force, lean meat colour, cooking loss, drip loss and thaw loss, but was removed for attributes where pH was not significant in the model.

Chapter 4. Results

4.1 Live Animal Measurements

The start live weights for steers at three months of age did not differ between treatments (*P*=0.772; Table 4.1), as a result of the experimental design in which steers were randomly pre-allocated to a slaughter group and balanced for live weight. Final live weight increased with each slaughter age (*P*<0.001; Table 4.1), with the final live weight of the twelve-month group being 95.4 kg and 43.3 kg heavier than the eight- and ten-month slaughter groups respectively. There was no difference in growth rates between individual slaughter age treatments when calculated from weaning until each respective slaughter date at eight, ten and twelve months of age (*P*=0.793; Table 4.1). Growth rates also did not differ between time periods when calculated from: weaning to eight months, eight to ten months and ten to twelve months (declining number of animals) (*P*=0.144; Table 4.1). However, there was greater variation in growth rates between eight and ten months of age (Figure 4.1).

Table 4.1 Mean (±SEM) live weight and growth characteristics of Hereford x Friesian-Jersey steers at 8, 10 and 12 months of age

	Slaughter age treatment			***P*-value (age)**
	8 months	**10 months**	**12 months**	
Start live weight (kg)	102±2.0[a]	105±2.9[a]	104±2.3[a]	0.772
Final live weight (kg)	252±5.6[a]	304±4.0[b]	347±4.9[c]	**<0.001**
Average daily gain (kg/day)[1]	0.88±0.02	0.85±0.02	0.87±0.02	0. 793
Average daily gain (kg/day)[2]	0.88±0.01	0.84±0.01	0.87±0.02	0.144

[a,b,c] Within a row, means with different superscript letters differ significantly (*P*<0.05)
[1] ADG calculated from weaning until each respective slaughter. Includes only animals allocated to that treatment group (n=20)
[2] ADG calculated for different time periods using all steers still on-farm: 8 months = weaning to 8 months of age, n=60; 10 months = 8 months to 10 months of age, n=40; 12 months = 10 months to 12 months of age, n=20

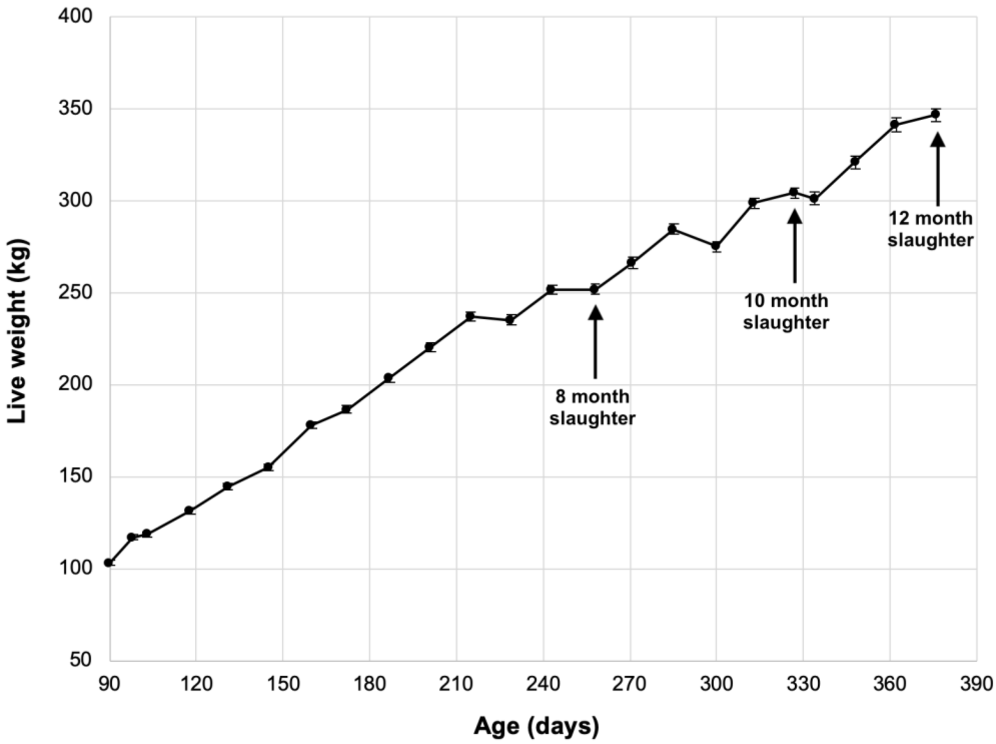

Figure 4.1 Mean unfasted live weight from three to twelve months of age for Hereford x Friesian-Jersey steers slaughtered at 8, 10 and 12 months of age (3-8 months n=60; 8-10 months n=40; 10-12 months n=20)

The wither height of the steers differed for each slaughter age, with height increasing as the steers became older (P<0.001). Average heights at each slaughter date were 1088±5 mm at eight months, 1171±5 mm at ten months, and 1203±5 mm at twelve months of age. Ultrasound measurements measured on all steers on-farm prior to each group being sent to slaughter increased between each slaughter age for rib fat depth, P8 fat depth (over the rump) and eye muscle area (P<0.001; Table 4.2).

Table 4.2 Means (±SEM) for P8 fat depth, rib fat depth and eye muscle area measured by ultrasound on Hereford x Friesian-Jersey steers at 8 (n=60), 10 (n=40), and 12 (n=20) months of age. Means presented were not adjusted for carcass weight.

