

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

THE EFFECT OF SIRE
ON GROWTH AND MEAT PRODUCTION OF
BEEF-CROSS-DAIRY CATTLE IN NEW ZEALAND

A thesis presented in partial fulfilment of the
requirements for the degree of

Doctor of Philosophy
in
Animal Science

at Massey University, Manawatū,
New Zealand

Natalia de la Paz Martín

2021

ABSTRACT

Beef-cross-dairy cattle are the progeny produced by mating dairy-breed cows with beef-breed sires. Little is known about the performance of beef-breed sires for growth, carcass and meat quality traits when used to generate beef-cross-dairy cattle in pasture-based systems. Yet, beef-cross-dairy cattle make up around 30% of the finishing cattle in New Zealand, and so improving their performance would enhance the efficiency and productivity of the beef industry.

The general aim of this study was to investigate the effect of sire on growth and meat production of beef-cross-dairy cattle in New Zealand. The specific objectives were: to evaluate live weight from 4 months of age until slaughter, carcass and meat quality traits of a selection of Angus and Hereford sires via progeny testing of beef-cross-dairy offspring grown on hill country pasture; to quantify the relationship between the performance of the beef-cross-dairy progeny and sires' estimated breeding values (EBV) for growth and carcass traits; and to assess skeletal size and temperament measured within the first 200 days of life as predictors of carcass and meat quality traits for beef-cross-dairy cattle.

Data from 1101 beef-cross-dairy calves born to 2-year-old or mixed-aged dairy-breed cows were used to analyse live weight, carcass and meat quality traits of 73 beef-breed sires (34 Angus and 39 Hereford). Meat samples were obtained for analysis in the laboratory from 326 progeny of 33 sires used via artificial breeding (AB) on mixed-aged dairy-breed cows. Progeny group means for live weight, carcass weight, eye muscle area (EMA), rib fat depth, marbling scores and intramuscular fat (IMF) of 29 Angus and 34 Hereford AB sires, were regressed against sire EBV within breed. Finally, 486 beef-cross-dairy calves had measurements of skeletal size and temperament evaluated as predictors of carcass and meat traits.

The mean of the progeny group means for live weight was 118.6 kg at 131d, and increased to 503.6 kg at 800d. Mean of the progeny group means was 277.3 kg for carcass weight, 240.3 cm for carcass length, 73.6 cm² for eye muscle area (EMA), 7.4 mm for rib fat depth, 0.91 for marble score, 3.05 for fat colour score and 3.01 for meat colour score. Sire affected ($P < 0.05$) live weight of the progeny at all ages and all carcass traits, but few meat quality traits (fat yellowness b^* , meat redness a^* and yellowness b^* , cook loss and shear force). Differences in live weight between the lightest and heaviest progeny group means increased from 19 kg at 131d to 90 kg at 800d, and there was a 46 kg difference in carcass weight between the heaviest and lightest sire tested. The coefficient of variation (CV) among sires for EMA was

5% and for measured rib fat depth was 19%, with no sire mean below 3 mm and most progeny (97%) grading “P” fat class. For marble scores, there was 35% CV between sires even though all progeny had low marble scores between 0 and 3. There were small sire effects for carcass length, cook loss and shear force ($P < 0.05$). Meat and fat colour scores were not affected by sire, and although there were small sire differences in fat yellowness b^* , no progeny carcasses were classified as being too yellow.

Live weight of the progeny groups increased with sire EBV for live weight at 400, 600 and 800 days of age (between 0.24-0.43 kg increase in progeny live weight per extra kilogram of sire EBV), although sire EBV had no effect on the live weight of the progeny at 200 days of age ($P > 0.05$). For the Hereford sires in this experiment, progeny carcass weight increased 0.27 kg and EMA 0.70 cm² per extra 1 unit in sire EBV for each trait ($P < 0.05$). For the Angus sires, progeny rib fat depth increased 6.9 mm, marble score 0.91 and estimated IMF 2.26% per extra 1 unit in sire EBV for each trait ($P < 0.05$).

Live weight at birth, 129d and 200d predicted future carcass size ($P < 0.05$). In heifers, the accuracy of predictions of carcass weight from live weight were low to moderate ($R^2 = 17$ to 31%) and increased if live weight was combined with hip-height. In steers, live weight alone could predict carcass weight with moderate accuracy ($R^2 = 39$ to 48%). Accuracy of prediction for carcass weight of steers increased with age, or with combining live weight with body length at 0d, or with hip-width at 129d. Thicker cannon bones at birth also gave an indication of heavier carcasses for both heifers and steers. Cattle in this study were calm at 200d (mean exit velocity of 1.2 m/s and crush score of 1.4) and temperament did not influence production traits in this study.

The data presented in this study indicated that using genetically superior beef-breed sires over dairy-breed cows increased the growth, carcass and meat production of their beef-cross-dairy progeny. Dairy farmers should consider BREEDPLAN EBV when selecting beef-breed sires to mate their dairy-breed cows, not only for positive calving outcomes but for achieving desirable and economically important carcass and meat quality traits. The beef cattle finisher should consider the calves’ potential for growth and fattening when purchasing beef-cross-dairy calves for beef production, by utilising both genetic and phenotypic live weight information.

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my fantastic team of supervisors: Associate Professor Rebecca Hickson, Dr. Nicola Schreurs, Professor Steve Morris, Professor Nicolás López-Villalobos and Dr. Julie McDade. I couldn't have asked for a better team- what a great mix of knowledge and experience in academia, research and industry! I have learnt a great deal on progeny testing, cattle growth and meat quality, but also a lot about the New Zealand livestock industry, research and people amongst all.

A huge thanks goes to my main supervisor, Rebecca. You are phenomenal! Thanks for the guidance, patience, encouragement, fixing my spanglish (part of my essence!), reading and commenting and discussing things at very complicated and tight timelines. Thanks for making yourself available when it was needed, for helping to shape my thoughts and being understanding but not complacent. Gracias!

Thank you to my co-supervisors for sharing your knowledge, constructive discussions, support and reassurance throughout these years. To Nicola, for teaching the ropes in the chiller and in the lab, and all the meat related things in-between. To Steve, for your big-picture view, your positive feedback and sharing your expertise in the beef industry and academia. To Nicolás, for the coaching the way through statistics. To Julie, for the mentoring and giving the business perspective.

Thanks to Beef+Lamb New Zealand Genetics for running the Dairy-Beef Progeny Test in first instance, to the Angus and Hereford bull breeders for donating semen, to the C. Alma Baker Trust for providing support and the farm to run the cattle, and to Greenlea Premier Meats for giving access and integrating the research activities within the plant. I am very grateful to have been a recipient of a Callaghan Innovation - R&D Student-Fellowship Grant for 3 years, and to the Peter Densem, John Hodgson and DJ McGowan postgraduate scholarships for providing extra financial assistance during my PhD.

I would like to acknowledge all the people that worked behind the scenes. To the farm staff at Limestone Downs, especially Dave Milne, Campbell Lourie, Paul Mahoney, Alec and Wendy, that looked after the cattle and where always willing to accommodate my requests. To the plant staff at Greenlea Premier Meats, particularly Aaron Craig, Greg Clark and Scott Green, who organised the logistics around processing of the animals and the work inside the plant. To the staff of School of Sport, Matthew Barnes and Adam Miller, for lending equipment. To those

within the College of Sciences who provide advice on protocols, measures and methodology, and to the technical staff and students that helped me in the field and in the lab: Anne Riddler, Bill Pomroy, Geoff Purchas, Dean Burnham, Catriona Jenkinson, Bede Jennings, Kayla (Huai Xuan) Wong, Sam Pike and all the extra helping hands. Thank you!

A very special thanks goes to my PhD colleague Lucy Coleman, the other half of the Limestone Downs Dairy-Beef PhD team: thank you enormously for your assistance, data collection, discussions and laying the way. We still have our joint publications to get out of this project!

Muchas gracias to my family and friends, the ones from Argentina and the ones from New Zealand, from university and life. Luckily, I have too many to name, but you know who you are. Thanks for the many mates, asados, chats, walks, laughs and gatherings, face-to-face or in the distance! You have kept me positive and sane during these crazy and hard times.

Muchas gracias a mi familia y amigos, los de Argentina y los de Nueva Zelanda, a los que conocí en la Universidad y a los de la vida. Tengo la suerte de tener muchos para nombrar a cada uno, pero ustedes saben quienes son. Gracias por tantos mates, asados, charlas, caminatas, risas y reuniones, presenciales o a la distancia! Ustedes me mantuvieron positiva y cuerda en estos tiempos de locura y tan difíciles. Espero poder abrazarlos pronto.

Finally, my biggest loving GRACIAS goes to my beautiful kiwicross family: Grant, Tomás and Emma. Thanks for your smiles, laughs and giggles, your constant support and making me feel so full of life. Thanks for being my strength and standing feet in this messy world. I'm very fortunate to have you and I hope that, as I did my PhD when a lot of people thought I was crazy for doing so (even myself), you know you can conquer anything that you set your mind to!

TABLE OF CONTENTS

ABSTRACT	I
ACKNOWLEDGEMENTS	III
TABLE OF CONTENTS	V
LIST OF FIGURES	VIII
LIST OF TABLES	X
LIST OF APPENDICES.....	XIII
ABBREVIATIONS	XIV
CHAPTER 1 GENERAL INTRODUCTION	1
CHAPTER 2 LITERATURE REVIEW.....	5
2.1. Beef industry in New Zealand	6
2.1.1. Cattle population	8
2.1.2. Dairy-origin cattle	8
2.2. Parents and progeny: the genetic basis of meat production	11
2.2.1. Cattle traits for selection	11
2.2.2. Estimated Breeding Values	12
2.2.3. Cattle breeds and sire lines.....	13
2.3. Animal growth and performance.....	15
2.3.1. Live weight and growth	15
2.3.2. Skeletal size	16
2.3.3. Temperament.....	18
2.3.4. Heritability and correlations	19
2.4. The beef carcass.....	20
2.4.1. Beef carcass grading in New Zealand.....	21
2.4.2. Carcass weight and length.....	23
2.4.3. Meat yield and muscle area.....	24
2.4.4. Fat depots: subcutaneous and intramuscular fat	25
2.4.5. Heritability and correlations	28
2.5. Meat quality	29
2.5.1. Ultimate pH	30
2.5.2. Marbling	31
2.5.3. Meat and fat colour	32
2.5.4. Tenderness	34
2.5.5. Water-holding capacity	35
2.5.6. Heritability and correlations	35
2.6. Summary of the review of literature and hypotheses of the thesis	36
CHAPTER 3 SIRE EFFECTS ON POST-WEANING GROWTH OF BEEF-CROSS-DAIRY CATTLE	41
3.1. Abstract.....	42
3.2. Introduction	42

3.3. Materials and Methodology	44
3.3.1. Animals.....	44
3.3.2. Feed management at the beef farm.....	46
3.3.3. Measurements	47
3.3.4. Statistical Analysis	48
3.4. Results	50
3.4.1. Live weight of beef-cross-dairy progeny.....	50
3.4.2. Comparison of progeny means for live weight at different ages	53
3.5. Discussion	54
3.6. Conclusions and implications	57
 CHAPTER 4 SIRE EFFECTS ON CARCASS AND MEAT QUALITY OF BEEF-CROSS-DAIRY CATTLE	 59
4.1. Abstract	60
4.2. Introduction.....	61
4.3. Materials and Methodology	62
4.3.1. Animals and management.....	63
4.3.2. Slaughter	64
4.3.3. Measurements	65
4.3.4. Statistical Analysis	68
4.4. Results	70
4.4.1. Weight and carcass traits of beef-cross-dairy progeny.....	70
4.4.2. Meat quality traits of beef-cross-dairy progeny	73
4.4.3. Comparison of progeny means for carcass traits.....	77
4.5. Discussion	78
4.6. Conclusions and implications	82
 CHAPTER 5 PERFORMANCE OF BEEF-CROSS-DAIRY PROGENY IN RELATION TO ESTIMATED BREEDING VALUES OF THE SIRE	 83
5.1. Abstract	84
5.2. Introduction.....	84
5.3. Materials and Methodology	86
5.3.1. Animals.....	86
5.3.2. Measurements and progeny means calculations	88
5.3.3. Statistical Analysis	89
5.4. Results	90
5.4.1. Regression of progeny means on sire EBV for live weight	90
5.4.2. Regression of progeny means on sire EBV for carcass traits.....	92
5.5. Discussion	94
5.6. Conclusions and implications	98

CHAPTER 6	SIZE AND TEMPERAMENT OF BEEF-CROSS-DAIRY CATTLE MEASURED EARLY IN LIFE AS PREDICTORS OF CARCASS AND MEAT TRAITS	101
6.1.	Abstract.....	102
6.2.	Introduction	102
6.3.	Materials and Methodology	104
6.3.1.	Animals and management.....	104
6.3.2.	Measurements.....	106
6.3.3.	Statistical Analysis	108
6.4.	Results.....	109
6.4.1.	Predictions of carcass size, muscularity and fat using skeletal size measurements.....	110
6.4.2.	Predictions of growth and meat traits using temperament measurements.....	117
6.5.	Discussion.....	120
6.6.	Conclusions and implications.....	123
CHAPTER 7	GENERAL DISCUSSION.....	125
7.1.	Introduction	126
7.2.	Major findings of the study.....	126
7.3.	Implications of the findings.....	128
7.4.	Limitations of the study	131
7.5.	Recommendation for future research	133
7.6.	Conclusion.....	136
REFERENCES	137
APPENDICES	153

LIST OF FIGURES

Figure 2.1. Primal, secondary and offal cuts for export from Greenlea Premier Meats Ltd. Primal high-value cuts are the striploin (14), tenderloin (15) and ribeye roll (17).....	7
Figure 2.2. Comparative growth and weight gain of large-framed and small-framed cattle. Source: NSW Department of Primary Industries (2007).	18
Figure 2.3. Subdivision of the beef-animal body into its component parts of importance to beef production. LMY%, lean meat yield; M:B, muscle to bone ratio; Fat%, carcass fat. Source: Purchas (2003).	20
Figure 2.4. Original and tracing of the eye muscle area (EMA) on a carcass.	25
Figure 2.5. Proportions of muscle, fat and bone as carcass weight increases, for large adult-sized animal with a 450-kg carcass (solid line) and small adult-sized animal with a 300-kg carcass (dashed line). Source: Figure 21.4 from Thonney (2015).....	25
Figure 2.6. AUS-MEAT & MSA marbling reference standards. Source: AUS-MEAT Limited (2017).	27
Figure 2.7. Relationship between MSA marbling score (USMB) and chemical intramuscular fat (%) and equation: $USMB = 213.7 + 38.59 * IMF\% - 0.629 * IMF\%^2$ ($R^2 = 54\%$). Source: McPhee <i>et al.</i> (2016).	27
Figure 2.8. Kinetics of glycogen loss, pH decline and lactate increase in the muscle <i>M. Longissimus lumborum</i> from an unstimulated bovine carcass. Source: Young <i>et al.</i> (2004).....	30
Figure 2.9. Flow diagram showing whether or not glycogen-depleting events affect ultimate muscle pH. Source: Purchas (2003).....	31
Figure 2.10. AUS-MEAT meat colour reference standards. Source: AUS-MEAT Limited (2017).	32
Figure 2.11. AUS-MEAT fat colour reference standards Source: AUS-MEAT Limited (2017).....	33
Figure 2.12. Relationship between ultimate meat pH and Warner-Bratzler shear values, from meat samples of 80 bulls and 80 steers, with the quadratic regression line and the 95% confidence limits for prediction. Source: Purchas (1990).....	35
Figure 3.1. Pasture quality as metabolizable energy (MJ/kg DM) and crude protein (%DM), and pasture mass as cover (kg DM/ha) for grazing herds at Limestone Downs, as averages from 2017 to 2020.....	47

Figure 3.2. Predicted live weight (LWT) across age for beef-cross-dairy cattle (n=1101 with a total of 33111 predicted weights calculated with centred moving average of 3 values), according to sex.	51
Figure 3.3. Fit regression plot for predicted live weights calculated with centred moving average of 3 values (predicted LWT), to actual live weight (LWT, total of 23426 actual liveweight records) for beef-cross-dairy cattle.....	51
Figure 3.4. Distribution of least-squares means of the progeny groups of sires for live weight (LWT) at 131, 200, 400, 600 and 800 days of age.....	52
Figure 3.5. Regression of least-squares means of the progeny groups for live weight (LWT) at 400, 600 and 800 days of age, on least-squares means of the progeny groups for live weight at either (A) 131 or (B) 200 days of age.	53
Figure 4.1. Division of <i>M. Longissimus lumborum</i> (striploin) meat sample and order of analysis for meat quality.	67
Figure 4.2. Distribution of least-squares means of the progeny groups of sires for: (A) live weight (LWT) at slaughter, (B) carcass weight and (C) dressing-out percentage.....	71
Figure 4.3. Distribution of least-squares means of the progeny groups of sires for: (A) carcass length, (B) eye muscle area (EMA), (C) rib fat depth and (D) marble scores.....	72
Figure 4.4. Distribution of least-squares means of the progeny groups of sires for: (A) fat colour score, (B) meat colour score and (C) ultimate pH.....	74
Figure 4.5. Distribution of least-squares means of the progeny groups of sires for meat quality traits measured on meat samples in the laboratory: (A) ultimate pH, (B) shear force, (C) thaw loss and (D) cook loss.	75
Figure 4.6. Scatter plots of least-squares means of the progeny groups for: (A) rib fat depth and marble score, (B) rib fat depth and eye muscle area (EMA) and (C) EMA and marble score.....	78
Figure 5.1. Regression of least-squares means of the progeny groups for live weight on sire EBV for live weight at: (A) 200, (B) 400, (C) 600 and (D) 800 days of age.....	91
Figure 5.2. Regression of least-squares means of the progeny groups on sire EBV for: (A) carcass weight, (B) eye-muscle area, (C) rib fat depth and (D) estimated intramuscular fat.	93
Figure 6.1. Diagram of skeletal size measurements on live animals.	107

LIST OF TABLES

Table 2.1. Livestock slaughter statistics of New Zealand cattle for 2019/20 (year ended September 2020), in numbers and average carcass weight at slaughter. Source: Ministry for Primary Industries (2020).	8
Table 2.2. Carcass fat classes for steer and heifer. Source: New Zealand Meat Classification Authority (2004).	21
Table 2.3. Muscling classes. Source: New Zealand Meat Classification Authority (2004).	22
Table 3.1. Estimated breeding values (EBV; mean \pm SD) for live weight at 200, 400, 600 days of age for 37 Angus and 40 Hereford sires (BREEDPLAN, April 2020).	45
Table 3.2. Least-squares means (\pm SE) of the Angus and Hereford progeny groups for live weight (LWT) at 131, 200, 400, 600 and 800 days of age.	53
Table 3.3. Estimates of regression coefficients (intercept and slope) of least-squares means of the progeny groups for live weight (LWT) at 400, 600 and 800 days of age, on least-squares means of the progeny groups for live weight at 131 or 200 days of age, for 73 sires.	54
Table 4.1. Estimated breeding values (EBV; mean \pm SD) for carcass and meat quality traits, for 37 Angus and 40 Hereford sires (BREEDPLAN, April 2020).	63
Table 4.2. Slaughter date, number of cattle, mean age (\pm SD), unadjusted mean live and carcass weights (\pm SD), and number of animals according to carcass fat grade for each grazing herd of beef-cross-dairy cattle processed in the experiment (n=1017).	64
Table 4.3. Least-squares means (\pm SE) of the Angus and Hereford progeny groups for weight traits at slaughter (age, live weight, carcass weight and dressing-out) and carcass traits (carcass length, eye muscle area (EMA), rib fat depth and marble score).	73
Table 4.4. Least-squares means (\pm SE) of the Angus and Hereford progeny groups for meat quality traits measured on the carcass (fat colour score, meat colour score and ultimate pH) and on meat samples in the laboratory (ultimate pH, fat lightness L*, redness a* and yellowness b*, meat lightness L*, redness a* and yellowness b*, shear force, thaw loss and cook loss).	76
Table 5.1. Estimated breeding values (EBV; mean \pm SD) with total range, accuracy and percentile bands for live weight and carcass traits, for 31 Angus and 34 Hereford sires (BREEDPLAN, April 2020).	87

Table 5.2. Estimates of regression coefficients (intercept and slope) of least-squares means of the progeny groups for live weight (LWT) on sire EBV for live weight at 200, 400, 600 and 800 days of age, for 29 Angus and 34 Hereford sires.....	90
Table 5.3. Estimates of regression coefficients (intercept and slope) of least-squares means of the progeny groups on sire EBV for carcass weight, eye-muscle area (EMA), rib fat depth, marble score and estimated intramuscular fat (IMF), for 29 Angus and 34 Hereford sires.....	92
Table 6.1. Crush score assessed on individual cattle while they are loosely restrained for weighing in the crush (20 seconds).....	108
Table 6.2. Summary of number of animals, unadjusted mean (\pm SD), range and coefficient of variation (CV%) of live animal measurements (weight, skeletal size and temperament at 0, 129, 200 and 800 days of age), carcass and meat traits (slaughter age and live weight, carcass weight and length, eye-muscle area (EMA), rib fat depth, ultimate pH and meat colour score) for beef-cross-dairy heifers and steers.	110
Table 6.3. Estimates of regression coefficients (<i>P-value</i> in brackets) using live weight (LWT) and skeletal size measurements (hip-height, body length, hip-width and cannon bone circumference) at birth (0 days of age) to predict carcass weight, carcass length, eye muscle area (EMA) and rib fat depth for Angus- and Hereford-sired heifers.....	112
Table 6.4. Estimates of regression coefficients (<i>P-value</i> in brackets) using live weight (LWT) and skeletal size measurements (hip-height, body length, hip-width and cannon bone circumference) at birth (0 days of age) to predict carcass weight, carcass length, eye muscle area (EMA) and rib fat depth for Angus- and Hereford-sired steers.	113
Table 6.5. Estimates of regression coefficients (<i>P-value</i> in brackets) using live weight (LWT) and hip-height at 129 days of age to predict carcass weight, carcass length, eye muscle area (EMA) and rib fat depth for Angus- and Hereford-sired heifers.....	115
Table 6.6. Estimates of regression coefficients (<i>P-value</i> in brackets) using live weight (LWT) and hip-height at 129 days of age to predict carcass weight, carcass length, eye muscle area (EMA) and rib fat depth for Angus- and Hereford-sired steers.	115
Table 6.7. Estimates of regression coefficients (<i>P-value</i> in brackets) using live weight (LWT) and skeletal size measurements (hip-height, body length and hip-width) at 129 days of age to predict carcass weight, carcass length, eye muscle area (EMA) and rib fat depth for a subset of Angus- and Hereford-sired steers.....	116

Table 6.8. Estimates of regression coefficients (*P-value* in brackets) using live weight (LWT) and temperament measurements (crush score and exit velocity) at 200 days of age to predict carcass weight, rib fat depth, ultimate pH and meat colour for Angus- and Hereford-sired heifers.... 118

Table 6.9. Estimates of regression coefficients (*P-value* in brackets) using live weight (LWT) and temperament measurements (crush score and exit velocity) at 200 days of age to predict carcass weight, rib fat depth, ultimate pH and meat colour for Angus- and Hereford-sired steers. 119

LIST OF APPENDICES

Appendix 1. Estimated Breeding Values and their accuracy for live weight, carcass and meat quality traits, for 37 Angus and 40 Hereford sires (BREEDPLAN, April 2020).....	154
Appendix 2. Pooled pasture mass cover, metabolizable energy, crude protein, neutral detergent fibre and organic matter digestibility from August 2017 to February 2020, for grazing cattle born in 2016 and 2017 at Limestone Downs.....	157
Appendix 3. Least-squares means (\pm SE) of the progeny groups for live weight and individual ranking at 131, 200, 400, 600 and 800 days of age, for 34 Angus and 39 Hereford sires..	159
Appendix 4. Least-squares means (\pm SE) of the progeny groups for weight traits at slaughter (age, live weight, carcass weight and dressing-out) and individual ranking for 34 Angus and 39 Hereford sires.	162
Appendix 5. Least-squares means (\pm SE) of the progeny groups for carcass traits (carcass length, eye muscle area, rib fat depth and marble score) and individual ranking for 34 Angus and 39 Hereford sires.	164
Appendix 6. Least-squares means (\pm SE) of the progeny groups for meat quality traits (fat colour score, meat colour score and ultimate pH) and individual ranking for 34 Angus and 39 Hereford sires.....	166
Appendix 7. Least-squares means (\pm SE) of the progeny groups for meat quality traits measured on meat samples in the laboratory (fat lightness L*, redness a* and yellowness b*, meat lightness L*, redness a* and yellowness b*, shear force, thaw loss and cook loss), for 15 Angus and 18 Hereford sires.....	168

ABBREVIATIONS

AB	artificial breeding
CP	crude protein
CV	coefficient of variation
d	day
DM	dry matter
EBV	estimated breeding value
EMA	eye muscle area
h^2	heritability
IMF	intramuscular fat
LWT	live weight
ME	metabolizable energy
r	correlation
r_g	genotypic correlation
r_p	phenotypic correlation
SD	standard deviation of the mean
SE	standard error of the least-square means

CHAPTER 1

GENERAL INTRODUCTION

Cattle born in the dairy industry contribute to about two-thirds of New Zealand's beef production on a per-head basis, and the dairy industry is also the source of 1.8 million surplus calves slaughtered at 4-14 days of age each year (Davison, 2020; Ministry for Primary Industries, 2020; van Selm *et al.*, 2021). The number of dairy-origin cattle slaughtered annually highlights that the decisions about the genetics of cattle that are harvested in the beef industry in New Zealand are largely made by dairy farmers.

Rearing surplus calves from the dairy industry for finishing in the beef industry (dairy-beef cattle systems), can reduce the number of beef breeding cows (Morris, 2017), presenting an opportunity to increase the conversion efficiency of feed into product on beef cattle farms (Burggraaf *et al.*, 2020) while reducing annual greenhouse gas emissions for beef production (van Selm *et al.*, 2021). In addition to making better use of animal and feed resources, rearing dairy-origin calves for beef production can mitigate consumer concerns around the commercial meat processing of bobby calves (Fisher *et al.*, 2017). However, the beef produced from these dairy-origin calves, and their growth and performance in a finishing system, needs to be competitive with other beef cattle and livestock industries.

Beef-cross-dairy cattle are the progeny produced by mating dairy-breed cows with beef-breed sires, and it is estimated that around 20% of the New Zealand dairy herd is mated to beef breeds (Burggraaf, 2016), with scope to increase this proportion. Dairy farmers typically use beef-breed sires selected for easy calving, either using estimated breeding values (EBV) or based on assumptions about a particular breed or source of sire, without considering the growth potential of the sire. The result is that many beef-cross-dairy calves are slow growing when combining dairy genetics with small birth weight beef cattle genetics. Reasonably, farmers that are beef finishers are often not satisfied with the performance of beef-cross-dairy calves and continue to pay a premium for pure beef-breed calves at weaning. To make dairy-origin calves a more desirable resource to beef cattle finisher farms, improvement in their potential for growth and meat quality is needed. This is likely to enhance the profitability of dairy-beef cattle finishing systems as a whole.

Coleman (2020) demonstrated that sires of Angus and Hereford breeds have a wide variation in performance for gestation length and birthweight, two very important traits for the dairy farmer, and that these traits are well predicted by their EBV. These sires also have a range of EBV available for live weight later in life and carcass quality traits. However, little is known about the performance of beef-breed sires producing beef-cross-dairy cattle, and how useful the EBV of beef-breed sires are for selecting on finishing potential when used over dairy-breed

cows. Such information is needed in order to determine the value of selecting beef-breed sires with better EBV for growth and finishing traits.

Furthermore, many beef cattle finishers buy dairy-origin calves from the sale yards, where selection is made based on the calf's phenotype. Thus, it is worth exploring the phenotypic characteristics of the calves early in life that could predict harvest results, to be able to improve the currently used visual selection of animals.

The general aim of this study was to investigate the effect of sire on growth and meat production of beef-cross-dairy cattle in New Zealand. The specific objectives were: to evaluate live weight from 4 months of age until slaughter, carcass and meat quality traits of a selection of Angus and Hereford sires via progeny testing of beef-cross-dairy offspring grown on hill country pasture (Chapters 3 and 4); to quantify the relationship between the performance of the beef-cross-dairy progeny and sires' EBV for growth and carcass traits (Chapter 5); and to assess skeletal size and temperament measured within the first 200 days of life as predictors of carcass and meat traits for beef-cross-dairy cattle (Chapter 6).

The calves used in this experiment were those born in cohorts 1 and 2 of the Dairy-Beef Progeny Test, funded by Beef+Lamb New Zealand Genetics. All calves in those cohorts were born in Limestone Downs and used in Chapter 3 (growth) and in Chapter 4 (carcass traits). Meat quality in Chapter 4 was assessed on a subset of cattle from cohort 1. The calves in cohort 1 & 2 that were born to mixed-aged cows were used in Chapter 5, and only calves born in cohort 2 were used in Chapter 6. Differences in the cattle used within each chapter largely reflected differences in the information available on the animals in the project. This PhD project began when the first cohort were 10 months old, just prior to birth of the second cohort, and the fieldwork component of the research was completed in February 2020 at harvest of the second cohort. Consequently, early-life skeletal size parameters were only measured on the second cohort and meat samples were collected only from the first cohort.

CHAPTER 2
LITERATURE REVIEW

2.1. Beef industry in New Zealand

The beef industry in New Zealand is based on a herd of around 3.7 million beef cattle and 6.4 million dairy cattle (Beef+Lamb New Zealand Economic Service, 2020). Annually, around 2.6 million adult cattle and 1.8 million bobby calves are slaughtered for beef production (Beef+Lamb New Zealand Economic Service, 2019; Ministry for Primary Industries, 2020), with 85 to 90% of processing occurring during November to June (Morris, 2013). This seasonality of the industry is because most beef comes from pasture-based production systems.

The New Zealand climate favours pasture growth over much or all of the year, and hence grazed pasture and forage crops supply in excess of 95% of the livestock diet on New Zealand farms (Morris *et al.*, 2014a; Valentine *et al.*, 2017). It is this efficient and relatively low-cost system that allows New Zealand to compete globally as a major exporter of food and fibre (Morris *et al.*, 2014a). However, the supply of pasture is seasonal for most of the country, because dry summers (e.g. Waikato and Wairarapa) and low winter temperatures (e.g. Wairarapa, Canterbury, Southland and Central Otago) limit pasture growth (Valentine *et al.*, 2017). This may be even more pronounced in the pastoral land occupied by sheep and beef cattle, which are usually farmed together in the steeper hill country, with permanent pastures on lower fertility soils, where it is uneconomic to cultivate or renew pasture (Morris *et al.*, 2014a).

There are two main end uses for New Zealand beef: prime and processing beef (Beef+Lamb New Zealand, 2017b). Prime or table beef are those cuts of meat of suitable quality to be sold as primal cuts in high-value markets (e.g. eye fillet from tenderloin primal, sirloin from striploin primal and ribeye from ribeye roll primal, Figure 2.1) and they come from steers, heifers and bulls (Beef+Lamb New Zealand, 2017b). Alternatively, processing or manufacturing beef are those cuts that do not reach the high-quality standards to be sold as primal cuts, and therefore are ground, mixed with trimmings, and used in processed foods (e.g. hamburgers). This type of meat comes from older bulls, cows and the forequarters of steers and heifers primarily (Beef+Lamb New Zealand, 2017b).

The beef sector has a strong export focus, with 94% of production available for exporting (Beef+Lamb New Zealand Economic Service, 2019; Morris *et al.*, 2014a). During the year 2017/18, New Zealand produced 680000 tonnes of beef and 413065 tonnes were exported (including carcasses, cuts and boneless beef). North America is the dominant export market for beef accounting for 49% of beef exports, whilst North Asia (principally China) accounts for 38% of exports by volume (Beef+Lamb New Zealand Economic Service, 2019).



Figure 2.1. Primal, secondary and offal cuts for export from Greenlea Premier Meats Ltd. Primal high-value cuts are the striploin (14), tenderloin (15) and ribeye roll (17). Reproduced with permission.

2.1.1. Cattle population

From the 3.7 million beef cattle in New Zealand, about 1.0 million are beef breeding cows and heifers that produce 0.8 million calves annually (Morris, 2019). An estimated 0.62 million calves born from dairy cows are also retained for dairy-beef production (Beef+Lamb New Zealand Economic Service, 2019), representing around 44% of the total calves entering the beef cattle herd annually. This number would include both dairy and beef-cross-dairy calves.

In the past 3 years (2017/18 to 2019/20, Table 2.1), around 2.6 million adult cattle and 1.8 million bobby calves were slaughtered (Beef+Lamb New Zealand Economic Service, 2019; Ministry for Primary Industries, 2020). It is estimated that cattle born in the dairy industry contribute at least 66% of the New Zealand's total beef production on a per-head basis, including surplus dairy cows and heifers, Holstein-Friesian bulls and beef-cross-dairy cattle (Davison, 2020; van Selm *et al.*, 2021). Of these, Holstein-Friesian bulls and beef-cross-dairy steers and heifers are known in the industry as dairy-beef cattle, because these animals have a dairy origin, but are reared on beef cattle farms to adult categories for beef production. Dairy-beef cattle represented between 56% and 67% of the total cattle grown for beef export production in New Zealand during the years 2016/17 to 2019/20 (Davison, 2020). The numbers presented here highlight the importance of the dairy industry in the total beef production of New Zealand.

Table 2.1. Livestock slaughter statistics of New Zealand cattle for 2019/20 (year ended September 2020), in numbers and average carcass weight at slaughter. Source: Ministry for Primary Industries (2020).

Class of Animal	Steer	Heifer	Cow	Bull	Calves
Number (heads/year)	591303	510441	1040842	542582	1874388
Dairy	76327	118631	812931	142276	1874388
Beef	514976	391810	227911	400306	-
Carcass weight (kg/head)	312	243	203	299	16
Dairy	294	226	194	290	16
Beef	314	248	234	303	-

Note: cattle slaughter numbers and weights are disaggregated according to whether they are from dairy or beef cattle farms at the time of slaughter and as registered in the NAIT (National Animal Identification and Tracing) system by farmers.

2.1.2. Dairy-origin cattle

2.1.2.1. Bobby calves

Bobby calves is a term used in New Zealand for those calves born in the dairy industry that are slaughtered at 4-14 days of age. Bobby calves are typically Jersey-cross, Holstein-Friesian-cross-Jersey and Holstein-Friesian male calves (Boulton *et al.*, 2018). Each year, around 1.8 million bobby calves are slaughtered for veal production and by-products (Ministry for

Primary Industries, 2020). When the beef price is low, the bobby calf kill increases; conversely, when beef price is high, the proportion of dairy-origin calves raised for beef production, such as entire bulls or beef-cross-dairy cattle, increases (Morris, 2013). New Zealand's beef production could be further increased within a relatively short period if more of these calves were retained and finished for beef production, rather than slaughtering them at a few days of age (Morris, 2013).

Bobby calves are a potential issue for market access for all New Zealand animal production. The breeding of essentially "unwanted" dairy calves and disposing of them within days of being born is vulnerable to sentiment and negative social perception (Cook, 2014; Fisher *et al.*, 2017). Market access can be impeded immediately, and product value affected significantly. For the dairy industry to maintain its "social licence" to operate, the amount of bobby calves should decrease, and part of the solution is to produce calves that can be reared for beef production.

2.1.2.2. Holstein-Friesian bulls

The dairy industry is a source of bull calves born from artificial insemination mating of the dairy cows to produce the heifer replacements. These bull calves raised for finishing as bull beef are typically Holstein-Friesian, rather than Jersey or Holstein-Friesian-cross-Jersey crossbred, as they have larger frame, higher growth potential and are paid better at slaughter compared with the other dairy breeds (Muir *et al.*, 2001).

Bulls are purchased as 10–12-week-old weaners and farmed for 14 to 18 months. Bulls grow 10–20% faster and are heavier than steers and heifers at the same age, produce larger steaks (i.e. higher meat yield) and have about a third of the intramuscular fat content (Burnham *et al.*, 2005; Purchas, 1990; Purchas *et al.*, 2002). They are also more flexible in terms of sale time if pastures deteriorate, because they can be slaughter irrespective of fatness level (Beef+Lamb New Zealand, 2017b). The target carcass weight for a 16-month-old bull is about 250 kg, which requires a daily weight gain of over 1 kg. Some farmers slaughter heavy bulls as 2½-year-olds (30 months) at 350 kg carcass (Beef+Lamb New Zealand, 2017b). However, mature bulls can be difficult to handle, and their meat is usually of low quality and mostly destined to processing beef.

2.1.2.3. Beef-cross-dairy cattle

It is estimated that around 20% of the New Zealand dairy herd is mated to beef-breed sires to produce beef-cross-dairy calves (Burggraaf, 2016), and these calves make up around 30% of the total cattle grown for beef export production in the country (Davison, 2020). Using beef semen on a portion of the dairy herd or beef-breed sires for natural mating can be profitable for dairy farmers, mainly due to the greater price received for beef-cross-dairy calves compared to dairy calves at 4 days of age or later auction (Burggraaf, 2016; Dal Zotto *et al.*, 2009). In addition, integrated dairy-beef cattle systems reduce the number of beef breeding cows (Morris, 2017), increase the conversion efficiency of feed into product (Burggraaf *et al.*, 2020) while reducing annual greenhouse gas emissions for beef production (van Selm *et al.*, 2021), thus enhancing the efficiency and productivity of the beef industry.

This dairy-beef system has important differences compared with beef cow-calf systems, particularly around rearing and finishing. In a beef cow-calf system, calves are reared on their dams until weaning at a set date, around 5-7 months of age (150-210 days) and a range of 180-240 kg live weight (Beef+Lamb New Zealand, 2017d). In the dairy-beef system, calves are reared artificially on surplus milk from the dairy herd or on calf milk replacer, until weaning at a set weight, usually around 80-100 kg at 8-12 weeks of age (Beef+Lamb New Zealand, 2017b; Muir *et al.*, 2000b). Key trading points for these calves are 4 days of age, when they may pass from the dairy farmer to the rearer, and 100 kg (around 3-4 months of age) when they may pass from the dairy farmer or rearer to the finisher.

In New Zealand, steer and heifer carcasses are subject to a grading system comprising of sex, maturity, fat content and muscling conformation (New Zealand Meat Classification Authority, 2004). Consequently, these categories of cattle must be at their best condition to meet the criteria in the grading system at the time of slaughter to achieve good returns. Beef-breed heifers are mostly finished for domestic consumption, with target weights of 220-250 kg carcass at 18-22 months of age (Beef+Lamb New Zealand, 2017b). Beef-breed steers are typically either slaughtered at 18-22 months to avoid the cost of a second winter, at about 500 kg live weight and less than 300 kg carcass, or those that go through another winter are slaughtered at 27-30 months, at 600 kg live weight and well in excess of 300 kg carcass (Beef+Lamb New Zealand, 2017b; Morris, 2013). In contrast, dairy-bred cattle are often slaughtered after their second winter (older age) to achieve heavier weights and avoid penalties associated with leanness and conformation (Bown *et al.*, 2016). This will be discussed further in the section of "Beef carcass grading in New Zealand".

2.2. Parents and progeny: the genetic basis of meat production

2.2.1. Cattle traits for selection

Characteristics of an animal that are controlled by genetics can be included in animal breeding objectives to make improvements of future generations, and consequently increase the productivity and profitability of farming systems. Well-developed breeding objectives determine mating schemes, identifies traits to select for and the relative weight and direction of the selection pressure to be placed on those traits (Lopez-Villalobos *et al.*, 2005).

To be included in a breeding objective, traits must be economically important, measurable, heritable and exhibit variability in the population (Beef+Lamb New Zealand, 2017e). For cattle, important and measurable characteristics can be categorised as traits of growth (e.g. live weight, height), carcass (e.g. carcass weight, rib fat thickness), reproduction (e.g. gestation length, scrotal circumference) and other, such as health (e.g. survival, worm resistance) and management (e.g. temperament). The relative importance of each trait will be different to different producers. Traits with greater variation in performance among individuals in a population will have more scope for change, and so great improvement can be made by selecting the best animals. Additionally, traits can be correlated with each other, meaning that a high value or increase in one trait will occur with high value or increase in another trait (or decrease in value, if the correlation is negative). The genetic correlations between traits need to be considered in breeding objectives and genetic evaluations (Beef+Lamb New Zealand, 2017e) and correlated measures that can be used as indirect selection criteria for traits that are often difficult and costly to measure, such as carcass and meat quality traits (Reverter *et al.*, 2003b).

Heritability (h^2) is the degree of phenotypic variation of a trait that is controlled by genes. The higher the h^2 of a trait, the greater the parental genetic merit can be predicted on the phenotype of the offspring. Growth and carcass traits of beef cattle are moderately heritable (Baker *et al.*, 1975; Reverter *et al.*, 2003b; Rios Utrera *et al.*, 2004). Within liveweight traits, yearling weight (400 days of age, 400d) has higher h^2 estimates and thus is more effective selection criterion than birth or weaning weight for improving progeny growth performance (Baker *et al.*, 1975). The carcass traits with highest estimates of h^2 are carcass weight, fat depth, *Longissimus* muscle area and marbling score (Rios Utrera *et al.*, 2004). Most of the meat quality traits, on the other hand, are low to moderately heritable (Warner *et al.*, 2010). The h^2 and correlation of relevant traits will be discussed further in the following sections.

2.2.2. Estimated Breeding Values

Estimated breeding values (EBV) are predictions of the relative genetic merit of an animal for a particular trait (BREEDPLAN, 2015a). The EBV have been developed to quantify the genetic potential of breeding animals (Nicol *et al.*, 1985), and on average, half of this relative genetic merit will be passed on to the animal's progeny (BREEDPLAN, 2015a).

The EBV are calculated using the measured deviation in the trait from the herd average (contemporary group of the same breed, sex, under same management, season and year) for a particular animal, heritability of the trait, information on the trait from the animal's relatives and correlations with related traits (Beef+Lamb New Zealand, 2017e; Nicol *et al.*, 1985). The EBV are reported in units relevant to the trait (e.g. 400d weight is in kg, eye muscle area is in cm², rib fat depth is in millimetres) and they are expressed as deviations from a base average, which is set from a particular year for each EBV for each breed (Morris *et al.*, 2009; Nicol *et al.*, 1985).

In New Zealand, the EBV for beef cattle for a range of economically important traits are produced by BREEDPLAN (Agricultural Business Research Institute, Australia) and these are breed specific. The traits include weight (e.g. birth weight, 400d weight, mature weight), fertility (e.g. gestation length, calving ease), carcass (e.g. eye muscle area, fat depth, retail beef yield, intramuscular fat), among other traits (e.g. docility). The availability of EBV will depend on having enough data recorded, and therefore the full range of EBV may not be available for each particular breed (BREEDPLAN). Further, the amount of information available to calculate an EBV will determine the reliability or accuracy of that EBV as an estimate of an animal's true breeding value. The higher the accuracy, the lower the likelihood of change in the animal's EBV. In numbers, an EBV with an accuracy lower than 50% is considered preliminary, while an EBV with an accuracy greater than 90% is highly reliable (BREEDPLAN, 2015a).

Animals can be ranked according to their EBV for the different traits, and EBV are a powerful tool in selecting animals to improve profitability through selection indexes. The higher a sire is ranked in the breed for economically important traits, the greater the genetic progress and the more profit the sire will generate (Morris *et al.*, 2009). Examples of selection programs to improve genetic merit for beef production in New Zealand are the Angus Pure Index with emphasis on marbling (Angus New Zealand Inc.), and the Hereford Dairy Terminal Index with emphasis on EBV for live weight at 600d and retail beef yield targeting the production of dairy-beef progeny for beef (BREEDPLAN, 2011).

When comparing sires of different breeds, breed effects may have a large impact on the ranking sires for most of the carcass and meat quality traits (Van Vleck *et al.*, 1992). Even so,

sires of the same breed may have greater variability than sires of different breeds (Baker *et al.*, 1975; Van Vleck *et al.*, 1992). Additionally, the relative ranking of breeds, sires within each breed and their crossbred progeny may change in different locations or systems, due to genotype by environment interactions (Charteris *et al.*, 1997; Morris *et al.*, 2009). A scaling genotype by environment interaction exists when the difference in the phenotypic production performance of genotypes is smaller at a low feeding level compared to a high feeding level, while a re-ranking genotype by environment interaction occurs when genotypes rank differently for different production or feeding systems (Hammami *et al.*, 2009). Evidence from previous beef progeny testing in New Zealand has demonstrated that sires that ranked highest on their EBV were generally amongst the top bracket once progeny tested (Baker *et al.*, 1975; Beef+Lamb New Zealand Genetics, 2017, 2019).