	Slaughter age treatment			***P*-value (age)**
Trait	**8 months**	**10 months**	**12 months**	
Rib fat depth (mm)[1]	1.2 ± 0.1[a]	1.7 ± 0.1[b]	2.1 ± 0.1[c]	<0.001
P8 fat depth (mm)[2]	1.7 ± 0.1[a]	2.2 ± 0.1[b]	2.9 ± 0.2[c]	<0.001
EMA (cm^2)[3]	38.2 ± 0.5[a]	41.5 ± 0.4[b]	52.0 ± 0.7[c]	<0.001

[a,b,c] Within a row, means with different superscript letters differ significantly (P<0.05)
[1] Subcutaneous fat depth over eye muscle
[2] Subcutaneous fat depth over rump.
[3] Eye muscle (*Longissimus thoracis*) area

4.2 Carcass Characteristics

Hot carcass weight, carcass length, femur length, outside weight and muscle to bone ratio was greater at each progressive slaughter age (P<0.001; Table 4.3). Femur weight, knuckle weight and topside weight were all greater for steers slaughtered at ten and twelve months of age than at eight months of age (P<0.001; Table 4.3), but did not differ between ten and twelve months of age (P>0.05; Table 4.3). The dressing-out percentage, eye muscle area and intramuscular fat percentage in the striploin were greater for steers slaughtered at 12 months of age (P<0.001; Table 4.3), but did not differ between steers slaughtered at eight and ten months of age (P>0.05; Table 4.3). There was no change in muscularity index with slaughter age (P=0.180). Yellowness of carcass fat assessed visually was similar at eight and ten months of age, but increased at twelve months of age (P<0.001).

Carcass weight was significant as a covariate for all carcass characteristics (P<0.05; Table 4.3) except for intramuscular fat (P=0.416; Table 4.3). Carcass weight was not included as a covariate in the statistical model for the means presented, to allow practical comparisons to be made between the different slaughter ages. Since carcass weight tends to be strongly correlated with age, it is not logical to adjust the age treatments to a common carcass weight.

Table 4.3 Means for carcass characteristics from Hereford x Friesian-Jersey steers at 8, 10 and 12 months of age. Means presented have not been adjusted for carcass weight.

	Slaughter age (SA)				***P*-value**	
Carcass characteristics	**8 months**	**10 months**	**12 months**	**SEM**	**SA**	**CW[1] covariate**
Carcass						
Hot carcass weight (kg)	119.0[a]	146.2[b]	173.9[c]	2.7	<0.001	
Dressing-out (%)	47.2[a]	47.4[a]	50.0[b]	0.3	<0.001	0.002
Carcass length (mm)	1793[a]	1862[b]	1920[c]	11	<0.001	<0.001
Muscling						
Eye muscle area (cm^2)	52.9[a]	55.8[a]	65.2[b]	2.1	<0.001	<0.001
Knuckle weight (kg)	2.65[a]	3.29[b]	3.40[b]	0.09	<0.001	<0.001
Outside weight (kg)	2.91[a]	3.38[b]	3.84[c]	0.10	<0.001	<0.001
Topside weight (kg)	3.48[a]	4.38[b]	4.44[b]	0.11	<0.001	<0.001
M:B ratio	4.6[a]	5.1[b]	5.3[c]	0.1	<0.001	<0.001
Muscularity	0.46	0.46	0.46	0.01	0.180	<0.001
Femur bone						
Femur length (mm)	351[a]	375[b]	383[c]	2	<0.001	<0.001
Femur weight (kg)	1.97[a]	2.15[b]	2.21[b]	0.04	<0.001	<0.001
Fat						
IMF in striploin (%)	1.0[a]	0.9[a]	2.1[b]	0.2	<0.001	0.416
Visual fat colour score	2.1[a]	2.3[a]	2.7[b]	0.1	<0.001	0.049

[a,b,c] Within a row, means with different superscript letters differ significantly (P<0.05)

[1] CW = Carcass weight, which was not included as a covariate in the model, was tested to verify that age and weight were linked for each carcass characteristic

4.3 Meat Quality Attributes

4.3.1 Effect of Slaughter Age

Ultimate pH was lowest for steers slaughtered at eight months of age (Table 4.4, $P<0.001$), but there was no difference between steers slaughtered at ten and twelve months of age. Warner-Bratzler shear force values for peak force ($P=0.414$), average force ($P=0.155$) and peak area ($P=0.661$) did not differ between slaughter ages (Table 4.4). There was no difference in the myofibrillar fragmentation index ($P=0.466$) or sarcomere length between slaughter ages ($P=0.179$).

When measured by chromameter, lightness values for lean meat colour decreased at each slaughter age ($P<0.001$), while redness and yellowness increased at each progressive slaughter age (Table 4.4, P<0.001). There was also an interaction between slaughter age and ageing treatment for yellowness ($P=0.012$). Thaw loss was similar for steers slaughtered at eight and ten months of age but greatest at twelve months of age ($P<0.001$). There was an interaction between slaughter age and ageing treatment for thaw loss ($P=0.032$). Cooking loss was similar at eight and ten months of age, but lower at twelve months of age ($P<0.001$). Drip loss did not differ between slaughter ages at either 24 hours (P=0. 430) or 48 hours ($P=0.431$).

4.3.2 Effect of Postmortem Ageing

Ultimate pH was greater for aged samples than for unaged samples ($P<0.001$), although the effect of ageing was smaller than the effect of slaughter age on pH. Postmortem ageing had a positive effect on shear force values; as peak force, average force and peak area were all lower for samples that had been aged for 21 days compared with unaged samples ($P<0.001$). There was no interaction between slaughter age and postmortem ageing treatment for shear force values.

There was no difference between unaged and aged beef samples for lightness values ($P=0.273$); however, redness ($P<0.001$) and yellowness ($P=0.002$) values were greater for aged samples than unaged samples. Postmortem ageing did not have an effect on thaw loss overall ($P=0.205$), although there was a significant interaction between slaughter age and postmortem ageing treatment ($P=0.032$). There was no difference in cooking loss between aged and unaged samples ($P=0.470$). However, drip loss at both 24 and 48 hours was greater for samples that had undergone ageing compared with unaged samples ($P<0.001$).

Table 4.4 Means (±SEM) for meat quality attributes of unaged and aged (21 days) *Longissimus lumborum* (striploin) muscle samples from Hereford x Friesian-Jersey steers slaughtered at 8, 10 or 12 months of age (n = 20 per group). Ultimate pH was included as a covariate when significant in the model.

Postmortem ageing (A):	Unaged			Aged 21 days			*P*-value			
Slaughter age (SA):	**8 months**	**10 months**	**12 months**	**8 months**	**10 months**	**12 months**	**SA**	**A**	**SA x A**	**pH covariate**
Ultimate pH	$5.31{\pm}0.01^{a}$	$5.51{\pm}0.01^{c}$	$5.52{\pm}0.01^{c}$	$5.36{\pm}0.01^{b}$	$5.57{\pm}0.01^{d}$	$5.56{\pm}0.01^{d}$	<0.001	<0.001	0.724	
Tenderness										
WB peak force (kgF)	$5.11{\pm}0.18^{b}$	$5.42{\pm}0.18^{b}$	$5.50{\pm}0.18^{b}$	$4.78{\pm}0.18^{a}$	$4.59{\pm}0.18^{a}$	$4.77{\pm}0.18^{a}$	0.414	<0.001	0.170	<0.001
WB average force (kgF)	$1.58{\pm}0.05^{a}$	$1.59{\pm}0.05^{a}$	$1.60{\pm}0.05^{a}$	$1.25{\pm}0.05^{b}$	$1.25{\pm}0.05^{b}$	$1.35{\pm}0.05^{b}$	0.155	<0.001	0.212	<0.001
WB peak area ($kgF.s^{-1}$)	$20.2{\pm}0.7^{a}$	$21.6{\pm}0.7^{a}$	$20.2{\pm}0.7^{a}$	$16.2{\pm}0.7^{b}$	$16.4{\pm}0.7^{b}$	$17.5{\pm}0.7^{b}$	0.661	<0.001	0.130	<0.001
MFI (%)	$97.2{\pm}0.5^{a}$	$97.4{\pm}0.5^{a}$	$97.3{\pm}0.5^{a}$	$98.4{\pm}0.5^{b}$	$98.9{\pm}0.5^{b}$	$98.5{\pm}0.5^{b}$	0.466	0.017	0.761	NS
Sarcomere length (µm)	1.72±0.02	1.74±0.02	1.75±0.2				0.179			NS
Meat colour										
L* (lightness)	$44.6{\pm}1.0^{a}$	$38.3{\pm}0.6^{b}$	$35.6{\pm}0.6^{c}$	$42.6{\pm}0.8^{a}$	$38.1{\pm}0.8^{b}$	$36.0{\pm}0.7^{c}$	<0.001	0.273	0.113	0.001
a* (redness)	$12.3{\pm}0.3^{a}$	$13.1{\pm}0.3^{b}$	$13.9{\pm}0.3^{c}$	$13.1{\pm}0.3^{a}$	$14.0{\pm}0.3^{b}$	$15.3{\pm}0.3^{c}$	<0.001	<0.001	0.130	NS
b* (yellowness)	$3.4{\pm}0.2^{a}$	$3.8{\pm}0.2^{b}$	$4.2{\pm}0.2^{c}$	$3.3{\pm}0.2^{a}$	$4.7{\pm}0.2^{b}$	$5.1{\pm}0.2^{c}$	<0.001	0.002	**0.012**	NS
Water-holding capacity										
Thaw loss (%)	$1.0{\pm}0.3^{a}$	$2.0{\pm}0.2^{b}$	$3.5{\pm}0.2^{c}$	$1.3{\pm}0.3^{a}$	$1.4{\pm}0.3^{a}$	$2.8{\pm}0.2^{b}$	<0.001	0.205	**0.032**	0.002
Cooking loss (%)	$28.0{\pm}0.3^{b}$	$27.6{\pm}0.3^{b}$	$26.1{\pm}0.3^{a}$	$27.8{\pm}0.3^{b}$	$27.9{\pm}0.3^{b}$	$25.5{\pm}0.3^{a}$	<0.001	0.470	0.256	NS
Drip loss 24h (%)	$4.3{\pm}0.4^{a}$	$4.0{\pm}0.4^{a}$	$5.1{\pm}0.4^{a}$	$1.6{\pm}0.4^{a}$	$2.4{\pm}0.4^{a}$	$1.7{\pm}0.4^{a}$	0.430	<0.001	0.051	NS
Drip loss 48h (%)	$5.7{\pm}0.4^{a}$	$5.7{\pm}0.4^{a}$	$6.2{\pm}0.4^{a}$	$2.1{\pm}0.4^{a}$	$3.3{\pm}0.4^{a}$	$2.8{\pm}0.4^{a}$	0.431	<.0001	0.097	NS

[a,b,c] Within a row for both unaged and aged treatments, means with differing superscripts are significantly different ($P<0.05$)
NS Indicates effect was not significant and removed from the model
WB: Warner-Bratzler shear force

Chapter 5. Discussion

The objective of this study was to characterise and compare the growth, carcass characteristics and objective meat quality attributes of dairy-origin cross steers slaughtered at eight, ten and twelve months of age, in a New Zealand pasture-based system. The study also aimed to identify if an eight, ten or twelve month slaughter age is optimal for yearling beef production in terms of growth, carcass and meat quality, and if proteolytic ageing would affect meat quality attributes.