The selection of a sire will depend on what production system the farmer operates and what is the goal or breeding objective (Lopez-Villalobos *et al.*, 2005; Morris *et al.*, 2009), and is especially challenging in a dairy-beef system where the farmer who selects the sire is not usually the farmer who is rearing and finishing the progeny. The correlation between traits is particularly important when choosing sires for dairy-beef systems, because traits important for the dairy producer (e.g. calving ease) can be antagonistic with the traits important for beef production (e.g. carcass merit). Breeding programs to generate beef-breed sires for use over dairy-breed cows should, therefore, aim to produce sires with good genetic merit for both calving ease and carcass weight (Berry *et al.*, 2019), colloquially referred to as “curve benders”.

2.2.3. Cattle breeds and sire lines

The main beef cattle breeds in New Zealand include Angus (34% of the total beef cattle), Hereford (11.5%), Angus-cross-Hereford (11.5%), Holstein-Friesian (13%), Holstein-Friesian-cross-Hereford (5.5%), mixed (18%) and others (6%) (Beef+Lamb New Zealand Economic Service, 2019).

Angus and Hereford are early maturing British breeds, with moderate to high size and growth, low to moderate milk production, relatively low incidence of calving difficulties, adaptable to hill country and producing high-quality carcass under these conditions (Bartoň *et al.*, 2006; Beef+Lamb New Zealand, 2017c; Buchanan *et al.*, 2015; Kinghorn *et al.*, 2015; Purchas, 2003). Angus are black (or red) polled cattle, stocky and well-muscled animals attaining puberty at early age and are noted for their hardiness and ability to thrive on poor pasture and hill country, producing highly marbled and tender meat (Buchanan *et al.*, 2015). Hereford cattle

have distinctive red-and-white body markings and a white face, are hardy and can be run in a wide range of environmental conditions, producing moderately marbled and tender meat (Buchanan *et al.*, 2015). Angus and Hereford cattle have similar weights, although Angus calves are usually smaller at birth than other British or Continental breeds (Arango *et al.*, 2002; Cundiff *et al.*, 2007; Morris *et al.*, 1993).

The main dairy breeds in New Zealand are Holstein-Friesian-cross-Jersey (48% of the total dairy cattle) and Holstein-Friesian (33%), followed by Jersey (9%) and other breeds making up 10% (Beef+Lamb New Zealand Economic Service, 2019; LIC *et al.*, 2019). From these, Holstein-Friesian and Holstein-Friesian-cross-beef make up 18% of the total beef cattle (Beef+Lamb New Zealand Economic Service, 2019). The Holstein breed originated in the Continental Europe, with large size and growth, early puberty, very high milk production and moderate marbling (Buchanan *et al.*, 2015). The New Zealand Holstein-Friesian, however, is a considerably smaller animal than the original Continental Holstein, because of the genetic selection within the outdoor seasonal grazing system (Macdonald *et al.*, 2008). The Jersey breed, on the contrary, is a British breed, small in size and growth, attaining early puberty, with high milk production, butterfat and marbling (Buchanan *et al.*, 2015) and accepted as more efficient or profitable (per 4.5 ton DM eaten) than the Holstein-Friesian in grazing systems (Holmes *et al.*, 2007; Macdonald *et al.*, 2008). The Holstein-Friesian-cross-Jersey, also known as Kiwicross (TMLivestock Improvement Corporation), has milk production parameters and live weights in-between the Holstein-Friesian and Jersey breeds (Holmes *et al.*, 2007), and offers heterosis advantages contributing to its popularity within the New Zealand dairy industry. The increasing proportion of these crossbred dairy cows in the dairy herd means that increasingly dairy-origin calves reared for beef production will have some Jersey genetics.

Variation within and among breeds of cattle is an important genetic resource that can be utilized to increase efficiency of beef production and value of beef products, to better match genetic potential with feed, environment and market preferences (Cundiff *et al.*, 2007). Sires with different attributes from dams can be used to produce calves that exhibit traits from both breeds (Morris *et al.*, 2009), and this is the basis of crossbreeding. Crossbreeding is an effective tool for increasing performance and profitability through hybrid vigour and complementarity of attributes (Beef+Lamb New Zealand, 2017e; Cunningham *et al.*, 1987). Hybrid vigour (i.e. direct heterosis) is the extra performance of the crossbreds over the weighted average of their parent breeds (Kinghorn *et al.*, 2015), while complementarity is the compensation of the weakness of one breed for the strength of the other breed (e.g., a breed with easy calving and poorer carcass

merit, versus a breed excelling in carcass merit but, on average, more difficult calving (Berry *et al.*, 2019)).

In a terminal breeding system, both replacement females and sires come from external sources, and all resulting progeny are slaughtered (Beef+Lamb New Zealand, 2017e). This type of system is suitable for a portion of the dairy herd, where yearling heifers and surplus cows could be mated to a beef-breed sire, to produce beef-cross-dairy calves. Given that the terminal sire has a direct genetic effect on the growth potential of the progeny, beef-breed sires with improved genetics can be used in dairy herds to generate calves better able to satisfy the requirements of the dairy, grower and finisher farms, through to the meat processor. For this system to be successful, it is crucial that beef breeders embrace this market opportunity and breed the most appropriate animals for mating with dairy females (Berry *et al.*, 2019).

2.3. Animal growth and performance

Animal body size is an important genetic factor in beef cattle production (Hammack *et al.*, 2009), and favourable environmental conditions are necessary for the full expression of the individual's genetic capacity (Lawrie, 2006a). Under extensive pasture-based environments, diet composition and feed availability can fluctuate considerably, which in turn can alter an animal's growth from its genetic capability (Warner *et al.*, 2010). In addition to feed (type, quantity and quality), environmental conditions include weather, management and interactions with other animals, including humans. These interactions between genetics and environment will be developed in the next sections.

2.3.1. Live weight and growth

Live weight and growth trajectories of each animal are important. Cattle growth is measured by a few live weights per animal along their growth curve, which is related to adult size (Thonney, 2015). Thus, weights at different ages are highly correlated, and selection to increase weight or growth rate at a given age is associated with heavier adult weight (Thonney, 2015). However, there is possibility to change the shape of the growth curve by selecting sires with similar adult weight and size, but greater yearling growth rate (Archer *et al.*, 1998; Thonney, 2015). Live weight in cattle is moderately heritable ($h^2 = 0.12$ to 0.70 , refer to "Heritability and

correlations”) and therefore, the sire has a considerable direct genetic effect on the growth potential of the progeny.

Live weight is the main driver of energy requirements in grazing cattle (Nicol *et al.*, 2017). As live weight increases so does maintenance energy requirement and consequently the importance of measuring animal’s weight. Cattle with high feed conversion efficiency can produce more kilograms of meat per unit of feed consumed, and thus have higher growth rates and heavier live weights with the same feed allowance compared to less efficient cattle (Morris *et al.*, 2014b). These type of cattle that are more efficient in converting pasture into body weight are more desirable, because they get to target slaughter weight at a younger age and because they require less feed to achieve same results compared with a less efficient animal (Beef+Lamb New Zealand, 2017a; Berry *et al.*, 2013). Further, finishing growth path can have important effects on carcass characteristics, particularly fatness. Animals on fast growth path generally had higher intramuscular, rump and rib fat thickness than animals on slow growth path, especially if animals were fed a high concentrate feedlot diet versus a pasture diet (McIntyre *et al.*, 2009). Thus, these differences in fat content are likely a combination of diet and growth rate.

Cattle live weights are influenced by environmental factors including digestible feed intake, physical activity, stress due to extreme weather and weighing conditions (Thonney, 2015). In New Zealand, most cattle destined for beef production are farmed in extensive conditions, on hill country pasture with minimal supplementation (Beef+Lamb New Zealand, 2017c). The supply of pasture is seasonal for most of the country, because dry summers and low winter temperatures limit pasture growth (Valentine *et al.*, 2017). Typical values of cattle growth rate under pastoral conditions are around 0.6-0.7 kg/d, with lower growth rates when pasture is limiting (winter and summer) and compensatory growth when pasture becomes abundant (Beef+Lamb New Zealand, 2017b).

2.3.2. Skeletal size

Animal size was first estimated by height or length, until weight became more common. Although height and weight are related, the relationship depends on muscling and shape characteristics, and so their rates of maturity differ (Hammack *et al.*, 2009). Frame or skeletal size usually is measured as length of specific bones, or wither or hip height, while weight is a mass measurement (Owens *et al.*, 1993).

Linear skeletal growth (i.e. height and length) increases faster and matures earlier than thickness growth (i.e. width of hooks and weight (Guilbert *et al.*, 1952)). This is because long

bones cease to increase in length after epiphyseal closure, which occurs sometime around puberty (Owens *et al.*, 1993). Puberty in cattle is determined by both weight and age, although some environmental factors (e.g. temperature, day length, specific nutrients) can also have an influence. Accordingly, it has been reported that cattle reach about 80% of mature height but only 35 to 45% of mature weight by 7 months of age, while about 90% of mature height and only 50 to 60% of mature weight is reached at 12 months (Hammack *et al.*, 2009). Cattle achieve mature height at around 3 years of age, whilst they can continue to gain weight until 7 years of age but at a decreased rate after 4 to 5 years of age, a time at which many studies set the limit for mature weight (Arango *et al.*, 2002). Thus, the height of a beef animal at a given age can be used as a measure of its maturity type, or growth potential.

Mature size is the main driver of growth rate and weight at a given age (Thonney, 2015). Even at birth, large correlations exist between various body measures, and these are partially due to sire genetics (Nugent *et al.*, 1991a) because of their moderate heritability (refer to “Heritability and correlations”). Large-framed (taller) and small-framed (shorter) cattle grow at their quickest and lean tissue growth predominates up until they reach physiological maturity (Figure 2.2). When the growth asymptote approaches, lean growth rate slows and fat accumulation in adipose tissue accelerates. Smaller-framed cattle reach that point at an earlier age and at a lighter weight than do large-framed cattle. Thus, at comparable weights, large-framed cattle will be younger, less mature and leaner than their small-framed counterparts (Chambaz *et al.*, 2001; Thonney, 2015). At the same age, large-framed cattle will be generally growing faster, resulting in larger carcasses compared with small-framed animals (NSW Department of Primary Industries, 2007). Similar comparisons of frame can be made between heifers and steers, as male animals are typically heavier than females of the same age (Garrick *et al.*, 1989), producing heavier carcasses, with less subcutaneous and intramuscular fat than heifers (McIntyre *et al.*, 2009). From this different growth trajectories derives the terminology of early (small-framed) or late (large-framed) maturing animals.

The animal’s height at a known age can be used to estimate future weight or age to get to specific targets. Frame score, for example, is a method of estimating skeletal size based on hip-height (on a 1-11 scale) between 5 and 21 months of age, and is a useful predictor of weight at puberty, maturity and slaughter (Hammack *et al.*, 2009). Frame score has been used in the development of prediction models, such as the “BeefSpecs” calculator in Australia (Walmsley *et al.*, 2014). The “BeefSpecs” calculator combines data and production parameters for an animal (e.g. sex, breed type, frame score, initial live weight, rump fat, feed), to provide a final live weight that producers can aim at to maximise rump fat depth and hot carcass weight (Walmsley *et al.*,

2014). In addition, live weight prior to slaughter is the best predictor for meat and bone weight, particularly in combination with height, stifle and hip-width (Afolayan *et al.*, 2002). Therefore, there is potential to measure skeletal size at an early age to predict the animal's finishing performance.

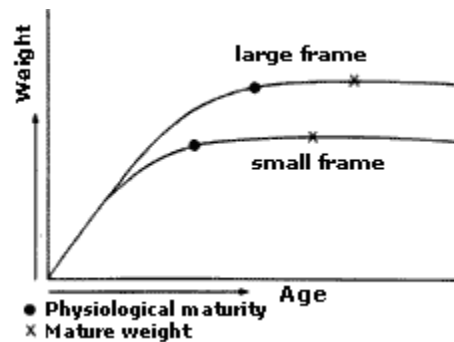


Figure 2.2. Comparative growth and weight gain of large-framed and small-framed cattle. Source: NSW Department of Primary Industries (2007). Copyright of State of New South Wales, Australia (<https://www.industry.nsw.gov.au/about/our-business/our-publications-and-websites/copyright>).

2.3.3. Temperament

Under the same environment, animals can have different responses depending on their temperament. Cattle temperament is related to stress responsiveness (Cafe *et al.*, 2011) and can be associated with animal performance and meat quality (Behrends *et al.*, 2009; Ponnampalam *et al.*, 2017), particularly in *Bos indicus* breeds (i.e. Brahman) and entire bulls. The temperament of cattle can be assessed by flight speed or escape velocity (EV) and crush score (CS). These traits are persistent over time (Cafe *et al.*, 2011), even though animals may become acclimatised to handling. However, the variation measured at first working at weaning in beef cattle may re-emerge at the time of harvest, given that these are the two most stressful times in a calf's life (Behrends *et al.*, 2009). Consequently, evaluation of temperament early in life may be a helpful tool, because animals could be allocated to different management groups for yarding, feeding, production systems or end markets.

Cattle with flightier temperaments (faster EV or greater CS) can have lower growth rates, produce smaller carcasses with less rib fat cover, reduced *M. longissimus lumborum* muscle area and have darker meat that is greater in shear force and compression, all economically detrimental (Cafe *et al.*, 2011; Ponnampalam *et al.*, 2017). The lower growth rate of temperamental animals may be a result of lower feed intake (as kg DM or time spent eating per day) and/or more use of energy in avoidance behaviour (Boles *et al.*, 2015; Burrow *et al.*,

1997). Conversely, animals with good temperaments (slower EV) can grow faster, have higher percentage of boneless, closely trimmed retail cuts, or higher cutability (lower muscling class), and greater tenderness (Behrends *et al.*, 2009; Boles *et al.*, 2015; Burrow *et al.*, 1997). Thus, temperament should be considered in genetic selection programs for meat-producing ruminants (Ponnampalam *et al.*, 2017).

Temperamental cattle have a greater stress response to handling and transport, resulting in chronic hypothalamic-pituitary-axis activation to switch to anaerobic pathways quicker, higher depletion of muscle glycogen and less lactate accumulation in the muscle post-mortem (Boles *et al.*, 2015; Cafe *et al.*, 2011). This results in reduced meat quality because of greater carcass pH (Cafe *et al.*, 2011; Ferguson *et al.*, 2008), which will be discussed further in the “Ultimate pH” section.

2.3.4. Heritability and correlations

Live weight in cattle is moderately heritable. Estimates for heritability (h^2) across different beef breeds, including Angus and Hereford, range from 0.25-0.45 for birth weight (Angus New Zealand; Baker *et al.*, 1975; Beef+Lamb New Zealand, 2017e; Garrick *et al.*, 1989; Gregory *et al.*, 1995), 0.12-0.34 for weight at 200d (Angus New Zealand; Beef+Lamb New Zealand, 2017e; Gregory *et al.*, 1995), 0.19-0.60 for weight at 400d or yearling age (Afolayan *et al.*, 2007; Angus New Zealand; Baker *et al.*, 1975; Beef+Lamb New Zealand, 2017e; Crews *et al.*, 2003; Garrick *et al.*, 1989) and 0.40-0.70 for mature weight (Angus New Zealand; Beef+Lamb New Zealand, 2017e; Su *et al.*, 2017).

Heritability estimates are also moderate for linear measurements across breeds, including Hereford and Angus (crossed with Jersey, Wagyu, Angus, Hereford, South Devon, Limousin and Belgian Blue), with $h^2= 0.42-0.60$ for height and $h^2= 0.19-0.25$ for length (Afolayan *et al.*, 2007).

Temperament traits have low to moderate h^2 estimates, depending on the measurement and breed, but usually between 0 and 0.61 across *Bos Taurus* beef breeds (Beef+Lamb New Zealand, 2017e; Haskell *et al.*, 2014). A review by Haskell *et al.* (2014) reported $h^2= 0.03-0.46$ for chute behaviour (or crush score), $h^2= 0.20-0.49$ for flight speed and flight time (or exit velocity), and $h^2= 0-0.61$ for flight distance and docility in *Bos Taurus* (including Angus and Hereford).

Live weight at different ages are genetically correlated, with genetic correlations (r_g) between 0.30 and 0.85 from birth through to 18-months old ($r_g= 0.46$ birth-yearling weight, $r_g=$

0.30 birth-18-month weight, $r_g = 0.80$ weaning-yearling weight, $r_g = 0.79$ weaning-18-month weight and $r_g = 0.85$ yearling-18-month weight) (Baker *et al.*, 1991). Linear measures are highly correlated with each other, particularly with measurements at the same age: e.g. $r_g = 0.61$ to 0.90 for height, length and girth at yearling age (Afolayan *et al.*, 2007). Likewise, linear measures and live weight at the same age are correlated: e.g. live weight and height $r_g = 0.66$, length $r_g = 0.89$ and girth $r_g = 0.91$ at yearling age (Afolayan *et al.*, 2007). Temperament measurements of EV and CS are phenotypically correlated with each other ($r_p = 0.57$ to 0.66) (Boles *et al.*, 2015) but can decrease over time (Cafe *et al.*, 2011). Correlations between temperament and live weight in *Bos Taurus* breeds are usually not strong ($r_p = -0.10$ to 0.08) (Boles *et al.*, 2015; Haskell *et al.*, 2014).

2.4. The beef carcass

The beef carcass is made up of muscle, fat, and bone (Figure 2.3), with fat being the most variable component. The value of an animal at slaughter is determined by the yield of saleable meat, the quality of that beef and the value of co-products, such as hide and offal (Purchas, 2003). Some of these key points will be discussed in the following sections.

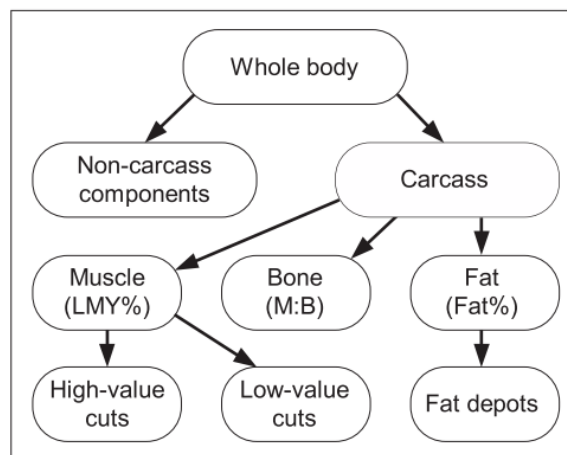


Figure 2.3. Subdivision of the beef-animal body into its component parts of importance to beef production. LMY%, lean meat yield; M:B, muscle to bone ratio; Fat%, carcass fat. Source: Purchas (2003). Reproduced with permission.

2.4.1. Beef carcass grading in New Zealand

The current New Zealand system classifies carcasses according to age, sex, fat content and muscling. Within each fat grading class, an increase in carcass weight will increase the value of the carcass for the farmer, as weight is the most relevant attribute for payment purposes. The penalty for lighter carcasses reflects a reduced dilution of fixed costs for the abattoir (e.g. boning) per carcass (Berry *et al.*, 2019). There are also penalties for any faults within the carcass, such as damage and bruising (Bown *et al.*, 2016). The eating quality of the beef will be considered for some markets after carcass grading.

There are 5 fat cover classes for steers and heifers (Table 2.2), ranging from devoid (no fat) to excessive (17 mm and over). An accurate measurement of the depth of subcutaneous fat over the fourth quarter of the eye muscle at the 12th rib can be indicative of the yield of the carcass and its suitability for a particular market (AUS-MEAT Limited, 2018). In practice, company graders and auditors use it as a guide while also considering the fat content of the whole carcass (New Zealand Meat Classification Authority, 2004). The “P” grade (3-10 mm) is typically the best paid in the New Zealand market. There is a penalty of around 10 cents/kg when carcasses fall into an “L” grade (< 3 mm) (Bown *et al.*, 2016) or a downgrade to “cow” category (processing or manufacturing), and around 10 to 15 cents/kg when carcasses rise into an “T” or “F” grade (>10 mm, Aaron Craig, Operations Manager for Greenlea Premier Meats Ltd, personal communication, 15 January 2020). The final payment decision is up to the discretion of each meat company, which usually considers a number of factors including the relationship with the supplier (e.g. loyalty, volume of cattle), procurement pressure and volume of other type of animals (Aaron Craig, Operations Manager for Greenlea Premier Meats Ltd, personal communication, 15 January 2020).




Table 2.2. Carcass fat classes for steer and heifer. Source: New Zealand Meat Classification Authority (2004).

Fat cover description	Fat Class	Fat Depth
Devoid	A	Nil
Light, patchy	L	Under 3 mm
Light to medium	P	3-10 mm
Heavy	T	11-16 mm
Excessive	F	17 mm and over

For steers and heifers, there are 3 muscling classes (Table 2.3), where a class 1 carcass has excellent muscle development with convex profiles and a class 3 carcass has muscles lacking development with concave profiles. Most of cattle slaughtered in New Zealand fall into muscling

class 2 (85%), so farmers are either paid a bonus if carcasses are class 1 (10% of carcasses, around 5 cents/kg extra) or penalised if carcasses are class 3 (5% of carcasses, around 10 cents/kg discount), depending on the season and the meat company involved (Bown *et al.*, 2016). The penalty on poorer conformation reflects that the carcass has less meat yield, and hence less meat that can be sold from it.

Table 2.3. Muscling classes. Source: New Zealand Meat Classification Authority (2004).

		
<p>Class 1</p>	<p>Class 2</p>	<p>Class 3</p>
<ul style="list-style-type: none"> • profiles convex to super convex • excellent muscle development <hr/> <p>Round: Very rounded</p> <hr/> <p>Rump: Very rounded</p> <hr/> <p>Loin: Full</p>	<ul style="list-style-type: none"> • profiles on the whole, straight but may vary from slightly convex to slightly concave • good muscle development <hr/> <p>Round: Well developed to average development</p> <hr/> <p>Rump: Rounded to average development</p> <hr/> <p>Loin: Generally full</p>	<ul style="list-style-type: none"> • profiles on the whole, concave <hr/> <p>Round: Lacking development</p> <hr/> <p>Rump: Straight profile lacking development</p> <hr/> <p>Loin: Average to shallow development</p>
<p>Carcasses with any two of the three attributes qualify.</p>	<p>Carcasses with any two of the three attributes qualify.</p>	

Further to hot carcass grading, carcasses can be assessed for eating quality by qualified assessors to specific standards for some markets, after chilling but prior to boning and trimming. Some processors in New Zealand use the AUS-MEAT scheme, which provides a means of

describing meat characteristics and of classifying product prior to packaging. These characteristics include the colour of meat and fat, the amount of marbling, eye muscle area, rib fat thickness and maturity, as well as ultimate pH and subcutaneous fat distribution (AUS-MEAT Limited, 2017). From these characteristics, eye muscle area and fat thickness are carcass traits of high importance during processing of the carcass into cuts, because they are indicative of retail yield (Boles *et al.*, 2015). The other characteristics are related to meat eating and visual quality, and will be described in the “Meat quality” section. While these characteristics of beef are important, the New Zealand meat grading system does not reward quality and the general approach is still a volume commodity mindset (Julie McDade, Business Development Manager for Greenlea Premier Meats Ltd, personal communication, 15 January 2020).

2.4.2. Carcass weight and length

Carcass weight and length are indicators of carcass size. Carcass length is a measure of the animal’s skeletal size, which increases with slaughter weight (Chambaz *et al.*, 2001). Carcass length is routinely measured as the distance from the distal end of the tarsal bones to the mid-point of the cranial edge of the first rib (Purchas *et al.*, 2007). Hot carcass weight is the weight of the inspected animal after commercial dressing (head, knuckles, intestines and pelt removed) but before drying, cooling or further processing has taken place (Beef+Lamb New Zealand, 2017b; Ministry for Primary Industries, 2019). Trimming of bruises or excess fat from the carcass will reduce carcass weight (Owens *et al.*, 1993).

Carcass weight is often considered the ultimate weight measurement because it provides a direct estimate of saleable product (Owens *et al.*, 1993), and it is positively related to the ribeye area, one of the high-value primal cuts (Boles *et al.*, 2015). Within each fat grade class, higher carcass weights increase the value of the whole carcass. Thus, New Zealand farmers are rewarded for producing heavy carcasses and so many farmers elect to “carry-through” some or all of their cattle for a second winter such that they range in age from 27 to 34 months at slaughter (Morris, 2013). On farms with high levels of animal performance (i.e. high growth rates), cattle can be slaughtered at around 300 kg carcass weight at 18 to 24 months of age. Besides reaching slaughter weight at a younger age, animals with high growth rates (~1.3 kg/d) during their lifetime can have higher carcass weights compared with animals that grew at a slow rate (~0.6 kg/d), when slaughtered at similar live weights (McIntyre *et al.*, 2009).

The weight of the hot carcass as a percentage of the pre-slaughter live weight is known as dressing-out percentage. Typically, this value is around 50% for steers and heifers, but ranges

from 45-70% for cattle in New Zealand (Beef+Lamb New Zealand, 2017b), and usually increases with increasing carcass weight (Purchas, 2003). Although variation in dressing-out percentage can clearly affect the lean meat yield per kg of live weight (Figure 2.3), values for dressing-out percentage are heavily dependent on the level of gut-fill at the time the live animal was weighed and need to be interpreted with caution (Purchas, 2003).

Compared to beef cattle slaughtered at similar age, dairy cattle have lighter carcasses and lower dressing-out percentages (Barton *et al.*, 1997; Muir *et al.*, 2000a; Purchas *et al.*, 2007), and poorer conformation as indicated by greater carcass length (at a set weight) and greater legginess (Purchas *et al.*, 2007). Further, dairy carcasses have heavier bone weight than beef carcasses (Barton *et al.*, 1997). This poorer conformation or muscling class score is one of the reasons for the lower value of carcasses from dairy-breed cattle compared with carcasses from beef-breed cattle under the New Zealand grading system, despite the heavy reliance of the beef industry on animals produced from the dairy industry (Bown *et al.*, 2016).

2.4.3. Meat yield and muscle area

Meat yield can be measured as the lean or retail beef yield, and can significantly influence the value of a carcass (McIntyre *et al.*, 2009). Lean meat yield (LMY%, Figure 2.3) is the boneless product with no visible fat except intramuscular or marbling fat (Purchas, 2003). Retail (or saleable) beef yield is the total weight of boneless cuts, trimmed to 3 mm fat cover, expressed as a percentage of recovered side or carcass weight (Perry *et al.*, 2001).

Eye muscle area (EMA, Figure 2.4) is the surface area of the *M. longissimus thoracis* at the 12th/13th rib site (AUS-MEAT Limited, 2018). This muscle is the main component of the ribeye high-value primal cut (Figure 2.1) and its area is significantly correlated with carcass weight and retail beef yield (Boles *et al.*, 2015; Realini *et al.*, 2001; Reverter *et al.*, 2003b). Therefore, it is expected that higher value will be obtained from a carcass with greater EMA.

Muscle yield can be predicted from the carcass weight, but only within genotypes of similar adult size (Figure 2.5, Thonney (2015)), because a genotype with a larger mature size (or late maturing) will be leaner than a smaller genotype at equivalent carcass weight (Purchas, 2003). Further, one animal will yield more meat than another (both total lean and saleable meat) if its dressing-out percentage is greater, if carcass fat percentage is lower, or if carcass muscle to bone ratio is higher, but superiority in any one of these could be offset by inferiority in one or more of the others (Purchas, 2003).



Figure 2.4. Original and tracing of the eye muscle area (EMA) on a carcass.

Carcasses from dairy breeds are associated with less lean or saleable meat yield, and lower muscle to bone ratio (M:B in Figure 2.3) compared with beef carcasses at the same final live weight (Barton *et al.*, 1997; Purchas, 2003). Correspondingly, the eye muscle area of beef bred cattle is greater than in dairy bred cattle (Barton *et al.*, 1997). Some studies comparing Angus and Hereford, both earlier maturing beef breeds with similar mature size (Bartoň *et al.*, 2006; Purchas, 2003), have shown that Angus has greater EMA and higher total meat yield than Hereford carcasses (Bartoň *et al.*, 2006; Barton *et al.*, 1997)

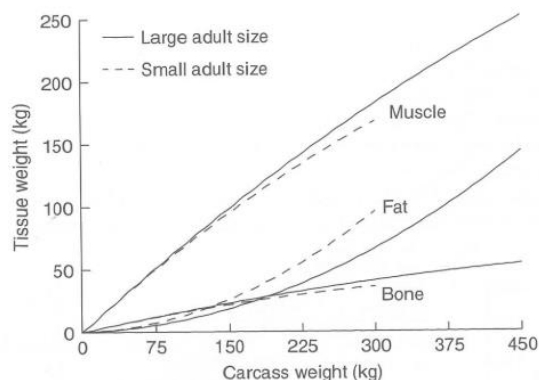


Figure 2.5. Proportions of muscle, fat and bone as carcass weight increases, for large adult-sized animal with a 450-kg carcass (solid line) and small adult-sized animal with a 300-kg carcass (dashed line). Source: Figure 21.4 from Thonney (2015). Reproduced with permission.

2.4.4. Fat depots: subcutaneous and intramuscular fat

Total carcass fat is the most variable component of the carcass (Figure 2.3) and increases markedly with increasing carcass weight (Figure 2.5)(Purchas, 2003). However, the way in which total fat is partitioned between fat depots, or distributed within a depot, is a characteristic of commercial importance because it is a major contributor to differences in conformation between cattle (Berg *et al.*, 1968; Purchas, 2003), and consequently the carcass grade achieved.

The subcutaneous fat is the fat immediately under the skin (Purchas, 2003) and it is measured over the fourth quarter of the eye muscle at the 12th/13th rib site (New Zealand Meat Classification Authority, 2004). Rib fat depth is used as a proxy for total fat of the carcass, which increases as carcass weight increases (Purchas, 2003). Carcasses require a minimum of 3 mm of fat to receive the best payment (Table 2.2), as this is sufficient for meat quality and saleable meat yield purposes, as well as ensures adequate protection for cold-shortening of the muscles. Excessive fat requires trimming, and so it is an extra cost to the processor (Beef+Lamb New Zealand, 2017b). In practice, graders do not often measure the subcutaneous fat on the carcasses, but they use it as a guide while also considering the fat content of the whole carcass (New Zealand Meat Classification Authority, 2004).

Intramuscular fat (IMF) is the adipose tissue deposited between perimysium surrounding muscle bundles within the muscle, and is visible to the human eye as spots of fat known commercially as marbling (Pethick *et al.*, 2004; Warner *et al.*, 2010). Marbling is visually scored (Figure 2.6) on the chilled carcass at the *M. longissimus thoracis* muscle (AUS-MEAT Limited, 2018) whilst IMF% is the chemically measured fat content, which includes membrane lipids (Warner *et al.*, 2010). The AUS-MEAT scores are accompanied by Meat Standard Australia (MSA) specific marbling and the relationship between the MSA-specific marbling score with IMF% is presented in Figure 2.7 (McPhee *et al.*, 2016). Marbling and IMF are highly genetically correlated ($r_g = 0.96$), suggesting that both are measurements of the same trait at a genetic level (Reverter *et al.*, 2003a). Regardless of how it is measured, the IMF content of the *M. longissimus thoracis* is, on average, about the same as the average carcass muscle IMF content (Pethick *et al.*, 2004) and can significantly influence the value of a carcass (McIntyre *et al.*, 2009). For this reason, the implications of IMF on meat quality will be developed further under the “Meat quality” section.

Intramuscular fat is a later-developing fat depot compared with the intermuscular and subcutaneous fat depot, so that its concentration will increase as the animal gets heavier and fatter (McIntyre *et al.*, 2009), and is highly influenced by energy intake (Hocquette *et al.*, 2010). Animals raised on faster growth paths start marbling at an earlier age, and so produce carcasses with more fat and more IMF% than those grown on slower growth paths (McIntyre *et al.*, 2009; Pethick *et al.*, 2004). Diets with an increased energy density will drive greater rates of fat synthesis as well (Pethick *et al.*, 2004), particularly if comparing grain versus pasture diets. Even on pasture alone, cattle grown fast and slaughtered at 16-18 months of age can achieve greater IMF% compared with cattle under restricted growth and slaughtered at 24-28 months of age (Purchas *et al.*, 2002).

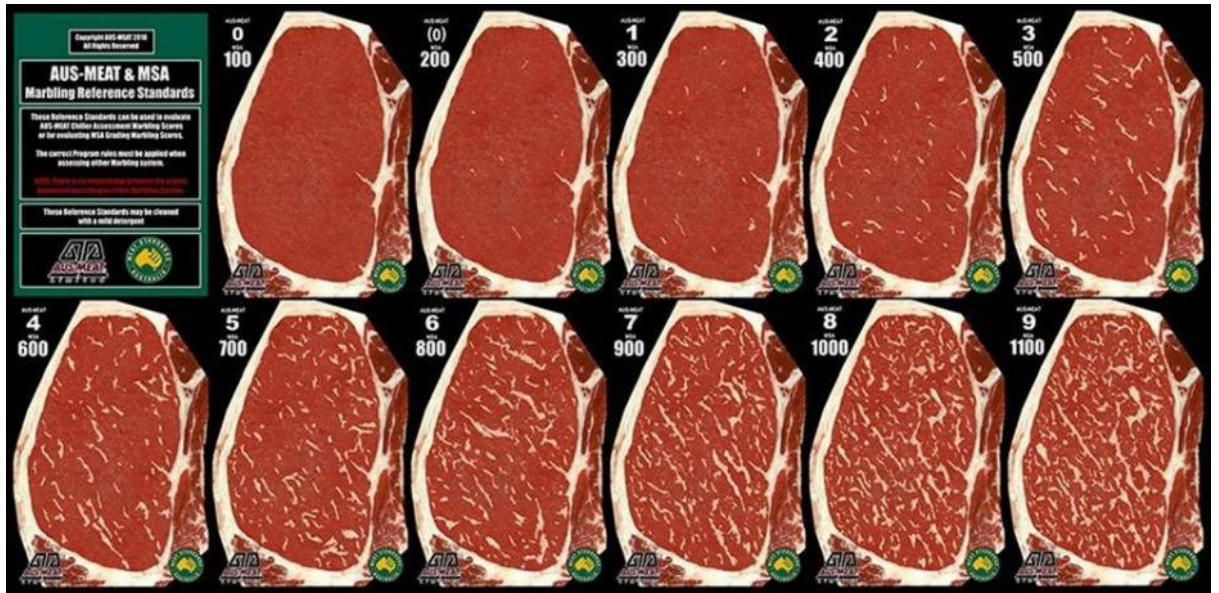


Figure 2.6. AUS-MEAT & MSA marbling reference standards. Source: AUS-MEAT Limited (2017). Reproduced with permission.

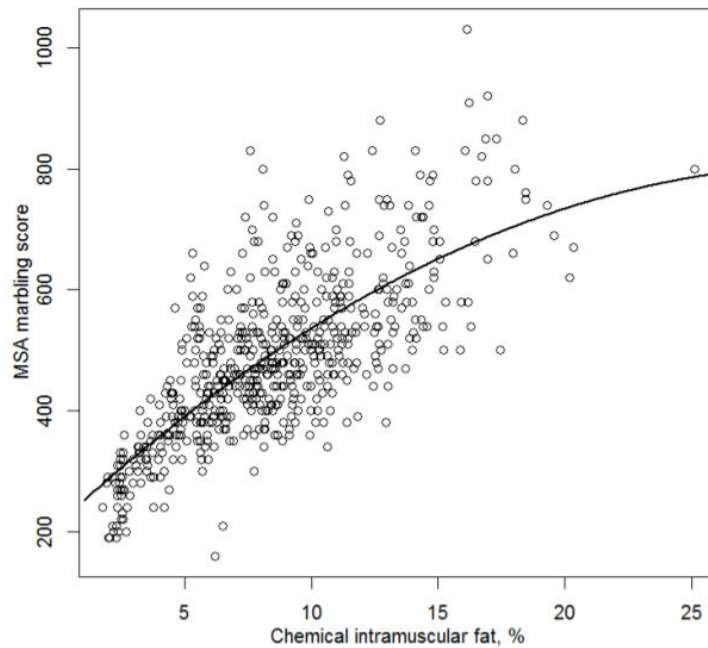


Figure 2.7. Relationship between MSA marbling score (USMB) and chemical intramuscular fat (%) and equation: $USMB = 213.7 + 38.59*IMF\% - 0.629*IMF\%^2$ ($R^2 = 54\%$) (solid line). Source: McPhee *et al.* (2016). Reproduced with permission.

New Zealand cattle are mostly finished on mixed pastures and are usually slaughtered at 24-30 months of age. Values of IMF% range from 2.4 to 4.3% IMF for beef breeds, including Angus, Hereford, Stabilizer, Simmental and Charolais breeds measured via ultrasound at 18

months of age, (Beef+Lamb New Zealand Genetics, 2019), and are equivalent to 326 to 390 MSA marbling scores at slaughter or marble scores between 1 to 2 in the AUS-MEAT scale (AUS-MEAT Limited, 2018; McPhee *et al.*, 2016). Dairy and dairy-cross animals, including Friesian, Jersey-Friesian and Hereford-Friesian, have values in the range of 2.2 to 5.3% IMF measured via ultrasound at 12-24 months of age, and 2.9 to 3.9% IMF measured by Soxhlet extraction at slaughter at 22-27 months of age (Coleman *et al.*, 2016; Purchas *et al.*, 2007; Schreurs *et al.*, 2014).

Traditional beef-bred cattle, such as Angus and Hereford, can attain similar subcutaneous fat thickness (Bartoň *et al.*, 2006; Purchas, 2003) and achieve the 3 mm minimum fat depth (and therefore a “P” grade) at a lighter carcass weight and with a younger animal compared with dairy-bred cattle (Bown *et al.*, 2016). This is because dairy breed carcasses have a different fat deposition pattern. Dairy animals have large metabolically active internal organs (e.g. liver) and non-carcass fat depots (e.g. omental, mesenteric, kidney or channel fat) to support their greater lactation requirements, thus producing carcasses that leaner, with less subcutaneous and IMF relative to non-carcass fat, compared with beef animals at same live weight (Barton *et al.*, 1997; Bown *et al.*, 2016; Muir *et al.*, 2000a; Purchas, 2003; Purchas *et al.*, 2007). Not achieving the minimum fat depth is the main reason for the lower value of carcasses from dairy-breed cattle under the New Zealand grading system (Bown *et al.*, 2016). Nevertheless, research indicates that there is no difference between dairy (e.g. Friesian) and traditional beef breeds used in New Zealand (e.g. Angus, Hereford) for lean meat yield and meat quality when grazed under similar conditions and slaughtered at the same level of maturity or fatness (Bown *et al.*, 2016; Purchas, 2003).

2.4.5. Heritability and correlations

Carcass traits of beef cattle are moderately to highly heritable. Carcass weight has $h^2=0.23-0.54$ and *Longissimus* muscle area has $h^2=0.20-0.47$, for breeds including Angus, Hereford and other temperate breeds (Angus New Zealand; Beef+Lamb New Zealand, 2017e; Gregory *et al.*, 1995; Reverter *et al.*, 2000; Reverter *et al.*, 2003a; Reverter *et al.*, 2003b; Rios Utrera *et al.*, 2004; Su *et al.*, 2017). Retail beef yield has $h^2=0.28-0.68$ (Angus New Zealand; Beef+Lamb New Zealand, 2017e; Gregory *et al.*, 1995; Reverter *et al.*, 2000; Reverter *et al.*, 2003a; Rios Utrera *et al.*, 2004). Rib fat is also moderately heritable, with $h^2=0.25-0.45$ (Afolayan *et al.*, 2007; Angus New Zealand; Beef+Lamb New Zealand, 2017e; Gregory *et al.*, 1995; Reverter *et al.*, 2000; Reverter *et al.*, 2003a; Rios Utrera *et al.*, 2004; Su *et al.*, 2017). Similarly, IMF is moderately

heritable, with $h^2 = 0.15-0.49$ (Angus New Zealand; Beef+Lamb New Zealand, 2017e; Gregory *et al.*, 1995; Reverter *et al.*, 2000; Reverter *et al.*, 2003a; Reverter *et al.*, 2003b; Warner *et al.*, 2010). Dressing-out has the lowest heritability for carcass traits of $h^2 = 0.15-0.32$ (Beef+Lamb New Zealand, 2017e; Gregory *et al.*, 1995; Rios Utrera *et al.*, 2004).

Carcass traits are correlated with each other, but with variable strength. Carcass weight is correlated with retail beef yield ($r_g = -0.12$ to 0.63), EMA ($r_g = -0.35$ to 0.66), IMF ($r_g = -0.49$ to 0.01), marbling ($r_g = -0.15$ to 0.31) and rib fat ($r_g = -0.46$ to 0.13) (Gregory *et al.*, 1995; Reverter *et al.*, 2000; Reverter *et al.*, 2003a; Reverter *et al.*, 2003b). Rib fat is correlated to IMF ($r_g = 0.03$ to 0.39) and marbling ($r_g = 0.11$ to 0.44) (Gregory *et al.*, 1995; Reverter *et al.*, 2000). The *Longissimus* muscle area is correlated with weight of boneless retail cuts and retail beef yield ($r_g = 0.14$ to 0.48) (Reverter *et al.*, 2000; Reverter *et al.*, 2003b).

Some carcass traits are correlated with live animal measures. Carcass weight is correlated with live weight prior to slaughter ($r_g = 0.89$ to 0.93) and birth weight ($r_g = 0.18$) (Coyne *et al.*, 2019; Gregory *et al.*, 1995; Reverter *et al.*, 2003b), and tends to be negatively correlated with EV (Cafe *et al.*, 2011). Fat depth and marbling are lowly correlated to birth weight ($r_g = -0.08$ to -0.06) but moderately to slaughter weight ($r_g = 0.23$ to 0.27) (Gregory *et al.*, 1995), and negatively correlated with EV as well (Boles *et al.*, 2015; Cafe *et al.*, 2011). Eye muscle area is moderately correlated to birth ($r_g = 0.17$) and slaughter weight ($r_g = 0.45$) (Gregory *et al.*, 1995).

2.5. Meat quality

Meat quality is “the combination of all those intrinsic and extrinsic characteristics of a beef product that determine or affect its level of acceptability for a consumer” (Purchas, 2003). The intrinsic properties of meat that are important for the consumer include colour and texture of the meat, fat colour, amount and distribution of fat as well as the absence of excess water in the packaging. Once cooked, consumer satisfaction is largely determined by how tender the meat is as well as its flavour and juiciness (Verbeke *et al.*, 2010; Warner *et al.*, 2010). Extrinsic properties that require information about where the meat came from are becoming increasingly important to some consumers (Purchas, 2003), but these aspects are not measurable on a piece of meat and will not be discussed in this document.

2.5.1. Ultimate pH

Ultimate pH is a measure of the acidity of the meat, usually measured with a pH spear on the surface of the *M. longissimus thoracis* at the quartering site. Many qualities of meat depend on pH, such as meat colour, water holding capacity and tenderness. Generally, beef in the pH range 5.4 to 5.6 has the most desirable properties for eating quality (Young *et al.*, 2004).

For a muscle to reach a pH of around 5.5 post-mortem, it must contain a sufficient concentration of glycogen at slaughter (Warriss, 1990; Young *et al.*, 2004). Muscle glycogen is the main fuel of the anaerobic glycolysis after slaughter when muscles are no longer supplied with oxygen, and lactate is the product of the anaerobic glycogen breakdown (Pösö *et al.*, 2005). The accumulation of lactate results in acidification of the muscle tissue (decline in pH, Figure 2.8) and is a prerequisite for turning muscles into high quality meat (McDade, 2010; Warriss, 1990).

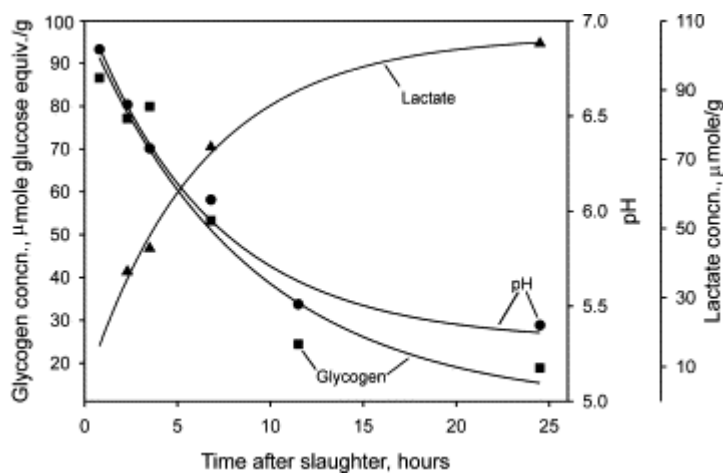


Figure 2.8. Kinetics of glycogen loss, pH decline and lactate increase in the muscle *M. Longissimus lumborum* from an unstimulated bovine carcass. Source: Young *et al.* (2004). Reproduced with permission.