5.1 Growth Characteristics

Final live weight and wither height increased with slaughter age, which was expected given that the animals were constantly growing. This is consistent with other studies investigating young growing cattle (Marti *et al*., 2013; Nogalski *et al*., 2018). Growth rates from arriving on-farm to each respective slaughter did not differ between the three treatment groups, which is similar to other studies comparing a small age range. This was expected given the cattle were managed as a single group and were all the same breed.

There was also no difference in growth rates between the periods of three to eight months, eight to ten months and ten to twelve months of age. Although the physiology of animals allows for accelerating growth until around twelve months of age under optimal environmental conditions, differences in growth rates would not be expected over such a small age range (Marti *et al*., 2013). In addition, livestock on-farm are rarely grown under optimal conditions due to changes in feed availability and environmental conditions. Although feed conversion efficiency was not measured in this present study, a decline in feed conversion efficiency in steers slaughtered between 10 and 14 months of age was reported by Marti *et al*. (2013). The increased variation in growth rates between eight and ten months of age was likely due to restricted feed availability while being break-fed over winter.

5.2 Carcass Characteristics

Steers slaughtered at twelve months of age produced heavier and longer carcasses, greater dressing-out percentages and larger eye muscle areas compared with steers slaughtered at eight or ten months of age. The increase in carcass weight and length with older slaughter age reflects the greater live weights of the steers at the time of slaughter. This effect is typically observed in studies where cattle were slaughtered at pre-determined ages rather than at set live weight or level of finish (Ahnström *et al*., 2012; Bureš & Bartoň, 2012; Nogalski *et al*., 2018; Pogorzelska-Przybyłek *et al*., 2018). Differences in carcass weights between all slaughter ages also reflects that the steers were randomly pre-allocated to slaughter-age treatment groups, rather than selecting the heaviest animals at each age to be sent to slaughter, as would typically occur on a commercial farm (Purchas *et al*., 1997). Random allocation of steers to slaughter-age groups balanced for live weight, was used in this experiment to compare the effect of slaughter age, as opposed to slaughter weight.

Dressing-out percentage did not differ between steers slaughtered at eight or ten months, but increased at twelve months of age. The increase in dressing-out percentage at twelve months of age is likely attributed to increased muscle and fat deposition within the carcass, and slower growth of non-carcass components such as fat (Keane, 2011). The dressing-out percentages ranged from 47.2% to 50.0% in this present study, which was lower than studies that have implemented yearling slaughter ages. Steers slaughtered between 10 and 15 months of age obtained dressing-out values between 51.9% and 56.5% (Marti *et al*., 2013; Nogalski *et al*., 2018; Pogorzelska-Przybyłek *et al*., 2018). However, cattle in the prementioned studies were fed concentrate-based diets, and consequently achieved much higher carcass weights and greater fat deposition. Lower dressing-out percentages are also observed when cattle are fed on pasture and forages due to increased gut-fill (Steen *et al*., 2003).

A decline in dressing-out percentages is sometimes observed in older cattle (24 to 36 months of age), as a result of excess non-carcass fat deposition (Bown *et al*., 2016). This would not be expected in steers slaughtered at ages of between eight and twelve months, given the low levels of fat deposition occurring at these ages (Keane, 2011); however, gut-fill effects could be more prominent (Steen *et al*., 2003).

Ultrasound measurements for subcutaneous fat depths and transverse eye muscle areas increased progressively with age, consistent with Coleman *et al*. (2016). Subcutaneous fat depths at all ages were less than 3 mm, which is the current minimum fat depth required for steers to be classified as 'P' (light to medium fat cover) (New Zealand Meat Classification Authority, 2004). This would have implications for the carcass value, as carcasses graded under fat classes 'L' (3-10 mm fat) or 'A' (devoid of fat) are penalised with a lower price on a cents/kg basis. Ultrasound results from Coleman *et al*. (2016) found steers reached a 3 mm fat depth between twelve and eighteen months of age. Subcutaneous fat depths increased at slower rates compared with eye muscle area between eight and twelve months of age, as would be expected since more energy is being directed towards lean deposition than fat deposition at these younger ages (Beermann, 2014).

The increase in eye muscle area with age was expected due to increased muscle deposition as a result of hypertrophy (Maltin *et al*., 1998; Purchas & Grant, 1995; Wolcott *et al*., 2001; Schreurs *et al*., 2008). Since a larger eye muscle area is generally associated with a higher proportion of lean meat in the carcass, it is likely that the lean and saleable meat yield also increased with age (Johnson *et al*., 1992; Wolcott *et al*., 2001), although this was not measured in these animals.

An increase in intramuscular fat with age was also consistent with literature that has shown intramuscular fat deposition to increase with age and carcass weight (Purchas & Grant, 1995; Irshad *et al*., 2013; Coleman *et al*., 2016). Intramuscular fat levels were still low compared with steers finished to an age of 24 to 36 months (Wolcott *et al*., 2001; Coleman *et al*., 2016). Since intramuscular fat is a late-developing fat depot, significant increases in intramuscular fat deposition would not be expected in cattle until they are older and nearing maturity (Purchas & Grant, 1995; Irshad *et al*., 2013; Coleman *et al*., 2016). Low intramuscular fat levels may influence eating quality attributes such as juiciness and flavour (Moletta *et al*., 2014), so further investigation would be beneficial to understand the impact of a younger slaughter age on subjective meat quality attributes.

Improved muscularity is often associated with higher meat yields when the level of fatness is constant, because it is often correlated with higher muscle to bone ratios (Purchas *et al*., 1991). Muscularity was lower than what is typically observed from 24- to 36-month-old steers indicating lower meat yields, as would be expected for younger cattle (Purchas *et al*., 1991). Muscularity did not change between ages, but the increase in muscle to bone ratios that was observed with increasing slaughter ages is consistent with literature (Purchas *et al*., 1991). Although not measured, the increase in muscle to bone ratios indicate saleable meat yield likely increased progressively with age. Processing yearling steers at twelve months of age may therefore be more economical in terms of processing costs and efficiency, compared with a slaughter age of eight or ten months.

The increase in yellowness of carcass fat with age can be attributed to the accumulation of carotenoid pigments, particularly as a result of the steers' diet being pasture-based, which contains high levels of carotenoid pigments (Purchas, 2003). Although fat colour increased with age, carcass fat colour was still lighter than would typically be observed from a steer carcass slaughtered at finishing ages of 24 to 36 months. Due to cattle in a yearling beef production system being slaughtered at younger ages, there is less time for carotenoid pigments to accumulate, potentially reducing the incidence of yellow fat. This could allow animals with a high proportion of Jersey genetics, which are often associated with greater incidence of yellow fat, to be utilised with less risk of yellow fat occurring compared with slaughter ages of 24 to 36 months (Burke, *et al*., 1998; Muir *et al*., 2000; Purchas & Morris, 2007). The influence of the Jersey component of cattle used in this study on yellow fat for yearling steers seems to be minimal, as visual fat colour scores were all less than three out of a scale of nine.

5.3 Meat Quality Attributes

5.3.1 Effect of Slaughter Age

Objective meat quality attributes of ultimate pH, lean meat colour and water-holding capacity were affected by differences in slaughter ages between eight and twelve months of age. A low ultimate pH value of 5.3 was observed at eight months of age, while ultimate pH values at ten and twelve months of age were within the expected range of 5.4-5.6 (Purchas, 2003; Oliete *et al*., 2005). Studies that have reported increases in pH with slaughter age have been explained by a reduction in glycogen levels that can occur in bulls as they become older and more aggressive (Bouton *et al*., 1978; Du Plessis & Hoffman, 2007; Bureš & Bartoň, 2012). However, given the cattle used in the present study were young steers, it is unlikely that this was the cause of the change in pH with age.

The low pH value observed at eight months of age may have been influenced by pre-slaughter factors, although steers at all slaughter ages were managed the same prior to slaughter. Another cause could have been that there were more active lactate dehydrogenase enzymes in the meat from the younger steers, which are responsible for converting glycogen into lactate, resulting in a lower pH (Schreurs *et al*., 2008). Where significant, ultimate pH was also included as a covariate for objective meat quality measurements to account for the variation in pH between slaughter ages and the effects this can have on tenderness, colour and water-holding capacity.

Shear force values did not differ between slaughter ages. It was expected that increasing age may have an adverse effect on shear force values and therefore tenderness, attributed to a decline in collagen solubility with age, as observed in many studies which have compared animals over a wide age range (Goll *et al.,* 1964; Bouton *et al*., 1978; Purchas & Grant, 1995; Li *et al*., 2011; Yim & Hur, 2019). However, studies comparing the effect of slaughter age over a small age range of four months or less have also found shear force values to generally be unaffected by slaughter age, as the relationship between age and collagen solubility is less consistent when cattle of a narrow age range are compared (Bureš & Bartoň, 2012; Marti *et al*., 2013; Pogorzelska-Przybyłek *et al*., 2018; Nogalski *et al*., 2018).

There was also only small variation in shear force values both within and between slaughter ages. Inconsistencies in beef tenderness is considered to be one of the main causes of consumer dissatisfaction with beef, with increasing age often associated with greater variation in tenderness (Maltin *et al*., 1998; Lucero-Borja *et al*., 2014). Slaughtering steers at or prior to twelve months of age could therefore produce a beef product with more consistent tenderness (Yim & Hur, 2019).

The small increase in intramuscular fat content at twelve months of age may have also counteracted any reduction in collagen solubility that potentially occurred during the same period. Greater intramuscular fat is associated with improved tenderness due to dilution of muscle fibres (Purchas & Barton, 1976; Muir *et al*., 2000). However, for beef, the effect of intramuscular fat on tenderness is considered to be very low, except for breeds which are capable of depositing high amounts of intramuscular fat of at least 8% (Savell & Cross, 1988; Nishimura *et al*., 1999).

Shear force values across all three slaughter ages ranged between 5.0 kgF and 5.2 kgF, which is considerably lower than what has previously been reported from steers slaughtered at ages of 24 to 36 months. In comparison, peak shear force observed from 24-month-old, beef-dairy prime steers averaged 9.6 kgF (Coleman *et al*., 2016), while vealer calves slaughtered between six and nine months of age typically averaged 3-6 kgF (Domaradzki *et al*., 2017). This more clearly demonstrates the potential decline in tenderness with age, likely due to increased collagen cross-linking resulting in a reduction in collagen solubility (Purchas & Grant, 1995). Shear force values above 10 kgF for beef are detectable to consumers as “tough”, while values below 7 kgF can be recognised by consumers as “tender” (Bickerstaffe *et al*., 2001). Given that peak shear force values for all slaughter ages were less than 7 kgF, in general, the tenderness can be considered to be of acceptable eating quality even without ageing.