Glycogen reserves at slaughter are a function of the initial levels of glycogen and the losses (use of glycogen, Figure 2.9) due to stresses placed on the animals during the immediate pre-slaughter period (Purchas, 2003). Handling, transportation, and pre- and post-slaughter conditions (yards, weather, animal and/or human interactions) contribute to muscle ultimate pH post-mortem (Dixon *et al.*, 1996; McDade, 2010; Njisane *et al.*, 2017).

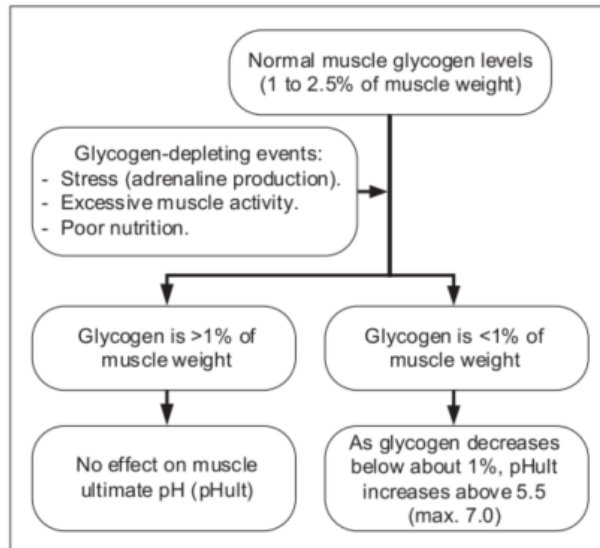


Figure 2.9. Flow diagram showing whether or not glycogen-depleting events affect ultimate muscle pH. Source: Purchas (2003). Reproduced with permission.

2.5.2. Marbling

As previously discussed in “Fat depots: subcutaneous and intramuscular fat” section, marbling are the spots of fat in the muscle visible to the human eye (Pethick *et al.*, 2004; Warner *et al.*, 2010), whilst IMF% is the chemically measured fat content, which includes membrane lipids (Warner *et al.*, 2010). Marbling is scored on the chilled carcass at the *M. longissimus thoracis* muscle (Figure 2.6).

The amount and distribution of fat within the muscle is a very important attribute of the meat and so can significantly influence the value of a carcass (McIntyre *et al.*, 2009). Intramuscular fat directly affects juiciness and flavour, and indirectly influences tenderness by separating and diluting perimysial collagen fibres and disorganizing the structure of intramuscular connective tissue (Hocquette *et al.*, 2010). In general, some IMF is important to palatability and at IMF levels lower than 8%, this is most likely primarily through improved juiciness and flavour (Warner *et al.*, 2010).

Marbling is a critical component for several branded beef programmes in New Zealand (e.g., Eating Quality System from Silver Fern Farms, <https://www.silverfernfarms.com/what-were-made-of/guaranteed-eating-quality/>), and along with pH is a major reason for carcasses failing to meet specifications (Beef+Lamb New Zealand Genetics, 2017).

2.5.3. Meat and fat colour

The colour of red meat is the first quality attribute seen by the consumer (Troy *et al.*, 2010). The colour of the meat is the light reflected from a muscle that has been exposed to air, and it can be assessed visually (e.g. using AUS-MEAT colour reference standards, Figure 2.10) or using a spectrophotometer or colorimeter that will distinguish into colour attributes (redness and yellowness) and brightness (lightness) (Hughes *et al.*, 2014b). Meat colour is dependent on the concentration and chemical state of the meat pigments (primarily myoglobin and haemoglobin), on the physical characteristics and the antioxidant potential of meat, and on the type and level of IMF (Hughes *et al.*, 2014b; Ponnampalam *et al.*, 2017; Troy *et al.*, 2010). Additionally, during retail display environmental factors such as temperature, oxygen availability, type of lighting, microbial growth and packaging all influence meat colour (Troy *et al.*, 2010).

The colour attributes (redness and yellowness) tend to be strongly associated with the pigment myoglobin (Hughes *et al.*, 2014b). The myoglobin concentration of muscle is affected by muscle pH and fibre type, animal's age, breed, sex, genetics, activity level and diet, and environmental factors and animal management pre-slaughter (Troy *et al.*, 2010). Myoglobin has three natural colours, depending on its exposure to oxygen and the chemical state of the iron: 1] Oxymyoglobin when meat is exposed to air (e.g. retail display) and the meat is bright red, 2] Deoxymyoglobin when no oxygen is present (e.g. vacuum packed) and the meat appears purple red, and 3] Metmyoglobin when only very small amounts of oxygen are present (e.g. two bright red pieces of meat are stacked on each other excluding the oxygen) or when iron has oxidized (e.g. meat late in display), and meat appears tan or brown.

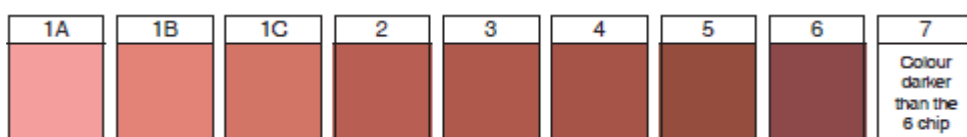


Figure 2.10. AUS-MEAT meat colour reference standards. Source: AUS-MEAT Limited (2017). Reproduced with permission.

Dark-cutting meat, commercially known as DFD (dark, firm and dry), is meat with lower reflectance values (lightness L^* , redness a^* and yellowness b^*) as a consequence of high pH by which the pigment myoglobin remains in the purple deoxygenated form, rather than the bright red of the oxygenated form (Purchas, 1990; Tarrant *et al.*, 1980; Warriss, 1990). As this is not

the normal or expected colour, consumers will discriminate these cuts, as they associate the dark colour with older or poorly managed meat, with undesirable eating quality (Ponnampalam *et al.*, 2017). Studies found difference in the incidence of dark-cutting due to sex stress response, weather (temperature and rain) and pasture quality effects, and due to individual variability in temperament and stress (Mahmood *et al.*, 2019; Ponnampalam *et al.*, 2017). Dark meat colour is primarily a reflection of ultimate pH and less likely to be a consequence of animal type.

Meat Standards Australia classifies carcasses as dark-cutting when the meat colour score is greater than 3 and/or has an ultimate pH greater than 5.70 (Hughes *et al.*, 2014a). The prevalence of dark cutting beef on animals finished on pasture in New Zealand, has been estimated around 4.3% (pH \geq 5.8) (Ponnampalam *et al.*, 2017). Despite the potential losses in sales due to dark colour, there are no grading penalties for carcasses with dark meat in New Zealand.

The colour of the subcutaneous fat is another important component of beef quality. The fat colour is normally assessed visually (e.g. against AUS-MEAT fat colour reference standards, Figure 2.11) and it depends on the age, sex and breed of cattle, with diet being the most significant external factor affecting it (Dunne *et al.*, 2009).

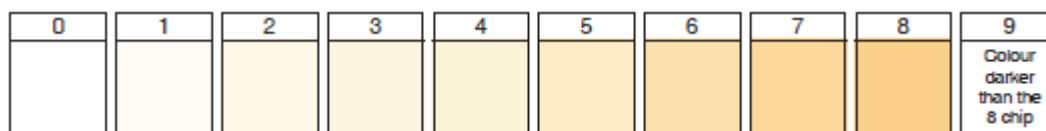


Figure 2.11. AUS-MEAT fat colour reference standards Source: AUS-MEAT Limited (2017). Reproduced with permission.

Cattle produced under intensive concentrate or grain-fed production systems generally have whiter carcass fat, while cattle from extensive grass-based production systems have carcass fat which is more yellow (Dunne *et al.*, 2009). The yellow pigmentation comes from the accumulation of carotenoids from green forage in the fat (Dunne *et al.*, 2009; Morgan *et al.*, 1969). Further, some cattle breeds such as Jersey, Brown Swiss and Guernsey dairy breeds, cannot metabolise the chlorophyll from grass and so their fat is remarkably yellow (Nozière *et al.*, 2006). Yellow fat is negatively regarded in many countries, with the misconception that carcasses with such fat come from older animals and hence, produce less tender meat. Thus, those animals with remarkably yellow fat are downgraded to “cow” category (manufacturing) at time of carcass grading as penalty (New Zealand Meat Classification Authority, 2004). The

determination of the downgrade is purely subjective and due to market perception (Aaron Craig, Operations Manager for Greenlea Premier Meats Ltd, personal communication, 15 February 2019).

2.5.4. Tenderness

Tenderness is measured by objective methods as the force necessary to bite through a section of meat (e.g. Warner-Bratzler shear force and MIRINZ tenderometer) or by subjective sensory tasting panels. Tenderness is a characteristic affecting the palatability of beef, and will determine the consumer's eating experience and thus, repeat consumption (Bickerstaffe *et al.*, 2001; Mateescu, 2015). Beef is considered "tender" by consumers with shear force values of 4.1 kg or less with Warner-Bratzler (Huffman *et al.*, 1996) and 7.9 kgF or less measured by the MIRINZ tenderometer (Bickerstaffe *et al.*, 2001), although caution is recommended when applying thresholds due to potential sources of variation from methodological, sample type and consumer preference differences (Holman *et al.*, 2020).

Meat tenderness is determined by intrinsic factors such as the amount and solubility of connective tissue (collagen), sarcomere shortening during rigor development and post-mortem proteolysis (Purchas, 1990; Purchas *et al.*, 1993; Purchas *et al.*, 2002). Intramuscular fat also indirectly influences meat tenderness, but the relationship varies considerably. All of these, in turn, are affected by the animal's age and pattern of growth, length and form of ageing of the meat, and ultimate pH levels.

There is a quadratic relationship between pH and shear force (Figure 2.12). Shear force increases as pH increases from pH 5.4-5.5 to 6-6.2, with maximal toughness around pH 6-6.2, and a decrease in shear force thereafter (Ertbjerg *et al.*, 2017; Purchas, 1990; Purchas *et al.*, 1993). Although shear force decreases with pH above 6.2, this high pH is associated with other changes in meat quality (such as texture, taste, colour and shelf life) that makes it less desirable.

British breeds typically have a slight advantage in tenderness over Continental breeds (Cundiff *et al.*, 2007), but little difference has been found between *Bos Taurus* beef breeds, dairy breeds or dairy-beef crossbreeds (Bown *et al.*, 2016; Muir *et al.*, 2000a; Purchas *et al.*, 1976; Purchas *et al.*, 2007).

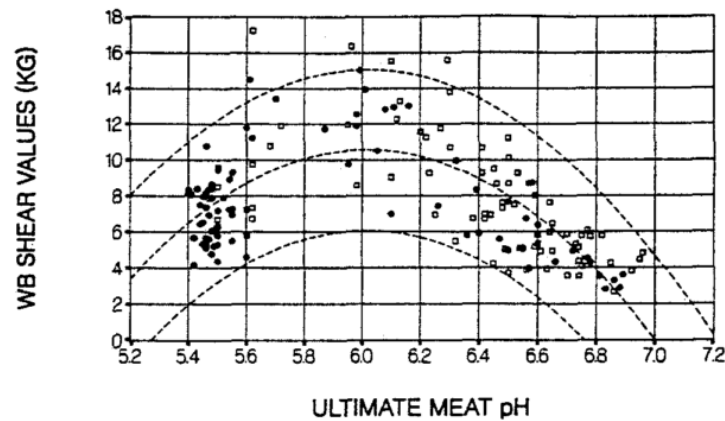


Figure 2.12. Relationship between ultimate meat pH and Warner-Bratzler shear values, from meat samples of 80 bulls (white squares) and 80 steers (black circles), with the quadratic regression line (centre line) and the 95% confidence limits for prediction. Source: Purchas (1990). Reproduced with permission.

2.5.5. Water-holding capacity

Lean muscle contains approximately 75% water (Huff-Lonergan *et al.*, 2005; Lawrie, 2006b) and water-holding capacity is the ability of meat to retain moisture. Maintaining as much water as possible in the meat is the goal of many processors, to minimise loss of saleable weight and protein (Huff-Lonergan *et al.*, 2005). Product weight losses due to drip can average 6-10% in fresh retail cuts (Coleman, 2016; Coleman *et al.*, 2016; Purchas *et al.*, 2007). Further, meat loses water when thawing (1.7-3.6%, (Coleman, 2016)) and cooking (20.2-30.0%, (Coleman, 2016; Coleman *et al.*, 2016; Purchas, 1990; Purchas *et al.*, 2007). All these losses affect the palatability of the meat to the final consumer.

As rigor mortis progresses, the sarcomere shrinks so the space for water to be held in the myofibrils is reduced and fluid can be forced out of the muscle as drip or purge (Ertbjerg *et al.*, 2017; Huff-Lonergan *et al.*, 2005). The pH decline, ionic strength and protein oxidation have a direct effect on the ability of myofibrillar protein, myofibrils and muscle cells to hold onto water (Huff-Lonergan *et al.*, 2005).

2.5.6. Heritability and correlations

Marbling and IMF are moderately heritable, with $h^2=0.17-0.48$ for marbling (Gregory *et al.*, 1995; Reverter *et al.*, 2003a; Rios Utrera *et al.*, 2004; Su *et al.*, 2017; Van Vleck *et al.*, 1992) and $h^2=0.15-0.49$ for IMF (Angus New Zealand; Beef+Lamb New Zealand, 2017e; Gregory *et al.*, 1995; Reverter *et al.*, 2000; Reverter *et al.*, 2003a; Reverter *et al.*, 2003b; Warner *et al.*, 2010).

In breeds like the Japanese Black, marbling area can be more heritable ($h^2 = 0.54$ (Maeda *et al.*, 2014)).

The rest of the meat quality traits are low to moderately heritable, with $h^2 = 0.02\text{--}0.10$ for ultimate pH (Johnston *et al.*, 2003; King *et al.*, 2010), $h^2 = 0.04\text{--}0.30$ for tenderness and shear force (Reverter *et al.*, 2003b), $h^2 = 0.05\text{--}0.25$ for water-holding traits (Gregory *et al.*, 1995; Mateescu, 2015; Warner *et al.*, 2010), $h^2 = 0.05\text{--}0.25$ for meat colour (Reverter *et al.*, 2003a; Reverter *et al.*, 2003b; Warner *et al.*, 2010) and $h^2 = 0.05$ for fat colour (Reverter *et al.*, 2003a).

Some meat quality traits are correlated with each other. Marbling and IMF are genetically correlated with consumer panel tenderness ($r_g = 0.32$ to 0.74) and shear force ($r_g = -1.00$ to -0.32) (Gregory *et al.*, 1995; Mateescu, 2015; Reverter *et al.*, 2003b; Van Vleck *et al.*, 1992). Shear force is correlated to meat colour ($r_g = 0.03$ to 0.58), and meat colour is lowly correlated to muscle lightness L^* ($r_g = -0.29$) for temperate breeds, likely due to limited variation in colour scores (Reverter *et al.*, 2003b).

Correlations between shear force and live weights are usually low ($r_g = -0.08$ to 0.29), variable between shear force and EMA ($r_g = -0.48$ to 0.10) and negative between shear force and rib fat ($r_g = -0.23$) (Gregory *et al.*, 1995; Reverter *et al.*, 2003b). Heavier carcasses are genetically associated with increased muscle lightness (L^* , $r_g = 0.66$) and decreased redness (a^* , $r_g = -0.56$) colour (Reverter *et al.*, 2003b). Tenderness and temperament are genetically correlated ($r_g = 0.30$ to 0.40) especially in tropical cattle, although the phenotypic relationship is low (Warner *et al.*, 2010).

2.6. Summary of the review of literature and hypotheses of the thesis

Around 2.6 million adult cattle and 1.8 million bobby calves are slaughtered for beef production each year in New Zealand (Beef+Lamb New Zealand Economic Service, 2019; Ministry for Primary Industries, 2020). Of the adult cattle, animals born in the dairy industry contribute to about two-thirds of the beef production on a per-head basis (Davison, 2020; Ministry for Primary Industries, 2020; van Selm *et al.*, 2021), highlighting the importance of the dairy industry in the total beef production of New Zealand.

New Zealand's beef production could be further increased if more dairy-origin calves were retained and finished for beef production, under dairy-beef cattle systems, rather than slaughtering them at a few days of age (Morris, 2013). Dairy-beef cattle systems reduce the

number of beef breeding cows (Morris, 2017), increase the conversion efficiency of feed into product (Burggraaf *et al.*, 2020) while reducing annual greenhouse gas emissions for beef production (van Selm *et al.*, 2021). In addition to making better use of the available animal resources, it can mitigate consumer concerns around the processing of bobby calves, helping to maintain the dairy industry “social licence” to operate (Cook, 2014; Fisher *et al.*, 2017).

It is estimated that around 20% from the New Zealand dairy herd is mated to beef-breed sires to produce beef-cross-dairy calves (Burggraaf, 2016). Sires for these systems should perform well at calving on the dairy farm (i.e. easy calving) and have good finishing performance of the progeny (i.e. quick growth on pasture, high carcass yield and desirable meat quality traits). In New Zealand, most cattle destined for beef production are farmed on hill country pasture until slaughter with minimal feed supplementation (Beef+Lamb New Zealand, 2017c). Thus, animals that are more efficient in converting pasture into body weight are more desirable, because they grow faster and get to target slaughter weight at a younger age (Beef+Lamb New Zealand, 2017a; Berry *et al.*, 2013). Growth path can have important effects on carcass characteristics as well, most of which relate to the composition of the animal, particularly fatness (McIntyre *et al.*, 2009). Therefore, live weight and growth trajectories of each animal are important.

In addition, an animal suited for beef production should produce a heavy carcass with an appropriate amount of subcutaneous fat, because carcass weight and fat grade drive the payment to farmers in the New Zealand meat payment schedule (Bown *et al.*, 2016). The “P” fat class grade typically achieves the highest price per kilogram of carcass weight and requires 3-10 mm of subcutaneous fat over the eye muscle at the 12th rib. Farmers are rewarded for producing heavy carcasses (Morris, 2013), with high saleable meat yields.

Meat quality characteristics are those attributes of the beef product that determine the acceptability and value for the consumer (Purchas, 2003). The attributes can include visual aspects that influence purchasing decisions (e.g. meat and fat colour), and eating quality characteristics that influence the demand for the product and inform repurchasing decisions (e.g. tenderness) (Verbeke *et al.*, 2010; Warner *et al.*, 2010). Many characteristics of meat are influenced by ultimate pH and generally, beef with a pH range of 5.4 to 5.6 has the most desirable properties for appearance and eating quality (Ertbjerg *et al.*, 2017; Purchas, 1990; Purchas *et al.*, 1993; Warriss, 1990; Young *et al.*, 2004). Thus, animals suited for beef production are required to grow quickly and produce heavy carcasses with adequate fat cover and of suitable eating quality for particular markets.

Angus and Hereford are breeds widely used in New Zealand farming systems (Beef+Lamb New Zealand Economic Service, 2018), and both breeds have selection programs to improve the genetic merit for beef production. The predicted relative genetic merit of a sire for a particular trait is known as their EBV (BREEDPLAN, 2015a), and the EBV for Angus and Hereford cattle are produced within each breed by BREEDPLAN (Agricultural Business Research Institute, Australia). Sires can be ranked based on their EBV for the different traits, and genetically superior animals are expected to perform better than inferior counterparts, particularly for weight, fat and carcass traits (Afolayan *et al.*, 2007; McIntyre *et al.*, 2009). Given that the terminal sire has a considerable direct genetic effect on the growth potential of the progeny, then beef-breed sires with improved genetics can be used in crossbreeding systems to generate beef-cross-dairy calves better able to satisfy the requirements of the dairy, grower and finisher farmers, through to the meat processor.

Coleman (2020) demonstrated that sires of Angus and Hereford breeds have a wide variation in performance for gestation length and birthweight (important traits for the dairy farmer) and that these traits are well predicted by their EBV. These sires also have a range of EBV for live weight later in life (200d, 400d and 600d), as well as for carcass quality traits. The issue is that there are some significant differences between the beef (where the EBV from beef-breed sires are produced) and dairy-beef systems, particularly around rearing, weaning and finishing age. In a beef cow-calf system, calves are reared on their dams until weaning at a set date, around 5-7 months of age (150-210 days and 180-240 kg live weight (Beef+Lamb New Zealand, 2017d)). In contrast in a dairy-beef system, calves are “artificially” reared until weaning at a set weight, usually of 80-100 kg live weight, achieved at 8-12 weeks of age (56-84 days (Beef+Lamb New Zealand, 2017b; Muir *et al.*, 2000b)). Furthermore, beef-bred cattle are slaughtered at 18-22 months of age (Beef+Lamb New Zealand, 2017b), whereas beef-cross-dairy cattle are often slaughtered after their second winter to achieve heavier weights and avoid penalties associated with leanness and conformation (Bown *et al.*, 2016).

Given the considerable differences between beef and dairy-beef cattle systems mentioned above, it is possible that scaling or re-ranking of sires may occur due to genotype by environment interactions (Charteris *et al.*, 1997; Morris *et al.*, 2009; Santana *et al.*, 2013). In addition, EBV for different traits might predict performance more or less precisely, depending on the accuracy and heritability of the trait (Afolayan *et al.*, 2007; Baker *et al.*, 1976). To date, little is known about the performance of beef-breed sires for growth, carcass and meat quality traits in a dairy-beef system with beef-cross-dairy cattle in a pasture-based system. There is also no information to quantify how useful beef EBV are to select sires on finishing potential in a

dairy-beef system. Such information is needed in order to determine the value of selecting beef-breed sires with better EBV for growth and finishing traits to use on dairy-breed cows.

Furthermore, many producers buy calves from the sale yards, which rarely have the information of their sire, and instead judgment must be made based on the calf's phenotype to determine future performance. Body size is an important genetic factor in beef cattle production (Hammack *et al.*, 2009). Generally growth rates at a given age are related to mature size (Thonney, 2015) and the animal's height and age early in life can be used to estimate future weights (Hammack *et al.*, 2009). Carcass weight, plus meat, bone and fat weights within the carcass, can be predicted accurately using a combination of measures on the live animal prior to slaughter, with live weight being the best predictor for meat and bone weight (Afolayan *et al.*, 2002). Because body size is highly heritable, measuring skeletal size in early life could predict carcass results.

Animal performance and meat quality can also be associated with cattle temperament and their stress responsiveness (Behrends *et al.*, 2009; Cafe *et al.*, 2011; Ponnampalam *et al.*, 2017). Temperamental cattle have lower growth rates, produce smaller carcasses with less fat cover, and have darker meat that is tougher to eat (Behrends *et al.*, 2009; Burrow *et al.*, 1997; Cafe *et al.*, 2011). However, calves born on a dairy farm are usually taken off their dams within 24 hours of birth and reared by humans. Phenotypic temperament may change because of this intensive hand-rearing, and therefore, the potential relationship between temperament and meat quality is unclear for hand-reared beef-cross-dairy calves.

The general hypothesis of this study was that the use of genetically superior beef-breed sires can increase the growth and meat production of calves born on dairy farms. The specific hypotheses were: 1] Sire influences the growth of beef-cross-dairy calves that graze on hill country conditions (Chapter 3); 2] Carcass and meat quality traits differ among sires used to produce beef-cross-dairy calves finished on pasture, and the selection of appropriate sires will increase the muscle and fat that contributes to saleable meat yield without disadvantage to meat quality traits (Chapter 4); 3] The performance of beef-cross-dairy offspring is related to their sire EBV for the traits measured (Chapter 5); 4] Skeletal size of beef-cross-dairy calves at early age, in conjunction with live weight, can be used to predict future carcass traits (Chapter 6); 5] Temperament of beef-cross-dairy calves within the first 200 days of life, will affect carcass weight and meat characteristics (Chapter 6).

CHAPTER 3

SIRE EFFECTS ON POST-WEANING GROWTH OF BEEF-CROSS-DAIRY CATTLE

Publications arising from this Chapter:

Martín NP, Schreurs NM, Morris ST, López-Villalobos N, McDade JL, Hickson RE (2020). Sire effects on post-weaning growth of beef-cross-dairy cattle: a case study in New Zealand. *Animals* 10. DOI: 10.3390/ani10122313.

Martín NP, Schreurs NM, Morris ST, McDade JL, Coleman LW, Hickson RE (2018). Live weight of beef-cross-dairy calves during the first year of life. *Proceedings of the World Congress on Genetics Applied to Livestock Production 11 (Electronic Poster Session - Biology - Growth and Development)*. Auckland, New Zealand. Pp697.

3.1. Abstract

Little is known about the growth performance of beef-breed sires used over dairy-breed cows in New Zealand. This experiment aimed to evaluate the growth of Angus and Hereford sires via progeny testing of beef-cross-dairy offspring born to dairy-breed cows and grown on hill country pasture. Live weights at 131d, 200d, 400d, 600d and 800d were analysed, from a dataset of 5208 records from 1101 progeny of 73 sires. The means of the progeny group means for live weight were 118.6 kg at 131d, 159.1 kg at 200d, 284.2 kg at 400d, 427.0 kg at 600d and 503.6 kg at 800d, and the overall daily growth rate was 0.58 kg/d from 131d to 800d. Sire affected ($P < 0.05$) live weight of their progeny at all ages. Differences in live weight between the lightest and heaviest progeny group means increased from 19 kg at 131d to 90 kg at 800d, although the overall coefficient of variation across sires remained unchanged (3%). Even though growth of calves was likely restricted to 200d, live weight at 200d explained 51-56% of the variation in live weights at 400d and 600d ($P < 0.05$). Thus, the use of beef-breed sires selected for growth has the potential to increase the live weight of cattle born on dairy farms for meat production.

3.2. Introduction

Cattle born in the dairy industry contribute around 66% of New Zealand's beef production on a per-head basis (Davison, 2020; Ministry for Primary Industries, 2019; van Selm *et al.*, 2021). Most cattle destined for beef production are farmed on hill country pasture until slaughter with minimal supplementation (Beef+Lamb New Zealand, 2017c). Animals that are more efficient in converting pasture into body weight are more desirable in this type of system, because they grow faster and get to target slaughter weight at a younger age, and because they require less feed to achieve same results compared with a less efficient animal (Beef+Lamb New Zealand, 2017a; Berry *et al.*, 2013). Similarly, animals with same mature size and maturation rate, but greater yearling growth rate (Archer *et al.*, 1998), will be wanted for this system as they may need less time and feed to achieve their slaughter weight. Growth path can have important effects on carcass characteristics as well, most of which relate to the composition of the animal, particularly fatness (McIntyre *et al.*, 2009): cattle on a fast growth path generally have greater fat thickness and intramuscular fat than cattle that grow slowly. These differences in fat content are likely to be a result of both diet and growth rate. Thus, live weight and growth trajectories of each animal are important.

Crossbreeding is an effective tool for increasing performance and profitability through hybrid vigour (Beef+Lamb New Zealand, 2017e; Cunningham *et al.*, 1987).

Crossbreeding is an effective tool for increasing performance and profitability through heterosis and complementarity of attributes (Beef+Lamb New Zealand, 2017e; Cunningham *et al.*, 1987). Crossbreeding using beef-breed sires over dairy-breed cows can increase income from sales of the beef-cross-dairy calves born on the dairy farm. The increase in the price of these calves is based on the expected greater performance, that is, higher growth rates producing heavier animals with higher dressing-out or meat yield percentages compared with dairy-bred cattle (Dal Zotto *et al.*, 2009; Morris *et al.*, 1992). Furthermore, there is possibility to identify sires with good genetic merit for both calving ease and carcass weight (Berry *et al.*, 2019). These sires will produce calves that have lighter birth weight but high growth rates, making them desirable for dairy-beef systems, as they will ensure calving success (particularly important in young cows at their first parturition) without compromising meat production. Given that the terminal sire has a considerable direct genetic effect on the growth potential of the progeny in crossbreeding systems, then beef-breed sires with improved genetics can be used to generate beef-cross-dairy calves better able to satisfy the requirements of the dairy, grower and finisher farmers, through to the meat processor.

Dairy farmers use genetic information or the estimated breeding values (EBV) of dairy sires calculated by New Zealand Animal Evaluation Limited (DairyNZ), with the aim of obtaining progeny of higher genetic merit for farm profit than the average of the herd. However, dairy farmers that use beef-breed sires on specific groups of cows (e.g., the late calving cows or primiparous heifers) do not necessarily acquire sires with genetic records. The Angus and Hereford are breeds widely used in New Zealand farming systems (Beef+Lamb New Zealand Economic Service, 2018), and both breeds have selection programs to improve the genetic merit for beef production. Coleman (2020) demonstrated that sires of Angus and Hereford breeds have a wide variation in performance for gestation length and birthweight, two very important traits for the dairy farmer, and that these traits are well predicted by their EBV. These beef-breed sires also have a range of EBV for growth or live weight later in life (200, 400 and 600 days of age). However, EBV are calculated by BREEDPLAN (Agricultural Business Research Institute) within each specific breed. Little is known about the performance of beef-breed sires for growth traits in a dairy-beef system with beef-cross-dairy cattle. The hypothesis is that growth trajectories differ among sires used to produce beef-cross-dairy cattle that graze on hill country conditions. Sires may change ranking as the progeny grows and some sires will be considered “curve benders”, having light progeny at birth but heavy progeny at slaughter.

The aim of this experiment was to evaluate live weight post-weaning from day 131 to 800, of a selection of Angus and Hereford sires via progeny testing of beef-cross-dairy offspring grown on hill country pasture. Live weight at arrival at the beef farm at day 131, and at 200, 400, 600 and 800 days of age were analysed and compared among sires. Sires were ranked according to their progeny live weight at each time point.

3.3. Materials and Methodology

This experiment was conducted at Limestone Downs, near Port Waikato, New Zealand (37°28'S, 174°45'E) with approval from the Massey University Animal Ethics Committee (15/65 and 18/50).

3.3.1. Animals

Angus-sired and Hereford-sired calves born to dairy-breed cows in spring 2016 (n=584) and 2017 (n=517), were included in the project. Calves were born to 2-year-old (primiparous) and mixed-aged (3+ years old, multiparous) dairy-breed cows, which were predominantly Holstein-Friesian or Holstein-Friesian-cross-Jersey crossbred. Calves were 131.4 days old (SD 17.2, 4 months of age, 131d) and 124.8 kg (SD 16.0) at the start of the experiment. Heifers went to slaughter at a mean age of 823 days of age (range 693-934) targeting an average live weight of 500 kg, whereas steers went to slaughter at a mean age of 887 days of age (range 821-955) targeting an average live weight of 600 kg. From the initial 1101 calves, a total of 915 cattle reached 800 days of age (800d, n=429 born in 2016 and n=486 born in 2017). Of the 186 cattle that did not reach 800d, 111 were processed prior to 800d and 75 were excluded from the project prior to slaughter as detailed in the “Data cleaning” section.

3.3.1.1. Sire selection

Lactating mixed-aged cows were individually inseminated with semen from Angus and Hereford bulls, as described by Coleman (2020). Semen was rotationally allocated to mating days, and randomly allocated to cows in oestrus on each mating day. Cows were bred in spring for 63 days in 2015 (9 October to 11 December) and 54 days in 2016 (10 October to 3 December). Sires were selected for the project based on their EBV so that, within each breed, a spread of birth weight, gestation length and live weight at 600 days of age (600d) was achieved, except

that birth weight EBV was restricted to the lighter 50% of the breed at the time of selection. When similar sires were available, those with superior EBV for intramuscular fat and eye muscle area were selected. The sire team over the 2 seasons included a total of 31 Angus and 34 Hereford bulls (Appendix 1), of which 14 Angus and 11 Hereford sires were used in both seasons.

The 15-month-old replacement dairy heifers were joined with either Angus or Hereford bulls by natural mating. Each breed was used in separate groups of heifers and heifers were randomly allocated to each group, to ensure that similar number of heifers were mated to each breed. Heifers were mated in spring for 69 days in 2015 (1 October to 9 December) with 4 bulls of each breed, and 66 days in 2016 (1 October to 6 December) with 2 bulls of each breed. Sires for the first calving heifers were selected to be in the lightest 15% of breed for birth weight and cost less than NZD 2500 at time of purchase. The sire team over the 2 seasons included a total of 6 Angus and 6 Hereford bulls (Appendix 1), all of which were used for one season only. There was no overlap of sires between those used on heifers and those used on mixed-aged cows.

The EBV of each sire were obtained from the online databases of Angus and Hereford breed associations (Agricultural Business Research Institute) and updated in April 2020 (Appendix 1). The data collected in this experiment was not included for the calculation of the BREEDPLAN EBV for these sires. Mean and range of EBV for weight traits by breed of sire are presented in Table 3.1.

Table 3.1. Estimated breeding values (EBV; mean \pm SD) for live weight at 200, 400, 600 days of age for 37 Angus and 40 Hereford sires (BREEDPLAN, April 2020).

Trait	Angus			Hereford		
	n	EBV	EBV range	n	EBV	EBV range
200d weight (kg)	37	39 \pm 10	18 to 59	40	30 \pm 7	18 to 48
400d weight (kg)	37	75 \pm 14	41 to 110	40	54 \pm 13	31 to 79
600d weight (kg)	37	96 \pm 21	49 to 135	40	73 \pm 19	35 to 114

n: Number of sires used at mating; final number of sires included for data analysis: 30 Angus and 34 Hereford

3.3.1.2. Calving and rearing at the dairy farm, before current experiment

All calves had date of birth, sex and live weight recorded within 24 hours of birth, and were DNA parentage verified as part of a previous experiment described by Coleman (2020). Mean birth date was 3 August 2016 and 5 August 2017 for the calves included in the present experiment, with an overall mean birth weight of 36.4 kg (SD 4.7). Fewer than 1% of calves born to mixed-aged cows and fewer than 7% of calves born to 2-year-old cows (8% in 2016 and 4% in 2017) were assisted at calving (Coleman, 2020). Calves were artificially reared on an allowance

of 4 litres of milk/head/day, and calf meal (CP 17% to 20%) was offered during the transition from milk to pasture. Calves were weaned at a minimum of 85 kg live weight, resulting in a mean weaning live weight of 93.1 kg (SD 7.2) at a mean age of 81.8 days (SD 11.4). Once weaned, calves were moved from the dairy platform to the sheep and beef hill-country platform of the same farm. Male calves were castrated before 4 months of age.

3.3.2. Feed management at the beef farm

At 4 months of age (December of 2016 and 2017) and a mean age of 131.4 days (SD 17.2, 131d), calves were allocated to 6 grazing herds based on live weight (light, intermediate and heavy) and sex (female and male) and balanced for sire so that, where possible, all sires were represented in each grazing herd within year. In total, there were 12 grazing herds (2 years x 2 sexes x 3 liveweight groups), and animals remained in those herds throughout the experiment.

All cattle were grazed on summer-dry hill country pasture on the coastal farm under commercial conditions. Typical pasture species at Limestone Downs farm included ryegrass (*Lolium perenne*), kikuyu (*Pennisetum clandestinum*), ratstail (*Sporobolus africanus*) and some legumes such as white clover (*Trifolium repens*) and birdsfoot trefoil (*Lotus corniculatus*), with varying composition throughout the year (Puha *et al.*, 2008). Pasture mass and quality was measured every 2-3 months from July 2017 to February 2020 (Figure 3.1 and Appendix 2). Pasture mass was measured with a rising plate meter (Filip's folding plate pasture meter, made by Jenquip, Feilding, New Zealand), in 2-4 different areas per paddock with transects of 50 plunks, avoiding wetlands or patches of weeds that animals would likely avoid. Pasture quality was assessed by taking 10-20 grab samples from each paddock (5 from each transect) and processed through Massey University Nutrition laboratory, Palmerston North, New Zealand. Analysis included: residual dry matter (DM), crude protein (CP; AOAC 968.06, Dumas method, N-P = 6.25), neutral detergent fibre (NDF), acid detergent fibre (ADF) and lignin (NDF/ADF/Lignin; Tecator Fibertec, AOAC 2002.04, 973.18), organic matter (OM) and ash (OM/ash; AOAC 930.15/925.10/942.05), Organic Matter Digestibility (OMD; Roughan & Holland 1977) and calculated Metabolizable Energy (ME). Overall, pasture was of medium to low quality, with a mean ME 10.1 MJ/kgDM (range 7.0-12.5), CP 18.8 %DM (range 5.1-31.5), NDF 48.9 %DM (range 32.7-63.3) and OMD 69.3 %DM (range 50.9-84.0). Particularly low quality was found during summer (December to February), with high pasture covers (average 2968 kgDM/ha) but

low energy (9.2 MJME/kgDM), low protein (CP 12.6 %DM) and high fibre content (NDF 55.8 %DM).

Two herds of the 2016-born heifers were supplemented with 1 kg/head/day of calf meal (CP 15%, with main ingredients being barley, maize and wheat), in March 2017 (intermediate for 37 days and heavy for 28 days). Two herds of the 2017-born steers were intermittently supplemented with palm kernel and tapioca at 2 kg/head/day during May-September 2019 (intermediate for 60 days and light for 83 days). No other supplementation was provided.

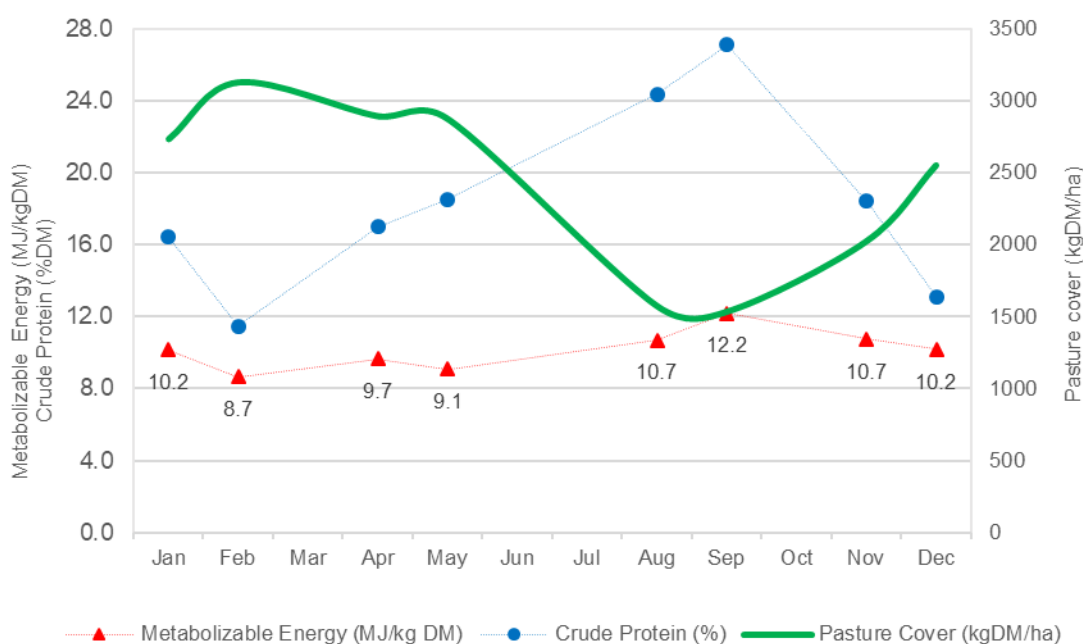


Figure 3.1. Pasture quality as metabolizable energy (MJ/kg DM) and crude protein (%DM), and pasture mass as cover (kg DM/ha) for grazing herds at Limestone Downs, as averages from 2017 to 2020 (details in Appendix 2).

3.3.3. Measurements

3.3.3.1. Live weight

Animals were weighed on the farm through a weigh crate (cattle crush model Cattlemaster Titan, made by Te Pari Products Ltd, Oamaru, New Zealand, with internal dimensions H 203.2 cm x L 300.6 cm x W 75.0 cm; weight scales model XR5000 (version 3.3.1.10433), Tru-Test, Auckland, New Zealand) within 3-hours after yarding from a nearby paddock. Live weights were recorded to the nearest 0.5 kg up to 200 kg live weight, and to the nearest 1.0 kg beyond 200 kg. Live weights were measured at monthly intervals from 4 to 12

months of age, and then at a minimum of 2-monthly intervals until slaughter (between 22.7 and 31.3 months of age).

3.3.4. Statistical Analysis

3.3.4.1. Data cleaning

Animals born to sires with a minimum of 5 progeny across grazing herds were included in analysis (excluded n=9 progeny of 3 sires in 2016 and n=3 progeny of 1 sire in 2017). With heritabilities ranging from 0.12 to 0.60 (refer to Chapter 2), the minimum number of 5 progeny per sire allowed for accuracies greater than 50% for growth traits (medium accuracy, (BREEDPLAN, 2015a)), compared with accuracies of 44% if including sires with 3 progeny (low accuracy). Animals that went missing, were recorded to have ill health, were removed from their grazing herd for more than 2 months or that died were excluded from analysis of traits measured after they first left their herd (n=47 in 2016 and n=28 in 2017). The dataset consisted of 23426 liveweight records from 1101 progeny of 73 sires.

3.3.4.2. Predicting weights at specific age

Short-term fluctuations in live weight were smoothed out by calculating centred moving averages of 3 liveweight records per animal (using previous, current and subsequent liveweight record) using the Expand procedure (SAS 9.4, SAS Institute Inc., Cary, NC, USA). This procedure was found to be the best suited for the data available. Other approaches tested were Legendre orthogonal polynomials and non-linear models with Brody, Gompertz, Logistic and Von Bertalanffy functions.

Predicted live weights for each animal at 131d, 200d, 400d, 600d and 800d were calculated by interpolation of the smoothed liveweight curves. Predicted live weights (33111 records) were fitted to actual live weight data (23426 records) using a regression model. Predicted live weights were used to plot growth curves across age for all progeny, grouping by sex of the animal.

The dataset used for analysis consisted of 5208 predicted weights at 131d, 200d, 400d, 600d and 800d, from 1101 progeny of 73 sires. Average daily live weight gain (in kilograms per day) was calculated as the difference of the predicted live weights divided the number of days between two ages.

3.3.4.3. Contemporary groups

For comparisons among sires, contemporary group was defined as the group of animals in the same grazing herd (n=6) and year (n=2, 2016 and 2017), that were progeny of dams of the same age (n=2, 2-year-old and mixed-aged) and progeny of sires of the same breed (n=2, Angus and Hereford). Sex was already accounted for in the grazing herd effect. These contemporary groups (n=48) had between 4 and 47 animals, with an age range of 11 to 65 days between the youngest and oldest animal in each group. For analysis at 131d, the contemporary groups included year, sex, age of dam and breed of sire ($2 \times 2 \times 2 \times 2 = 16$ groups). One contemporary group (light Angus-sired steers born to 2-year-old cows in 2016) had 2 animals from 1 sire from 600d, and so was excluded from analysis for 600 and 800d.

For comparisons between breeds, contemporary group was defined as the group of animals grazing in the same herd (n=6), year (n=2) and progeny of dams of the same age (n=2). These contemporary groups (n=24) had between 12 and 89 animals, with an age range of 16 to 65 days between the youngest and oldest animal in each group. For analysis at 131d, the contemporary groups included year, sex and age of dam ($2 \times 2 \times 2 = 8$ groups).

3.3.4.4. Statistical models

Linear mixed models (SAS 9.4, SAS Institute Inc., Cary, NC, USA) were used to estimate least-squares means of the progeny groups for live weight at 131d, 200d, 400d, 600d and 800d.

The model to compare sires included the fixed effect of sire within breed, and the random effect of contemporary group (n=48). Cunningham (1965) showed that the estimated breeding value (EBV_i) for sire i (s_i) can be derived from the solution for sires (\hat{s}_i) from this model, using the following regression: $[EBV_i = b_i \hat{s}_i]$, where $[b_i = 2n_i / [n_i + (\hat{\sigma}_e^2 / \hat{\sigma}_s^2)]]$, $\hat{\sigma}_e^2$ and $\hat{\sigma}_s^2$ are the estimates of variance components for residual and sires respectively, and n_i is the number of daughters for sire i. Henderson (1978) showed that the regressed least-squares solutions for sire effects, considering sire as fixed effect, are equivalent to the best linear unbiased predictors (BLUP) for sires from the mixed model equations, considering sire as a random effect, if $\hat{\sigma}_e^2$ and $\hat{\sigma}_s^2$ are known and the pedigree of the sires is not considered. An important assumption to consider sire as a random effect, and to use the BLUP solutions, is that sires are assumed to be a random sample of a population of Angus and Hereford bulls. This assumption could not be met in the current experiment because the sires tested were a non-random sample, given that they were selected on the basis of birth weight EBV (and other EBV). In this study, the effect of

these specific sires was the primary interest, and so sire was fitted as a fixed effect to allow calculation of progeny group performance.

The model to compare breeds included the fixed effects of breed of sire (Angus or Hereford) and sire within breed, and the random effect of contemporary group (n=24). The effect of breed was tested against the residual variation.

Least-squares means of the progeny groups were used to rank sires within the experiment at each time point (individual rank 1 to 73, where 1 is the heaviest animal for weight at that age). An overall mean of the least-squares means of the progeny groups was calculated for each age, with equal weighting per sire regardless of number of progeny. A coefficient of variation (CV) was calculated with the standard deviation and the mean of least-squares means of the progeny groups at each age. The distribution of the least-squares means of the progeny groups were graphed with boxplots. Least-squares means of the progeny groups for live weights at 400d, 600d and 800d were regressed against least-squares means of the progeny groups for live weights at 131d and 200d using random regression weighted by the number of progeny for each sire.

3.4. Results

3.4.1. Live weight of beef-cross-dairy progeny

3.4.1.1. Growth curves of beef-cross-dairy progeny

Growth curves with the predicted live weights calculated with centred moving averages of 3 values are presented in Figure 3.2. These predicted live weights were a close fit to actual live weights ($P < 0.001$, $R^2 = 99.75\%$, Figure 3.3).

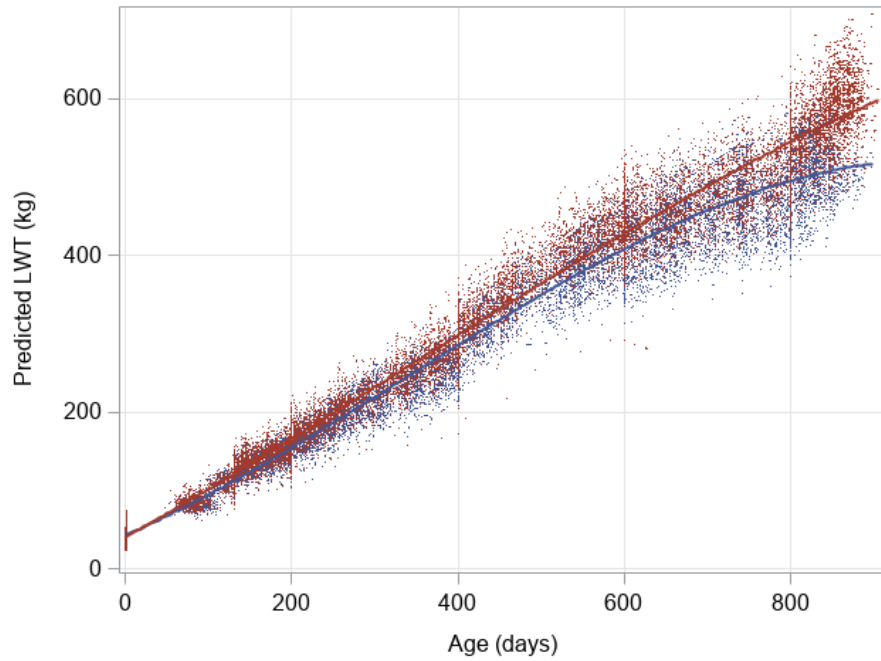


Figure 3.2. Predicted live weight (LWT) across age for beef-cross-dairy cattle (n=1101 with a total of 33111 predicted weights calculated with centred moving average of 3 values), according to sex (• heifers in blue, • steers in red).

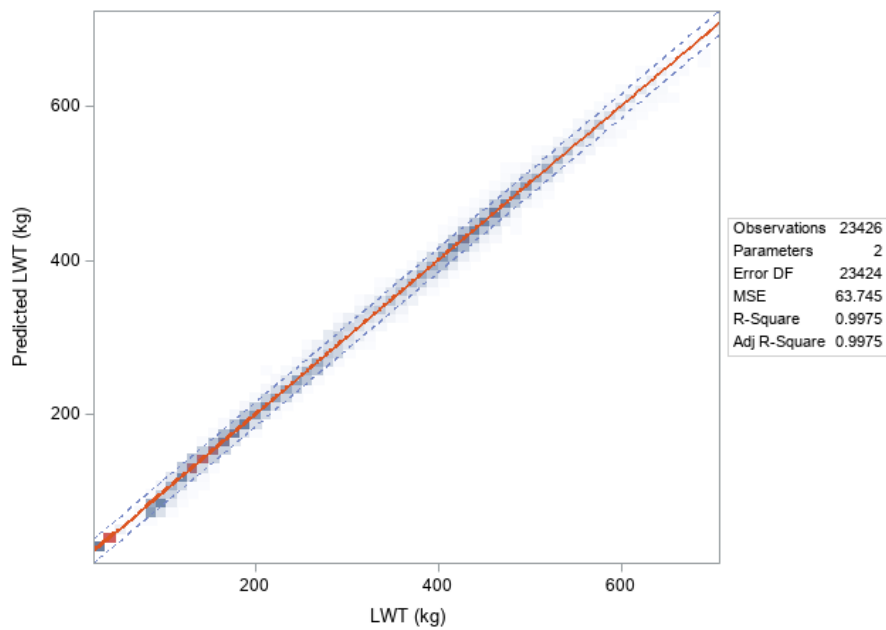


Figure 3.3. Fit regression plot for predicted live weights calculated with centred moving average of 3 values (predicted LWT), to actual live weight (LWT, total of 23426 actual liveweight records) for beef-cross-dairy cattle. Regression equation: Predicted LWT = -0.49 + 1.00 * LWT (P<0.001, R²=99.75%).

3.4.1.2. Live weight by sire

Least-squares means of the progeny groups with individual sire ranking within the experiment for live weights at 131d, 200d, 400d, 600d and 800d are presented in Appendix 3 and their distribution is graphed in Figure 3.4. Sire had effects on live weight of their progeny at all ages ($P < 0.05$). Cattle grew at an overall rate of 0.58 kg/d, with a mean of 0.59 kg/d from 131d to 200d, 0.63 kg/d from 200d to 400d, 0.71 kg/d from 400d to 600d and 0.38 kg/d from 600d to 800d. Differences in live weight between the lightest and heaviest sires was 19 kg at 131d (range 110.6-129.7 kg, inter-quartile range 115.7-121.0 kg, CV 3%) and increased to 90 kg at 800d (range 454.5-544.8 kg, inter-quartile range 492.7-514.8 kg, CV 3%).

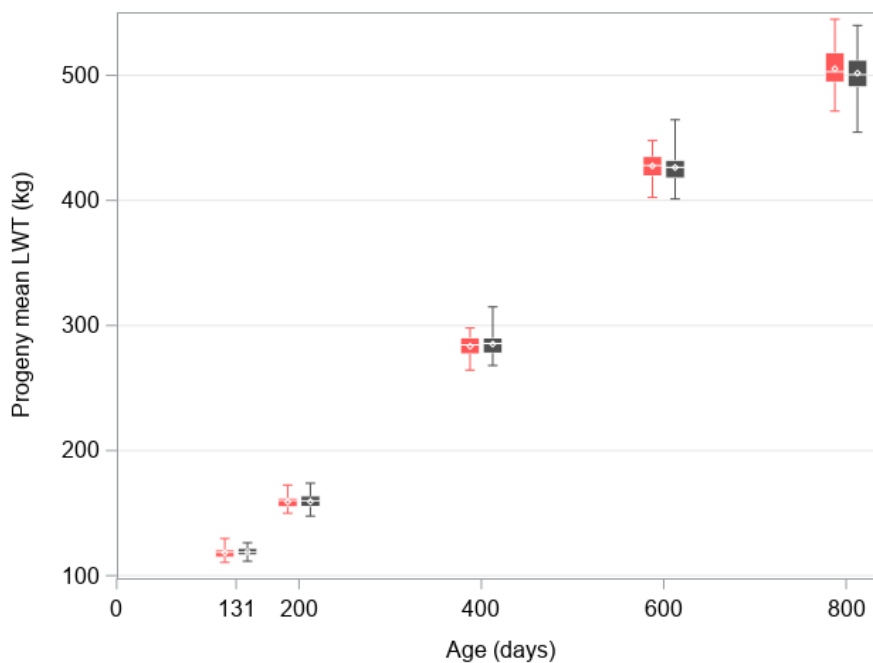


Figure 3.4. Distribution of least-squares means of the progeny groups of sires (Angus, ■ grey; Hereford, ■ red) for live weight (LWT) at 131, 200, 400, 600 and 800 days of age. Each box represents the inter-quartile range (25th to 75th percentiles), with the median value indicated by a line and the mean value indicated by a marker (◊). Whiskers extend to the minimum and maximum values.

3.4.1.3. Live weight by breed of sire

Least-squares means of the progeny groups for live weight at 131d, 200d, 400d, 600d and 800d according to the breed of the sire are presented in Table 3.2. Breed of sire had no effect on live weight at any age from 131d to 800d ($P > 0.05$).

Table 3.2. Least-squares means (\pm SE) of the Angus and Hereford progeny groups for live weight (LWT) at 131, 200, 400, 600 and 800 days of age.

Trait	n	Angus	Hereford	Breed effect P-value
LWT 131d (kg)	1101	119.0 \pm 2.3	118.4 \pm 2.3	0.335
LWT 200d (kg)	1086	159.2 \pm 2.3	158.9 \pm 2.4	0.699
LWT 400d (kg)	1069	285.3 \pm 4.0	283.3 \pm 4.0	0.116
LWT 600d (kg)	1037	426.4 \pm 5.9	427.5 \pm 6.0	0.531
LWT 800d (kg)	915	502.3 \pm 7.7	505.0 \pm 7.8	0.253

3.4.2. Comparison of progeny means for live weight at different ages

Least-squares means of the progeny groups were compared at different ages, and the scatterplots and estimates of the regression coefficients are shown in Figure 3.5 and Table 3.3.

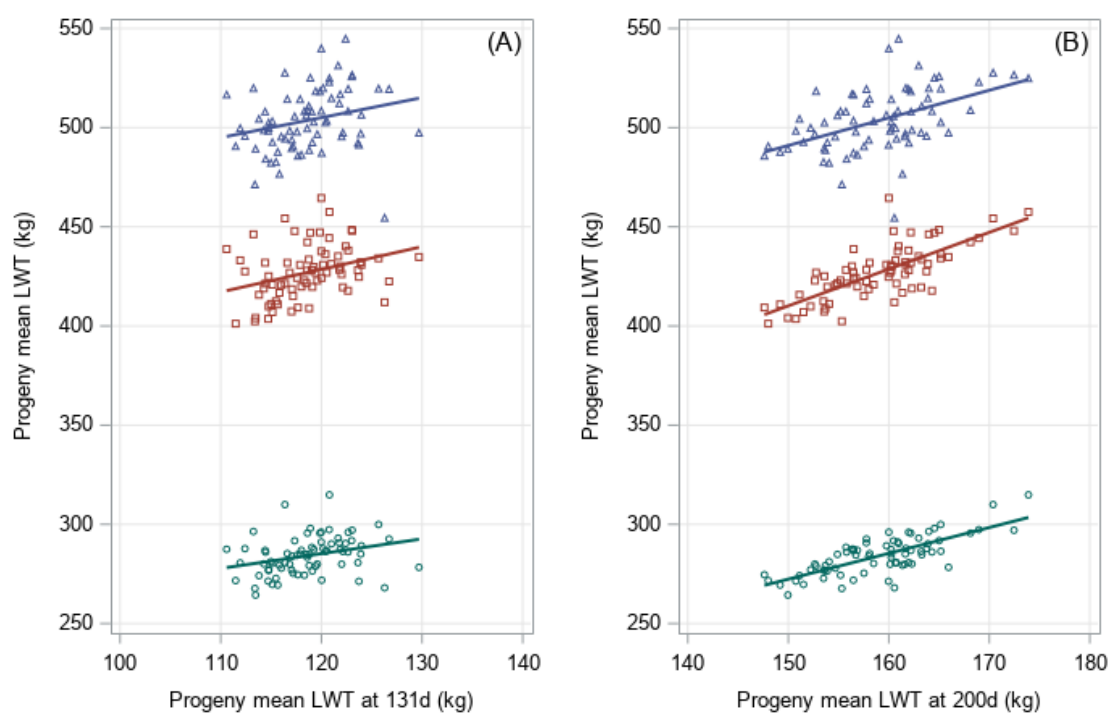


Figure 3.5. Regression of least-squares means of the progeny groups for live weight (LWT) at 400, 600 and 800 days of age, on least-squares means of the progeny groups for live weight at either (A) 131 or (B) 200 days of age. Individual sires are represented by one data point, at 400 (\circ green circles), 600 (\square red squares) and 800 (\triangle blue triangles) days of age. The respective regressions are indicated by solid lines.

Table 3.3. Estimates of regression coefficients (intercept and slope) of least-squares means of the progeny groups for live weight (LWT) at 400, 600 and 800 days of age, on least-squares means of the progeny groups for live weight at 131 or 200 days of age, for 73 sires.

Progeny mean	LWT 131d				LWT 200d			
	Intercept	Slope	P-value	R ²	Intercept	Slope	P-value	R ²
LWT 400d (kg)	235.5±33.2	0.41±0.28	0.149	0.03	81.8±23.4	1.27±0.15	<0.001	0.51
LWT 600d (kg)	332.6±43.7	0.79±0.37	0.035	0.06	144.1±30.2	1.78±0.19	<0.001	0.55
LWT 800d (kg)	461.0±57.2	0.35±0.48	0.466	0.01	296.2±53.2	1.30±0.33	<0.001	0.18

R²: coefficient of determination.

3.5. Discussion

The aim of this experiment was to evaluate the post-weaning growth of Angus and Hereford sires via progeny testing of beef-cross-dairy offspring born to dairy-breed cows and grown on hill country pasture. Live weights at 131d, 200d, 400d, 600d and 800d were analysed, and sires were ranked according to their progeny live weight at each time point.

Beef-cross-dairy cattle in the present experiment entered the beef system at 131d, slightly older and heavier than the typical 84-100 days old and 100 kg live weight weaner calf from dairy breeds purchased by beef finishers (Morris *et al.*, 2016; Muir *et al.*, 2000b). At 200d, progeny mean live weight in this study did not reach the minimum 200d live weight reported by a recent Beef Progeny Test in New Zealand, which ranged from 199.9-212.3 kg for beef cattle (Beef+Lamb New Zealand Genetics, 2019). Cattle in this study were removed from their dams within 24 hours of birth, group fed on an allowance of 4 litres of milk/head/day and weaned at a minimum of 85 kg live weight (Coleman, 2020). This resulted in weaning occurring at a mean age of 82d (range 47-119 days, or approximately 1.5-4 months old), compared to the weaning age reported in the Beef Progeny Test of 200d (or approximately 6-7 months old). Furthermore, young cattle (recently weaned) require pasture with greater than 11.4 MJME/kgDM and covers higher than 2200 kgDM/ha to grow at 1 kg/d (Beef+Lamb New Zealand, 2017b), or alternatively, they need to be supplemented with concentrate feed to increase liveweight gain (Pettigrew *et al.*, 2017). Calves in this study were on low quality pasture during summer season (averages of 9.2 MJME/kgDM, CP 12.6 %DM and NDF 55.8 %DM). Therefore, lower growth rates to 200d of beef-cross-dairy calves compared with beef-breed calves were expected, given the reduced time they were fed milk combined with low quality feed on offer.

Higher growth rates followed after 200d. It has been previously shown that the loss in performance during scarcity of feed (or a dry season) could be proportionately compensated for

in the following wet season when feed become abundant (Afolayan *et al.*, 2007). At 400d, beef-cross-dairy cattle had weights in the range of 264.4-314.9, which were heavier than those reported in the Beef Progeny Test of 261.0-288.2 kg (Beef+Lamb New Zealand Genetics, 2019). At 600d, progeny mean live weights were between 401.2-464.5 kg with a mean of 427.0 kg, which were lower than live weights for sires in the Beef Progeny Test in New Zealand at 18 months of age (approximately 550d) with a mean of 437.4 kg and a range of 416.8-455.2 kg (Beef+Lamb New Zealand Genetics, 2019). Lastly at 800d, least-squares means of the progeny groups were in the range of 454.5-544.8 kg, with a mean of 503.6 kg live weight. Assuming a typical value of around 50% dressing-out (Beef+Lamb New Zealand, 2017b), the 503.6 kg live weight would yield 251.8 kg carcass weight, or considering the lightest and heaviest sire in this study, they would yield 227.3 to 272.4 kg carcass (45 kg difference). These weights are consistent with the range of carcass weights for New Zealand in 2019: an average of 242 kg/head for heifers and 313 kg/head for steers (Ministry for Primary Industries, 2019). This indicates that there are beef-breed sires that can be used on dairy-breed cows to produce cattle of comparable growth to cattle from the beef industry.

Growth trajectories differed among beef-breed sires used to produce beef-cross-dairy cattle on grazing hill country conditions. Differences between the lightest and heaviest sires increased from entry to the beef farm (131d in this study) to finishing (800d). This was expected, as differences in mature size drive different growth rates from early ages. Calves entered the beef system recently weaned and at similar live weight, because weaning occurred at a minimum of 85 kg live weight (Coleman, 2020), which meant that lighter or slower growing calves were fed milk for more days to achieve the target weaning weight, and so may have had an advantage compared with the heavier or faster growing calves. As time progressed, each animal's genetic capability to grow was expressed, and consequently, differences in live weight amongst sires increased. Cattle from smaller-framed sires would have reached physiological maturity at an earlier age and at a lighter weight, while cattle from large-framed sires would have been less mature at comparable age, thus leaner, growing faster and with greater final weights (NSW Department of Primary Industries, 2007; Thonney, 2015).

Cattle growth rate in this study was similar to New Zealand industry values of around 0.6-0.7 kg/d (Beef+Lamb New Zealand, 2017b). However, the rate of daily growth in this study was likely an underestimation of the growth potential of the cattle, because favourable environmental conditions are necessary for the full expression of the individual's genetic capacity (Lawrie, 2006a). The medium to low-quality pasture in the present experiment, with an overall 10.1 MJME/kgDM but dropping to 9.2 MJME/kgDM over the summer months, is likely to

have restricted animal performance to less than a third of the growth rate of cattle fed higher quality grasses (based on the requirements of a 400 kg live weight growing steer grazing on pasture with 10.1 versus 11 MJ/kgDM all year round, assuming that intake was not limited by herbage mass availability). This has been shown across different sheep and beef farms in New Zealand, particularly in regions where summer temperature is high (Litherland *et al.*, 2002). Animals were unable to consume enough feed to meet nutrient requirements of energy and protein for high growth, due to the slow digestion of fibre and low protein content of mature pasture (Burke *et al.*, 2002). Therefore, the 90 kg difference in live weight between the lightest and heaviest sire at 800d could have been greater if pasture or diet with higher quality was offered.

Even though growth of calves was likely restricted prior to 200d, live weight at 200d explained 51-56% of the variation in live weight at 400d and 600d. This is because weights at different ages are highly correlated and related to adult size (Thonney, 2015). Farmers could use the 200d live weight to estimate mature weights and therefore, time and feed required to achieve good finishing condition to send the animal to slaughter. On the contrary, live weight at 131d explained little of the total variation of live weight later in life. It is likely that live weight at 131d reflected the artificial rearing and set weaning weight implemented rather than differences in genetic growth.

Growth trajectories were similar between Angus and Hereford beef breeds used in this experiment, although the experiment was not designed to compare breeds given that the selection of sires was based on average to better than average performance for birth weight and 600d weight. Nevertheless, this result indicates that it is more important to choose the right sire within the beef breed that will fit in the farming system, to produce beef-cross-dairy calves that perform well in a dairy-beef system.

One limitation of this experiment was the scarce information on the dams, and so maternal breed was not accounted for. Dams were predominantly Holstein-Friesian or Holstein-Friesian-cross-Jersey crossbred. A greater proportion of Holstein-Friesian genetics would produce heavier calves with faster growth rates, while a greater proportion of Jersey genetics would produce smaller animals with slower growth rates (Barton *et al.*, 1994; Buchanan *et al.*, 2015; Handcock *et al.*, 2018). Nevertheless, it is unlikely that there would be a bias favouring particular sires in the data from this study because sires were rotationally allocated to mating days and randomly allocated to cows in oestrus on each mating day, and cows had similar live weight, body condition score and milk production regardless of the sire they were bred to (Coleman, 2020; Coleman *et al.*, 2019).

3.6. Conclusions and implications

Live weight of beef-cross-dairy cattle on grazing hill country conditions differed among sires. There are beef-breed sires that could be used on dairy-breed cows to produce cattle of comparable growth to cattle from the beef industry. Even though growth of beef-cross-dairy calves was likely restricted to 200d, live weight at 200d explained a large proportion of live weights at 400d and 600d. Differences between the lightest and heaviest sires increased from entry to the beef farm to finishing, and this difference at 800d may have been greater if pasture of higher quality was available. Thus, the use of genetically superior beef-breed sires has the potential to increase the growth of cattle born in dairy farms for meat production. Further research will evaluate if the difference in growth rates on farm translate into variability in carcass and meat quality from these beef-cross-dairy cattle.

CHAPTER 4

SIRE EFFECTS ON CARCASS AND MEAT QUALITY OF BEEF-CROSS-DAIRY CATTLE

Publications arising from this Chapter:

Martín NP, Schreurs NM, Morris ST, López-Villalobos N, McDade JL, Hickson RE (2021). Sire effects on carcass of beef-cross-dairy cattle: a case study in New Zealand. *Animals* 11: 636-648. DOI:10.3390/ani11030636.

Martín NP, Schreurs NM, Morris ST, López-Villalobos N, McDade JL, Hickson RE (under review) Meat quality of beef-cross-dairy cattle was not affected by sire. *Meat Science*.

4.1. Abstract

Little is known about the performance of beef-breed sires for carcass and meat quality traits of beef-cross-dairy cattle in a pasture-based system. The aim of this experiment was to evaluate carcass and meat quality traits of a selection of Angus and Hereford sires via progeny testing of beef-cross-dairy offspring grown on hill country pasture. Weights, carcass and meat quality traits were analysed from a dataset of 1017 animals and 1002 carcasses from 73 sires, and 326 meat samples from 33 sires. Heifers were slaughtered at 27 months and 520 kg live weight, whilst steers were slaughtered at 29 months and 614 kg live weight. The means of the progeny group means were 567.2 kg for live weight at slaughter, 277.3 kg for carcass weight and 48.9% for dressing-out, 240.3 cm for carcass length, 73.6 cm² for eye muscle area (EMA), 7.4 mm for rib fat depth, 0.91 for marble score, 3.05 for fat colour score, 3.01 for meat colour score and 5.68 for ultimate pH, and for meat traits measured in the laboratory were 64.22 for fat lightness L*, 6.19 for fat redness a*, 13.72 for fat yellowness b*, 37.18 for meat lightness L*, 17.54 for meat redness a*, 7.31 for meat yellowness b*, 4.56 kgF for shear force peak, 0.92% for thaw loss and 25.64% for cook loss. Sire had effects ($P < 0.05$) on all weight and carcass traits, but few meat quality traits (fat yellowness b*, meat redness a* and yellowness b*, cook loss and shear force). There was a 46 kg difference in carcass weight between the heaviest and lightest sire tested. The coefficient of variation (CV) among sires for EMA was 5% and for measured rib fat depth was 19%, with no sire mean below 3 mm and most progeny (97%) grading "P" fat class. There were sire and breed differences for carcass length (Hereford-sired cattle were 2.0 cm longer than Angus-sired cattle, 1% CV), although these were small. For marble scores, there was 35% CV between sires and 16% CV between breeds (Angus-sired cattle had 0.21 higher marble scores than Hereford-sired cattle), even though all progeny had low marble scores between 0 and 3. There was no correlation between progeny group means for marble score, rib fat depth or EMA ($P > 0.05$). Shear force differed among sires and between breeds, in similar trend but reduced magnitude to marble scores. Ultimate pH and fat colour scores were not affected by either sire or breed, and although there were small sire differences in fat yellowness b*, no progeny carcasses were classified as being too yellow. Meat colour scores were not affected by sires and breed differences were small. There were small sire and breed effects for cook loss. Given the great variability among beef-breed sires for weight and carcass traits, with few differences for meat quality, the use of genetically superior beef-breed sires over dairy-breed cows has the potential to increase carcass weights from surplus calves born in the dairy industry, while maintaining adequate fat levels and meat quality to receive optimum payment.

4.2. Introduction

An animal suited for beef production should grow quickly, produce a heavy carcass with an appropriate amount of subcutaneous fat which in turn needs to be of suitable eating quality for a particular market. Carcass weight and fat grade drive the payment to farmers in the New Zealand meat payment schedule (Bown *et al.*, 2016). The current system classifies carcasses according to maturity, sex, fat content and muscling (New Zealand Meat Classification Authority, 2004), where the “P” fat class grade typically achieves the highest price per kilogram of carcass weight and requires 3-10 mm of subcutaneous fat over the eye muscle at the 12th rib. Within each grading class, an increase in carcass weight range (in 20 kg bands) will increase the value of the carcass. Therefore, farmers are rewarded for producing heavy carcasses (Morris, 2013), with high saleable meat yields and within some constraints in terms of quality and appearance.

Meat quality characteristics are those attributes of the beef product that determine the acceptability and value for the consumer (Purchas, 2003). The attributes can include visual aspects that influence purchasing decisions, such as meat and fat colour, as well as the absence of excess water in the packaging. They can also include eating quality characteristics that influence the demand for the product and inform repurchasing decisions, such as tenderness, flavour and juiciness after cooking (Verbeke *et al.*, 2010; Warner *et al.*, 2010). For instance, intramuscular fat in the muscle, commercially known as marbling, is a very important attribute of the meat particularly related to cooking quality (Pethick *et al.*, 2004; Warner *et al.*, 2010). Many characteristics of meat, such as meat colour, water holding capacity and tenderness, are influenced by ultimate pH (Warriss, 1990; Young *et al.*, 2004). Ultimate pH of beef produced in New Zealand under grazing conditions typically ranges between 5.5 and 5.8 (Coleman *et al.*, 2016; Purchas *et al.*, 2007; Purchas *et al.*, 2002; Schreurs *et al.*, 2014). Generally, beef with a pH range of 5.4 to 5.6 has the most desirable properties for appearance and eating quality, while ultimate pH above 6.0 is associated with undesirable changes in those meat quality characteristics (Ertbjerg *et al.*, 2017; Purchas, 1990; Purchas *et al.*, 1993; Warriss, 1990; Young *et al.*, 2004).

The main commercial driver for using beef-bred cattle for beef production in New Zealand appears to be their ability to achieve the minimum of 3 mm of subcutaneous fat and greater saleable meat yield with a higher proportion of meat distributed in the high-value primal cuts, at a lighter carcass weight and with a younger animal compared with dairy-bred cattle (Bown *et al.*, 2016). However, cattle born in the dairy industry contribute to 66% of the New Zealand’s beef production on a per-head basis, and around 44% of calves reared in the beef

industry were born on a dairy farm (Beef+Lamb New Zealand Economic Service, 2019; Davison, 2020; Ministry for Primary Industries, 2020; Morris, 2019; van Selm *et al.*, 2021).

Crossbreeding is an effective tool for increasing performance and profitability of beef production systems through hybrid vigour and complementarity of attributes (Beef+Lamb New Zealand, 2017e; Cunningham *et al.*, 1987). Thus, given that the terminal sire has a considerable direct genetic effect on the progeny, beef-breed sires with improved genetics can be used to generate beef-cross-dairy calves better able to satisfy the requirements of the dairy, grower and finisher farms, through to the meat processor.

Angus and Hereford are breeds widely used in New Zealand farming (Beef+Lamb New Zealand Economic Service, 2018), and both breeds have selection programs to improve genetic merit for beef production. Examples are the Angus Pure Index with selection for animals with higher marbling (Angus New Zealand Inc.) and the Hereford Dairy Terminal Index targeting the production of dairy-beef progeny for beef (BREEDPLAN, 2011). Sire estimated breeding values (EBV) are calculated by BREEDPLAN (Agricultural Business Research Institute, Australia) for each specific breed. Little is known about the performance of beef-breed sires for carcass and meat quality traits of beef-cross-dairy cattle in a pasture-based system. The hypothesis is that carcass and meat quality traits differ among sires used to produce beef-cross-dairy calves finished on pasture, and the selection of appropriate sires will increase the muscle and fat that contribute to saleable meat without disadvantage to meat quality traits.

The aim of this experiment was to evaluate carcass and meat quality traits of a selection of Angus and Hereford sires via progeny testing of beef-cross-dairy offspring grown on hill country pasture. The analysis included live weight pre-slaughter, carcass weight, carcass length, eye muscle area, rib fat depth, marbling score, ultimate pH, meat and fat colour, shear force (tenderness), thaw and cook losses.

4.3. Materials and Methodology

This experiment was conducted at Limestone Downs, near Port Waikato, New Zealand (37°28'S, 174°45'E) with approval from the Massey University Animal Ethics Committee (15/65 and 18/50). Animals were processed commercially through Greenlea Premier Meats Ltd, Hamilton plant (37°48'S 175°15'E), according to standard New Zealand industry practice (Animal and Animal Products Directorate, 2017), with Halal certification.

4.3.1. Animals and management

Angus-sired and Hereford-sired cattle born on Limestone Downs' dairy farm, in spring 2016 (n=531) and 2017 (n=486), were included in the study. Calves were born to 2-year-old (primiparous) and mixed-aged (3+ years old, multiparous) dairy-breed cows, which were predominantly Holstein-Friesian or Holstein-Friesian-cross-Jersey crossbred. For full details, refer to Chapter 3. Briefly, lactating mixed-aged cows were individually inseminated with semen from Angus and Hereford sires, which were selected on the basis of their EBV so that, within each breed, a spread of birth weight, gestation length and live weight at 600 days of age (600d) was achieved, except that birth weight EBV was restricted to the lighter 50% of the breed at the time of selection. When similar sires were available, those with superior EBV for intramuscular fat (IMF) and eye muscle area (EMA) were selected. The 15-month-old heifers were joined with either Angus or Hereford bulls by natural mating, and these sires were selected to be in the lightest 15% of breed for birth weight and cost less than NZD 2500 at time of purchase.

The EBV of each sire were obtained from the online databases of Angus and Hereford breed associations and updated in April 2020 (Appendix 1). The data collected in this experiment was not included for the calculation of the BREEDPLAN EBV for these sires. Mean and range of EBV for carcass and meat quality traits by breed of sire are presented in Table 4.1.

Table 4.1. Estimated breeding values (EBV; mean \pm SD) for carcass and meat quality traits, for 37 Angus and 40 Hereford sires (BREEDPLAN, April 2020).

Trait	Angus			Hereford		
	n	EBV	EBV range	n	EBV	EBV range
Carcass weight (kg)	37	49 \pm 16	18 to 80	40	53 \pm 14	25 to 84
Eye Muscle Area (cm ²)	37	4.6 \pm 2.5	-2.2 to 9.7	40	2.9 \pm 1.9	0.3 to 8.0
Rib Fat (mm)	37	0.9 \pm 1.8	-2.0 to 6.1	40	0.8 \pm 0.9	-1.8 to 2.7
Intramuscular Fat (%)	37	1.3 \pm 1.4	-2.1 to 4.4	40	0.4 \pm 0.7	-1.0 to 2.0

n: Number of sires used at mating; final number of sires included for data analysis: 30 Angus and 34 Hereford

Calves were artificially reared on an allowance of 4 litres of milk/head/day, and weaned at a mean live weight of 93.1 kg (SD 7.2) at a mean age of 81.8 days (SD 11.4). Once weaned, all calves were moved from the dairy platform to the sheep and beef hill country platform of the same farm, where they were managed under commercial conditions. Male calves were castrated before 4 months of age. At 4 months of age (131.4 days old, SD 17.2), calves were allocated to 6 grazing herds based on live weight (light, intermediate and heavy) and sex (female and male) and balanced for sire so that, where possible, all sires were represented in each

grazing herd within year. Therefore, there was a total of 12 grazing herds (2 years x 2 sexes x 3 liveweight groups), and animals remained in those herds throughout the experiment.

4.3.2. Slaughter

Target live weight for slaughter was 500 kg for heifers and 600 kg for steers (Table 4.2). Each grazing herd was slaughtered as a complete group on the same day, when the mean live weight reached the slaughter target weight. While this is not the standard industry practice, this criterion allowed for a comparison amongst sires at similar weight and age. However, it also meant that animals with different mature weight may not be in the ideal condition to go to slaughter.

The target slaughter weight was set so that most carcasses from steers and heifers achieved the “P” fat class grading (3-10 mm of subcutaneous fat). In addition, animals were visually assessed by a livestock buyer to ensure that most cattle reached “P” grade and 2 (or 1) conformation score as a pre-slaughter requirement, which in the industry is known as “finishing” condition. The buyer’s criteria were that cattle had a flat back, a second roll starting to appear on the tail and a full brisket (Greg Clark, Livestock Buyer for Greenlea Premier Meats Ltd, personal communication). Animals were processed commercially through Greenlea Premier Meats Ltd, according to standard New Zealand industry practice (Animal and Animal Products Directorate, 2017).

Table 4.2. Slaughter date, number of cattle, mean age (\pm SD), unadjusted mean live and carcass weights (\pm SD), and number of animals according to carcass fat grade for each grazing herd of beef-cross-dairy cattle processed in the experiment (n=1017).

Animal category	Grazing Herd	n	Slaughter date	Age (days)	Live [‡] weight (kg)	Carcass weight (kg)	Grade [‡]	
							P2	L2
Heifer	2016 Heavy	86	30/07/2018	739 \pm 10	494 \pm 34	250 \pm 20	86	0
Heifer	2016 Intermediate	86	24/10/2018	813 \pm 16	527 \pm 36	257 \pm 19	82	4
Heifer	2016 Light	85	18/11/2018	823 \pm 16	503 \pm 32	250 \pm 18	84	1
Heifer	2017 Heavy	74	31/10/2019	827 \pm 13	537 \pm 34	258 \pm 17	74	0
Heifer	2017 Intermediate	82	27/11/2019	841 \pm 14	523 \pm 33	253 \pm 18	82	0
Heifer	2017 Light	82	28/01/2020	896 \pm 16	541 \pm 35	261 \pm 18	81	1
Steer	2016 Heavy	101	27/11/2018	858 \pm 10	589 \pm 40	287 \pm 22	85	16
Steer	2016 Intermediate	87	15/01/2019	894 \pm 16	623 \pm 38	306 \pm 21	86	1
Steer	2016 Light	86	20/01/2019	883 \pm 17	616 \pm 42	300 \pm 21	85	1
Steer	2017 Heavy	82	10/12/2019	867 \pm 9	609 \pm 37	305 \pm 23	81	1
Steer	2017 Intermediate	87	4/02/2020	913 \pm 14	642 \pm 37	317 \pm 20	86	1
Steer	2017 Light	79	19/02/2020	917 \pm 16	610 \pm 34	286 \pm 18	77	2

[‡]Live weight: measured on-farm (prior transport). [‡]Grade: Fat cover class P (light to medium, 3-10 mm) or L (light, under 3 mm), with muscle conformation score 2.

4.3.3. Measurements

4.3.3.1. Weights

On the day of slaughter, live weight was measured on the farm through a weigh crate (cattle crush model Cattlemaster Titan, made by Te Pari Products Ltd, Oamaru, New Zealand; weigh scales model XR5000, Tru-Test, Auckland, New Zealand), within one hour after yarding and prior to transport. The bodies were dressed to commercial specifications and carcasses were halved through the midline. Hot carcass weight (kg) was obtained as the sum of the weight of each carcass half recorded prior to the carcasses going into the chiller. Dressing-out percentage was calculated as the hot carcass weight divided by the live weight measured on farm (x100).

4.3.3.2. In-chiller assessments for carcass and meat quality traits

Carcasses were chilled ($4\pm 1^{\circ}\text{C}$) overnight and the following morning (approximately 8 to 15 hours after slaughter), the length of one side of the carcass 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.*, 2007). The other side of the carcass was cut between the 12th and 13th rib to expose the ribeye muscle (*M. longissimus thoracis*) for in-chiller assessment of marbling score, meat and fat colour scores, rib fat thickness and EMA. The EMA (cm^2) was traced onto waterproof paper and subsequently measured using a Planimeter (Placom KP-90N, Tokyo, Japan). The rib fat thickness (mm) was measured with a ruler as the subcutaneous fat depth at the 13th rib over the deepest part of the eye muscle.

Carcasses were assessed for marbling, meat and fat colour by an assessor qualified to AUS-MEAT standards (AUS-MEAT Limited, 2018). Marbling and meat colour were scored against the AUS-MEAT / MSA reference standards, after the eye muscle had been exposed to air for 30 minutes. Possible marbling scores ranged from 0 (nil) to 9 (abundant) and assessed the amount of marbling present in the eye muscle (Figure 2.6 in Chapter 2). Meat colour scores ranged from 1 (light) to 7 (dark) and assessed the colour of the lean muscle (Figure 2.10 in Chapter 2). Fat colour was assessed on the intermuscular fat lateral to the ribeye muscle and adjacent to the *M. iliocostalis*, scored against the AUS-MEAT fat colour reference (Figure 2.11 in Chapter 2), with possible scores ranging from 0 (white) to 9 (yellow).

For the 2017 cohort only, ultimate pH was measured by pH spear (Eutech Instruments, Singapore) on the chilled carcass, at three points from medial to lateral across the *M. longissimus thoracis* (ribeye muscle) at the quartering site. The mean of the three measurements was used

for analysis. For the 2016 cohort, pH was measured on meat samples at the laboratory (refer to following section).

4.3.3.3. Laboratory meat quality traits from meat samples

Meat samples from a subset of animals born in 2016 were collected for meat quality. The number of samples was restricted to a subset due to budget and time constraints to do all the analyses, but it was enough to identify variability in meat quality amongst sires.

The animals selected were from all sires used on mixed-aged cows via artificial breeding, that had at least 1 progeny in each of the 6 grazing herds. If a selected sire had 3 or fewer progeny in a given grazing herd, all progeny in that herd were selected; where there were more progeny in a grazing herd, a maximum of 3 progeny were randomly selected at the time of weighing prior to slaughter, taking the total maximum of 18 progeny per sire across the 6 grazing herds.

For the selected animals, carcasses were identified and after chilling of the carcasses for 12 hours, a sample of 1 to 2 kg of the striploin (*M. longissimus lumborum*, adjacent to *M. longissimus thoracis*) from the cranial end was obtained. Meat samples were vacuum packed and chill-aged at Greenlea Premier Meats for 21 days at $0\pm 1^{\circ}\text{C}$, then transported chilled to Massey University and stored frozen at -20°C . At the meat laboratory, samples were defrosted over 24-36 hours at $0\pm 1^{\circ}\text{C}$. To minimise freezing time effects on meat quality assessment, a set time of 3-5 weeks after slaughter was used as the testing period for all samples.

To get an indication of thaw loss, the thawed striploin in its packaging was dried of external moisture and weighed. The sample was then taken out of its vacuum pack, pat-dried with paper towels and weighed. Likewise, the packaging was dried with paper towels and weighed (Figure 4.1). Thaw loss was calculated as:

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

From the cranial end, the first slice of ~2 cm width was cut to straighten the samples for the preparation of steaks and to remove the outer portion so that tests were performed only on internal subsamples. The striploin was then portioned into three steaks of 2.5 cm width, cut transverse across the sample (steaks 1, 2 and 3, Figure 4.1). The remaining caudal end of the striploin was discarded.

The pH was measured on steak 1 by pH spear (Eutech Instruments, Singapore) at three points from medial to lateral across a transverse internal cut surface of the striploin. The mean

of the three measurements was used for analysis. The pH spear was calibrated using standard buffers at pH 4.01, 7.0 and 10.01, at 10°C.

After 30-min exposure to air (steak 1), the muscle and fat were measured for L* (lightness), a* (redness) and b* (yellowness) values using a calibrated Minolta CR-200 chromameter (Illuminant D65, 8 mm diameter aperture, 0° viewing angle; CR-200; Konica Minolta, Mahwah, NJ, USA).

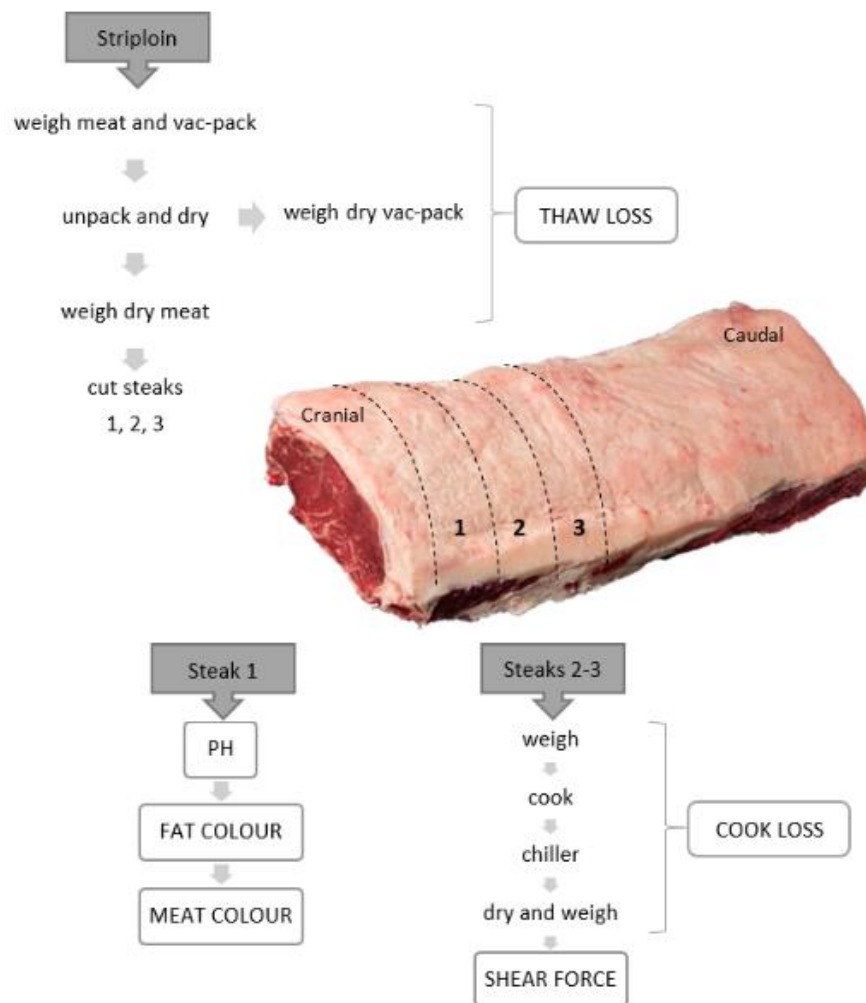


Figure 4.1. Division of *M. Longissimus lumborum* (striploin) meat sample and order of analysis for meat quality.

Steaks 2 and 3 were weighed, placed into plastic bags and cooked by immersion in a water bath (70°C for 90 minutes). After cooking, samples were rested at room temperature and then chilled for 4 hours. After chilling, each steak was blotted dry with paper towels and reweighed to determine the cooking loss as:

$$\text{Cook loss (\%)} = \frac{\text{pre cooking weight} - \text{post cooking weight}}{\text{pre cooking weight}} \times 100$$

The cooked steaks (steaks 2 and 3) were used to assess shear force by the peak force required to shear 13 mm diameter cylindrical cores. The cores were produced by cutting with a corer along the grain of the muscle so that shears were made perpendicular to the direction of the muscle fibres (Purchas *et al.*, 1993). Each core was sheared once using a TMS-Pilot Texture Analyzer (Food Technology Corporation, USA) equipped with a V-shaped blade and a blade speed of 20 mm/s. The peak force required to shear through the core was recorded by TL-Touch texture software (version 1.18-408) and expressed in kilograms of force (kgF). The mean peak force to shear 6 cores for each meat sample was used for analysis.

4.3.4. Statistical Analysis

4.3.4.1. Data cleaning

Animals born to sires with a minimum of 5 progeny across grazing herds were included in the analysis (n=1101 animals from 73 sires), following the same criteria explained in Chapter 3. Animals that went missing, were recorded with ill health, or were removed from their grazing herd for more than 2 months were excluded from analysis of slaughter, carcass and meat quality traits (n=53 in 2016 and n=31 in 2017). Any carcass recorded with a defect was excluded from analysis of carcass traits due to potential trimming of the carcass prior to weighing (n=12 in 2016 and n=3 in 2017). In-chiller assessments of marbling, meat and fat colour score for the heavy steers born in 2016 were not recorded (n=101). The final dataset consisted of 1017 animals and 1002 carcasses from 73 sires, and 326 meat samples from 33 sires.