Lean meat colour became darker and redder as the steers became older, which can be attributed to the increase in myoglobin concentration in the muscle as animals get older (Young & West, 2001; Marencic *et al*., 2018). These trends in colour change are in agreement with most age-related studies for cattle (Purchas & Grant, 1995; Purchas *et al*., 1997), although some studies conducted over a small age range did not observe changes in colour (Bureš & Bartoň, 2012; Marencic *et al*., 2018; Nogalski *et al*., 2018; Yim & Hur, 2019).

When compared to beef from 24-month-old, beef-dairy prime steers from Coleman *et al*. (2016), lightness and redness values were similar to the steers slaughtered at ten and twelve months of age in this experiment, while meat from eight-month-old steers was lighter. In contrast, redness and lightness values from veal calves slaughtered between one and ten months tended to have much higher lightness values and lower redness values than observed in the present study, due to a lower myoglobin concentration (Biss *et al*., 1993; Tarantola *et al*., 2003; Gottardo *et al*., 2005; Domaradzki *et al*., 2017). Beef from pasture-raised steers slaughtered between eight and twelve months of age can be considered to be redder when compared with veal. Differences in colour may influence consumers' perception of the product (Young & West, 2001), highlighting the need to differentiate this yearling product from veal.

Cooking loss declined with age, which has been reported in previous studies (Ahnström *et al*., 2012; Pogorzelska-Przybyłek *et al*., 2018; Yim & Hur, 2019). A decrease in cooking loss with age has been found to be related to increased intramuscular fat deposition (Ahnström *et al*., 2012; Pogorzelska-Przybyłek *et al*., 2018). Since cooking loss mainly occurs through the release of water bound to protein, greater levels of intramuscular fat mean a lower proportion of lean protein in the beef, and thus there is less water able to be lost (Ueda *et al*., 2007; Ahnström *et al*., 2012). The decrease in cooking loss observed at twelve months of age is consistent with the small increase in intramuscular fat that occurred at this age. The decline in cooking loss may have also been a result of the greater weight of the steaks from the twelve-month-old steers, as there is less surface area per unit weight.

There was no change in drip loss with increasing slaughter age, although thaw loss increased slightly. Water-holding capacity can be affected by carcass composition, as lean protein is associated with a greater ability to retain water than fat (Ueda *et al*., 2007). Considering there was only four months' difference in age between treatments and little change in carcass composition, it would be expected there would also be minimal change in water-holding capacity. The relationship between fat, protein and water-holding capacity tends to be inconsistent at low fat levels (Ueda *et al*., 2007), which may explain why the increase in intramuscular fat at twelve months affected cooking loss and thaw loss, but not drip loss. It should be noted, however, that the lowest intramuscular fat level considered in Ueda *et al*. (2007) was approximately 5%, which is higher than those observed in the present study.

Drip loss was comparatively lower than for 24-month-old beef-dairy cross steers in a previous study, which measured 6.2% at 24 hours, and 8.0% at 48 hours (Coleman *et al*., 2016). These values are approximately twice the percentages observed in this present study. The young steers slaughtered in the current experiment were considerably leaner than the 24-month-old steers in Coleman *et al*. (2016), which may explain the lower drip loss values (Bureš & Bartoň, 2012; Marti *et al*., 2013; Pogorzelska-Przybyłek *et al*., 2018). The greater water-holding capacity of beef from steers slaughtered at eight to twelve months of age is likely to be beneficial for eating quality, potentially negating the effect of reduced intramuscular fat levels on juiciness.

5.3.2 Postmortem Ageing

Ultimate pH was slightly higher for samples that had undergone postmortem ageing. A trend of increasing pH with ageing time has previously been reported and has been attributed to changes in charges caused by proteolytic enzymes during ageing and the formation of compounds from proteolysis (Boakye & Mittal,1993; Obuz *et al*., 2014). The difference in pH between aged and unaged samples was numerically small (unaged pH 5.45, aged pH 5.50), so unlikely to have a noticeable effect on other meat quality attributes, given both values were within the normal expected range for beef of 5.4-5.6 (Purchas, 2003; Oliete *et al*., 2005).

The tenderness of beef improved as a result of postmortem ageing, expressed by a reduction in Warner-Bratzler shear force values. Postmortem ageing is known to improve meat tenderness, as a result of enzymes causing degradation of myofibril proteins and associated proteins such as desmin, titin and nebulin (Jones *et al*., 1991; Aalhus *et al*., 1992; Mandell *et al*., 2001; Oliete *et al*., 2005; Stanišić *et al*., 2012; Lucero-Borja *et al*., 2014; Wu *et al*., 2014; Yim & Hur, 2019). Although ageing reduced shear force values, it is uncertain whether the relatively small reduction in shear force values as a result of ageing yearling beef would be noticeable by consumers in terms of eating quality, since the unaged beef was already very tender due to shear force values below 7 kgF (Bickerstaffe *et al*., 2001). Given the meat is already very tender, it is possible that meat could be aged for a shorter period of time.

Myofibrillar fragment index increased after postmortem ageing. Improvements in tenderness from ageing are generally associated with an increase in myofibrillar fragmentation index, as a result of proteolytic enzymes degrading the muscle structure (Oliete *et al*., 2005). The increase in myofibrillar fragment index observed in this study, however, was very small compared to changes observed with beef from 24- to 36-month-old steers (Purchas, 2004). It is likely that the change in myofibrillar fragmentation index was small due to the unaged meat already being very tender.