4.3.4.2. Contemporary groups

For comparisons among sires, contemporary group was defined as the group of animals grazing in the same herd (n=12), that were progeny of dams of the same age (n=2, 2-year-old and mixed-aged) and progeny of sires of the same breed (n=2, Angus and Hereford). These contemporary groups (n=47) had between 6 and 43 animals, with an age range of 11 to 65 days between the youngest and oldest animal in each group. One contemporary group (light Angus-sired steers born to 2-year-old cows in 2016) had 2 animals from 1 sire, and so was excluded from analysis.

For comparisons between breeds, contemporary group was defined as the group of animals grazing in the same herd (n=12) and progeny of dams of the same age (n=2). These

contemporary groups (n=24) had between 9 and 83 animals, with an age range of 16 to 65 days between the youngest and oldest animal in each group.

4.3.4.3. Statistical models

Linear mixed models (SAS 9.4, SAS Institute Inc., Cary, NC, USA) were used to estimate the least-squares means of the progeny groups for live weight, carcass and meat quality traits. The model to compare sires included the fixed effects of sire within breed, and the random effect of contemporary group (n=47), following the same criteria explained in Chapter 3. The model to compare breeds included the fixed effects of breed of sire (Angus or Hereford) and sire within breed, and the random effect of contemporary group (n=24). The effect of breed was tested against the residual variation.

To adjust for differences in age between progeny, the age deviation within contemporary group was fitted as a covariate for weight traits (live weight, carcass weight and dressing-out). Carcass weight was fitted as a covariate for all carcass traits (carcass length, EMA, rib fat depth and marble score), to allow comparison of carcass composition at a uniform carcass weight. Ultimate pH was fitted as a covariate for all meat quality attributes known to be affected by pH (shear force, meat lightness L*, redness a* and yellowness b*, thaw and cook losses).

Least-squares means of the progeny groups were used to rank sires within the experiment for live weight pre-slaughter, carcass weight, dressing-out, carcass length, EMA, rib fat depth, marble score, fat colour score and meat colour score (individual rank 1 to 73, where 1 is the best ranked animal for that trait). Sires with progeny records for ultimate pH were also ranked (from 1 to 66, because 7 sires did not have pH records as they were used only in year 1 and were not selected for meat sampling).

A mean and standard deviation of least-squares means of the progeny groups were calculated for each trait, with equal weighting per sire regardless of number of progeny. A coefficient of variation (CV) was calculated with the standard deviation and the mean of least-squares means of the progeny groups for each trait. The distribution of the least-squares means of the progeny groups were graphed with boxplots. Further, sires were grouped post-hoc for carcass weight, EMA and marble score according to 1 standard deviation from the mean for each trait, and rib fat depth according to fat grade class (less than 3 mm, between 3 and 10 mm, and over 10 mm), to explore how sires were distributed within each trait. A Chi-square test was used to determine if the proportion of Angus and Hereford sires within each post-hoc groups were different from 50:50. A correlation analysis was performed between least-squares means of the

progeny groups for EMA, rib fat depth and marble score across all contemporary groups, using random regressions (weighted by the number of progeny for each sire) and graphed with scatter plots, grouping by carcass weight.

4.4. Results

4.4.1. Weight and carcass traits of beef-cross-dairy progeny

Heifers (n=495) were slaughtered at a mean age of 27 months (SD 2) and 520 kg live weight (SD 38), whilst steers (n=522) were slaughtered at a mean age of 29 months (SD 1) and 614 kg live weight (SD 42). Most carcasses (97%) were graded as “P” fat class (3-10 mm of subcutaneous fat) and only 28 carcasses (3%) were graded “L” (less than 3 mm of fat). All carcasses received a conformation score of 2 and had low marble scores between 0 and 3 (from a total possible range 0-9).

4.4.1.1. Weight traits by sire

Least-squares means of the progeny groups for weights at slaughter are presented in Appendix 4 and the distribution of these traits are presented in Figure 4.2 Individual sire ranking for live weight pre-slaughter, carcass weight and dressing-out percentage are included in the table in the appendix.

Least-squares means of the progeny groups for age at slaughter had 103 days range (804-907 days of age) and was different among sires ($P < 0.05$). All weight traits differed among sires ($P < 0.05$) after adjustment for the age deviation of each animal within its contemporary group (covariate effect $P > 0.05$). As shown in Figure 4.2, live weight pre-slaughter ranged from 534 to 617 kg (total spread of 82 kg, 3% CV, $P < 0.05$), carcass weight from 258 to 304 kg (46 kg, 3% CV, $P < 0.05$) and dressing-out from 47.4 to 50.3% (1% CV, $P < 0.05$). Low CV in weight traits reflected that cattle went to slaughter on a set target weight, with some variation within each grazing herd.

The highest ranked sire for carcass weight was A30 (Angus, 304 kg carcass, 617 kg live weight), followed by H34 (Hereford, 296 kg carcass, 599 kg live weight), A14 (Angus, 295 kg carcass, 603 kg live weight) and A36 (Angus, used on heifers, 293 kg carcass, 598 kg live weight). The sires with dressing-out greater than 50% were A17 (Angus, 50.29%, 284 kg carcass, 564 kg

live weight), A32 (Angus, used on heifers, 50.16%, 283 kg carcass, 566 kg live weight) and H31 (Hereford, 50.11%, 284 kg carcass, 568 kg live weight).

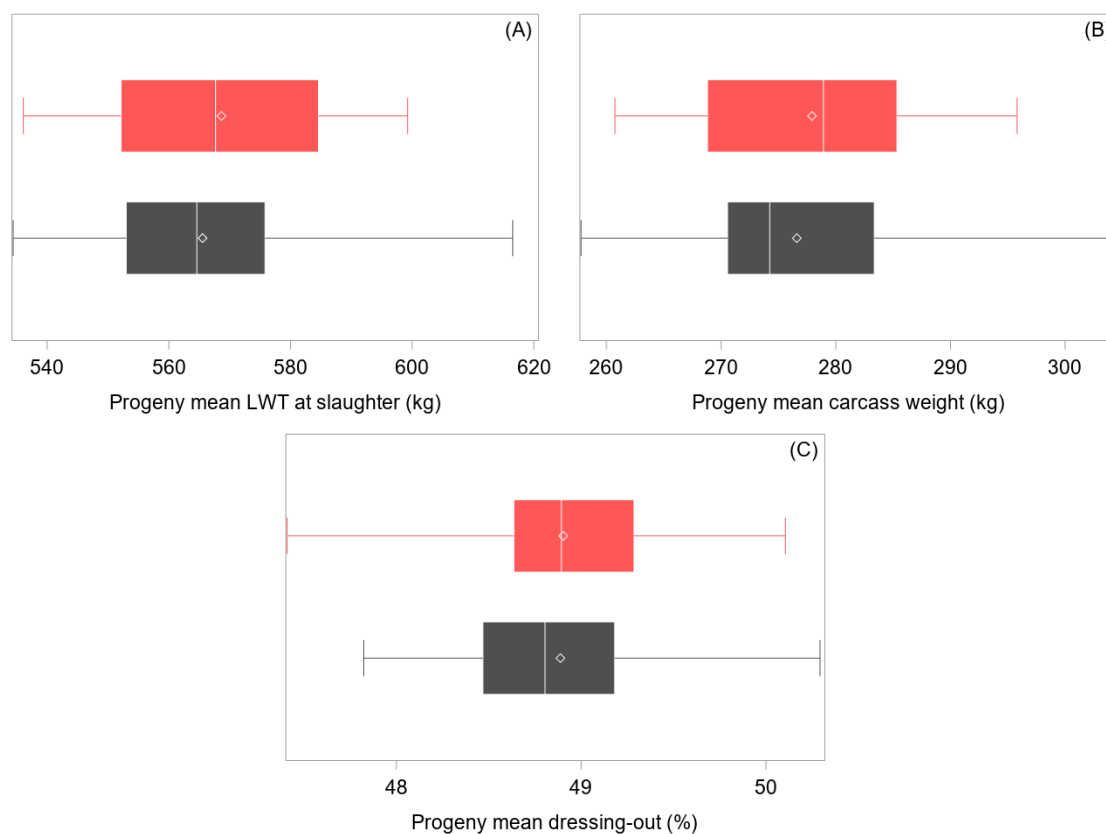


Figure 4.2. Distribution of least-squares means of the progeny groups of sires (Angus, ■ grey; Hereford, ■ red) for: (A) live weight (LWT) at slaughter, (B) carcass weight and (C) dressing-out percentage. Weight traits were adjusted by age deviation of the progeny within contemporary group. Each box represents the inter-quartile range (25th to 75th percentiles), with the median value indicated by a line and the mean value indicated by a marker (◊). Whiskers extend to the minimum and maximum values.

4.4.1.2. Carcass traits by sire

Least-squares means of the progeny groups for carcass traits are presented in Appendix 5 and the distribution of these traits are presented in Figure 4.3. Individual sire ranking for carcass length, EMA, rib fat depth and marble score are included in the table in the appendix.

All carcass traits differed among sires ($P < 0.05$) after adjustment for carcass weight (covariate effect $P < 0.05$ for carcass length, EMA and rib fat depth, but $P > 0.05$ for marble scores). As shown in Figure 4.3, carcass length ranged from 234.5 to 245.2 cm (total spread of 10.7 cm, 1% CV, $P < 0.05$), EMA from 65.5 to 82.9 cm² (17.5 cm², 5% CV, $P < 0.05$), rib fat depth from 4.3 to 11.3 mm (6.9 mm, 19% CV, $P < 0.05$) and marble scores from 0.21 to 1.58 (1.37 scores, 35% CV, $P < 0.05$).

The highest ranked sires for carcass length were H27 (Hereford, 245 cm), H30 (Hereford, 245 cm), H40 (Hereford, used on heifers, 244 cm) and A14 (Angus, 244 cm). The highest ranked sires for EMA were H26 (Hereford, 82.9 cm²), A32 (Angus, used on heifers, 80.5 cm²), A33 (Angus, used on heifers, 79.3 cm²) and H8 (Hereford, 79.2 cm²). The highest ranked sires for rib fat depth were H23 (Hereford, 11.3 mm), H2 (Hereford, 10.3 mm), H34 (Hereford, 9.5 mm) and H20 (Hereford, 9.8 mm). No sires had least-squares means below the 3 mm rib fat depth. The highest ranked sires for marbling scores were H24 (Hereford, 1.58), A1 (Angus, 1.54) and A28 (Angus, 1.53).

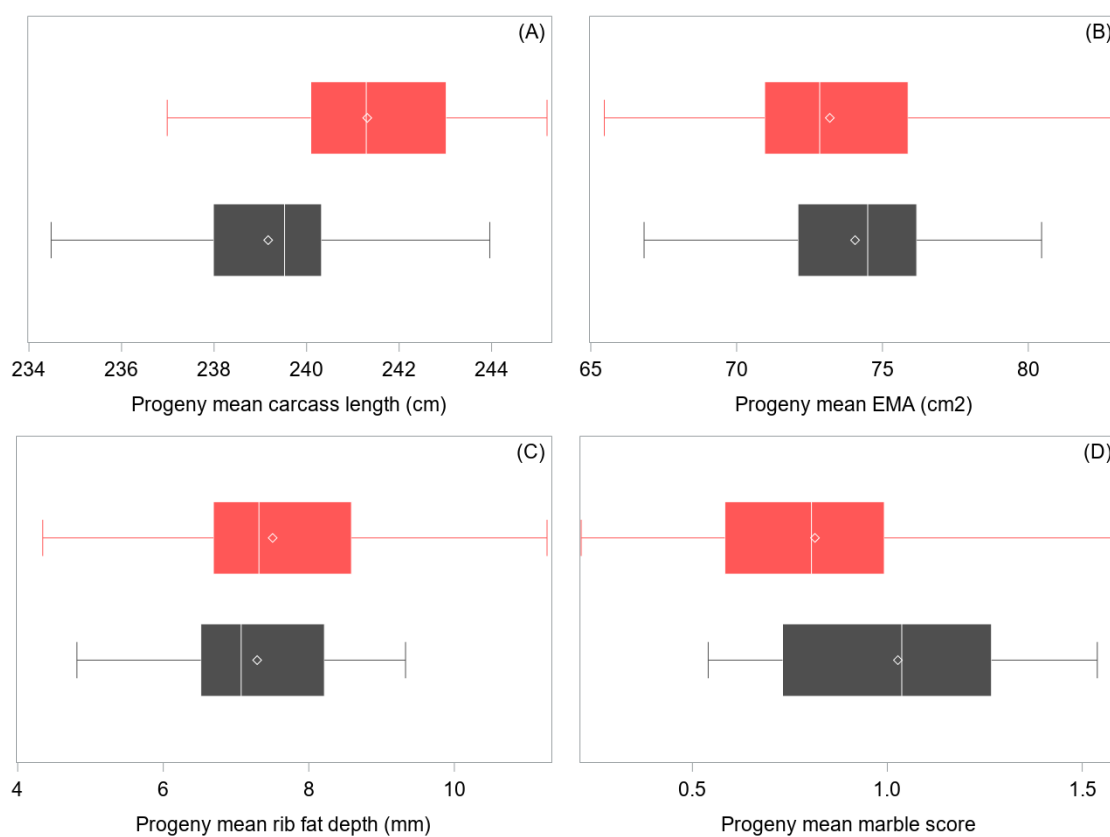


Figure 4.3. Distribution of least-squares means of the progeny groups of sires (Angus, ■ grey; Hereford, ■ red) for: (A) carcass length, (B) eye muscle area (EMA), (C) rib fat depth and (D) marble scores. Carcass traits were adjusted by carcass weight. Each box represents the inter-quartile range (25th to 75th percentiles), with the median value indicated by a line and the mean value indicated by a marker (◊). Whiskers extend to the minimum and maximum values.

4.4.1.3. Weight and carcass traits by breed of sire

Least-squares means of the Angus and Hereford progeny groups for slaughter weights and carcass traits are presented in Table 4.3. There were no differences in age, live weight,

carcass weight, dressing-out, EMA or rib fat depth between breeds of sire ($P>0.05$). Carcasses of Hereford-sired cattle were 2.0 cm longer (1% CV, $P<0.05$) than Angus-sired cattle, and this is shown in the distribution of progeny mean for carcass length by sire (Figure 4.3 A). Carcasses from Angus-sired cattle had marble scores that were 0.21 greater (on a scale of 0-9, 16% CV, $P<0.05$) compared with Hereford-sired cattle, also illustrated in the distribution of progeny mean for marble score by sire (Figure 4.3 D).

The age deviation of each animal within contemporary group had no effects on any of the weight attributes (covariate effect $P>0.05$). Carcass weight had a significant positive effect on carcass length, EMA and rib fat depth (covariate effect $P<0.05$), indicating that these traits increased with heavier carcasses. Carcass weight had no effect on marble scores (covariate effect $P>0.05$).

Table 4.3. Least-squares means (\pm SE) of the Angus and Hereford progeny groups for weight traits at slaughter (age, live weight, carcass weight and dressing-out) and carcass traits (carcass length, eye muscle area (EMA), rib fat depth and marble score). Weight traits were adjusted by age deviation of the progeny within contemporary group and carcass traits were adjusted by carcass weight.

Trait	n	Angus	Hereford	Breed effect P-value	Age effect P-value	Carcass effect P-value
Age (days)	1017	854.1 \pm 2.3	855.2 \pm 2.3	0.733	-	-
Live weight (kg)	1017	566.7 \pm 13.1	568.6 \pm 13.3	0.407	0.656	-
Carcass weight (kg)	1002	276.9 \pm 6.5	277.9 \pm 6.6	0.423	0.876	-
Dressing-out (%)	1002	48.9 \pm 0.2	48.9 \pm 0.3	0.548	0.081	-
Carcass length (cm)	1001	239.4 \pm 1.7	241.3 \pm 1.8	<0.001	-	<0.001
EMA (cm ²)	997	74.1 \pm 0.7	73.2 \pm 0.8	0.094	-	<0.001
Rib fat depth (mm)	996	7.3 \pm 0.3	7.5 \pm 0.3	0.300	-	0.006
Marble score	904	1.03 \pm 0.07	0.81 \pm 0.07	<0.001	-	0.072

4.4.2. Meat quality traits of beef-cross-dairy progeny

From the in-chiller assessments, carcasses had meat colour scores between 1 and 6 (from a total possible range 1-7) with 87% of carcasses scoring 3 or less. Fat colour scores ranged from 1 to 5 (total possible range 0-9), with 78% of carcasses scoring 3 or less. Mean ultimate pH measured in the chiller was 5.62 (SD 0.14), with 1.9% (n=9/486) of carcasses with pH over 6.0. From the 2016 cohort, a total of 326 meat samples were obtained for laboratory analysis. Mean ultimate pH was 5.75 (SD 0.16), with 3.4% (n=11/326) of samples with pH over 6.0. For shear force, 24.9% (n=78) of samples had values lower than 4.1 kgF, 75.5% (n=246) had values between 4.1 and 7 kgF, and 2 samples had values over 7 kgF.

4.4.2.1. Meat quality traits by sire

Least-squares means of the progeny groups for meat quality traits measured on the carcass are presented in Appendix 6 and those measured on meat samples in the laboratory in Appendix 7. The distribution of these traits are presented in Figure 4.4 and Figure 4.5. Individual sire ranking for fat and meat colour scores and ultimate pH are included in the table in the appendix.

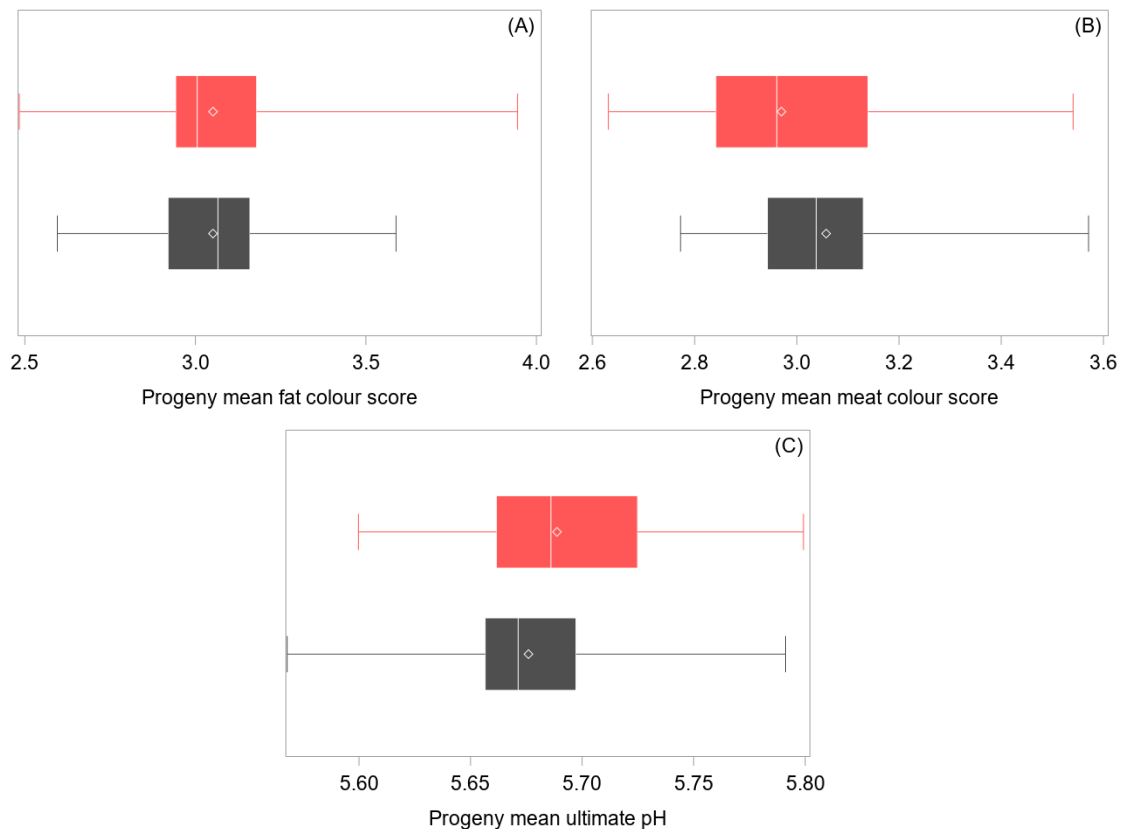


Figure 4.4. Distribution of least-squares means of the progeny groups of sires (Angus, ■ grey; Hereford, ■ red) for: (A) fat colour score, (B) meat colour score and (C) ultimate pH. Each box represents the inter-quartile range (25th to 75th percentiles), with the median value indicated by a line and the mean value indicated by a marker (◊). Whiskers extend to the minimum and maximum values.

Fat colour scores (Figure 4.4 A, range 2.48-3.94), fat lightness L* (range 61.21-66.97) and redness a* (range 4.78-8.78) were similar among sires ($P>0.05$). Fat yellowness b* differed among sires (range 12.03-16.15, 7% CV, $P<0.05$), with 1 Hereford (H5) and 1 Angus (A16) sires having reflectance values over 16.

Meat colour scores were similar among sires (range 2.63-3.57, $P>0.05$). For the meat colour measured with the chromameter in the laboratory, sires differed in redness a* (range 16.15-19.30, 4% CV, $P<0.05$) and yellowness b* (range 6.49-8.31, 6% CV, $P<0.05$), but were

similar in lightness L^* (range 35.60-39.45, $P>0.05$), after adjustment for ultimate pH (covariate effect $P<0.05$).

Ultimate pH was similar among sires, with least-squares means of the progeny groups ranging from 5.57 to 5.80 ($P>0.05$, Figure 4.4 C). Ultimate pH measured on meat samples was also similar among the 33 sires included in the subset ($P>0.05$, data not shown) and ranged from 5.67 to 5.91 (1% CV, Figure 4.5 A).

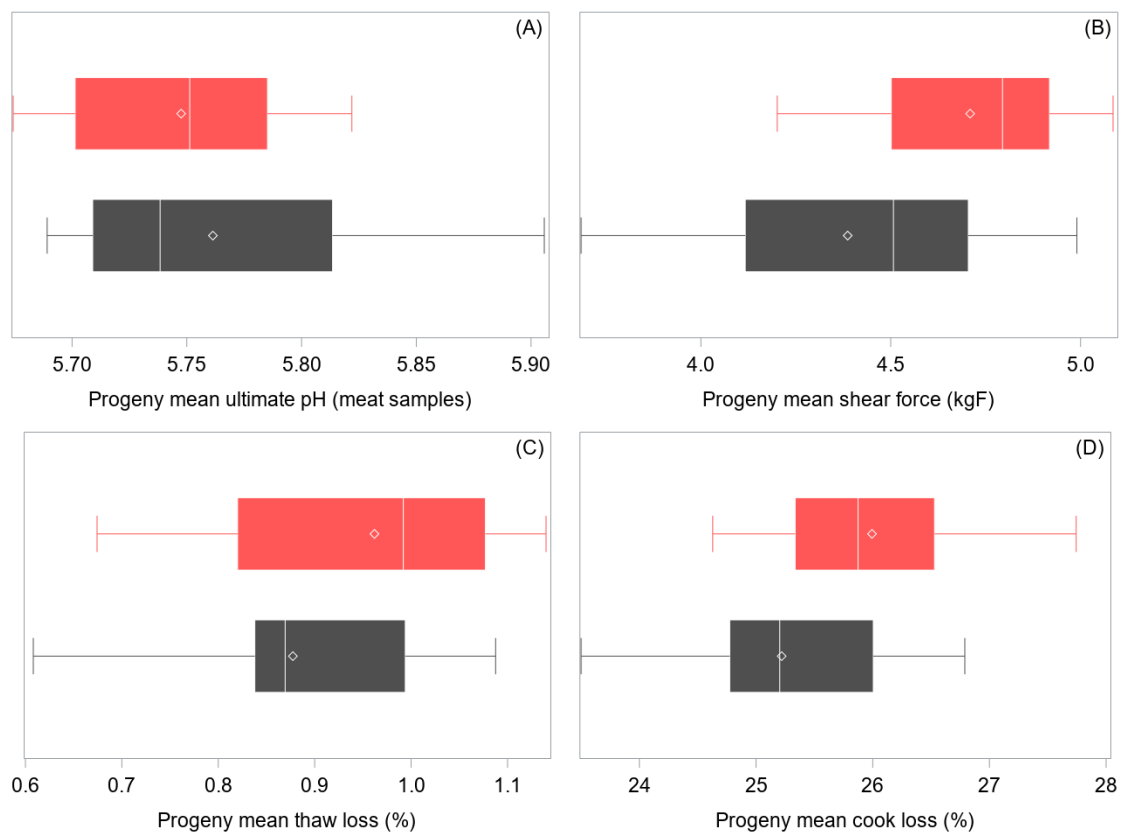


Figure 4.5. Distribution of least-squares means of the progeny groups of sires (Angus, ■ grey; Hereford, ■ red) for meat quality traits measured on meat samples in the laboratory: (A) ultimate pH, (B) shear force, (C) thaw loss and (D) cook loss. Shear force, thaw and cook loss were adjusted by ultimate pH. Each box represents the inter-quartile range (25th to 75th percentiles), with the median value indicated by a line and the mean value indicated by a marker (◇). Whiskers extend to the minimum and maximum values.

Sire had no effect ($P>0.05$) on thaw loss (range 0.61-1.14%), whilst cook loss and shear force differed among sires ($P<0.05$) after adjustment for ultimate pH (covariate effect $P<0.05$). As shown in Figure 4.5 B and D, shear force ranged from 3.68 to 5.09 kgF (1.40 kgF difference, 8% CV, $P<0.05$) and cooking loss from 23.50 to 27.74% (4% CV, $P<0.05$).

The sires with lowest shear force (most tender) were A23 (Angus, 3.68 kgF), A16 (Angus, 3.92 kgF) and A13 (Angus, 3.96 kgF). The sires with lowest cooking loss were A16 (Angus, 23.50%), A11 (Angus, 24.13%) and A1 (Angus, 24.34%).

4.4.2.2. Meat quality traits by breed of sire

Least-squares means of the Angus and Hereford progeny groups for meat quality traits are presented in Table 4.4. There were no differences in ultimate pH, fat colour (either measured in the chiller as a score or in the laboratory with a chromameter) or thaw loss between breeds of sire ($P>0.05$). Carcasses from Angus-sired cattle had meat colour scores that were 0.09 greater (on a scale of 1-7, 2% CV, $P<0.05$) with 0.57 higher meat redness a^* (2% CV, $P<0.05$) and 0.43 higher meat yellowness b^* (4% CV, $P<0.05$) compared with Hereford-sired cattle, and this is shown in the distribution of progeny mean for meat colour scores by sire (Figure 4.4 B). Meat from Angus-sired cattle had 0.32 kgF lower shear force (5% CV, $P<0.05$) and 0.77% lower cook loss values (2% CV, $P<0.05$) compared with Hereford-sired cattle, also illustrated in the distribution of progeny means by sire (Figure 4.5 B and D respectively).

Ultimate pH was used as a covariate and had a significant negative effect on meat lightness (L^*), redness (a^*) and yellowness (b^*), thaw and cook losses (covariate effect $P<0.05$), indicating that these traits decreased with higher pH. On the contrary, pH had a positive effect on shear force (covariate effect $P<0.05$), indicating increased toughness with higher pH.

Table 4.4. Least-squares means (\pm SE) of the Angus and Hereford progeny groups for meat quality traits measured on the carcass (fat colour score, meat colour score and ultimate pH) and on meat samples in the laboratory (ultimate pH, fat lightness L^* , redness a^* and yellowness b^* , meat lightness L^* , redness a^* and yellowness b^* , shear force, thaw loss and cook loss). Meat colour L^* , a^* and b^* , shear force, thaw and cook loss were adjusted by ultimate pH.

Trait	n	Angus	Hereford	Breed effect P-value	pH effect P-value
Fat colour Score	916	3.04 \pm 0.10	3.05 \pm 0.10	0.885	-
Meat colour Score	916	3.06 \pm 0.06	2.97 \pm 0.06	0.022	-
Ultimate pH	857	5.67 \pm 0.03	5.69 \pm 0.02	0.126	-
Fat colour L^*	326	64.47 \pm 0.78	63.97 \pm 0.77	0.192	-
Fat colour a^*	326	6.18 \pm 0.61	6.22 \pm 0.60	0.868	-
Fat colour b^*	326	13.63 \pm 0.43	13.8 \pm 0.42	0.467	-
Meat colour L^*	326	37.40 \pm 0.60	36.96 \pm 0.59	0.097	0.002
Meat colour a^*	326	17.85 \pm 0.35	17.28 \pm 0.34	0.001	<0.001
Meat colour b^*	326	7.54 \pm 0.42	7.11 \pm 0.42	<0.001	<0.001
Shear force peak (kgF)	326	4.39 \pm 0.09	4.71 \pm 0.08	<0.001	0.037
Thaw loss (%)	313	0.87 \pm 0.07	0.96 \pm 0.07	0.056	0.045
Cook loss (%)	325	25.22 \pm 0.57	25.99 \pm 0.56	<0.001	<0.001

4.4.3. Comparison of progeny means for carcass traits

Sires were grouped post-hoc for carcass weight according to 1 standard deviation of the mean (mean 277.3 and SD 9.3 kg), resulting in 13 sires with carcasses heavier than 286.6 kg (5 Angus and 8 Hereford sires), 13 sires with carcasses lighter than 268.1 kg and 47 sires with carcasses in the middle range. Grouping for EMA (mean 73.6 and SD 3.6 cm²) resulted in 11 sires with EMA bigger than 77.1 cm² (5 Angus and 6 Hereford sires), 13 sires with EMA smaller than 70.1 cm² and 49 sires with EMA in the middle range. Grouping for marble score (mean 0.91 and SD 0.32) resulted in 14 sires with marble score greater than 1.24 (10 Angus and 4 Hereford sires, this proportion being different to 50:50, P<0.05), 13 sires with marble score lower than 0.59 and 46 sires with marble score in the middle range. Grouping for rib fat depth (mean 7.4 and SD 1.4 mm) according to fat grade classes resulted in only 2 sires with more than 10 mm of rib fat depth (both Hereford) and 71 sires with fat between 3 and 10 mm.

A correlation analysis was performed between least-squares means of the progeny groups for carcass attributes from all sires, adjusted for the number of progeny of each sire. There was no correlation between marble score, rib fat depth or EMA (P>0.05, Figure 4.6), and no clear pattern of carcass weight distribution across any of these traits.

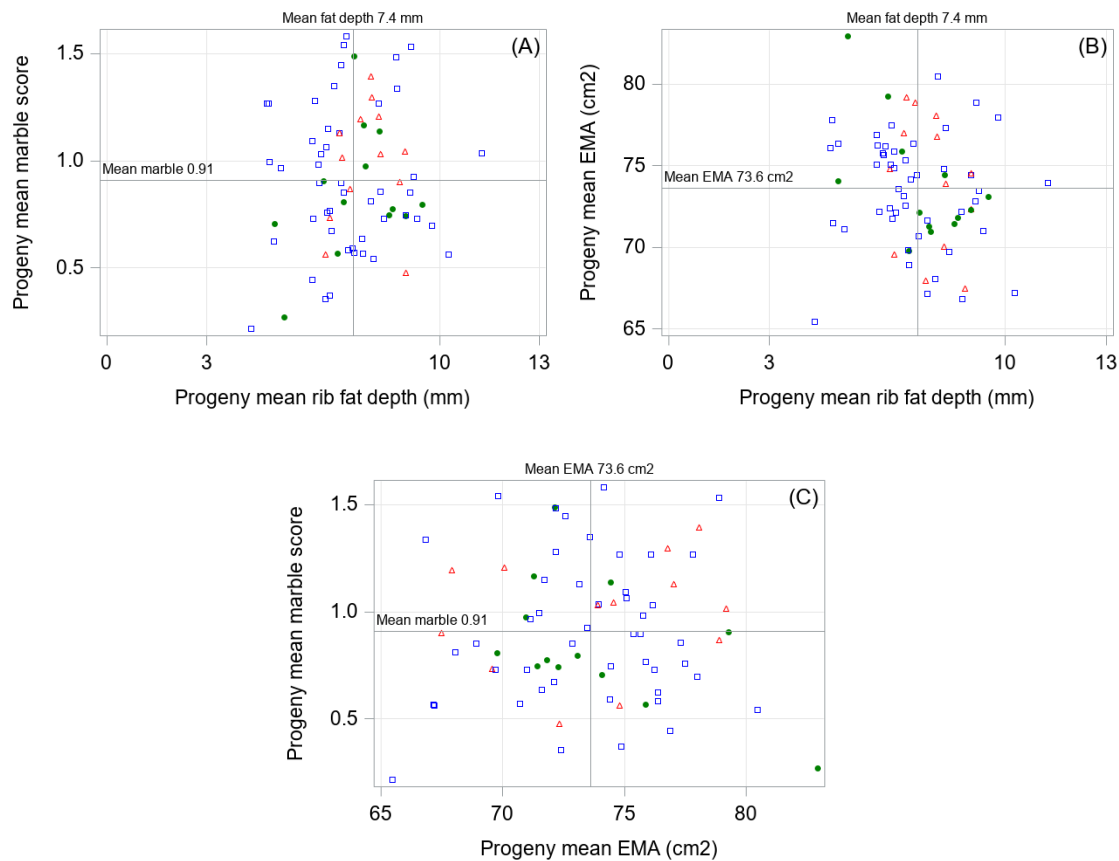


Figure 4.6. Scatter plots of least-squares means of the progeny groups for: (A) rib fat depth and marble score, (B) rib fat depth and eye muscle area (EMA) and (C) EMA and marble score. Individual sires are represented by one data point ($n=73$), grouped by carcass weight according to mean ± 1 SD: below 268.1 kg (Δ red triangles), mid-range (\square blue squares) and heavier than 286.6 kg (\bullet green circles).

4.5. Discussion

The aim of this experiment was to evaluate carcass and meat quality traits of a selection of Angus and Hereford sires via progeny testing of beef-cross-dairy offspring grown on hill country pasture. The analysis included live weight pre-slaughter, carcass weight, carcass length, EMA, rib fat depth, marbling score, ultimate pH, meat and fat colour, shear force, thaw and cook losses.

The carcass weights obtained in this study were consistent with the range of carcass weights for New Zealand in 2019: 242 kg/head for heifers and 313 kg/head for steers (Ministry for Primary Industries, 2019). However, slaughter and carcass weights differed among sires, with the potential to increase carcass weight by 46 kg through selecting the best versus the worst sire tested. With an average price of \$5.75 per kilogram of carcass (average price paid by Greenlea Premier Meats to the 2017 steer cohort), the 46 kg difference in carcass weight

represented \$266 difference in carcass value between progeny of the top and bottom sires in this study. In addition, the difference in carcass weight was achieved through selection of sires with a spread in live weight at 600 days of age, rather than the carcass weight it-self, and therefore greater differences could be obtained by selecting specifically for carcass weight.

All dressing-out percentages in this experiment were within typical values for beef cattle of around 50% (Beef+Lamb New Zealand, 2017b) but there were differences among sires. The sires with dressing-out greater than 50% had progeny with average live weights at slaughter (between 3 kg lighter to 0.5 kg heavier) but above average carcass weights (6 to 7 kg heavier), supporting previous evidence that dressing-out percentages increases with increasing carcass weight (Purchas, 2003). Thus, selecting sires with heavier carcass weight will also improve dressing-out percentages and will result in a greater economic return to the farm.

Most carcass traits were dependent on carcass weight, which was consistent with previous studies (Chambaz *et al.*, 2001; Nour *et al.*, 1983; Purchas, 2003; Thonney, 2015). When progeny were compared at the same carcass weight, rib fat depth and EMA differed among sires, with no differences found between breeds. Among sires, EMA had a 5% CV, indicating low variability and hence low potential to improve retail beef yield or carcass weight by selection of sires with greater EMA (Boles *et al.*, 2015; Realini *et al.*, 2001; Reverter *et al.*, 2003b). Rib fat depth had a 19% CV among sires, with no sires being below 3 mm and only 2 above 10 mm. The range 3-10 mm of subcutaneous fat or “P” fat class grade (New Zealand Meat Classification Authority, 2004) is typically the best paid grade for the New Zealand market. Within this range, carcasses have adequate amount of fat for meat eating quality and contribution to saleable meat yield without the requirement for trimming (AUS-MEAT Limited, 2018; Beef+Lamb New Zealand, 2017b; Purchas, 2003). Only 3% of carcasses were classified as “L” fat class grade (subcutaneous fat below 3 mm). These results indicate that adequate amounts of rib fat depth can be achieved with beef-cross-dairy progeny when grazed on pasture. In addition, it demonstrates that the cattle in this experiment were processed at similar carcass weight and condition as most cattle on commercial farms, so the results are relevant to what could be expected in the industry.

All the beef-cross-dairy progeny of the sires included in this study had low marble scores (0 to 3 on a scale of 0-9), which is supported by previous studies with cattle finished on mixed pastures and slaughtered at 24-28 months of age in New Zealand (Beef+Lamb New Zealand Genetics, 2019; Coleman *et al.*, 2016; Purchas *et al.*, 2007; Schreurs *et al.*, 2014). Adjusted progeny average values recorded within a recent Beef Progeny Test in New Zealand, including Angus, Hereford, Stabilizer, Simmental and Charolais breeds, reported values from 2.4 to 4.3% IMF (Beef+Lamb New Zealand Genetics, 2019). Other studies in New Zealand have shown mean

values in the range of 3.0-3.9% IMF for Angus and Hereford-Angus and 2.9% IMF for Hereford-Friesian steers (Coleman *et al.*, 2016; Purchas *et al.*, 2007; Schreurs *et al.*, 2014). These IMF values are equivalent to marble scores between 1 to 2 in the AUS-MEAT scale (AUS-MEAT Limited, 2018; McPhee *et al.*, 2016).

Even with overall low marble scores, there was large variation between sires (35% CV), and moderate between breeds (16% CV) for marble scores, after adjustment to the same carcass weight. There were 14 sires with marble scores greater than 1.24, of which 4 were Hereford and 10 were Angus. The fact that there were more Angus than Hereford sires in the higher range of marble scores in this experiment can be explained by the big emphasis on marbling as part of the AngusPure brand in New Zealand and the larger spread of EBV for IMF within Angus compared with Hereford breeds. The New Zealand Angus breeders have been selecting animals for higher marbling, specifically through the AngusPure Index, “targeting the production of grass finished steers at 525 kg live weight (280 kg carcass weight and 10 mm rib fat depth) at 18 months of age with a significant premium paid for marbling” (Angus New Zealand Inc.). To qualify for AngusPure premiums, heifers and steers require a minimum marbling score of 2 (New Zealand AngusPure). Thus, greater marble scores can be achieved in beef-cross-dairy animals by selecting sires that have been included in this type breeding index.

There were sire and breed differences for carcass length (after adjustment to the same carcass weight), although these were small and the variation was only 1% CV for both analyses. There were 10.7 cm difference between shortest and longest sire, while carcasses from Hereford-sired cattle were, on average, 2.0 cm longer than Angus-sired animals. Carcass length is an indirect measure of animal frame and size, as shorter animals have shorter carcasses (Purchas *et al.*, 2007). Smaller-framed animals are typically early maturing compared with larger-framed animals, and tend to be younger when they move into a fattening phase of their growth (NSW Department of Primary Industries, 2007; Thonney, 2015). This could be added as a partial explanation of the differences in marble score between Angus and Hereford.

There were no differences due to sire or breed for ultimate pH, in agreement with the low heritability estimates ($h^2 = 0.02-0.10$) found for ultimate pH in beef (Johnston *et al.*, 2003; King *et al.*, 2010). Ultimate pH was found to be within the normal pH range for beef, with the exception of 2.5% of animals with a pH greater than 6.0. These cattle didn't belong to a specific sire or breed. This is supported by earlier studies that showed that environment effects such as handling, transportation, and pre- and post-slaughter conditions, rather than genetic effects, contribute to muscle ultimate pH post-mortem (Dixon *et al.*, 1996; McDade, 2010; Njisane *et al.*,

2017). In addition, pH did affect all meat quality traits when it was fitted as a covariate (Hughes *et al.*, 2014b; Purchas *et al.*, 1993).

Shear force differed among sires and between breeds in this experiment, although differences were small and may not be sufficient to be detected by consumers (Huffman *et al.*, 1996). The 3 sires with lowest shear force values were Angus (A23, A13 and A16), had meat samples with ultimate pH between 5.77 and 5.83, and marble score between 1.09 and 1.48 (above the mean of 0.91). When looking at breed differences, Angus-sired cattle had lower shear force values and higher marbling than Hereford-sired cattle too, with no differences in ultimate pH. Shear force increases with ultimate pH until around pH 6-6.2 (Ertbjerg *et al.*, 2017; Purchas, 1990; Purchas *et al.*, 1993). Further, IMF indirectly influences tenderness by separating and diluting perimysial collagen fibres, disorganizing the structure of intramuscular connective tissue that contributes to increased meat toughness, although the relationship varies considerably (Hocquette *et al.*, 2010). There are also genetic correlations between IMF and tenderness, of $r_g = 0.32$ to 0.74 with consumer panel tenderness and $r_g = -1.00$ to -0.32 with shear force (Gregory *et al.*, 1995; Mateescu, 2015; Reverter *et al.*, 2003b; Van Vleck *et al.*, 1992; Warner *et al.*, 2010). Therefore, there may be potential to decrease shear force (increase tenderness) by selecting sires with high marbling genetics, as long as ultimate pH remains within adequate levels.

Fat colour scores were not affected by either sire or breed, in agreement with its low heritability ($h^2 = 0.05$ (Reverter *et al.*, 2003a)). Although there were sire effects for yellowness b^* when measured objectively with a chromameter, no carcasses were downgraded or classified as being too yellow. Fat can be yellow from animals grown on a pasture-based diet, because the yellow pigmentation comes from the accumulation of carotenoids from green forage in the fat (Dunne *et al.*, 2009; Morgan *et al.*, 1969). This is especially true for those animals with Jersey parentage (Dunne *et al.*, 2009; Nozière *et al.*, 2006). The difference among sires were small and only detected by the measurements with the chromameter, which is more sensitive to changes in colour compared to visual scores.

Meat colour scores and measured lightness L^* were not affected by sires, although meat redness a^* and yellowness b^* were different among sires, with 4 to 6% CV. Furthermore, Angus-sired cattle had higher meat colour score, redness a^* and yellowness b^* values compared with Hereford-sired cattle, but the differences were also small with 2 to 4 % CV. Ultimate pH had a strong negative effect as a covariate on meat colour, so that higher pH had lower values for a^* , b^* and L^* . With high pH, the pigment myoglobin remains in the purple deoxygenated form, rather than the bright red of the oxygenated form, producing darker meat with lower reflectance values as a consequence (Purchas, 1990).

Thaw and cook losses were affected by ultimate pH, and there were both sire and breed effects for cook loss. Nonetheless, the differences were small with just 4% CV among sires, and 2% CV between breeds, and all progeny had cooking losses within expected ranges (Coleman *et al.*, 2016; Purchas, 1990).

One limitation of this experiment was the scarce information on the dams, and so maternal breed was not accounted for. Dams were predominantly Holstein-Friesian or Holstein-Friesian-cross-Jersey crossbred. A greater proportion of Holstein-Friesian would produce animals with heavier carcasses and darker meat colour, while a greater proportion of Jersey would produce lighter carcasses, higher marbling and overall yellower fat, with greater variability in colour (Barton *et al.*, 1993; Bown *et al.*, 2016; Buchanan *et al.*, 2015; Purchas, 2003). Nevertheless, it is unlikely that there would be a bias favouring particular sires in the data from this study because sires were rotationally allocated to mating days and randomly allocated to cows in oestrus on each mating day, and cows had similar live weight and milk production regardless of the sire they were bred with (Coleman, 2020).

4.6. Conclusions and implications

There were differences among beef-breed sires for weight and carcass traits, but little variation in meat quality of beef-cross-dairy cattle. The use of genetically superior beef-breed sires over dairy-breed cows has the potential to increase carcass weights, while maintaining adequate fat levels and meat quality to receive optimum payment. Later chapters in this thesis will evaluate if the variability in carcass can be predicted from a combination of performance traits in the live animal (weight, skeletal size and temperament) and if BREEDPLAN EBV are effective for genetic selection for carcass and meat quality performance from beef-cross-dairy cattle.

CHAPTER 5

PERFORMANCE OF BEEF-CROSS-DAIRY PROGENY IN RELATION TO ESTIMATED BREEDING VALUES OF THE SIRE

Publications arising from this Chapter:

Martín NP, Coleman LW, López-Villalobos N, Schreurs NM, Morris ST, Blair H, McDade JL, Back PJ, Hickson RE (under review). Estimated breeding values of beef sires can predict performance of beef-cross-dairy progeny. *Frontiers in Genetics*

5.1. Abstract

In dairy-beef systems, it is not known how growth and carcass performance relates to the beef-breed sire estimated breeding values (EBV). Such information is needed to determine the value of selecting beef-breed sires based on existing EBV for use on dairy cows in New Zealand. The aim of this study was to evaluate the relationship between the EBV of Angus and Hereford sires, and the performance of their progeny for growth and carcass traits, via progeny testing of beef-cross-dairy offspring grown on hill country pasture. Progeny group means for live weight, carcass weight, eye muscle area (EMA), rib fat depth, marbling scores and intramuscular fat (IMF) of 29 Angus and 34 Hereford sires, were regressed against sire EBV using random regressions. Overall, BREEDPLAN EBV did predict progeny performance of the beef-cross-dairy cattle from this study. Live weight of the progeny groups increased with sire EBV for live weight at 400, 600 and 800 days of age (between 0.24-0.43 kg and 0.28-0.36 kg increase in progeny live weight per extra kilogram of sire EBV in Angus and Hereford respectively, $P < 0.05$). However, sire EBV for live weight had no effect on the live weight of the progeny at 200 days of age for either breed ($P > 0.05$), due to the difference in breeds and rearing systems used to calculate sire EBV by BREEDPLAN and progeny live weight in this study. In the present experiment, artificial rearing meant that there was no maternal influence through milk production on calf growth; instead, live weight at 200 days was the result of post-weaning liveweight gain on poor-quality pasture. For the Hereford sires in this experiment, progeny carcass weight increased 0.27 kg and EMA 0.70 cm² per extra 1 unit in sire EBV for each trait ($P < 0.05$). For the Angus sires, progeny rib fat depth increased 6.9 mm, marble score 0.91 and estimated IMF 2.26% per extra 1 unit in sire EBV for each trait ($P < 0.05$). EBV derived from beef-breed data work in dairy-beef systems but maybe slightly less than the expected 0.5 units of performance per unit of EBV. Farmers should consider BREEDPLAN EBV when selecting sires to mate dairy-breed cows or when buying beef-cross-dairy calves for beef production, because the use of genetically superior beef-breed sires over dairy-breed cows has the potential to increase growth, carcass weights and fat levels from calves born in dairy farms for meat production.

5.2. Introduction

Estimated breeding values (EBV) are predictions of the relative genetic merit of an animal for a particular trait (BREEDPLAN, 2015a). The EBV for most beef cattle breeds in New Zealand for a range of economically important traits are produced by BREEDPLAN (Agricultural

Business Research Institute, Australia) and these are breed specific. They are calculated using the measured deviation in the trait from the herd average for a particular animal, heritability of the trait, information on the trait from the animal's relatives and correlations with other traits (Beef+Lamb New Zealand, 2017e). On average, half of the animal's EBV will be passed on to the animal's progeny (BREEDPLAN, 2015a), and so the regression of straight-bred progeny performance on sire EBV is expected to have a 0.5 slope.

Animals can be ranked based on their EBV for the different traits, and they are a very powerful tool for selecting animals to improve farm profitability. The higher the sire is ranked in the breed, the greater the genetic progress and the more profit the sire will generate (Morris *et al.*, 2009). Genetically superior animals are expected to perform better than inferior counterparts, particularly for weight, fat and carcass traits (Afolayan *et al.*, 2007; McIntyre *et al.*, 2009). However, there can be genotype by environment interaction, by which phenotypic differences appear from one environment to another for the same genotype (Charteris *et al.*, 1997). If this occurs, the relative ranking or scaling of breeds, sires within each breed and their crossbred progeny may change in different locations or systems (Charteris *et al.*, 1997; Morris *et al.*, 2009; Santana *et al.*, 2013). In addition, EBV for different traits might predict performance more or less precisely, depending on the accuracy and heritability of the trait. For example, yearling weight has greater direct heritability estimate than birth or weaning weight, and consequently is a more effective selection criterion for improving progeny growth performance (Afolayan *et al.*, 2007; Baker *et al.*, 1975).

Dairy farmers can use beef-breed sires on a specific group of cows (for example, the late calving cows) as terminal sires, for which the important traits are calving success and performance in a finishing system. Coleman (2020) demonstrated that BREEDPLAN EBV for sires of Angus and Hereford breeds are good predictors of gestation length and birthweight in a dairy system. However, there are some significant differences between the beef and dairy-beef systems, particularly around rearing, weaning and finishing age. In a beef cow-calf system, calves are reared on their dams until weaning at a set date, around 5-7 months of age (150-210 days and 180-240 kg live weight (Beef+Lamb New Zealand, 2017d)). In contrast in a dairy-beef system, calves are "artificially" reared on an allowance of 4-5 litres of milk per day until weaning at a set weight, usually of 80-100 kg live weight, achieved at 8-12 weeks of age (56-84 days) (Beef+Lamb New Zealand, 2017b; Muir *et al.*, 2000b). Furthermore, beef-bred cattle are slaughtered at 18-22 months of age (Beef+Lamb New Zealand, 2017b), whereas beef-cross-dairy cattle are often slaughtered after their second winter to achieve heavier weights and avoid penalties associated

with leanness and conformation (Bown *et al.*, 2016). To date, there is no information to quantify how useful beef EBV are to select sires on finishing potential in a dairy-beef system.

Earlier Chapters (3 and 4) have demonstrated considerable variation among Angus and Hereford sires for growth and carcass traits, but it was not explored how the sire performance related to their EBV. Given the considerable differences between beef and dairy-beef systems mentioned above, it is possible that scaling or re-ranking of sires may occur due to genotype by environment interactions. Such information is needed in order to determine the value of selecting beef-breed sires with better EBV for finishing traits to use on dairy-breed cows. The hypothesis of this study was that the beef-cross-dairy offspring performance is related to their sire EBV for the traits measured. Therefore, the aim of this study was to evaluate the relationship between Angus and Hereford sires' EBV and the performance of their progeny for growth at different ages (live weight at 200, 400, 600 and 800 days of age) and carcass traits (carcass weight, eye muscle area, rib fat, marble score and intramuscular fat), via progeny testing of beef-cross-dairy offspring grown on hill country pasture.

5.3. Materials and Methodology

This experiment was conducted at Limestone Downs, near Port Waikato, New Zealand (37°28'S, 174°45'E) with approval from the Massey University Animal Ethics Committee (15/65 and 18/50). Animals were processed commercially through Greenlea Premier Meats Ltd, Hamilton plant (37°48'S 175°15'E), according to standard New Zealand industry practice (Animal and Animal Products Directorate, 2017), with Halal certification.

5.3.1. Animals

The animals reported here are a subset of those described in Chapters 3 and 4, with the exclusion of sires used on 15-month-old heifers by natural mating and their progeny. Yearling sires used on heifers were selected with a different criteria (i.e. sires were in the lightest 15% of each breed for birth weight and the budget allocated was NZD2500 at time of purchase), and they were used via natural mating on separate contemporary groups to those used on mixed-aged cows, with no crossover of sires between groups or years. These sires had lower accuracy of their EBV for live weight at 600d and for all carcass data. For these reasons, sires used on heifers were excluded from this chapter.

5.3.1.1. Sires

Lactating mixed-aged cows from Limestone Downs' dairy farm were individually inseminated with semen from Angus and Hereford bulls, as described by Coleman (2020). Semen was rotationally allocated to mating days, and randomly allocated to cows in oestrus on each mating day. Cows were bred for 63 days in 2015 and 54 days in 2016.

Sires were selected for the project on the basis of their EBV from BREEDPLAN prior each mating. Within each breed, a spread of birth weight, gestation length and live weight at 600 days of age (600d) EBV was achieved, except that birth weight EBV was restricted to the lighter 50% of the breed at the time of selection. When similar sires were available, those with superior EBV for intramuscular fat (IMF) and eye muscle area (EMA) were selected. The sire team over the 2 seasons included a total of 31 Angus and 34 Hereford bulls, of which 14 Angus and 11 Hereford sires were used in both seasons.

The EBV of each sire were obtained from the online databases of Angus and Hereford breed associations and updated in April 2020 (Appendix 1). The data collected in this experiment was not included for the calculation of the BREEDPLAN EBV for these sires and so EBV values are independent of the progeny results obtained in this study (Chapters 3 and 4). Mean and range of EBV for weight, carcass and meat traits by breed of sire, with their accuracy and percentile band fit are presented in Table 5.1.

Table 5.1. Estimated breeding values (EBV; mean \pm SD) with total range, accuracy and percentile bands for live weight and carcass traits, for 31 Angus and 34 Hereford sires (BREEDPLAN, April 2020).

Trait	Angus					Hereford				
	n	EBV	Range	Accuracy	Bands	n	EBV	Range	Accuracy	Bands
200d weight (kg)	31	41 \pm 9	23 to 59	70-99%	1-100 th	34	30 \pm 8	18 to 48	69-99%	0-99 th
400d weight (kg)	31	78 \pm 13	56 to 110	70-99%	1-99 th	34	55 \pm 14	31 to 79	69-99%	1-99 th
600d weight (kg)	31	101 \pm 18	70 to 135	70-99%	5-99 th	34	74 \pm 20	35 to 114	69-99%	0-100 th
Carcass weight (kg)	31	52 \pm 15	26 to 80	65-98%	1-99 th	34	54 \pm 15	25 to 84	58-98%	0-100 th
Eye Muscle Area (cm ²)	31	5.2 \pm 2.2	-0.3 to 9.7	62-98%	1-100 th	34	3.1 \pm 2	0.3 to 8	50-96%	0-100 th
Rib Fat (mm)	31	0.9 \pm 1.9	-2 to 6.1	64-98%	0-99 th	34	0.8 \pm 1	-1.8 to 2.7	52-97%	0-100 th
Intramuscular Fat (%)	31	1.5 \pm 1.4	-2.1 to 4.4	56-98%	0-100 th	34	0.4 \pm 0.7	-1 to 2	38-97%	1-100 th

n: Number of sires used at mating; final number of sires included for data analysis: 30 Angus and 34 Hereford. Bands: fit of EBV within the percentile bands for 2018 born calves for each breed, where 0 is the top value and 100 is the bottom value for the trait.

5.3.1.2. Progeny management and slaughter

Angus-sired and Hereford-sired calves born to mixed-aged dairy-breed cows on Limestone Downs' dairy farm, in spring 2016 (n=471) and 2017 (n=427) were included in the study. The calves included were a subset of those described in Chapters 3 and 4, being only those

born to mixed-aged (3+ years old, multiparous) dairy-breed cows. These cows were predominantly Holstein-Friesian or Holstein-Friesian-cross-Jersey crossbred. All calves had date of birth, sex and live weight recorded within 24 hours of birth, and were DNA parentage verified as part of a previous experiment described by Coleman (2020). Mean birth date was 6 August 2016 and 8 August 2017 for the calves included in this Chapter, with an overall mean birth weight of 36.7 kg (SD 4.8). Calves were artificially reared on an allowance of 4 litres of milk/head/day and weaned at a minimum of 85 kg live weight, resulting in a mean weaning live weight of 93.0 kg (SD 7.1) at a mean age of 81.7 days (SD 11.6). Once weaned, calves were moved from the dairy platform to the sheep and beef hill country platform of the same farm. Male calves were castrated before 4 months of age.

At 4 months of age (December of 2016 and 2017), at a mean age of 128.7 days (SD 16.8) and a mean live weight of 123.1 kg (SD 15.7), calves were allocated into 6 grazing herds based on live weight (light, intermediate and heavy) and sex (female and male) and balanced for sire so that, where possible, all sires were represented in each grazing herd within year. In total, there were 12 grazing herds (2 years x 2 sexes x 3 liveweight groups), and animals remained in those herds throughout the experiment until slaughter. All cattle were grazed on summer-dry hill country pasture on the coastal farm under commercial conditions (refer to Chapter 3 for full details).

Each grazing herd was slaughtered as a complete group on the same day, when the mean live weight reached the slaughter target live weight of 500 kg for heifers and 600 kg for steers (refer to Chapter 4 for full details). Heifers were slaughtered at a mean age of 820 days of age (range 693-923, 27 months old) and 518 kg (SD 37) live weight on-farm, whilst steers were slaughtered at a mean age of 885 days of age (range 821-954, 29 months old) and 613 kg (SD 43).

5.3.2. Measurements and progeny means calculations

5.3.2.1. Live weights

Animals were weighed on the farm using a weigh crate at a minimum of 2-monthly intervals, as described in Chapter 3. Short-term fluctuations in live weight were smoothed out by calculating centered moving averages of 3 liveweight records per animal using the Expand procedure (SAS 9.4, SAS Institute Inc., Cary, NC, USA). Predicted live weights for each animal at 200d, 400d, 600d and 800d were calculated by interpolation of the smoothed liveweight curves.

Linear mixed models (SAS 9.4, SAS Institute Inc., Cary, NC, USA) were used to estimate least-squares means for live weight at 200d, 400d, 600d and 800d for progeny groups, described in Chapter 3. The model included the fixed effects of sire within breed, and the random effect of contemporary group. Contemporary group was defined as the group of animals grazing in the same herd (n=12), that were progeny of sires of the same breed (n=2, Angus and Hereford).

5.3.2.2. Carcass traits

Each grazing herd was slaughtered as a complete group on the same day, as described in Chapter 4. The bodies were dressed to commercial specifications and hot carcass weight (kg) was recorded prior to the carcasses going into the chiller. Carcasses were chilled ($4\pm 1^{\circ}\text{C}$) overnight and the following morning, one side of the carcass was cut between the 12th and 13th rib to expose the eye muscle (*M. longissimus thoracis*) for in-chiller assessment of rib fat thickness (mm), eye muscle area (EMA in cm^2) and marbling score. Marbling was scored against the AUS-MEAT / MSA reference standards on a scale from 0 (nil) to 9 (abundant) (AUS-MEAT Limited, 2018). The AUS-MEAT marble scores are accompanied by MSA-specific marbling score, which were then converted to an estimate of intramuscular fat (IMF in %) using the equation from McPhee *et al.* (2016): $\text{MSA-specific marbling score} = 213.7 + 38.59 \cdot \text{IMF}\% - 0.629 \cdot \text{IMF}\%^2$.

Linear mixed models (SAS 9.4, SAS Institute Inc., Cary, NC, USA) were used to estimate least-squares means for carcass weight, EMA, rib fat depth, marbling scores and IMF for progeny groups, described in Chapter 4. The model included the fixed effects of sire within breed, and the random effect of contemporary group. Contemporary group was defined as the group of animals grazing in the same herd and slaughtered on the same day (n=12), that were progeny of sires of the same breed (n=2, Angus and Hereford). Age deviation at slaughter (within contemporary group) was fitted as a covariate for carcass weight. Carcass weight was fitted as a covariate for EMA, rib fat, marble score and IMF.

5.3.3. Statistical Analysis

5.3.3.1. Data cleaning

Sires with a minimum of 5 progeny across grazing herds were included in the analysis (excluded 1 Angus sire with 4 progeny in 2016 and 1 Angus sire with 3 progeny in 2017), as explained in Chapters 3 and 4.

5.3.3.2. Regressions of progeny means on sire EBV

Least-squares means of the progeny groups for live weight (at 200d, 400d, 600d and 800d), carcass weight, EMA, rib fat depth, marbling scores and IMF, were regressed against sire EBV using random regressions, to determine whether the regression coefficient differed from 0. The regressions were done separately for each breed of sire (Angus n=29 and Hereford n=34) and were weighted by the number of progeny of each sire for each trait. Sire EBV for live weight at 600d was used to regress with least-squares means of the progeny groups for live weight at 800d, as EBV for live weight at 800d are not included in BREEDPLAN. Sire EBV for IMF was used to regress with least-squares means of the progeny groups for marble scores, as EBV for marble scores are not included in BREEDPLAN.

5.4. Results

5.4.1. Regression of progeny means on sire EBV for live weight

The estimates of the regression coefficients of least-squares means of the progeny groups on sire EBV for live weight at different ages and by breed of sire are presented in Table 5.2 and Figure 5.1. Live weight of the progeny groups increased with sire EBV for live weight at 400d, 600d and 800d (sire EBV for live weight at 600d) for both breeds ($P < 0.05$). However, sire EBV for live weight had no effect on the live weight of the progeny at 200d for either breed ($P > 0.05$).

Table 5.2. Estimates of regression coefficients (intercept and slope) of least-squares means of the progeny groups for live weight (LWT) on sire EBV for live weight at 200, 400, 600 and 800 days of age, for 29 Angus and 34 Hereford sires.

Progeny mean	Angus				Hereford			
	Intercept	Slope	<i>P-value</i>	R ²	Intercept	Slope	<i>P-value</i>	R ²
LWT at 200d (kg)	152.5±4.7	0.13±0.11	0.248	0.05	155.9±3.7	0.08±0.12	0.477	0.02
LWT at 400d (kg)	265.0±8.2	0.24±0.10	0.030	0.16	267.5±5.6	0.28±0.10	0.007	0.21
LWT at 600d (kg)	388.0±11.5	0.36±0.11	0.004	0.27	402.0±6.6	0.32±0.08	0.001	0.31
LWT at 800d (kg)¥	458.5±11.7	0.43±0.11	0.001	0.34	478.7±9.5	0.36±0.12	0.006	0.21

R²: coefficient of determination. ¥Progeny mean LWT at 800d regressed with sire EBV for weight at 600d.

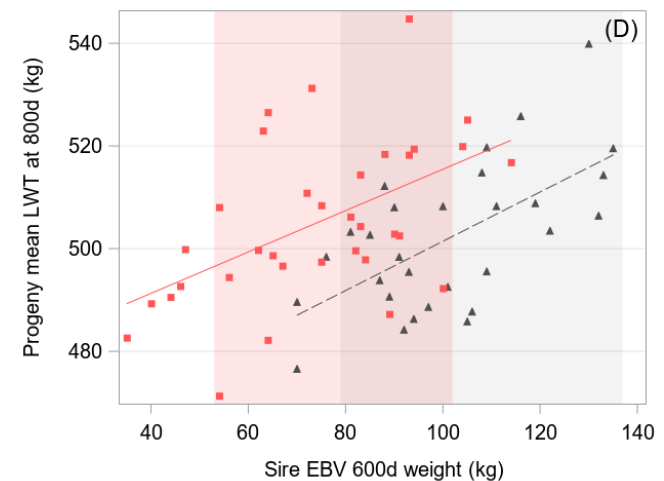
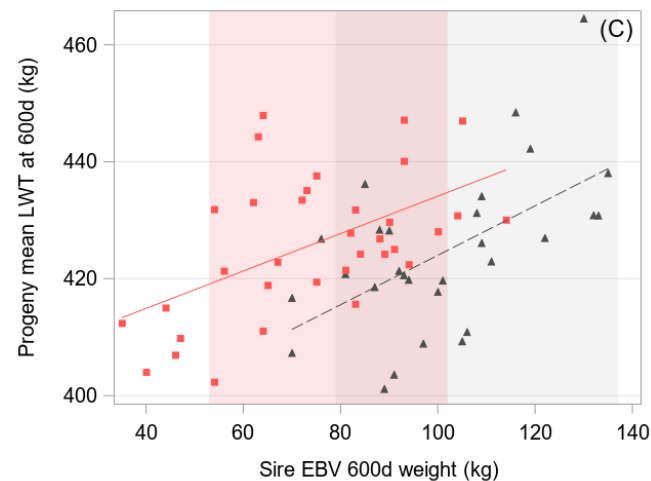
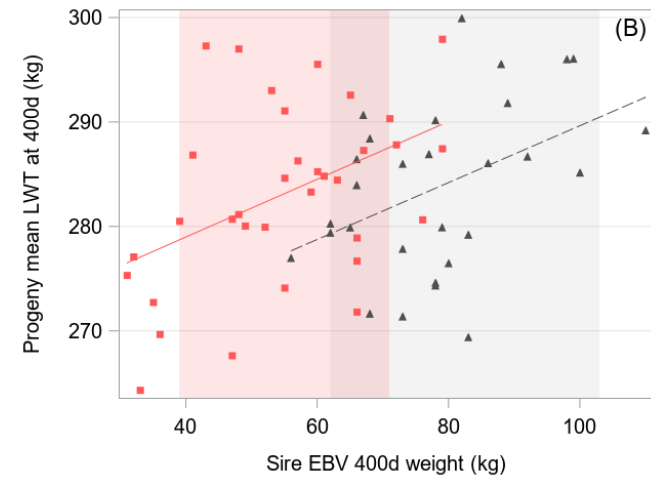
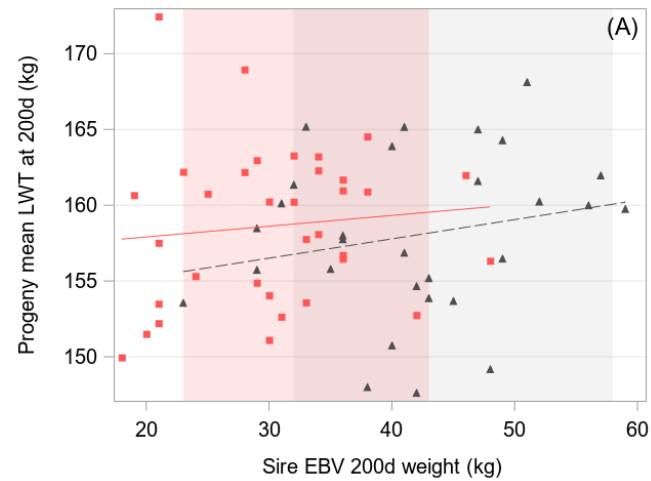


Figure 5.1. Regression of least-squares means of the progeny groups for live weight (LWT) on sire EBV for live weight at: (A) 200, (B) 400, (C) 600 and (D) 800 days of age. Individual sires are represented by one data point (Angus, \blacktriangle grey triangles, $n=29$; Hereford, \blacksquare red squares, $n=34$) and the regression lines by breed are indicated by lines (Angus, $- -$ dashed line; Hereford, $-$ solid line). Coloured bands indicate 5th to 95th EBV percentiles for the 2018 born calves within the BREEDPLAN population for each breed (Angus, \square grey band; Hereford, \square red band).

5.4.2. Regression of progeny means on sire EBV for carcass traits

The estimates of the regression coefficients of the least-squares means of the progeny groups on sire EBV for carcass and meat traits by breed of sire are presented in Table 5.3 and Figure 5.2. For the Angus sires, rib fat depth, marble score and estimated IMF increased with sire EBV ($P < 0.05$), carcass weight tended to increase with sire EBV ($P < 0.1$), but there was no relationship between EMA and sire EBV for EMA ($P > 0.05$). For the Hereford sires, carcass weight and EMA increased with sire EBV ($P < 0.05$), rib fat depth tended to increase with sire EBV ($P < 0.1$), but there was no relationship between marble score or estimated IMF and sire EBV for IMF ($P > 0.05$).

Table 5.3. Estimates of regression coefficients (intercept and slope) of least-squares means of the progeny groups on sire EBV for carcass weight, eye-muscle area (EMA), rib fat depth, marble score and estimated intramuscular fat (IMF), for 29 Angus and 34 Hereford sires.

Progeny mean	Angus				Hereford			
	Intercept	Slope	<i>P</i> -value	R ²	Intercept	Slope	<i>P</i> -value	R ²
Carcass weight (kg)	265.9±5.5	0.18±0.10	0.083	0.11	262.0±5.5	0.27±0.09	0.007	0.21
EMA (cm ²)	72.5±1.4	0.22±0.27	0.414	0.02	71.1±1.1	0.70±0.30	0.024	0.15
Rib fat depth (mm)	6.9±0.2	0.22±0.11	0.050	0.13	7.2±0.3	0.44±0.24	0.077	0.09
Marble score [‡]	0.91±0.08	0.10±0.04	0.011	0.22	0.79±0.06	0.02±0.07	0.796	0.00
IMF estimate (%)	2.26±0.21	0.28±0.10	0.011	0.22	1.98±0.15	0.05±0.19	0.804	0.00

R²: coefficient of determination. [‡] Progeny mean marble scores regressed with sire EBV for IMF.

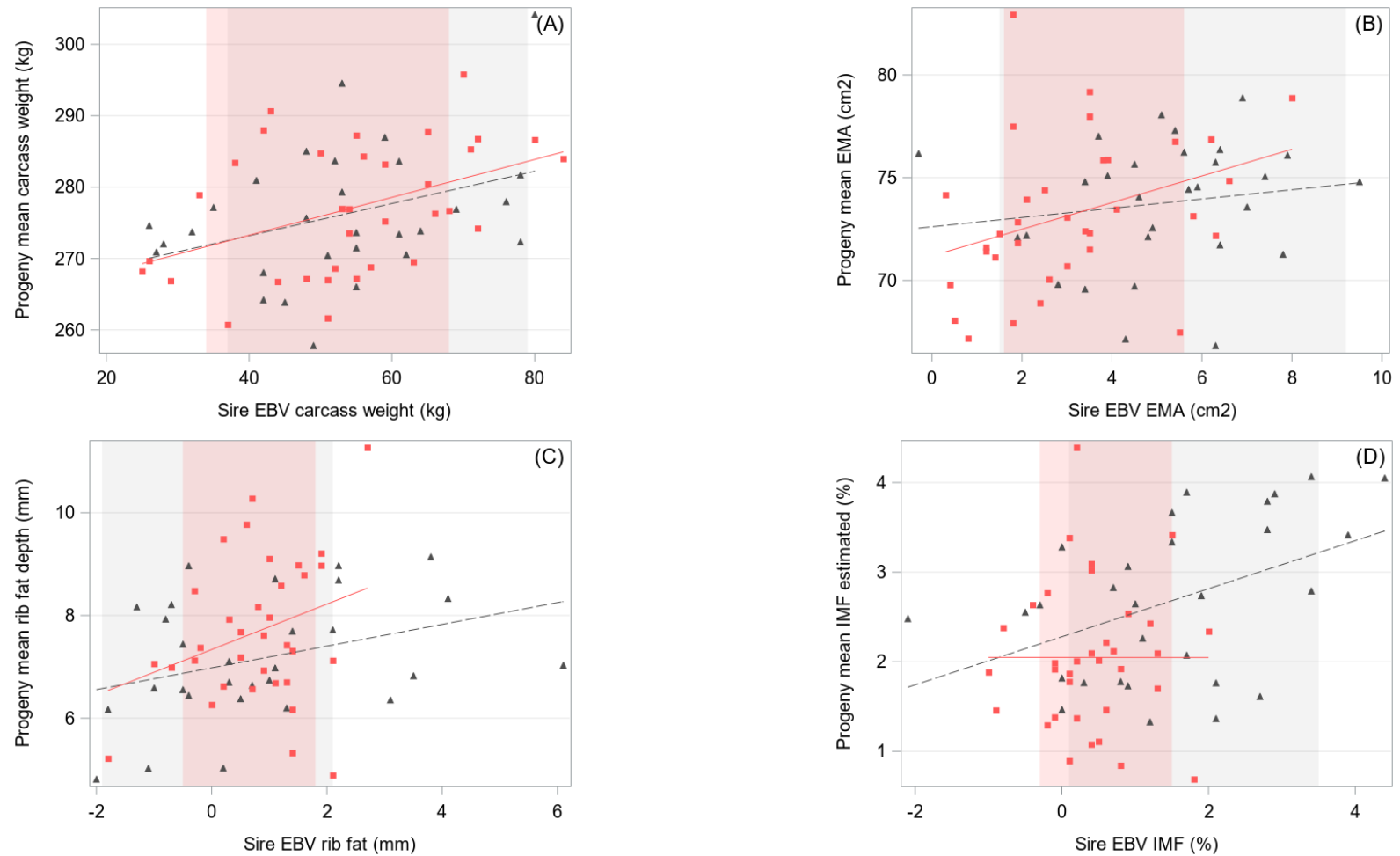


Figure 5.2. Regression of least-squares means of the progeny groups on sire EBV for: (A) carcass weight, (B) eye-muscle area (EMA), (C) rib fat depth and (D) estimated intramuscular fat (IMF). Individual sires are represented by one data point (Angus, \blacktriangle grey triangles, $n=29$; Hereford, \blacksquare red squares, $n=34$) and the regression lines by breed are indicated by lines (Angus, $---$ dashed line; Hereford, $---$ solid line). Coloured bands indicate 5th to 95th EBV percentiles for the 2018 born calves within the BREEDPLAN population for each breed (Angus, \square grey band; Hereford, \square red band).

5.5. Discussion

The aim of this experiment was to evaluate the relationship between Angus and Hereford sires' EBV and the performance of their progeny for growth at different ages and carcass traits, via progeny testing of beef-cross-dairy offspring grown on hill country pasture.

Sire EBV had a positive association with progeny live weight from 400d onwards, but not at 200d. The lack of association between sire EBV and progeny live weight at 200d was foreseeable given the differences in breeds and rearing systems used to calculate sire EBV and progeny live weight. Angus and Hereford sires' EBV for live weight at 200d are derived from straightbred beef calves, grown in cow-calf systems where calves are reared on their mother until 200d, and calculated from weaning weight phenotypes (recorded between 81d and 300d (Beef+Lamb New Zealand, 2017e)). This EBV typically measures pre-weaning growth, which is influenced by the calf's growth potential and feeding intensity, dam's milk production and the calculation includes the performance of all known relatives (Asheim *et al.*, 2016; Beef+Lamb New Zealand, 2017e). Recent results from a Beef Progeny Test in New Zealand, where 984 progeny of 52 sires of Angus, Hereford, Stabilizer, Simmental and Charolais breeds were considered for growth and carcass traits, showed that 1 kg extra in the sire EBV for 200d weight could predict 0.49 kg increase in live weight of the calves at weaning at 200d (Beef+Lamb New Zealand Genetics, 2019). In that study, mean live weight at weaning was 206.1 kg. In comparison, calves from the present experiment were removed from their dams within 24 hours of birth, and group fed on an allowance of 4 litres of milk/head/day until weaning. Weaning occurred at a minimum of 85 kg live weight (Coleman, 2020), rather than a fixed age as it happens in beef rearing systems. This meant that lighter or slower growing calves got fed milk for more days to achieve the target weaning weight, and so may have had an advantage compared with the heavier or faster growing calves.

After weaning at a mean live weight of 93.1 kg and 81.5 days old, calves went on a pasture-based diet, which was of low quality over the summer (ME 9.2 MJME/kgDM, CP 12.6 %DM, Chapter 3). Low quality pasture likely restricted animal performance, because calves grew at an average of 0.59 kg/d from 131d to 200d, compared with 0.69 kg/d pre-weaning (0d to 81.5d). Young cattle require pasture with greater than 11.4 MJME/kgDM and covers higher than 2200 kgDM/ha to grow at 1 kg/d (Beef+Lamb New Zealand, 2017b) and to express their genetic potential for growth, or alternatively when pasture quality is poor, they require supplementary concentrate feed to increase liveweight gain (Pettigrew *et al.*, 2017). Therefore, there was no

maternal influence through milk production on calf growth, and live weight at 200d was the result of post-weaning liveweight gain restricted by the poor-quality diet. Consequently, the genetic differences in growth at 200d may not have been able to be expressed in this study.

Sire EBV had a positive and increasing association with progeny live weight from 400d to 800d. The association with the progeny live weight at 400 and 600d in this study was between 59-80% of the yearling and finishing age value that was explained in the New Zealand Beef Progeny Test mentioned previously (Beef+Lamb New Zealand Genetics, 2019). In that study, an extra kg in the sire EBV could predict 0.41 kg and 0.45 kg increase in live weights of the calves at 400d and 600d respectively. When comparing the beef-cross-dairy progeny live weights at 800d with sire EBV for live weight at 600d, the association was much stronger and represented 80-95% of the value that was explained in the Beef Progeny Test at finishing age (Beef+Lamb New Zealand Genetics, 2019). It is likely that the effect of rearing conditions on calves' live weight carried over to influence 400d and 600d weights. In addition, growth of the cattle in this study (0.58 kg/d from 131d to 800d, Chapter 3) was probably an underestimation of the growth potential of the animals, because the low-quality pasture would have restricted animal performance (Burke *et al.*, 2002). Consequently, there was a lower than expected increase in progeny performance with increasing sire EBV. In another environment with better feed, it is likely that the beef-cross-dairy cattle would have reached a good finishing weight at 600d, and therefore the relationships with EBV at 600d could have been stronger.

Sire EBV had a positive association with the progeny carcass weight and EMA for the Hereford sires in this experiment, but this was not the case for Angus sires. For carcass weight, the EBV range and accuracy of those EBV for both breeds were similar (54 kg for Angus with 65-98% accuracy and 59 kg for Hereford with 58-98% accuracy). But Angus had sires with progeny group means on both extremes of carcass weights that did not match the sire EBV value, which had medium accuracy (below 74% according to BREEDPLAN (2015a)). Hereford sires didn't have these extreme weights and so the regression between progeny mean carcass weight and sire EBV had a better fit ($R^2=21\%$) and an extra kilogram of carcass in the sire EBV was associated with 0.27 kg heavier carcass in the progeny. This was greater than the result from the Beef Progeny Test previously mentioned, where 1 kg extra in sire EBV produced 0.15 kg extra in carcass weight across Angus, Hereford, Stabilizer, Simmental and Charolais breeds (Beef+Lamb New Zealand Genetics, 2019). In addition, New Zealand Hereford have encouraged crossbreeding with dairy by the Dairy Terminal Index "targeting the production of dairy-beef progeny where all progeny are slaughtered" (BREEDPLAN, 2011). In this index, steers are assumed to be marketed at 500 kg live weight (260 kg carcass weight and 6 mm rib fat depth) at

18 months of age, and there is emphasis on EBV for live weight at 600d and retail beef yield, and minor emphasis on EMA and IMF. Selecting animals using this selection index were likely to increase carcass weight and EMA primarily (BREEDPLAN, 2011).

Hereford sires' EBV had a positive association with the progeny EMA, although the regression had a low coefficient of determination at 15%. Both breeds had a large spread in EBV accuracy for this trait (Appendix 1): Angus ranged from 62 to 98% accuracy (10 cm² spread of EBV) and Hereford from 50 to 96% (7.7 cm² spread of EBV). To date, there is no direct financial benefit of having animals with greater EMA because the New Zealand meat payment schedule is based on carcass weight and fat grade (Bown *et al.*, 2016). Therefore, there has been no or very small emphasis (1-3% EBV weighting) to select animals with higher EMA for either breed (BREEDPLAN, 2011, 2015b).

On the other hand, sire EBV for IMF had a low to moderate positive association with marble score and IMF for the Angus sires in this experiment, but not for the Hereford sires. Firstly, the Angus sires used in the experiment had a wider range of EBV for IMF compared with Hereford sires (6.5% and 3.0% IMF spread of EBV respectively). Secondly, Angus-sired progeny had higher marble scores compared with Hereford-sired cattle (1.03 and 0.81 respectively, $P < 0.05$, Chapter 4), even though the range of scores was 0-3 for both breeds. More Angus than Hereford sires had higher marble scores in this experiment likely due to the physiological age at slaughter and the emphasis on marbling as part of the AngusPure brand. Even though both Angus and Hereford are considered early maturing breeds (Bartoň *et al.*, 2006; Purchas, 2003), Angus cattle are known to reach physiological maturity at an early age (Chambaz *et al.*, 2001) and to exhibit higher marbling than other beef breeds (Thonney, 2015). Given that the cattle in this study were slaughtered at a common age (which depended on the contemporary group reaching a mean target weight, rather than selecting those animals with the right finishing attributes), then it is possible that Hereford cattle were not as physiologically mature as the Angus cattle. This is supported by the fact that Hereford-sired cattle had longer carcasses than Angus-sired animals in this study (2.0 cm difference, $P < 0.05$, Chapter 4), indicating that Hereford could be larger-framed compared with Angus cattle, and so less mature than their smaller-framed counterparts (NSW Department of Primary Industries, 2007; Thonney, 2015). In addition, Angus breeders have been putting emphasis on marbling, specifically through the AngusPure Index, "targeting the production of grass finished steers at 525 kg live weight (280 kg carcass weight and 10 mm rib fat depth) at 18 months of age with a significant premium paid for marbling" (Angus New Zealand Inc.). To qualify for AngusPure premiums, heifers and steers require a minimum marbling score of 2 (New Zealand AngusPure). Thus, greater marble scores

can be achieved in beef-cross-dairy animals by selecting sires that rank highly in this breeding index.

Similarly to marbling, sire EBV had a positive association with rib fat depth for the Angus sires in this experiment, but not for the Hereford sires. Although rib fat depth was similar for both breeds ($P > 0.05$, Chapter 4), Hereford sires used in the experiment had greater spread in progeny rib fat depths and a narrower range of EBV (rib fat depth mean of 7.7 mm and range 4.9-11.3 mm, EBV range of 4.5 mm with 52-97% accuracy) compared with Angus sires, with progeny means less variable but a much bigger spread in sire EBV (rib fat depth mean of 7.2 mm and range 4.8-9.1 mm, EBV range of 8.1 mm with 64-98% accuracy). There were 2 Hereford sires with progeny means for rib fat over 10 mm, one of which had the highest EBV for the breed group but average accuracy (H23, EBV 2.7 mm with 54% accuracy). The other Hereford sire over 10 mm (H2, EBV 0.7 mm with 86% accuracy) had the same EBV to another Hereford sire with mean progeny fat of 6.6 mm (H15, EBV 0.7 mm with 83% accuracy). Angus sires didn't have these extreme rib fat depths within similar EBV and so the regression between progeny mean and sire EBV had a better fit. Nevertheless, the association was still weak ($R^2 = 13\%$) and the slope of the regression was 0.22 mm in progeny rib fat depth for 1 mm extra in sire EBV, which was a third of the result in the Beef Progeny Test of 0.75 mm for extra 1 mm in sire EBV (Beef+Lamb New Zealand Genetics, 2019). This is likely to be reflection of the maternal dairy genetics. Dairy animals have large metabolically active internal organs and non-carcass fat depots to support their greater lactation requirements, producing carcasses that leaner, with less subcutaneous and IMF relative to non-carcass fat, compared with beef animals (Bown *et al.*, 2016; Purchas, 2003).

One limitation of this experiment was the scarce information on the dams, and so maternal breed was not accounted for. Dams were predominantly Holstein-Friesian or Holstein-Friesian-cross-Jersey crossbred. A greater proportion of Holstein-Friesian would produce heavier calves with faster growth rates and heavier carcasses, while a greater proportion of Jersey would produce smaller animals with slower growth rates, lighter carcasses and higher marbling (Barton *et al.*, 1994; Bown *et al.*, 2016; Buchanan *et al.*, 2015; Handcock *et al.*, 2018). Nevertheless, it is unlikely that there would be a bias in the data from this study because sires were rotationally allocated to mating days and randomly allocated to cows in oestrus on each mating day, and cows had similar live weights and milk production regardless of the sire they were bred to (Coleman, 2020).

A further potential limitation is that sires used in this experiment were not random sample, as they were selected for the project on the basis of their EBV so that, within each breed,

a spread of birth weight (restricted to the lighter 50%), gestation length and live weight at 600d was achieved. With greater selection intensity (proportion of bulls selected from the total available), then the expected correlation between EBV in different systems decrease (Charteris, 1995). However, the selection to achieve a spread of EBV creates a more representative population than selection for the best EBV, and the EBV of the sires of both breeds did cover most of the range of possible EBV for each growth and carcass trait (spanning at least the percentiles 1st to 99th for all traits, except for Angus live weight at 600d (5-99th)).

Lastly, there was variation in the EBV accuracy, which ranged between 69-99% for growth traits, 50-98% for carcass size traits and 38-98% for carcass fat traits. Lower accuracy of the EBV, in addition to each sire having a low number of progeny (5-38 progeny for most traits), implies that both the available BREEDPLAN EBV and the measured phenotypic results could be an over or under-representation of the real sire merit. Errors in the independent variable, in this case EBV, can cause significant bias in estimated regression coefficient (Robinson, 2005), reducing the regression slope. On the other hand, increasing progeny numbers evaluated per sire can increase the accuracy and correlation between sire EBV in different environments (Blair *et al.*, 1994). For example, assuming the genetic correlation of a trait across environments is 1.0 and a heritability of the trait of 0.25, increasing number of progeny tested from 20 to 50 would increase the correlation between EBV from different environments from 0.38 to 0.76 (Charteris, 1995). Nevertheless, the number of progeny used in this study is comparable with other progeny tests done in New Zealand (Baker *et al.*, 1975; Beef+Lamb New Zealand Genetics, 2019), and the results presented allow useful progeny comparisons among the recorded sires.

5.6. Conclusions and implications

The use of genetically superior beef-breed sires over dairy-breed cows has the potential to increase growth, carcass weights and fat levels from calves born in dairy farms for meat production. Overall, BREEDPLAN EBV did predict progeny performance of the beef-cross-dairy cattle from this study, indicating that EBV derived from beef-breed data work in dairy-beef systems but may result in slightly less than the expected 0.5 unit increase in performance per unit of EBV. Sires of Angus and Hereford breeds had good associations between EBV and progeny growth, except at 200d. Hereford sires also had significant associations regarding carcass size traits while Angus sires had positive associations with carcass fat traits. Although EBV for carcass traits are currently useful, improvement in the information used to generate

them is still required to increase their accuracy and ability to predict progeny performance. Beef-cross-dairy cattle could also be included in joint genetic evaluations, given the strong dairy component in the cattle slaughtered in New Zealand. Farmers should consider BREEDPLAN EBV when selecting sires to mate dairy-breed cows or when buying beef-cross-dairy calves for beef production, to ensure the calves grow well to produce carcasses of suitable meat and fat composition.

CHAPTER 6

SIZE AND TEMPERAMENT OF BEEF-CROSS-DAIRY CATTLE MEASURED EARLY IN LIFE AS PREDICTORS OF CARCASS AND MEAT TRAITS

Publications arising from this Chapter:

Martín NP, Schreurs NM, Morris ST, López-Villalobos N, McDade JL, Hickson RE (under review).

Temperament of hand-reared beef-cross-dairy cattle does not influence production traits. New Zealand Journal of Animal Science and Production.

6.1. Abstract

There is potential to assess the phenotype of calves at an early age, to predict cattle finishing performance. The aim of this experiment was to analyse measurements of skeletal size and temperament in 486 Angus- and Hereford-sired cattle born to dairy-breed cows and finished on hill country pasture, and to evaluate the value of these measurements in early life, in conjunction with live weight, as predictors of carcass and meat traits. The traits analysed included carcass weight, carcass length, EMA, rib fat depth, meat colour scores and ultimate pH. Live weight at birth, 129d and 200d predicted future carcass size ($P < 0.05$) and, therefore, should be considered when purchasing calves from the sale yards or making price-setting decisions. For steers in the present study with a mean birth weight of 37.5 kg, the 26.5 kg difference in birth weight between the lightest and heaviest calf corresponded to a total of 40.3 kg carcass weight and \$231.61 difference in carcass value at harvest time. In heifers, the accuracy of predictions of carcass weight from live weight were low to moderate ($R^2 = 17$ to 31%) and increased if live weight was combined with hip-height. In steers, the relationships with linear measurements were not so clear. Live weight alone could predict carcass weight with moderate accuracy ($R^2 = 39$ to 48%). Accuracy of prediction for carcass weight of steers increased with age, or with combining live weight with body length at 0d, or with hip-width at 129d. Thicker cannon bones at birth also gave an indication of heavier carcasses for both heifers and steers. At harvest, rib fat depth had a negative relationship with live weight at birth, whilst eye muscle area (EMA) was positively related to live weight at 129d. Cattle in this study were calm at 200d, with mean exit velocity (EV) of 1.2 m/s (maximum of 3.05 m/s) and crush score (CS) of 1.4 (maximum of CS 3 on a 1-5 scale). The small variation among animals was likely consequence of cattle being acclimatised and tranquil in the presence of humans by 200d. Temperament did not influence production traits measured in this study.

6.2. Introduction

Earlier results (Chapters 3 and 4) have demonstrated considerable differences among Angus and Hereford beef-breed sires for growth and carcass traits in beef-cross-dairy progeny, and that sire performance was related to their EBV for most traits measured (Chapter 5). Farmers should consider BREEDPLAN EBV when selecting sires to mate dairy-breed cows or when buying beef-cross-dairy calves for beef production. However, many producers buy calves

from the sale yards, which rarely have the information of their sire, and instead judgment must be made based on the calf's phenotype to determine future performance.