The increase in water-holding capacity with postmortem ageing, indicated by the decrease in drip loss, can be related to the degradation of muscle structure during ageing (Hughes *et al*., 2014; Zeng *et al*., 2017). Ageing alters the structure of proteins within the meat, reducing the shrinkage that is associated with expelling water (Kristensen & Purslow, 2001). Despite an increase in water-holding capacity for aged samples, there was no change in cooking loss as a result of postmortem ageing, similar to other literature which suggest the relationship between drip loss and ageing does not hold true for cooking loss (Purchas, 2004; Hughes *et al*., 2014; Zeng *et al*., 2017). As a result of cooking, the degraded protein structure in aged meat has a reduced ability to trap or retain water, resulting in similar or greater cooking loss after ageing, as was observed in this current study (Hughes *et al*., 2014; Zeng *et al*., 2017).

In accordance with previous research, an increase in redness of beef as a result of ageing was also observed (Oliete *et al*., 2005; Mitchell *et al*., 1991; Boakye & Mittal, 1996; Stanišić *et al*., 2012). This is thought to be related to the lack of respiration from mitochondria during ageing, allowing oxygen levels in the muscle surface to increase, giving the meat a redder appearance due to greater formation of oxymyoglobin (Oliete *et al*., 2005).

No change in lightness values was observed as a result of postmortem ageing, unlike some studies that have reported an increase in lightness of aged beef from steers slaughtered at the ages of 24 to 36 months (Boakye & Mittal, 1996; Oliete *et al*., 2005; Stanišić *et al*., 2012; Hughes *et al*., 2014). The increase in lightness was attributed to proteolysis causing a change in the 3D molecular structure and increased extracellular space, allowing more light to be scattered and reflected (Hughes *et al*., 2014). Due to the young slaughter age of steers in this study, the lean meat colour was already lighter than beef from steers slaughtered at older ages of 24 to 36 months, which may explain why ageing did not cause an increase in lightness. The increase in yellowness values as a result of ageing is also difficult to explain, as it is unclear how ageing would specifically influence yellowness.

5.4 Limitations

Comparisons with a traditional beef product

This study did not include a control group of dairy-origin steers slaughtered at the traditional finishing age of between 18 and 36 months of age. Carcass and meat quality attributes could not be directly compared with 18- to 36-month-old steer carcasses or meat products. Where possible, comparisons were instead made with beef-dairy cross steers (Hereford x Angus-Kiwi) slaughtered in a previous study by Coleman *et al.* (2016) at 24 months of age. However, these steers originated from a beef-cow herd and were not of dairy origin. Future research will involve comparing results from the eight-, ten- and twelve-month slaughter treatments with steers from the same cohort that were recently slaughtered at 24 months of age.

Choice of breed

The experiment utilised Hereford x Friesian-Jersey calves. Although beef-dairy cross calves with Jersey genetics do contribute to the bobby calf trade, the majority of bobbies are small Friesian-Jersey (Kiwi-Cross) and Jersey calves. The literature review supports the theory that differences in carcass characteristics and meat quality attributes between breeds tend be much smaller than differences caused by variation in slaughter age. An experiment implementing a yearling slaughter age using straight dairy-breed calves would be beneficial in order to validate the carcass and meat quality attributes from these breeds at an intermediate slaughter age. In particular, the use of straight dairy breeds could influence growth rates and potential carcass weights achieved at a yearling age.

Random allocation of steers to slaughter age treatments

As slaughter age increased, so did carcass weights, which may have been the main factor influencing carcass and meat quality attributes rather than age. However, age and carcass weight cannot realistically be considered separately, because as animals get older, they get heavier. In order to clearly understand the effects of slaughter age and reduce the confounding effects of carcass weight, steers were randomly allocated to slaughter groups and balanced for live weight at eight months of age. This does not reflect normal on-farm practice, where the heaviest steers would be selected for slaughter first, while lighter animals would remain on-farm until target slaughter weights were reached. Carcass weights attained on a commercial farm at each slaughter age may therefore be greater than what was observed in this study.

However, given that differences in carcass characteristics and meat quality between slaughter ages in this study were small, the results can still be considered realistic for commercial conditions. The problem of having age and weight confounded could be overcome to some extent with further research by using a factorial design, with two weights at each slaughter age, although confounding effects of different growth rates would need to be taken in account.

Live and carcass measurements

Final live weights were obtained on-farm immediately off feed, as opposed to immediately prior to slaughter after being fasted. This may have underestimated dressing-out percentages. Fat depths were only measured by ultrasound on the live animals, as they were unable to be measured on the carcasses at the processor. Consequently, the actual carcass fat depths may have varied slightly, which should be taken into consideration when comparing these fat depths with other literature. The carcass fat percentage was also not measured; therefore, saleable and lean meat yields were unable to be calculated. However, because carcasses were young and lean, the weights of the cuts recorded act as a proxy for saleable meat yield.

Feeding management

Because the Manawatu region experienced an early dry period in January 2018, which limited pasture availability and quality, steers were fed on meal for an extended period up until the end of January. This may differ from what would occur on a commercial farm.

Assessment of subjective eating quality

Only objective meat quality attributes were able to be measured in this study, due to time and financial constraints. A consumer sensory panel would allow further investigation into subjective eating quality attributes such as flavour, tenderness, texture and juiciness. This would be useful to help better understand the general consumer acceptability and overall liking of the product, and to determine if consumers would be willing to pay a premium for this product.

5.5 Future Research

Potential for utilising bulls instead of steers

There is potential for bull calves to be used in a yearling beef production system. Due to slaughter occurring prior to puberty, beef from bulls may provide an equally acceptable product compared to steers, whilst also allowing scope for improved growth rates and efficiency associated with bulls (Marti *et al*., 2013). Utilising entire male cattle would also eliminate the need for castration, which could be advantageous for animal welfare. Further investigation would be beneficial to validate the growth potential and meat quality from dairy-origin bulls slaughtered at around one year of age.

Modelling of economics, farm system feasibility and environmental impacts

A modelling exercise is currently being undertaken to better understand the economic feasibility of the proposed yearling beef production system, compared with bull beef or steer/heifer finishing systems (Hunt *et al*., 2019). This includes identifying the break-even point (cents/kg) for profitability given current feed and non-feed costs for the three different potential slaughter ages. In addition, there is opportunity for OverseerFM or a model developed from first principles to be used to quantify the potential environmental footprint of the proposed system in comparison to a traditional bull beef or steer finishing system. There is also scope to investigate if finishing yearling steers could allow for an increased stocking rate, compared with finishing systems that slaughter calves at 18 to 36 months of age. Since younger animals have less feed demand per head, this may enable stock to be grazed more intensively, allowing similar carcass yields on a per hectare basis to be attained, compared with finishing systems that slaughter cattle at 18 to 36 months of age (Hunt *et al*., 2019).

Identifying appropriate markets

The meat quality results from this study highlight how the product from these animals differs from veal and beef derived from animals slaughtered at over 18 months of age. Since this is a new beef product, markets need to be identified and developed. For the New Zealand beef industry, having products going into high-end retail, such as restaurants and upscale supermarkets, is key to maximising returns. Therefore, market research is needed to determine the demand for this new product and to understand where the greatest premiums could be attained.

The meat quality data from this study could inform market research of potential, suitable markets. Not only will the new class of meat need to be accepted by the market, but also the cuts of meat are smaller, which may influence which consumers the product is suited to.

Development of an appropriate carcass classification and payment system

There is no existing classification system for light beef carcasses from young cattle in New Zealand. The current beef carcass classification system considers these carcasses as “underweight” with poor attributes for saleable meat yield. Therefore, light beef carcasses are classified as manufacturing beef, implying lower returns on a cents/kg basis, especially as the carcasses also have little fat deposition and would be graded under fat classes ‘L’ (light, patchy fat cover) or ‘A’ (devoid of fat), which also receive lower schedule prices. This combination results in very low returns for producers and would not currently be a sustainable production class (Hunt *et al*., 2019). A separate classification system that reflects market demand for a yearling beef product is required to make it viable. Data from this study could be used in the development of such a classification system.

Understanding the value of co-products

Co-products such as hides and offal could potentially be of value for the leather and pet food industries. Subsequent investigation into the value of co-products and potential uses could further enhance the profitability and feasibility of an accelerated-cycle beef production system, and determine if higher returns could be attained.

5.6 Conclusions and Implications

Growth rates above 0.8 kg/day can be obtained from beef-cross-dairy steers raised on a pasture and forage-based diet, indicating that the dairy influence does not negatively impact on growth. Carcass weights in this study were lighter than cattle in literature slaughtered between 18 and 36 months of age; however, they were proportional to those of older animals if feeding to maximise growth rates is attained. Although the muscularity indexes indicate a lower meat yield per head than cattle slaughtered at 18 to 36 months of age, there is potential to investigate if an increased stocking rate could achieve similar meat yields per hectare to existing beef cattle finishing systems in New Zealand.

A potential challenge with a production system in which cattle are bought at three months of age in November and slaughtered at or before twelve months, is that there would be no cattle on-farm when pasture growth rates are close to their maximum. This could be overcome with other complimentary livestock classes such as sheep or breeding cattle, as a yearling beef production system would increase feed availability for these livestock classes during spring.

Carcass characteristics tended to increase with age as hypothesised, although the differences between slaughter ages were relatively small. This was expected given there was only four months' difference in age between treatments. The greater saleable meat yields and dressing-out percentages that were achieved at ten or twelve months of age may, however, be advantageous in terms of processing efficiency and profitability. Although fat colour became more yellow with age, it was still light and was not negatively affected by the Jersey component in the breed.

The meat product obtained from yearling steers is lean, but very tender due to the young slaughter age. Therefore, it is likely to be of high eating quality and could justifiably be targeted to markets that offer a premium. There were few differences in the objective meat quality measures between the three slaughter age treatments. Although some attributes such as colour and water-holding capacity differed between slaughter ages, the differences were unlikely to be large enough to impact on the eating quality. Beef obtained from cattle slaughtered between the ages of eight and twelve months could therefore be classed and processed together under one category, which would offer farmers a degree of flexibility in terms of slaughter age. The meat product obtained was also a definitive red colour, which removes the connotation that it is veal, and provides an opportunity to market yearling beef as a new product category.

Tenderness and water-holding capacity improved as a result of postmortem ageing. However, the reduction in shear force values was small, so it is possible this difference may not be noticeable by consumers in terms of eating quality, since the meat is already very tender. If less ageing is required, this may offer cost savings for processors and allow the product to reach markets quicker.

Profitability for meat processors is directly correlated to the number of animals processed per day and the quantity of saleable meat per carcass. Compared with carcasses from 18- to 36-month-old cattle, the smaller carcasses from eight- to twelve-month-old cattle have less saleable meat per carcass, which may negatively impact profitability. However, this could be partly offset if the lighter carcasses allow for the animals to be processed faster, thus increasing the number of cattle processed per day. The decreased carcass yield may also be counteracted if premiums could be attained for the product, although this is likely to require considerable investment in marketing given it is a new product, and current premiums are generally associated with highly marbled steak cuts.

In terms of carcass yields and meat quality, pasture-based yearling beef production using dairy-origin cattle is feasible, and also offers potential benefits such as reduced environmental impacts and improved utilisation of bobby calves. Because yearling beef production can successfully be grown in a pasture and forage-based system, this would provide an opportunity to allow promotion utilising New Zealand's grass-fed systems appellations for red meat products.

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