Body size is an important genetic factor in beef cattle production (Hammack *et al.*, 2009). The skeletal or frame size of an animal is genetically driven and there is little variation in the bone growth due to the environment (Berg *et al.*, 1968). Large correlations exist between various body measures and live weight at birth, partially due to sire genetics (Nugent *et al.*, 1991a). Early in life, the animal's height and age can be used to estimate future weights or time to get to specific weight or fat targets, because the height gives an indication of the potential growth curve: by 7 months of age (210 days), cattle reach about 80% of mature height but only 35 to 45% of mature weight (Hammack *et al.*, 2009). Weights at different ages are highly correlated and generally growth rates at a given age are related to adult size (Thonney, 2015). Small-framed cattle reach their physiological maturity (when lean growth rate slows and fat accumulation accelerates) at an earlier age and at a lighter weight than do large-framed cattle. Thus, at comparable weights, small-framed cattle will be older, more mature and fatter than their large-framed counterparts (NSW Department of Primary Industries, 2007; Thonney, 2015). When comparing at the same age, small-framed cattle will be generally growing slower, resulting in smaller carcasses compared with large-framed animals with faster growth rates (NSW Department of Primary Industries, 2007). Later in life, carcass weight, plus meat, bone and fat weights within the carcass, can be predicted accurately using a combination of measures on the live animal prior to slaughter. From these measures, live weight is the best predictor for meat and bone weight, particularly in combination with height, stifle and hip-width (Afolayan *et al.*, 2002). Because skeletal size is highly heritable, then linear measures of skeletal size must also be highly repeatable, so measuring them in early life could predict harvest results. Therefore, there is potential to assess skeletal size at an early age to predict the animal's finishing performance.

Cattle temperament is related to stress responsiveness and can be associated with animal performance and meat quality (Behrends *et al.*, 2009; Cafe *et al.*, 2011; Ponnampalam *et al.*, 2017). The temperament of cattle can be assessed by escape velocity (EV) and crush score (CS), traits that are persistent over time (Cafe *et al.*, 2011). Temperamental cattle (faster EV or greater CS) have lower growth rates, produce smaller carcasses with less fat cover, and have darker meat that is tougher to eat, all economically detrimental (Behrends *et al.*, 2009; Burrow *et al.*, 1997; Cafe *et al.*, 2011). The slower growth may be a result of lower feed intake and/or more use of energy in avoidance behaviour. The reduced meat quality is likely a result of metabolic mechanisms. Temperamental cattle have a greater stress response to handling and

transport, resulting in depletion of muscle glycogen before slaughter, more transport of lactate from the muscle into the bloodstream (Boles *et al.*, 2015; Cafe *et al.*, 2011), and hence greater carcass pH and the associated characteristics. Even though animals may become acclimatised to handling, the variation in temperament measured at weaning (when the calf is separated from its dam) may re-emerge at the time of harvest, given that these are the two most stressful times in a beef calf's life (Behrends *et al.*, 2009). However, calves born on a dairy farm are usually taken off their dams within 24 hours of birth and reared by humans. These calves are intensively handled at early ages and see the human as a source of feed rather than a threat. Phenotypic temperament may change because of this hand-rearing, and therefore, the potential relationship between temperament and meat quality is unclear for hand-reared beef-cross-dairy calves.

The aim of this study was to analyse the skeletal size (hip-height, body length, hip-width and cannon bone circumference) and temperament measurements (crush score and exit velocity) measured within the first 200 days of life, of Angus- and Hereford-sired cattle born to dairy-breed cows and finished on hill country pasture, and to evaluate the value of these traits as predictors of carcass and meat traits (carcass weight, carcass length, eye muscle area, rib fat depth, ultimate pH and meat colour). The first hypothesis is that skeletal size at an early age, in conjunction with live weight, can be used to predict future carcass traits. The second hypothesis is that temperament of beef-cross-dairy calves at an early age, will affect carcass weight and meat characteristics.

6.3. Materials and Methodology

This experiment was conducted at Limestone Downs, near Port Waikato, New Zealand (37°28'S, 174°45'E) with approval from the Massey University Animal Ethics Committee (15/65 and 18/50).

6.3.1. Animals and management

Angus-sired and Hereford-sired cattle born on Limestone Downs' dairy farm, in spring 2017 (n= 517) were included in the study. The calves included were a subset of those described in Chapters 3 and 4, being those born in 2017 to 2-year-old (primiparous) and mixed-aged (3+ years old, multiparous) dairy-breed cows, which were predominantly Holstein-Friesian or

Holstein-Friesian-cross-Jersey crossbred. For full details, refer to Chapter 3. Briefly, lactating mixed-aged cows were individually inseminated with semen from Angus and Hereford sires, which were selected on the basis of their Estimated Breeding Values (EBV) so that, within each breed, a spread of birth weight, gestation length and live weight at 600 days of age was achieved, except that birth weight EBV was restricted to the lighter 50% of the breed at the time of selection. When similar sires were available, those with superior EBV for intramuscular fat and eye muscle area were selected. The 15-month-old heifers were joined with either Angus or Hereford bulls by natural mating, and these sires were selected to be in the lightest 15% of breed for birth weight and cost less than NZD 2500 at time of purchase.

All calves had date of birth, sex and live weight recorded within 24 hours of birth, and were DNA parentage verified as part of a previous experiment described by Coleman (2020). Mean birth date was 5 August 2017 for the calves included in the present experiment (with a 69 day-spread, from 5 July to 12 September), with an overall mean birth weight of 36.2 kg (SD 4.6). Calves were artificially reared on an allowance of 4 litres of milk/head/day, and calf meal was offered during the transition from milk to pasture. Calves were weaned at a minimum of 85 kg live weight, resulting in a mean weaning live weight of 95.9 kg (SD 7.5) at a mean age of 84.9 days (SD 11.3). Once weaned, calves were moved from the dairy platform to the sheep and beef hill country platform of the same farm. Male calves were castrated before 4 months of age.

At 4 months of age, at a mean age of 129.3 days (129d, SD 16.0), calves were allocated to 6 grazing herds based on live weight (light, intermediate and heavy) and sex (female and male) and balanced for sire so that, where possible, all sires were represented in each grazing herd within year. In total, there were 6 grazing herds (2 sexes x 3 liveweight groups), and animals remained in those herds throughout the experiment until slaughter. All cattle were grazed on summer-dry hill country pasture on the coastal farm under commercial conditions (refer to Chapter 3 for full details).

Each grazing herd was slaughtered as a complete group on the same day, when the mean live weight reached the slaughter target weight of 500 kg for heifers and 600 kg for steers (refer to Chapter 4 for full details). Heifers included in this study were slaughtered at a mean age of 856 days of age (range 789-934, 28 months old) and 533 kg (SD 35) live weight on-farm, whilst steers were slaughtered at a mean age of 899 days of age (range 844-955, 29 months old) and 621 kg (SD 39). Animals were processed commercially through Greenlea Premier Meats Ltd, Hamilton plant (37°48'S 175°15'E), according to standard New Zealand industry practice (Animal and Animal Products Directorate, 2017), with Halal certification.

6.3.2. Measurements

6.3.2.1. Live weight

Animals were weighed through a weigh crate within 24 hours of birth (0d, Coleman (2020)), at entry to the beef farm at around 4 months of age (129d), at typical weaning age in a beef cow-calf system around 6.5 months of age (200d) and prior to transport on slaughter day, as described in Chapters 3 and 4.

6.3.2.2. Skeletal size

Measurements of skeletal size included hip-height (distance from ground to the top-line between the hook bones), hip-width (distance between the left and right trochanter major), body length (distance along vertebral column from scapula to tuber ischia, or shoulder-to-rump) and cannon bone circumference (circumference at the narrowest point of metacarpus, of front left leg). Measures were recorded to the nearest 0.5 cm, using a height stick (hip-height), callipers (hip-width) or flexible tape measure (body length and cannon bone circumference), and are shown in Figure 6.1. All cattle had hip-height measured within 24 hours of birth (0d), at 129d and at 800d if they were yet to be harvested (n= 487). Body length, hip-width and cannon bone circumference were recorded for all cattle at 0d. In addition, 90 steers were selected as a subset, corresponding to 6 progeny per sire for 15 sires (2 steers from each 3 grazing herds), and were assessed for body length and hip-width at 129d and 800d.



Figure 6.1. Diagram of skeletal size measurements on live animals. Hip-height is the distance from ground to the top-line between the hook bones, hip-width is the distance between the left and right trochanter major, body length is the distance along vertebral column from scapula to tuber ischia (or shoulder-to-rump) and cannon bone circumference is the circumference at the narrowest point of metacarpus.

6.3.2.3. Temperament

Temperament was assessed as a visual crush score (CS) and escape velocity (EV). Crush score (scale 1-5, Table 6.1) was performed while animals were loosely restrained for weighing in the weigh crate (cattle crush model CattleMaster Titan, made by Te Pari Products Ltd, Oamaru, New Zealand; internal dimensions H 203.2 cm x L 300.6 cm x W 75.0 cm) at 200d, 800d and on the day of slaughter within one hour after yarding and prior to transport.

Escape velocity was measured as the time required to traverse 1.83 m distance after exiting the crush, once animals had been weighed at 200d and 800d. The time was measured using infrared photogates (TCi Wireless Timing System, Brower Timing Systems, UT, USA), and then converted to EV (m/sec). The first gate was 1.7 m in front of the weigh crate and the second was 1.83 m distance subsequently. Animals were loosely restrained in the weigh crate for 20 seconds before exiting. This methodology was based on Burrow *et al.* (1988) and adapted by Behrends *et al.* (2009) and Boles *et al.* (2015).

Table 6.1. Crush score assessed on individual cattle while they are loosely restrained for weighing in the crush (20 seconds) based on the behavioural scoring system described by Grandin (1993) and adapted by Cafe *et al.* (2011).

Score	Description
1	Calm – none or slow movements, head mostly still
2	Slightly restless - shifting, looking around more quickly, moving feet
3	Restless - moving backwards and forwards, occasional shaking crate, squirming, may try to put head through bale
4	Nervous - continuous vigorous movement backwards and forwards, snorting, shaking crate
5	Very nervous - continuous violent movement, attempting to jump out, rearing, twisting or violently struggling

6.3.2.4. Carcass and meat traits

As described in Chapter 4, each grazing herd was slaughtered as a complete group on the same day. The bodies were dressed to commercial specifications and hot carcass weight (kg) was recorded prior to the carcasses going into the chiller. Carcasses were chilled ($4\pm 1^{\circ}\text{C}$) overnight and the following morning, the length of one side of the carcass 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.*, 2007). The other side of the carcass was cut between the 12th and 13th rib to expose the eye muscle (*M. longissimus thoracis*) for in-chiller assessment of ultimate pH, rib fat thickness, eye muscle area (EMA) and meat colour score. Ultimate pH was measured by pH spear (Eutech Instruments, Singapore) on the eye muscle and the mean of three measurements was used for analysis. Rib fat thickness (mm) was measured with a ruler as the subcutaneous fat depth at the 13th rib over the deepest part of the eye muscle, and EMA (cm²) was traced onto waterproof paper and subsequently measured using a Planimeter (Placom KP-90N, Tokyo, Japan). Meat colour were scored against the AUS-MEAT / MSA reference standards (AUS-MEAT Limited, 2018). Possible meat colour scores ranged from 1 (light) to 7 (dark).

6.3.3. Statistical Analysis

6.3.3.1. Data cleaning

Animals born to sires with a minimum of 5 progeny across grazing herds were included in the analysis (excluded 3 progeny of 1 Angus sire), following the same criteria explained in Chapter 3 and 4. Animals that went missing, were recorded to have ill health, were removed from their grazing herd for more than 2 months or that died were excluded from analysis of traits measured after they first left their herd (n= 28 to 800d, n= 31 at slaughter). Any animal that had to be chased out of the exit race because they were too placid (n= 7 at 200d, n= 27 at 800d), because there was another animal in the way (n= 1 at 200d, n= 7 at 800d) or those that turned around and went through it backwards (n= 17 at 200d) were not considered for measures

of EV at that age. Any carcass recorded with a defect was excluded from carcass weight data due to potential trimming of the carcass prior to weighing (n= 3). The final dataset consisted of 486 animals.

6.3.3.2. Statistical models

The traits analysed included carcass weight, carcass length, EMA, rib fat depth, meat colour scores and ultimate pH (Table 6.2). General linear models (SAS 9.4, SAS Institute Inc., Cary, NC, USA) were used to estimate the association of live weight, skeletal size and temperament measurements with the 6 carcass and meat traits mentioned above. The analysis was done separately for steers and heifers, given the different target slaughter weight according to sex in the industry. Depending on the measurements available, analyses were done at birth (0d), entry to the beef farm at 4 months of age (129d) or at 6.5 months of age (200d). All models included the fixed effects of breed of sire (n= 2 breeds, Angus and Hereford) and grazing herd (n= 3 herds per sex, based on live weight light, intermediate and heavy). Given that exact age or date of birth of a calf at the saleyard is usually not known, age distribution of the calves was considered as a class effect in all models (n= 3 classes, classified as early [first quartile, from 5 July to 24 July], mid [second and third quartiles, from 24 July to 17 August] or late [fourth quartile, from 17 August to 12 September] born in the season). Live weight at the corresponding age was fitted as a covariate in all models. In addition, each trait measured was fitted one at the time in conjunction with live weight as covariates. Any trait with significant effect at $P < 0.05$ level, were fitted together in a final model as covariates, and their significance level was used to determine their importance in the model.

6.4. Results

Live animal measurements (weight, skeletal size and temperament), carcass and meat traits for Angus- and Hereford-sired steers and heifers born in 2017 are presented in Table 6.2.

Table 6.2. Summary of number of animals, unadjusted mean (\pm SD), range and coefficient of variation (CV%) of live animal measurements (weight, skeletal size and temperament at 0, 129, 200 and 800 days of age), carcass and meat traits (slaughter age and live weight, carcass weight and length, eye-muscle area (EMA), rib fat depth, ultimate pH and meat colour score) for beef-cross-dairy heifers and steers.

Trait	Heifer				Steer				
	N	Mean	Range	CV%	N	Mean	Range	CV%	
Live weight									
LWT (kg)	0d	238	34.8 \pm 4.3	(23.1-46.0)	12.33	248	37.5 \pm 4.6	(23.9-50.4)	12.18
	129d	238	128.6 \pm 15.5	(89.0-174.5)	12.06	248	132.5 \pm 15.4	(88.4-169.5)	11.65
	200d	237	168.6 \pm 19.7	(115.5-218.0)	11.66	248	170.1 \pm 18.1	(124.5-220.0)	10.63
Skeletal size									
Cannon bone circumference (cm)	0d	236	10.9 \pm 0.6	(9.4-12.5)	5.60	248	11.7 \pm 0.6	(9.8-14.0)	5.48
Hip-height (cm)	0d	215	80.3 \pm 3.5	(70.4-87.9)	4.36	230	81.7 \pm 3.1	(73.4-88.4)	3.76
	129d	238	96.8 \pm 3.1	(88.5-105.0)	3.16	248	96.9 \pm 3.4	(87.0-107.5)	3.48
	800d	236	130.0 \pm 3.6	(118.5-139.5)	2.76	248	136.4 \pm 3.6	(120.5-146.0)	2.62
Body length (cm)	0d	235	57.6 \pm 3.4	(50.0-69.2)	5.84	247	58.9 \pm 3.3	(48.8-69.0)	5.57
	129d	0				82	88.8 \pm 4.3	(80.0-101.0)	4.81
	800d	0				81	130.9 \pm 3.5	(121.0-140.0)	2.67
Hip-width (cm)	0d	212	16.3 \pm 1.0	(13.5-19.5)	5.86	234	16.5 \pm 1.0	(14.0-20.5)	6.08
	129d	0				82	27.6 \pm 1.5	(24.5-32.0)	5.59
	800d	0				81	51.9 \pm 1.7	(48.0-58.0)	3.28
Temperament									
Exit velocity (m/s)	200d	219	1.2 \pm 0.4	(0.1-2.4)	34.17	238	1.1 \pm 0.4	(0.2-3.1)	37.49
	800d	208	0.8 \pm 0.5	(0.1-2.4)	57.19	235	1.1 \pm 0.5	(0.2-2.7)	41.52
Crush score [‡]	200d	237	1.4 \pm 0.6	(1-3)	44.41	248	1.4 \pm 0.6	(1-3)	43.92
	800d	237	1.3 \pm 0.6	(1-3)	43.35	248	1.4 \pm 0.7	(1-4)	46.96
	slaughter	237	1.3 \pm 0.6	(1-3)	42.83	248	1.4 \pm 0.7	(1-4)	48.61
Carcass and meat									
Age (days)		238	855.8 \pm 33.3	(789.0-934.0)	3.89	248	898.8 \pm 26.3	(844.0-955.0)	2.92
LWT (kg)		238	533.4 \pm 34.6	(447.0-646.0)	6.49	248	620.8 \pm 39.2	(510.0-738.0)	6.32
Carcass weight (kg)		236	257.2 \pm 17.9	(212.0-321.0)	6.95	247	303.1 \pm 23.9	(245.6-363.6)	7.87
Carcass length (cm)		238	235.9 \pm 5.9	(218.0-251.0)	2.49	248	251.5 \pm 5.9	(234.0-266.5)	2.33
EMA (cm ²)		238	72.0 \pm 8.3	(48.0-97.1)	11.59	248	71.0 \pm 8.2	(50.7-97.1)	11.49
Rib fat depth (mm)		238	7.27 \pm 3.41	(1-22)	46.88	248	7.80 \pm 2.88	(3-16)	36.95
Ultimate pH		238	5.61 \pm 0.15	(5.4-6.6)	2.64	248	5.63 \pm 0.12	(5.4-6.0)	2.18
Meat colour score [‡]		238	3.15 \pm 0.63	(2-6)	20.00	248	2.97 \pm 0.23	(2-4)	7.66

[‡]Crush score: scale 1 (calm) to 5 (very nervous). [‡] Meat colour score: scale 1 (light) to 7 (dark).

6.4.1. Predictions of carcass size, muscularity and fat using skeletal size measurements

6.4.1.1. Skeletal size measurements at birth

The regression coefficients for the predictions of carcass weight, carcass length, EMA and rib fat depth using live weight and skeletal size measurements at birth (0d), measured on Angus- and Hereford-sired cattle, are presented in Table 6.3 and Table 6.4 for heifers and steers respectively.

For heifers, live weight and hip-height measured at birth were associated with carcass weight ($P < 0.05$, Table 6.3). Live weight at birth by itself was a significant predictor of carcass

weight ($R^2= 19\%$). The prediction of carcass weight improved by combining live weight with hip-height at birth ($R^2= 22\%$), such that an additional 1.02 kg of carcass weight was predicted per extra 1 cm tall ($P<0.05$) and an additional 1.15 kg of carcass weight per extra 1 kg live weight ($P<0.05$).

Significant predictors of carcass length in heifers were live weight, hip-height, body length and cannon bone circumference measured at birth ($P<0.05$, Table 6.3). Live weight at birth was a significant predictor of carcass length ($R^2= 29\%$). The ability to predict carcass length increased when combining live weight with body length ($R^2= 30\%$), combining live weight with cannon bone ($R^2= 31\%$) and combining live weight with hip-height ($R^2= 37\%$). When all of these significant measurements were included in the same model ($R^2= 39\%$), hip-height was the most significant predictor (additional 0.56 cm in carcass length per extra 1 cm tall, $P<0.05$), followed by cannon bone circumference (additional 1.65 cm in carcass length per 1 cm thicker cannon bone, $P<0.05$), but live weight and body length became non-significant ($P>0.05$).

For steers, live weight, length and cannon bone circumference measured at birth were associated with carcass weight ($P<0.05$, Table 6.4). Live weight by itself was a significant predictor of carcass weight ($R^2= 39\%$). The prediction of carcass weight was increased by combining live weight with cannon bone circumference ($R^2= 40\%$) or combining live weight with body length ($R^2= 40\%$). When live weight was combined with both body length and cannon bone circumference ($R^2= 41\%$), the best predictor was body length (additional 1.17 kg of carcass weight per 1 cm longer body, $P<0.05$), but live weight and cannon bone circumference became non-significant ($P>0.05$).

Carcass length in steers could be predicted with live weight and body length measured at birth ($P<0.05$, Table 6.4). Live weight by itself was a significant predictor of carcass length ($R^2= 21\%$), and combining live weight with body length increased the prediction ($R^2= 24\%$), with body length being the most significant predictor (0.36 cm additional carcass length per 1 cm longer body, $P<0.05$), followed by live weight at birth (0.23 cm additional carcass length per extra 1 kg live weight, $P<0.05$).

Rib fat depth was associated with birth weight, such that a decrease of 0.11 mm ($R^2= 18\%$) and 0.09 mm ($R^2= 7\%$) in fat depth were associated with an extra 1 kg live weight at birth in heifers and steers respectively ($P<0.05$). No measurements at birth could predict EMA ($P>0.05$), in either heifers or steers.

Table 6.3. Estimates of regression coefficients (*P*-value in brackets) using live weight (LWT) and skeletal size measurements (hip-height, body length, hip-width and cannon bone circumference) at birth (0 days of age) to predict carcass weight, carcass length, eye muscle area (EMA) and rib fat depth for Angus- and Hereford-sired heifers.

Dependent variable	LWT Od (kg)	Hip-height Od (cm)	Body length Od (cm)	Hip-width Od (cm)	Cannon bone circumference Od (cm)	Breed effect <i>P</i> -value [‡]	Age effect <i>P</i> -value [‡]	Grazing herd effect <i>P</i> -value [‡]	n	R ²
Carcass weight (kg)	1.60 (<0.001)					0.595	0.005	<0.001	236	0.19
	1.15 (0.002)	1.02 (0.023)				0.882	0.003	<0.001	213	0.22
	1.43 (<0.001)		0.35 (0.410)			0.554	0.006	<0.001	233	0.19
	1.39 (<0.001)			1.92 (0.265)		0.801	0.006	<0.001	210	0.20
	1.21 (<0.001)				4.43 (0.051)	0.454	0.009	<0.001	234	0.20
Carcass length (cm)	0.53 (<0.001)					0.128	0.104	<0.001	238	0.29
	0.22 (0.040)	0.61 (<0.001)				0.087	0.060	<0.001	215	0.37
	0.40 (<0.001)		0.26 (0.043)			0.122	0.137	<0.001	235	0.30
	0.44 (<0.001)			0.76 (0.145)		0.137	0.049	<0.001	212	0.32
	0.39 (<0.001)				1.59 (0.022)	0.169	0.101	<0.001	236	0.31
	0.01 (0.945)	0.56 (<0.001)	0.17 (0.208)		1.65 (0.016)	0.120	0.066	<0.001	210	0.39
EMA (cm ²)	0.01 (0.942)					0.440	0.309	0.520	238	0.02
	-0.02 (0.906)	0.09 (0.682)				0.344	0.297	0.378	215	0.03
	-0.06 (0.742)		0.13 (0.546)			0.464	0.306	0.495	235	0.03
	-0.04 (0.852)			0.33 (0.704)		0.293	0.354	0.279	212	0.03
	0.01 (0.941)				0 (0.998)	0.436	0.308	0.506	236	0.02
Rib fat depth (mm)	-0.11 (0.032)					0.415	0.364	<0.001	238	0.18
	-0.09 (0.196)	-0.05 (0.573)				0.245	0.471	<0.001	215	0.19
	-0.11 (0.101)		0 (0.978)			0.391	0.388	<0.001	235	0.18
	-0.05 (0.514)			-0.47 (0.157)		0.356	0.230	<0.001	212	0.19
	-0.07 (0.305)				-0.45 (0.304)	0.353	0.302	<0.001	236	0.19

R²: coefficient of determination. [‡]Breed effect *P*-value: n= 2 breeds, Angus and Hereford. [‡]Age effect *P*-value: n= 3 classes, early (first quartile, from 5 July to 24 July), mid (second and third quartiles, from 24 July to 17 August) or late (fourth quartile, from 17 August to 12 September) born in the season. [‡]Grazing herd effect *P*-value: n= 3 herds per sex, based on live weight (light, intermediate and heavy).

Table 6.4. Estimates of regression coefficients (*P*-value in brackets) using live weight (LWT) and skeletal size measurements (hip-height, body length, hip-width and cannon bone circumference) at birth (0 days of age) to predict carcass weight, carcass length, eye muscle area (EMA) and rib fat depth for Angus- and Hereford-sired steers.

Dependent variable	LWT 0d (kg)	Hip-height 0d (cm)	Body length 0d (cm)	Hip-width 0d (cm)	Cannon bone circumference 0d (cm)	Breed effect <i>P</i> -value*	Age effect <i>P</i> -value [†]	Grazing herd effect <i>P</i> -value [‡]	n	R ²
Carcass weight (kg)	1.52 (<0.001)					0.509	0.004	<0.001	247	0.39
	1.25 (0.001)	0.74 (0.181)				0.646	0.006	<0.001	229	0.40
	0.97 (0.005)		1.28 (0.006)			0.471	0.001	<0.001	246	0.40
	1.46 (<0.001)			0.65 (0.700)		0.492	0.019	<0.001	233	0.39
	1.10 (0.002)				4.75 (0.050)	0.745	0.017	<0.001	247	0.40
	0.67 (0.083)		1.17 (0.014)		3.92 (0.108)	0.656	0.006	<0.001	246	0.41
Carcass length (cm)	0.39 (<0.001)					<0.001	0.590	<0.001	248	0.21
	0.29 (0.003)	0.23 (0.119)				0.001	0.307	<0.001	230	0.24
	0.23 (0.016)		0.36 (0.006)			<0.001	0.404	<0.001	247	0.24
	0.42 (<0.001)			-0.25 (0.587)		<0.001	0.701	<0.001	234	0.23
	0.38 (<0.001)				0.07 (0.917)	<0.001	0.615	<0.001	248	0.21
EMA (cm ²)	0.06 (0.589)					0.403	0.229	0.003	248	0.10
	0.01 (0.927)	0.11 (0.644)				0.428	0.144	0.005	230	0.12
	-0.06 (0.678)		0.28 (0.157)			0.426	0.172	0.003	247	0.11
	-0.07 (0.644)			0.84 (0.232)		0.455	0.139	0.012	234	0.11
	-0.03 (0.828)				1.05 (0.294)	0.318	0.346	0.002	248	0.11
Rib fat depth (mm)	-0.09 (0.034)					0.750	0.971	0.008	248	0.07
	-0.12 (0.028)	0.10 (0.217)				0.570	0.754	0.030	230	0.06
	-0.12 (0.023)		0.07 (0.340)			0.727	0.933	0.008	247	0.07
	-0.07 (0.217)			-0.08 (0.764)		0.283	0.988	0.027	234	0.06
	-0.06 (0.246)				-0.31 (0.399)	0.650	0.914	0.007	248	0.07

R²: coefficient of determination. *Breed effect *P*-value: n= 2 breeds, Angus and Hereford. †Age effect *P*-value: n= 3 classes, early (first quartile, from 5 July to 24 July), mid (second and third quartiles, from 24 July to 17 August) or late (fourth quartile, from 17 August to 12 September) born in the season. ‡Grazing herd effect *P*-value: n= 3 herds per sex, based on live weight (light, intermediate and heavy).

6.4.1.2. Skeletal size measurements at entry to the beef farm

The regression coefficients for the predictions of carcass weight, carcass length, EMA and rib fat depth using live weight and skeletal size measurements at entry to the beef farm (129d), measured on Angus- and Hereford-sired cattle, are presented in Table 6.5 and Table 6.6 for all heifers and steers respectively. In addition, extra measures performed on a subset of steers are presented in Table 6.7.

For heifers, live weight at 129d by itself was a significant predictor of carcass weight ($R^2=17\%$) and length ($R^2=19\%$). The prediction of carcass weight was increased by combining live weight with hip-height at 129d ($R^2=20\%$, $P<0.05$, Table 6.5), such that an additional 0.60 kg of carcass weight was projected per extra 1 kg live weight and an additional 1.25 kg of carcass weight per extra 1 cm tall. Similarly, the best prediction of carcass length combined live weight with hip-height ($R^2=27\%$, $P<0.05$, Table 6.5), with hip-height being the most significant predictor (0.73 cm additional carcass length per extra 1 cm tall) and live weight becoming non-significant ($P>0.05$). No measurements at 129d could predict EMA or rib fat depth in heifers ($P>0.05$).

For steers, live weight at 129d was a predictor of carcass weight ($R^2=40\%$) and length ($R^2=21\%$). The prediction of carcass length was increased by combining live weight with hip-height at 129d ($R^2=25\%$, $P<0.05$, Table 6.6), with hip-height being the most significant predictor (0.49 cm additional carcass length per extra 1 cm tall), followed by live weight (0.12 cm additional carcass length per extra 1 kg live weight). Although live weight by itself was not associated with EMA ($P>0.05$), live weight partially explained EMA in combination with hip-height, so that an additional 0.14 cm² was associated with an extra 1 kg at 129d ($P<0.05$) when steers were of the same hip-height ($P>0.05$, $R^2=12\%$). No measurements at 129d could predict rib fat depth in steers ($P>0.05$).

For the subset of steers, live weight at 129d was a predictor of carcass weight ($R^2=43\%$), length ($R^2=18\%$) and EMA ($R^2=20\%$). The best model to predict carcass weight combined live weight and hip-width measured at 129d ($R^2=46\%$, $P<0.05$, Table 6.7), such that 5.34 kg extra carcass was obtained per extra 1 cm wider body on steers of the same live weight ($P>0.05$). The best model to predict carcass length combined live weight with hip-height ($R^2=22\%$, $P<0.05$, Table 6.7), such that an additional 1 cm hip-height at 129d was associated with additional 0.48 cm in carcass length for steers of the same live weight ($P>0.05$). Rib fat depth was associated with hip-height (additional 0.28 mm in fat depth per extra 1 cm tall, $R^2=24\%$, $P<0.05$) or length (additional 0.25 mm in fat depth per 1 cm longer body, $R^2=22\%$, $P<0.05$) for steers of the same live weight ($P>0.05$).

Table 6.5. Estimates of regression coefficients (*P*-value in brackets) using live weight (LWT) and hip-height at 129 days of age to predict carcass weight, carcass length, eye muscle area (EMA) and rib fat depth for Angus- and Hereford-sired heifers.

Dependent variable	LWT 129d (kg)	Hip-height 129d (cm)	Breed effect <i>P</i> -value [‡]	Age effect <i>P</i> -value [‡]	Grazing herd effect <i>P</i> -value [‡]	n	R ²
Carcass weight (kg)	0.75 (<0.001)		0.474	0.007	<0.001	236	0.17
	0.60 (<0.001)	1.25 (0.007)	0.832	0.004	<0.001	236	0.20
Carcass length (cm)	0.12 (0.004)		0.026	0.007	<0.001	238	0.19
	0.04 (0.340)	0.73 (<0.001)	0.170	0.002	<0.001	238	0.27
EMA (cm ²)	0.07 (0.306)		0.549	0.599	0.558	238	0.03
	0.10 (0.177)	-0.25 (0.285)	0.695	0.570	0.547	238	0.03
Rib fat depth (mm)	0.01 (0.651)		0.455	0.393	<0.001	238	0.17
	0.02 (0.435)	-0.09 (0.337)	0.363	0.371	<0.001	238	0.17

R²: coefficient of determination. [‡]Breed effect *P*-value: n= 2 breeds, Angus and Hereford. [‡]Age effect *P*-value: n= 3 classes, early (first quartile, from 5 July to 24 July), mid (second and third quartiles, from 24 July to 17 August) or late (fourth quartile, from 17 August to 12 September) born in the season. [‡]Grazing herd effect *P*-value: n= 3 herds per sex, based on live weight (light, intermediate and heavy).

Table 6.6. Estimates of regression coefficients (*P*-value in brackets) using live weight (LWT) and hip-height at 129 days of age to predict carcass weight, carcass length, eye muscle area (EMA) and rib fat depth for Angus- and Hereford-sired steers.

Dependent variable	LWT 129d (kg)	Hip-height 129d (cm)	Breed effect <i>P</i> -value [‡]	Age effect <i>P</i> -value [‡]	Grazing herd effect <i>P</i> -value [‡]	n	R ²
Carcass weight (kg)	0.87 (<0.001)		0.150	0.147	<0.001	247	0.40
	0.78 (<0.001)	0.57 (0.279)	0.224	0.135	<0.001	247	0.40
Carcass length (cm)	0.20 (<0.001)		<0.001	0.019	<0.001	248	0.21
	0.12 (0.010)	0.49 (0.001)	<0.001	0.014	<0.001	248	0.25
EMA (cm ²)	0.12 (0.051)		0.544	0.893	0.114	248	0.12
	0.14 (0.043)	-0.14 (0.506)	0.633	0.905	0.113	248	0.12
Rib fat depth (mm)	-0.02 (0.327)		0.868	0.494	0.003	248	0.05
	-0.03 (0.279)	0.04 (0.636)	0.938	0.496	0.004	248	0.05

R²: coefficient of determination. [‡]Breed effect *P*-value: n= 2 breeds, Angus and Hereford. [‡]Age effect *P*-value: n= 3 classes, early (first quartile, from 5 July to 24 July), mid (second and third quartiles, from 24 July to 17 August) or late (fourth quartile, from 17 August to 12 September) born in the season. [‡]Grazing herd effect *P*-value: n= 3 herds per sex, based on live weight (light, intermediate and heavy).

Table 6.7. Estimates of regression coefficients (*P*-value in brackets) using live weight (LWT) and skeletal size measurements (hip-height, body length and hip-width) at 129 days of age to predict carcass weight, carcass length, eye muscle area (EMA) and rib fat depth for a subset of Angus- and Hereford-sired steers.

Dependent variable	LWT 129d (kg)	Hip-height 129d (cm)	Body length 129d (cm)	Hip-width 129d (cm)	Breed effect <i>P</i> -value [‡]	Age effect <i>P</i> -value [†]	Grazing herd effect <i>P</i> -value [†]	n	R ²
Carcass weight (kg)	0.97 (<0.001)				0.311	0.362	<0.001	81	0.43
	0.88 (0.001)	0.65 (0.402)			0.376	0.393	<0.001	81	0.43
	1.10 (<0.001)		-0.61 (0.431)		0.266	0.461	<0.001	81	0.43
	0.56 (0.070)			5.34 (0.045)	0.389	0.378	<0.001	81	0.46
Carcass length (cm)	0.19 (0.009)				0.022	0.256	0.093	82	0.18
	0.12 (0.114)	0.48 (0.038)			0.039	0.281	0.103	82	0.22
	0.13 (0.132)		0.25 (0.280)		0.034	0.202	0.070	82	0.19
	0.07 (0.456)			1.53 (0.056)	0.029	0.223	0.068	82	0.22
EMA (cm ²)	0.28 (0.009)				0.944	0.602	0.043	82	0.20
	0.30 (0.013)	-0.10 (0.774)			0.974	0.616	0.043	82	0.20
	0.39 (0.004)		-0.47 (0.186)		0.905	0.446	0.069	82	0.22
	0.11 (0.415)			2.18 (0.074)	0.836	0.549	0.034	82	0.23
Rib fat depth (mm)	0.01 (0.890)				0.377	0.066	0.025	82	0.18
	-0.03 (0.381)	0.28 (0.020)			0.549	0.060	0.027	82	0.24
	-0.05 (0.278)		0.25 (0.046)		0.545	0.027	0.010	82	0.22
	-0.02 (0.759)			0.26 (0.540)	0.406	0.083	0.025	82	0.18

R²: coefficient of determination. [‡]Breed effect *P*-value: n= 2 breeds, Angus and Hereford. [†]Age effect *P*-value: n= 3 classes, early (first quartile, from 5 July to 24 July), mid (second and third quartiles, from 24 July to 17 August) or late (fourth quartile, from 17 August to 12 September) born in the season. [†]Grazing herd effect *P*-value: n= 3 herds per sex, based on live weight (light, intermediate and heavy).

6.4.2. Predictions of growth and meat traits using temperament measurements

6.4.2.1. Temperament measurements in early life

The regression coefficients for the predictions of carcass weight, rib fat depth, ultimate pH and meat colour, using live weight and temperament measurements at 200d on Angus- and Hereford-sired cattle, are presented in Table 6.8 and Table 6.9 for heifers and steers respectively.

For heifers, live weight at 200d was the best predictor of carcass weight ($R^2 = 31\%$, $P < 0.05$, Table 6.8). The addition of EV slightly increased the prediction of carcass weight ($R^2 = 32\%$, $P < 0.05$) such that an additional 0.76 kg of carcass weight was projected per extra 1 kg live weight ($P < 0.05$) and an additional 5.61 kg of carcass weight per extra 1 m/s increase in EV at 200d ($P < 0.05$). Live weight at 200d was also associated with ultimate pH, such that a 0.001 decrease in pH was projected per extra 1 kg live weight ($R^2 = 36\%$, $P < 0.05$). No temperament measurement at 200d could predict rib fat depth or meat colour scores ($P > 0.05$).

For steers, live weight at 200d was the only predictor of carcass weight ($R^2 = 48\%$, $P < 0.05$, Table 6.9). No temperament measurements at 200d were associated with rib fat depth, ultimate pH or meat colour scores ($P > 0.05$).

Table 6.8. Estimates of regression coefficients (*P*-value in brackets) using live weight (LWT) and temperament measurements (crush score and exit velocity) at 200 days of age to predict carcass weight, rib fat depth, ultimate pH and meat colour for Angus- and Hereford-sired heifers.

Dependent variable	LWT 200d (kg)	Crush Score 200d	Exit Velocity 200d (m/s)	Breed effect <i>P</i> -value [‡]	Age effect <i>P</i> -value [†]	Grazing herd effect <i>P</i> -value [†]	n	R ²
Carcass weight (kg)	0.76 (<0.001)			0.250	<0.001	<0.001	235	0.31
	0.76 (<0.001)	0.31 (0.839)		0.252	<0.001	<0.001	235	0.31
	0.76 (<0.001)		5.61 (0.026)	0.147	<0.001	<0.001	217	0.32
Rib fat depth (mm)	0.022 (0.215)			0.367	0.571	<0.001	237	0.18
	0.022 (0.216)	-0.057 (0.861)		0.367	0.573	<0.001	237	0.18
	0.021 (0.253)		0.433 (0.411)	0.511	0.599	<0.001	219	0.16
Ultimate pH	-0.001 (0.047)			0.054	0.076	<0.001	237	0.36
	-0.001 (0.048)	0.000 (0.990)		0.054	0.078	<0.001	237	0.36
	-0.001 (0.209)		0.009 (0.647)	0.067	0.254	<0.001	219	0.34
Meat colour score	-0.004 (0.187)			0.413	0.500	<0.001	237	0.14
	-0.004 (0.186)	0.057 (0.349)		0.406	0.461	<0.001	237	0.14
	-0.006 (0.100)		-0.055 (0.578)	0.443	0.388	<0.001	219	0.14

R²: coefficient of determination. [‡]Breed effect *P*-value: n= 2 breeds, Angus and Hereford. [†]Age effect *P*-value: n= 3 classes, early (first quartile, from 5 July to 24 July), mid (second and third quartiles, from 24 July to 17 August) or late (fourth quartile, from 17 August to 12 September) born in the season. [†]Grazing herd effect *P*-value: n= 3 herds per sex, based on live weight (light, intermediate and heavy).

Table 6.9. Estimates of regression coefficients (*P*-value in brackets) using live weight (LWT) and temperament measurements (crush score and exit velocity) at 200 days of age to predict carcass weight, rib fat depth, ultimate pH and meat colour for Angus- and Hereford-sired steers.

Dependent variable	LWT 200d (kg)	Crush Score 200d	Exit Velocity 200d (m/s)	Breed effect <i>P</i> -value [‡]	Age effect <i>P</i> -value [‡]	Grazing herd effect <i>P</i> -value [‡]	n	R ²
Carcass weight (kg)	0.81 (<0.001)			0.259	0.001	<0.001	247	0.48
	0.82 (<0.001)	-1.96 (0.284)		0.322	0.001	<0.001	247	0.48
	0.79 (<0.001)		-5.05 (0.076)	0.652	0.002	<0.001	237	0.48
Rib fat depth (mm)	-0.012 (0.431)			0.803	0.550	0.003	248	0.05
	-0.012 (0.409)	0.099 (0.740)		0.773	0.529	0.003	248	0.05
	-0.012 (0.429)		-0.345 (0.463)	0.927	0.546	0.002	238	0.05
Ultimate pH	-0.001 (0.124)			0.931	0.920	<0.001	248	0.43
	-0.001 (0.091)	0.011 (0.248)		0.954	0.847	<0.001	248	0.43
	-0.001 (0.184)		-0.004 (0.777)	0.731	0.953	<0.001	238	0.42
Meat colour score	0.001 (0.629)			0.513	0.425	0.001	248	0.08
	0.001 (0.452)	-0.043 (0.065)		0.378	0.487	<0.001	248	0.09
	0.001 (0.584)		-0.041 (0.253)	0.492	0.684	0.001	238	0.07

R²: coefficient of determination. [‡]Breed effect *P*-value: n= 2 breeds, Angus and Hereford. [‡]Age effect *P*-value: n= 3 classes, early (first quartile, from 5 July to 24 July), mid (second and third quartiles, from 24 July to 17 August) or late (fourth quartile, from 17 August to 12 September) born in the season. [‡]Grazing herd effect *P*-value: n= 3 herds per sex, based on live weight (light, intermediate and heavy).

6.5. Discussion

The aim of this experiment was to analyse measurements of skeletal size and temperament in Angus- and Hereford-sired cattle born to dairy-breed cows and finished on hill country pasture, and to evaluate the value of these measurements in early life as predictors of carcass and meat traits. This could assist producers in the decision of buying calves from the sale yards without having their parentage information, or in setting prices and contracts between dairy farmers, rearers and finishers.

Live weight at birth, 129d and 200d was highly significant to predict future carcass size. In heifers, the accuracy of predictions of carcass weight with live weight were low to moderate ($R^2= 17$ to 31%). In steers, the accuracy of the predictions of carcass weight with live weight were modest ($R^2= 39$ to 48%), increased with age, and remained similar when combining live weight with other skeletal size measurements. Live weights at different ages are highly correlated and related to adult size, as they are measures along the same growth curve for each animal (Thonney, 2015). Therefore, strong relationships between live weight and carcass weight were expected.

New Zealand industry recommendations are to rear male calves that are at minimum 40 kg at birth, and certainly no less than 35 kg, as these lighter calves tend to grow slower, require more milk replacer and have more health problems (Beef+Lamb New Zealand, 2018; Country-Wide, 2003; Muir *et al.*, 2002). The steers in the present study had a mean birth weight of 37.5, with a range from 23.9 to 50.4 kg (26.5 kg difference between lightest and heaviest calf). Considering the extremes, the -13.6 kg and +12.9 kg difference in birth weight between the lighter and heavier calf compared with the average calf, would represent a potential loss of 20.6 kg in carcass weight for the lighter and gain of 19.7 kg for the heavier calf (total of 40.3 kg carcass difference between lightest and heaviest calf). With an average price of \$5.75 per kilogram of carcass (average price paid by Greenlea Premier Meats for the 2017 steer cohort), this would represent a total of \$231.61 difference in carcass value between the lightest and heaviest calf at birth. If the available steers were split into groups according to birth weight, calves weighing less than 35 kg at birth would have a carcass weight 8.0 kg lighter than calves between 35-40 kg birth weight (worth \$45.70 per carcass). On the contrary, calves with greater than 40 kg birth weight would have 8.2 kg greater carcass weight (or \$47.05 per carcass) than calves between 35-40 kg birth weight. Consequently, some value in carcass is gained by rearing calves born heavier, without considering any other factors. This expected gain in carcass value could be

shared between finisher, rearer and dairy farmer, by paying a better price for those calves over 35 kg or 40 kg at birth.

The predictions of carcass weight and length had similar accuracies with the variables tested as predictors. Even though the relationship between skeletal size and mature weight is direct, it depends on muscling characteristics because weight is a mass measurement, not a linear one (Owens *et al.*, 1993). Carcass length increases with slaughter weight, but not at the same proportion in all types of cattle (Chambaz *et al.*, 2001). Purchas *et al.* (2007) have previously shown that longer carcasses can be lighter, if they have a greater proportion of “legginess” (difference between body length and carcass length). Thus, some differences in predictions of carcass weight and length were expected.

In heifers, the accuracy of predictions for both carcass weight and length increased if live weight was combined with hip-height. The increase in accuracy was equal at both 0d and 129d, and much greater for carcass length (+8%) than for carcass weight (+3%). It has been previously reported that by 7 months of age, cattle reach about 80% of mature height and 35-45% of mature weight (Hammack *et al.*, 2009). This is particularly true for heifers, because long bones (which contribute to the height of the animal) cease to increase in length after epiphyseal closure or growth plate fusion (Owens *et al.*, 1993), which occurs at puberty at around 10-15 months of age depending on the breed (García-Muñiz *et al.*, 1997; Hickson *et al.*, 2011). In this study, hip-height at 0d and 129d represented 62% and 75% of hip-height at 800d for heifers respectively (Table 6.2). Consequently, hip-height at early age explained a good proportion of the variation of carcass length and weight at slaughter in heifers, because of its association with hip-height at 800d. Hence, taller heifers within similar live weights at birth or entry to the beef cattle farm, are expected to have a greater carcass weight and value.

In steers, combining live weight with body length at 0d or live weight with hip-height at 129d increased the accuracy of prediction of carcass length (+3% and +4% respectively). Carcass length was measured from distal end of the tarsal bones (the hock or back-heel of the animal) to the mid-point of the cranial edge of the first rib. Thus, carcass length is a combination of body length and back legs of cattle, which represent their height.

Cannon bone circumference affected in similar magnitude and significance carcass weight of heifers ($P=0.0514$) and steers ($P=0.0499$), and to a lesser extent, carcass length in heifers. Furthermore, cannon bone circumference was highly correlated with live weight and all the other skeletal size measures taken at birth (data not shown). It has been previously shown that cannon bone can be larger in calves sired by bulls with larger birth weight EBV and lower

calving ease EBV, after removal of birth weight effects (Nugent *et al.*, 1991a; Nugent *et al.*, 1991b). Cannon bone seemed to be an indicator of skeletal size (Meyer, 1995), and together with heart girth, has been used to differentiate calves based on structural thickness (Nugent *et al.*, 1991b). Therefore, thicker cannon bones at birth gave an indication of longer and heavier carcasses because larger bones are consistent with more weightbearing capacity of cattle with increased body volume (Gilbert *et al.*, 1993). Given that the cannon bone is easily accessed, its measurement or visual inspection could be used as part of the assessment of calves at the time of purchase.

No measurements at birth could predict EMA. However, live weight partially explained EMA in all steers when they were the same hip-height at 129d, and live weight at 129d did explain EMA in the subset of steers, with and without adjustment for hip-height or length. This means that animals may have greater EMA if they are heavier, and likely wider, rather than longer or taller at 129d. This makes sense because EMA is a 2-dimensional measurement made on the *M. longissimus thoracis* muscle cross-section, on a transverse plane of the carcass between the 12th and 13th rib, and so is an indicator of muscle shape rather than total muscle in the carcass (McKiernan, 2007; Thonney, 2015). In addition, as animals age, muscle percentage in the whole carcass increases (until fattening phase (Berg *et al.*, 1968)), so EMA increases as the animal gets bigger because of its correlation to the size of the animal (McKiernan, 2007).

Rib fat depth was partially associated with birth weight, such that heavier calves at birth had lower fat depth on the carcass. Given that live weight is related to adult size, a genotype with larger adult size will be leaner than a smaller genotype at a given carcass weight (Thonney, 2015). Although greater rib fat depth was found in steers in the subset that were taller or longer adjusted to the same live weight at 129d, this result was not seen when all steers (or heifers) were considered. It is likely that the artificial rearing of the cattle influenced these results by altering the relationships of live weight to age, because all animals were weaned at a set weight and so smaller animals were fed milk for longer, thus increasing their weight gain compared with animals already weaned. This highlights that there is greater confidence in the selection of cattle based on phenotypic live animal measurements at birth compared to 129d, because at 129d, transient environmental effects on the phenotype can be very pronounced.

Carcass weight was highly explained by live weight at 200d. The addition of CS or EV didn't improve the overall prediction indicating that they explained only a very small proportion of the variance, although there were some minor effects (being EV positively affecting carcass weight in heifers and a negative tendency in steers). Further, ultimate pH and meat colour score were not affected by temperament measurements at 200d but were highly affected by grazing

herd. Handling, transportation, and pre- and post-slaughter conditions (yards, weather, animal and/or human interactions) contribute to muscle ultimate pH post-mortem (Dixon *et al.*, 1996; McDade, 2010; Njisane *et al.*, 2017). In turn, ultimate pH can alter meat colour by changing the chemical state of the pigment myoglobin (Purchas, 1990; Warriss, 1990). It was evident for the cattle in this experiment that the stress response during the immediate pre-slaughter period had more to do with the grazing herd the animals were in, rather than individual temperament driving the behaviours. Nevertheless, ultimate pH was mostly within normal ranges (98% below pH 6) as was meat colour (88% below colour score 3).

Animals in this study were calm at 200d, with mean EV of 1.2 m/s (maximum of 3.05 m/s) and CS of 1.4 (maximum of CS 3 in a 1-5 scale). This is supported by previous studies where the temperamental response of *Bos Taurus* breeds (such as Angus) has been low, particularly when comparing to other breeds containing *Bos Indicus* breeds (such as Brahman, Nelore or other tropical breeds) (Burrow *et al.*, 1997; Cafe *et al.*, 2011). In addition, animals can get used to the manipulations and environment (Della Rosa *et al.*, 2019), although it is expected that cattle expressed their different temperaments when exposed to the new environment, i.e. shipping and slaughterhouse lairage pens, before slaughter. Cattle in the present study were reared on a dairy farm by humans and were highly handled from birth. Consequently, the inherited temperament may not have been expressed at 200d. In addition, measurements at 200d may be too late and are not useful in assisting purchase decisions. Therefore, individual temperament measures in cattle which were artificially reared was not influential on production traits measured in this study.

It is important to highlight that the selection of cattle based on phenotypic live animal measurements may be more accurate at birth, because the rearing system has great environmental effect on the phenotype by 129d or 200d.

6.6. Conclusions and implications

Live weight at birth, 129d and 200d predicted future carcass size (weight and length), and therefore should be considered when purchasing calves from the sale yards or making price-setting decisions. In heifers, the accuracy of predictions of both carcass weight and length increased if live weight was combined with hip-height. In steers, the relationships with linear measurements were not so clear. Live weight itself could predict carcass weight with moderate accuracy, which increased with age, combining live weight with body length at 0d or hip-width

at 129d in the subset of steers. Thicker cannon bones at birth also gave an indication of heavier carcasses. Rib fat depth had a negative relationship with live weight at birth, whilst EMA was positively related to live weight at 129d. Overall, the current results showed that live weight is the best predictor of future carcass size.

Cattle in this study were calm at 200d, with little variation among animals, potentially because animals were acclimatised and tranquil in the presence of humans by 200d. Therefore, temperament in beef-cross-dairy cattle which were artificially reared on a dairy farm did not influence production traits measured in this study.

CHAPTER 7
GENERAL DISCUSSION

7.1. Introduction

Beef-cross-dairy cattle are the progeny produced by mating dairy-breed cows with beef-breed sires, and it is estimated that around 20% of the New Zealand dairy herd are mated to beef breeds (Burggraaf, 2016). Historically, there have been problems in terms of appropriate beef-breed sire selection to use over dairy-breed cows, mainly due to the lack of records or focussing only on the dairy cow outcome at parturition. Dairy farmers typically use sires selected for easy calving, either using estimated breeding values (EBV) or based on assumptions about a particular breed or source of sire, without considering the growth potential of the sire. The result is that many beef-cross-dairy calves are slow growing when combining dairy genetics with low birth weight beef genetics. Reasonably, beef cattle finisher farmers are often not satisfied with the performance of beef-cross-dairy calves and continue to pay a premium for pure beef-breed calves at weaning. This leaves a surplus of dairy-origin calves that are slaughtered at 4-14 days of age. To make dairy-origin calves a more desirable resource to beef cattle finisher farms, improvement in their potential for growth and meat quality is needed, without negatively impacting the dairy cow production.

The general hypothesis of this study was that the use of genetically superior beef-breed sires can increase the growth and meat production of calves born on dairy farms. The specific hypotheses were: 1] Sire influences the growth of beef-cross-dairy calves that graze on hill country conditions (Chapter 3); 2] Carcass and meat quality traits differ among sires used to produce beef-cross-dairy calves finished on pasture, and the selection of appropriate sires will increase the muscle and fat that contributes to saleable meat without disadvantage to meat quality traits (Chapter 4); 3] The performance of beef-cross-dairy offspring is related to their sire EBV for the traits measured (Chapter 5); 4] Skeletal size of beef-cross-dairy calves at early age, in conjunction with live weight, can be used to predict future carcass traits (Chapter 6); 5] Temperament of beef-cross-dairy calves within the first 200 days of life, will affect carcass weight and meat characteristics (Chapter 6).

7.2. Major findings of the study

The data presented in this study demonstrated that using genetically superior beef-breed sires over dairy-breed cows increases growth and carcass weight of their beef-cross-dairy progeny, while maintaining desirable carcass and meat quality. Live weight differed amongst

sires at all ages (after 200d), and this translated into differences in slaughter weight and carcass traits (Chapter 3 and 4). The 90 kg difference in live weight at 800d between the lightest and heaviest sires, resulted in 46 kg difference in carcass weight. The difference in carcass weight between the top and bottom sire of each breed represented a difference in carcass value per progeny of \$266 for Angus sires and of \$201 for Hereford sires used in this study. These differences may have been greater if pasture of higher quality was available because the expression of genetic potential is dependent on having favourable environmental conditions to express it (Cundiff *et al.*, 2007; Lawrie, 2006a; Warner *et al.*, 2010). Nevertheless, most of the progeny achieved adequate fat cover levels and typical carcass and meat quality values for beef in New Zealand. Thus, the general hypothesis set out to investigate was proven correct.

The EBV provided by BREEDPLAN were related to the progeny performance of the beef-cross-dairy cattle from this study (Chapter 5). For sires used on mixed-aged dairy-breed cows via artificial breeding (AB), live weight EBV had a positive association with progeny live weight for both breeds, except at 200d. Hereford AB sires used in this study also had positive associations of carcass weight and EMA EBV and the progeny performance for those carcass size traits, while Angus sires had positive associations between rib fat depth and IMF EBV and progeny performance for these carcass fat traits. Therefore, farmers should consider BREEDPLAN EBV when selecting sires to mate to dairy-breed cows or when buying beef-cross-dairy calves for beef production, because the use of genetically superior beef-breed sires does increase the potential for growth, carcass weights and finishing ability from calves born from dairy-breed cows.

For live weight, the association between progeny performance and sire EBV were weak to moderate but increased with age (Chapter 5). The failure of 200d weight EBV to predict progeny live weight at 200d could be partially explained by differences in the environment used to calculate sire EBV compared with the environment in which the progeny were grown (Chapter 3), with a large effect of rearing system (beef-breed calves reared on dam compared with dairy-breed calves reared artificially) and differences in breeds (pure or cross).

When no sire information is available, phenotypic data could be used to predict cattle performance at slaughter (Chapter 6). This would be useful when buying 4-day-old calves to rear or 100 kg weaned calves for finishing. Live weight was the best phenotypic predictor of carcass traits. Live weight at birth, 129d and 200d could predict carcass size (weight and length), although there was still a large spread in carcass weight for any range of live weight at younger age. In heifers, the accuracy of predictions of both carcass weight and length increased if live weight was combined with hip-height across ages. In steers, the relationships with linear

measurements were not so clear. Live weight across ages could predict carcass weight with moderate accuracy, and the accuracy increased with age and combining live weight with body length at 0d or hip-width at 129d in the subset of steers. Thicker cannon bones at birth also gave an indication of heavier carcasses.

Besides carcass weight, predicting the subcutaneous fat depth at slaughter was also of interest because the beef finisher is typically paid based on a fat class grade and carcass weight within that fat class (New Zealand Meat Classification Authority, 2004). Progeny live weight at birth was found to be negatively related to rib fat depth of the carcass (Chapter 6). However, only 3% of carcasses were classified as “L” fat class grade (subcutaneous fat below 3 mm, Chapter 4). These results indicated that carcasses with adequate amounts of rib fat depth can be achieved with beef-cross-dairy progeny when grazed on New Zealand hill-country pasture.

All the beef-cross-dairy progeny of the sires included in this study produced meat with low marble scores (between 0 and 3 on a 0-9 scale, Chapter 4). However, there were some sires (mostly Angus) that produced progeny with greater marbling within this low range, resulting in mean marble scores above 1.24. In addition, a low to moderate association of progeny performance and sire EBV for IMF was found for the Angus sires in this study (Chapter 5).

For the other meat traits measured (ultimate pH, meat colour, fat colour, shear force, thaw and cook losses), values were within the typical values for beef found in the literature (Chapter 4). Given that ultimate pH is one of the key drivers of meat quality and that pH depends on the amount of glycogen in the muscle prior to slaughter, it was important to investigate if the individual stress response (driven by temperament) at early ages was associated with ultimate pH and carcass characteristics. Carcass weight was explained by live weight at 200d and the addition of crush score or exit velocity didn't improve the overall prediction. Cattle in this study were overall calm at 200d (Chapter 6), with little variation among animals, likely due to being reared artificially at the dairy farm and being acclimatised to the presence of humans. Carcasses with pH greater than 6.0 were not from a specific sire or breed, rather they were from common grazing herds. Therefore, temperament in beef-cross-dairy cattle which were artificially reared on a dairy farm does not influence the production traits measured in this study.

7.3. Implications of the findings

This study demonstrated that using genetically superior beef-breed sires over dairy-breed cows increases the potential for growth, carcass weights and possibly carcass fat levels of

their beef-cross-dairy progeny, while maintaining desirable meat quality. This has a few implications along the dairy-beef chain of production, in which each agent has different and sometimes antagonist objectives.

In the first instance, dairy farmers and industry organisations that supply semen and coordinate the breeding in dairy herds (e.g. Livestock Improvement Corporation) should consider BREEDPLAN EBV when selecting beef-breed sires to mate to dairy-breed cows, not only for positive calving outcomes but also looking beyond the dairy farm gate in terms of carcass and meat value. In addition, given that BREEDPLAN EBV were good predictors of growth (but not excellent), sires to be used widely for AB on dairy farms should be progeny tested to ensure they offer the best option for all players in the chain. By doing so, the desirability of these calves produced on dairy farms would increase to beef cattle finishers.

Coleman (2020) recommended that sires to use on dairy-breed cows should have birth weights small enough to not increase the risk of dystocia, while minimising the disadvantage of smaller calves taking longer to reach the appropriate weaning weight. For rearing purposes, the industry recommendation (particularly for Holstein-Friesian bulls) has been to select calves that are at least 40 kg calves at 4 days of age (Muir *et al.*, 2002) to allow a good compromise between growth rate and cost of rearing, so that they reach weaning weight at an early age. However, a calf of 40 kg is a big calf for a Holstein Friesian-cross-Jersey cow (Hickson *et al.*, 2015) and this recommendation does not consider the potential to select progeny from sires with good growth rates. Easy calving paired with rapid growth to weaning (Coleman, 2020), followed by comparable growth to beef cattle to slaughter (Chapter 3) is achievable with beef-cross-dairy calves. Thus, an incentive in the price paid by beef cattle finishers for these dairy-origin calves would encourage the decision of mating dairy-breed cows to beef-breed sires of high growth EBV. In this regard, it becomes important to transfer the genetic information with the sale of beef-cross-dairy calves, given how different their potential for growth can be.

The beef cattle finisher should consider the calves' potential for growth and fattening when buying beef-cross-dairy calves for beef production. This will give more certainty of the final product, and thus should be paid at a higher price. The data presented in this study proved that both genetic and phenotypic live weight (i.e., sire's EBV for live weight or calf's own live weight) can be valuable tools for selecting beef-cross-dairy calves. If both sire and phenotypic liveweight information are available, and if beef cattle finishers are buying calves at birth, then they should choose those heavier calves sired by bulls with high EBV for 600d live weight. If beef cattle finishers are buying ~100 kg calves at weaning, they should consider the genetics first and choose calves sired by bulls with high EBV for 600d live weight that are heavier. This study

highlighted that recently weaned calves cannot achieve their growth potential on poor-quality pasture, as seen in the mismatched progeny live weight and EBV at 200d. To fulfil this genetic potential, good quality pasture or supplementary feed when pasture quality is low should be provided (de Clifford *et al.*, 2014; Handcock *et al.*, 2015; Pettigrew *et al.*, 2017). As animals got older, however, the associations between progeny performance and sire EBV improved. Consequently, the emphasis for selection of beef-cross-dairy calves for growth should be on 600d weight EBV.

If the sire information is not available at the time of sale, then live weight of the calves becomes the main selection tool. Heavier calves (and with thicker cannon bones) should be chosen to achieve faster growth rates and greater finishing weights. In addition, heavier, taller heifers at birth or weaning will grow to heavier weights than lighter, shorter ones.

Given that the price paid to the farmer for cattle at slaughter in New Zealand is largely explained by carcass weight, fat class and muscling grade (Bown *et al.*, 2016; Purchas, 2003), an animal with a heavy carcass and 3-10 mm of subcutaneous fat coverage will generate the greatest income. In addition, meat quality attributes (pH, marbling, fat depth and colour, meat colour) will be considered for some markets for premium payments (e.g., Silver Fern Farms Eating Quality System). The data presented in this study reinforced that high carcass weight with adequate amounts of rib fat depth and with typical meat quality characteristics for beef, can be achieved with beef-cross-dairy progeny when grazed on pasture. Thus, to encourage the use of beef-sires with superior genetics, the extra value obtained from this type of beef-cross-dairy carcass compared to a lighter or leaner carcass should be distributed back through the dairy-beef value chain.

To give an indication of the extra value, the difference between the lightest and heaviest sire in this study was 90 kg in live weight at 800d and 46 kg in carcass weight, which represented a difference of \$266 income for each progeny of the heavier sire. This sire's progeny would also require more feed, as live weight and liveweight gain drive the energy requirements (Nicol *et al.*, 2017). It was estimated that the heavier animal required an additional 6000 MJME or 594 kgDM (with an average pasture quality 10.1 MJME/kgDM, Chapter 3) to grow the extra 90 kg. Assuming a cost of 7 cents to produce a kilogram of DM (Shadbolt, 2007), which depends on the location and time of the year, this would represent an extra cost of \$44. Accordingly, the final extra value per progeny would be \$222, and this extra income should be shared between the cattle finisher, the calf rearer, the dairy farmer and the bull breeder or the semen company.

7.4. Limitations of the study

There are a number of limitations of this study, including the selection criteria of the sires, their EBV reliability, number of sires within breed, number of progeny per sire, heterosis effect of the maternal breed and the environment. These constraints were related to sires available and conducting the experiment under commercial farm conditions, with limited budget and resources. These points will be addressed in the next paragraphs.

Sires used in this experiment were not a random sample, as they were selected for the project on the basis of their EBV with greater emphasis on traits important for the dairy farmer. For mixed-aged cows, sires used via AB were restricted to the lighter 50% for birth weight, and then selection moved to gestation length, live weight at 600d and if similar sires were available, those with superior EBV for IMF and EMA were chosen. With greater selection intensity (proportion of bulls selected from the total available), then the expected correlation between EBV in different systems decrease (Charteris, 1995). In addition, reduced progeny numbers evaluated per sire can decrease the accuracy and correlation between sire EBV in different environments (Blair *et al.*, 1994). The EBV of the sires used via AB of both breeds did cover most of the range of possible EBV for each growth and carcass trait (spanning at least the percentiles 1th to 99th for all traits, except for Angus live weight at 600d (5-99th)). There was also a spread of the EBV reliability, with accuracies for sires ranging between 69-99% for growth traits, 50-98% for carcass size traits and 38-98% for carcass fat traits. Lower accuracy of the EBV, in addition to each sire having a low number of progeny (5-38 progeny for most traits), implies that both the available BREEDPLAN EBV and the measured phenotypic results could be an over or under-representation of the real sire merit. Nevertheless, these restrictions to the acceptable birth weight EBV were reflective of the bulls likely to be used in the dairy industry, as dairy farmers are averse to using sires with high birth weight that could result in calving difficulty and consequently, the death of the calves or cows. Therefore, this restricted population of sires is a good representation of the Angus and Hereford bulls likely to be used for mating dairy-breed cows in New Zealand.

Yearling sires used on first-calving heifers were selected with a different criteria (i.e. sires were in the lightest 15% of each breed for birth weight and the budget allocated was NZD2500 at time of purchase), and they were used via natural mating on separate contemporary groups to those used on mixed-aged cows (i.e. yearling sires of each breed were used in separate groups of heifers and heifers were randomly allocated to each group). Further, these sires had low accuracy of their EBV for live weight at 600d (64-68% accuracy) because they didn't have

their own 600d weight recorded and didn't have information of any progeny added to the calculation. Similar problem was encountered for EBV for carcass data (for example, 55-59% accuracy for carcass weight EBV). For these reasons, sires used on heifers were excluded from analysis of progeny performance in comparison with sire EBV.

Another consequence of mating in separate groups, is that natural mating for first-calving heifers occurred earlier than AB for mixed-aged cows. This meant that calves born from 2-year-old heifers were older at any given date, compared with calves born from mixed-aged cows. This can have implications in the social structure of their grazing herd, as older cattle can be more dominant (Schein *et al.*, 1955) and boost their growth rates because of this. It was not possible to differentiate the genetic effect of being born to a 2-year-old heifer and to a yearling bull, from the phenotypic effect of being born early. Nevertheless, these calves born to heifers showed excellent growth and potential value as a finished animal.

The focus of this study was on the effect of the beef-breed sire on the progeny performance. However, all progeny were beef-cross-dairy and the heterosis effect of the maternal dairy breed was unaccounted for, which could be significant particularly with growth and carcass fat traits. Dams were predominantly Holstein-Friesian or Holstein-Friesian-cross-Jersey crossbred, but their genetic information was not available. A greater proportion of Holstein-Friesian would produce heavier calves with faster growth rates and heavier carcasses, while a greater proportion of Jersey would produce smaller animals with slower growth rates, lighter carcasses, higher marbling and with greater variability in colour of the fat (Barton *et al.*, 1993; Barton *et al.*, 1994; Bown *et al.*, 2016; Buchanan *et al.*, 2015; Handcock *et al.*, 2018; Purchas, 2003). On the contrary, it has been shown that cow breeding worth was not an important trait to consider for the potential growth of the beef-cross-dairy calves during rearing or finishing (Burggraaf, 2016). It is unlikely that there would be a bias favouring particular sires in the data from the current study because sires were rotationally allocated to mating days and randomly allocated to cows in oestrus on each mating day. In addition, the cows in this study had similar live weight, body condition score and milk production regardless of the sire they were bred to (Coleman, 2020; Coleman *et al.*, 2019), indicating that a balanced spread of cow breed among sires had been achieved.

The environment where the beef-cross-dairy progeny were grown also played an important role in how these cattle performed. All cattle were grazed on a coastal farm on summer-dry hill country pasture (Chapter 3), with dominant species being ryegrass, kikuyu, ratstail and some legumes, with varying composition throughout the year (Puha *et al.*, 2008). Since this study was done on a commercial farm, there was little scope of altering or increasing

feed supply and quality to optimise liveweight gain. Calves were weaned at a minimum of 85 kg live weight and 1.5-4 months of age (Coleman, 2020), and then went onto low quality pasture. This is a weak point of dairy-beef finishing systems in general (Morris, 2019), because the early-weaned crossbred cattle are not only offered a low protein and energy feed, but also have an undeveloped rumen that is not prepared to digest low quality pastures. Perhaps in a different finishing farm where they were fed ad libitum and where pasture quality was higher, there might have been greater differences in growth and meat quality traits than observed here.

7.5. Recommendation for future research

This study demonstrated that there are sires within the Angus and Hereford breeds that produce progeny of high growth and adequate finishing weight and fat cover, after satisfying the need of easy calving on the dairy farm. However, comparison of performance with more sires of different beef breeds and across different environments is needed for wider use in the dairy industry. In this regard, the Dairy-Beef Progeny Test funded by Beef+Lamb New Zealand Genetics (<https://www.blNZgenetics.com/progeny-tests/beef-progeny-tests>) has been running for 6 years now, and mating of about 1400 mixed-age dairy cows for the next cohort of cattle is in progress. This mating in spring 2020 will include 23 sires of 8 breeds (Angus, Australian Lowline, Hereford, Murray Grey, Red Devon, Simmental, Speckle Park and Stabilizer) at Pamu Wairakei's Renown Farm (Taupo, New Zealand). This is a good step in providing more information to dairy farmers regarding the possibilities of using of beef-breed sires over their dairy herd, and to beef farmers about the potential for growth of these type of calves.

Given that dairy farmers already use the genetic information of dairy-breed sires to "identify animals whose progeny will be the most efficient converters of feed into farmer profit" (DairyNZ), using EBV of beef-breed sires does not add complications to their mating system, rather a different outlook of the potential calving and calf to be obtained for sale. In this respect, Beef+Lamb New Zealand Genetics has started working with Livestock Improvement Corporation, which is the largest dairy semen provider in New Zealand, estimated to be responsible for AB of 3.59 million cows (72.5%) during 2018/19 season (LIC *et al.*, 2019). This collaboration will make it easier for dairy farmers to access superior beef cattle genetics with accurate information at competitive costs, and it will also provide beef breeders with a potential path to the dairy market.

If more beef-breed sires are to be used for mating dairy-breed cows with the purpose of producing meat, then the calculation of beef-cross-dairy EBV for growth and carcass traits should be considered. However, Coleman (2020) calculated EBV for birth weight and gestation length with the data from this experiment, and found that there was a good relationship between these EBV and those calculated by BREEDPLAN with data from Angus or Hereford breeds. Similar assumptions can be made for growth and carcass traits EBV presented in this thesis, given the general good association between them and beef-cross-dairy progeny performance. A clear exception to this assumption with results from the present study, would be EBV for 200d live weight.

The EBV provided by BREEDPLAN are useful to select beef-breed sires for use on dairy-breed cows. A better proposition would be the design of a dairy-beef breeding index to rank and identify beef-breed sires, of any breed, with the best combination of traits important for both the dairy cow and the finishing performance of the calf. Selection indexes allow individual animals to be rewarded across a range of traits and therefore receive a higher monetary value. In Ireland for example, the Dairy Beef Index is a tool used to identify beef-breed bulls for use on dairy-breed cows cognizant of the demands of both the dairy producer (i.e., easy calving with short gestation length) and the beef sector (i.e., efficient growth of a good-quality carcass) (Berry *et al.*, 2019). In New Zealand, Hereford breeders have encouraged crossbreeding with dairy-breed cows by the Dairy Terminal Index “targeting the production of dairy-beef progeny where all progeny are slaughtered” (BREEDPLAN, 2011). Only recently is that New Zealand Angus released a Heifer/Dairy Terminal Index where “all progeny are marketed at approximately 510 kg live weight” (September 2020, <https://breedplan.une.edu.au/news/new-zealand-angus-release-new-selection-indexes/>). Even so, having sires of different breeds pooled together under the same index, will make it clearer for dairy farmers to compare beef genetics.

How to transfer the genetic information of the calves along the dairy-beef chain, from the dairy farmer through to the consumer, also needs consideration. Transferring the calf information across farms is feasible, because all cattle in New Zealand have a unique identification registered under the National Animal Identification and Tracing (NAIT <https://ospri.co.nz/our-programmes/nait/about-the-nait-programme/purpose/>), and there is widespread use of herd management systems, for example MINDA (<https://www.lic.co.nz/products-and-services/minda/>) for dairy farms and FARMIQ (<https://farmiq.co.nz/>) for any type of livestock farm. Another option to consider is using differential tags, similar to the ones used by AngusPure brand (<https://www.anguspure.co.nz/>) as an example. These AngusPure Source & Trace tags (black “A” tags) ensure a full line of traceability and guarantees access to the higher

premiums at approved processors. Therefore, any means of identifying calves with greater potential for growth and improved carcass weight and meat quality, as well as being able to transfer and trace the genetic information of these calves along the dairy-beef chain, should guarantee a better price paid and incentivise the use of superior beef-breed sires over dairy-breed cows.

Providing a good growth environment to fulfil the genetic potential of the beef-cross-dairy progeny could partially change some of the results of this study. Recently weaned calves could be allowed meal to balance pasture quality or graze on mixed-herb swards to avoid a growth check during their first summer and increase weight gain, particularly in environments with dry summer where pasture quality drops dramatically. Previous studies in 6-month-old dairy heifers and bulls have shown that mixed-herb swards (chicory, plantain, white clover and red clover) or pure-sward of lucerne during the dry summer period, resulted in young cattle growing at greater rates than those fed pasture (de Clifford *et al.*, 2014; Handcock *et al.*, 2015; Pettigrew *et al.*, 2017). The addition of supplementary concentrate also allowed for increased liveweight gain of cattle above that of those fed pasture alone (Pettigrew *et al.*, 2017). Thus, providing better feed to recently weaned beef-cross-dairy calves could increase growth rates and the relationship with sire genetics at 200d could be much stronger. In addition, providing a high growth environment may allow beef-cross-dairy cattle to achieve slaughter weights and adequate fat covers at 600d, rather than 800d as it happened in this study. If this was the case, the extra cost of providing high quality feed could be compensated by animals going to slaughter at younger age and potentially before their second winter. Alternatively, future studies could aim to identify sires that have progeny that are better able to perform under the conditions of the New Zealand hill country pasture.

Future research should consider mating first-calving heifers and mixed-aged cows at the same time. This will enable a fair comparison of the progeny to answer one of the most frequent question from farmers: is it worth keeping calves born to heifers for meat production, given that they are born smaller? Further, accounting for the maternal dairy breed and genetics could also identify some correlations with their progeny performance and meat production. In addition, a comparison of growth, carcass and meat quality of beef-cross-dairy cattle with a control group of pure dairy cattle (e.g. Holstein-Friesian or Holstein-Friesian-cross-Jersey crossbred cattle), grown under the same conditions from birth and slaughtered at same chronological age and at same maturity or fatness level, would identify the marginal benefit of crossbreeding with a beef-breed sire.

For high uptake of this practice of mating dairy-breed cows with beef-breed sires, it should be considered how to increase the capacity of beef cattle farmers to grow these calves and of processors to sell the meat obtained from them. It has been suggested that climate change and a raise in temperature will favour farming of cattle over sheep and deer in the next decades in New Zealand (Mcrae *et al.*, 2018). Moreover, the ratio of beef breeding cows and heifers in the national herd has reduced from 36% in 1972-73 to 28% in 2014-15 (Morris, 2017), and this trend is likely to continue, presenting an opportunity to artificially rear more surplus calves from the dairy industry. This would increase the conversion efficiency of feed into product on beef cattle farms (Burggraaf *et al.*, 2020) while reducing annual greenhouse gas emissions for beef production (van Selm *et al.*, 2021). Further reductions in greenhouse gases and increased efficiency of beef production could be achieved by choosing beef sires with high genetics for feed conversion or low residual feed intake (Archer *et al.*, 1999; Berry *et al.*, 2013; Morris *et al.*, 2014b).

7.6. Conclusion

In conclusion, the data presented in this study indicated that using genetically superior beef-breed sires over dairy-breed cows increased the growth, carcass and meat production of their beef-cross-dairy progeny. Dairy farmers should consider BREEDPLAN EBV when selecting beef-breed sires to mate their dairy-breed cows, not only for positive calving outcomes but for achieving desirable and economically important carcass and meat quality traits. The beef cattle finisher should consider the calves' potential for growth and fattening when purchasing beef-cross-dairy calves for beef production, by utilising both genetic and phenotypic live weight information.

REFERENCES

- Afolayan RA, Pitchford WS, Deland MP, McKiernan WA 2007. Breed variation and genetic parameters for growth and body development in diverse beef cattle genotypes. *Animal* 1: 13-20. DOI: 10.1017/s1751731107257933
- Afolayan RA, Deland MP, Rutley DL, Bottema CDK, Ewers AL, Ponzoni RW, Pitchford WS 2002. Prediction of carcass meat, fat and bone yield across diverse cattle genotypes using live-animal measurements. *Animal Production in Australia* 24: 13-16.
- Agricultural Business Research Institute BREEDPLAN: International Beef Recording Scheme. Retrieved 1 April 2020 <https://breedplan.une.edu.au/>
- Angus New Zealand Heritabilities of traits in Angus Group BREEDPLAN. Retrieved 21 June 2018 <http://angusnz.com/cattle/technical/ebvs/heritability/>
- Angus New Zealand Inc. Indexes. Retrieved 1 September 2020 (updated 13 August 2015): <http://angusnz.com/>
- Animal and Animal Products Directorate 2017. Red Meat Code of Practice Chapter 5: Slaughter and Dressing. Ministry for Primary Industries, Wellington, New Zealand. <https://www.mpi.govt.nz/consultations/code-of-practice-red-meat-slaughter-and-dressing/>
- Arango JA, Cundiff LV, Van Vleck LD 2002. Breed comparisons of Angus, Charolais, Hereford, Jersey, Limousin, Simmental, and South Devon for weight, weight adjusted for body condition score, height, and body condition score of cows. *Journal of Animal Science* 80: 3123-32.
- Archer JA, Herd RM, Arthur PF, Parnell PF 1998. Correlated responses in rate of maturation and mature size of cows and steers to divergent selection for yearling growth rate in Angus cattle. *Livestock Production Science* 54: 183-192. DOI: 10.1016/S0301-6226(97)00170-X
- Archer JA, Richardson EC, Herd RM, Arthur PF 1999. Potential for selection to improve efficiency of feed use in beef cattle: a review. *Australian Journal of Agricultural Research* 50: 147-162. DOI: 10.1071/A98075
- Asheim LJ, Johnsen JF, Havrevoll Ø, Mejdell CM, Grøndahl AM 2016. The economic effects of suckling and milk feeding to calves in dual purpose dairy and beef farming. *Review of Agricultural, Food and Environmental Studies* 97: 225-236. DOI: 10.1007/s41130-016-0023-4
- AUS-MEAT Limited 2017. Australian Beef Carcase Evaluation: Beef and Veal Chiller Assessment Language. Retrieved 12 November 2020 (updated February 2017): https://www.ausmeat.com.au/WebDocuments/Chiller_Assessment_Language.pdf

- AUS-MEAT Limited 2018. Handbook of Australian Beef Processing. 2018 ed. Queensland, Australia, AUS-MEAT Limited. www.ausmeat.com.au
- Baker RL, Carter AH 1976. The value of on-farm performance selection of Angus and Hereford bulls. *Proceedings of New Zealand Society of Animal Production* 36: 216-221.
- Baker RL, Carter AH, Beatson PR 1975. Progeny testing Angus and Hereford bulls for growth performance. *Proceedings of New Zealand Society of Animal Production* 35: 103-111.
- Baker RL, Morris CA, Johnson DL, Hunter JC, Hickey SM 1991. Results of selection for yearling or 18-month weight in Angus and Hereford cattle. *Livestock Production Science* 29: 277-296. DOI: 10.1016/0301-6226(91)90104-X
- Bartoň L, Řehák D, Teslík V, Bureš D, Zahrádková R 2006. Effect of breed on growth performance and carcass composition of Aberdeen Angus, Charolais, Hereford and Simmental bulls. *Czech Journal of Animal Science* 51: 47-53. DOI: 10.17221/3908-CJAS
- Barton RA, Pleasants AB 1993. Fat colour and meat colour in different breeds of steers in five consecutive years raised on pasture and slaughtered at 30 months of age. *Proceedings of New Zealand Society of Animal Production* 53: 389-391.
- Barton RA, Pleasants AB 1997. Comparison of the carcass characteristics of steers of different breeds and pre-weaning environments slaughtered at 30 months of age. *New Zealand Journal of Agricultural Research* 40: 57-68. DOI: 10.1080/00288233.1997.9513230
- Barton RA, Donaldson JL, Barnes FR, Jones CF, Clifford HJ 1994. Comparison of Friesian, Friesian-Jersey cross, and Jersey steers in beef production. *New Zealand Journal of Agricultural Research* 37: 51-58. DOI: 10.1080/00288233.1994.9513040
- Beef+Lamb New Zealand 2017a. Feeding and efficiency. In: Geenty K, Morris S ed. *Guide to New Zealand Cattle Farming*. Wellington, New Zealand, Beef+Lamb New Zealand. Pp. 37-47.
- Beef+Lamb New Zealand 2017b. Post weaning systems. In: Geenty K, Morris S ed. *Guide to New Zealand Cattle Farming*. Wellington, New Zealand, Beef+Lamb New Zealand. Pp. 23-36.
- Beef+Lamb New Zealand 2017c. Beef industry overview. In: Geenty K, Morris S ed. *Guide to New Zealand Cattle Farming*. Wellington, New Zealand, Beef+Lamb New Zealand. Pp. 2-12.
- Beef+Lamb New Zealand 2017d. Beef breeding cows. In: Geenty K, Morris S ed. *Guide to New Zealand Cattle Farming*. Wellington, New Zealand, Beef+Lamb New Zealand. Pp. 13-22.
- Beef+Lamb New Zealand 2017e. Genetic Improvement. In: Geenty K, Morris S ed. *Guide to New Zealand Cattle Farming*. Wellington, New Zealand, Beef+Lamb New Zealand. Pp. 62-81.
- Beef+Lamb New Zealand 2018. Profitable calf rearing (Farm Fact Sheet). www.knowledgehub.co.nz
- Beef+Lamb New Zealand Economic Service 2018. *Compendium of New Zealand Farm Facts 2018*. Farm Facts. 41 ed. Wellington, New Zealand, Beef+Lamb New Zealand. Pp. 32.

- Beef+Lamb New Zealand Economic Service 2019. Compendium of New Zealand Farm Facts 2019. Farm Facts. 43 ed. Wellington, New Zealand, Beef+Lamb New Zealand.
- Beef+Lamb New Zealand Economic Service 2020. Compendium of New Zealand Farm Facts 2020. Farm Facts. 44 ed. Wellington, New Zealand, Beef+Lamb New Zealand.
- Beef+Lamb New Zealand Genetics 2017. Performance Report (Beef Progeny Test). Duniden, New Zealand. 45 p. <https://www.blznzgenetics.com/progeny-tests/beef-progeny-tests>
- Beef+Lamb New Zealand Genetics 2019. Sire Report: Cohort 2 (Beef Progeny Test). Dunedin, New Zealand. 16 p. <https://www.blznzgenetics.com/progeny-tests/beef-progeny-tests>
- Behrends SM, Miller RK, Rouquette FM, Randel RD, Warrington BG, Forbes TDA, Welsh TH, Lippke H, Behrends JM, Carstens GE, Holloway JW 2009. Relationship of temperament, growth, carcass characteristics and tenderness in beef steers. *Meat Science* 81: 433-438. DOI: 10.1016/j.meatsci.2008.09.003
- Berg RT, Butterfield RM 1968. Growth Patterns of Bovine Muscle, Fat and Bone. *Journal of Animal Science* 27: 611-619. DOI: 10.2527/jas1968.273611x
- Berry DP, Crowley JJ 2013. Cell Biology Symposium: Genetics of feed efficiency in dairy and beef cattle. *Journal of Animal Science* 91: 1594-1613. DOI: 10.2527/jas.2012-5862
- Berry DP, Amer PR, Evans RD, Byrne T, Cromie AR, Hely F 2019. A breeding index to rank beef bulls for use on dairy females to maximize profit. *Journal of Dairy Science* 102: 10056-10072. DOI: 10.3168/jds.2019-16912
- Bickerstaffe R, Bekhit AED, Robertson LJ, Roberts N, Geesink GH 2001. Impact of introducing specifications on the tenderness of retail meat. *Meat Science* 59: 303-315. DOI: 10.1016/s0309-1740(01)00083-3
- Blair HT, Garrick DJ 1994. How relevant are current and emerging genetic technologies to the beef breeding cow? *Proceedings of New Zealand Society of Animal Production* 54: 337-344.
- Boles JA, Kohlbeck KS, Meyers MC, Perz KA, Davis KC, Thomson JM 2015. The use of blood lactate concentration as an indicator of temperament and its impact on growth rate and tenderness of steaks from Simmental x Angus steers. *Meat Science* 103: 68-74. DOI: 10.1016/j.meatsci.2015.01.003
- Boulton A, Kells N, Beausoleil N, Cogger N, Johnson C, Palmer A, O'Connor C, Webster J, Laven R 2018. Bobby calf welfare across the supply chain - Final Report for Year 1. Ministry for Primary Industries, Wellington, New Zealand. MPI Discussion Technical Paper No: 2018/44. 236 p. <https://www.mpi.govt.nz/dmsdocument/30005/direct>

- Bown MD, Muir PD, Thomson BC 2016. Dairy and beef breed effects on beef yield, beef quality and profitability: a review. *New Zealand Journal of Agricultural Research* 59: 174-184. DOI: 10.1080/00288233.2016.1144621
- BREEDPLAN BREEDPLAN: the traits explained. Retrieved 21 May 2018 <http://breedplan.une.edu.au/index.php>
- BREEDPLAN 2011. BREEDPLAN Tips: New Zealand Hereford Selection Indexes. In: University of New England ed. Armidale, Australia, International Beef Recording Scheme.
- BREEDPLAN 2015a. A basic guide to BREEDPLAN EBVs. University of New England ed. Armidale, Australia, International Beef Recording Scheme. 26 p. <http://breedplan.une.edu.au/>
- BREEDPLAN 2015b. BREEDPLAN Tips: New Zealand Angus Selection Indexes. In: University of New England ed. Armidale, Australia, International Beef Recording Scheme.
- Buchanan DS, Lenstra JA 2015. Breeds of Cattle. In: Garrick DJ, Ruvinsky A ed. *The Genetics of Cattle*. 2nd ed. Wallingford, United Kingdom, CAB International. Pp. 33-66. ISBN:978-1-78064-221-5.
- Burggraaf V 2016. Final report (Beef+Lamb NZ dairy-beef integration-project). AgResearch.
- Burggraaf VT, Craigie CR, Muir PD, Khan MA, Thomson BC, Knol FW, Lowe KA, Taukiri KR, Staincliffe M, McDermott A, Longhurst RD, McCoard SA 2020. Effect of rearing diet and early post-weaning pasture quality on the life-time growth, meat quality, carcass traits and environmental impact of dairy-beef cattle. *Livestock Science* 239: 104031. DOI: 10.1016/j.livsci.2020.104031
- Burke JL, Waghorn GC, Chaves AV 2002. Improving animal performance using forage-based diets. *Proceedings of New Zealand Society of Animal Production* 62: 267-272.
- Burnham DL, Purchas RW, Morris ST 2005. Relationships between on-farm and pre-slaughter behaviour and growth and meat quality for bulls and steers. *Proceedings of New Zealand Society of Animal Production* 65: 261-265.
- Burrow HM, Dillon RD 1997. Relationships between temperament and growth in a feedlot and commercial carcass traits of *Bos indicus* crossbreds. *Australian Journal of Experimental Agriculture* 37: 407-411. DOI: 10.1071/ea96148
- Burrow HM, Seifert GW, Corbet NJ 1988. A new technique for measuring temperament in cattle. *Proceedings of Australian Society of Animal Production* 17: 154-157.
- Cafe LM, Robinson DL, Ferguson DM, McIntyre BL, Geesink GH, Greenwood PL 2011. Cattle temperament: Persistence of assessments and associations with productivity, efficiency, carcass and meat quality traits. *Journal of Animal Science* 89: 1452-1465. DOI: 10.2527/jas.2010-3304

- Chambaz A, Morel I, Scheeder MRL, Kreuzer M, Dufey PA 2001. Characteristics of steers of six beef breeds fattened from eight months of age and slaughtered at a target level of intramuscular fat: I. Growth performance and carcass quality. *Archives of Animal Breeding* 44: 395-412. DOI: 10.5194/aab-44-395-2001
- Charteris PL 1995. Selection for beef cattle carcass and meat quality traits. Thesis presented in partial fulfilment of the requirements for the degree of Master of Agricultural Science in Animal Science. Massey University, Palmerston North, New Zealand. <http://hdl.handle.net/10179/5521>
- Charteris PL, Garrick DJ, Morris ST 1997. Sire by finishing environment interactions for carcass and meat quality traits in beef cattle. *Proceedings of New Zealand Society of Animal Production* 57: 192-195.
- Coleman LW 2016. Growth, carcass characteristics and meat quality of heifers and steers born to beef-cross-dairy cows. Thesis presented in partial fulfilment of the requirements for the degree of Master of Science in Animal Science. Massey University, Palmerston North, New Zealand
- Coleman LW 2020. The use of high genetic merit Angus and Hereford bulls in a New Zealand dairy herd. Thesis presented in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Animal Science. Massey University, Palmerston North, New Zealand. 197 p. <http://hdl.handle.net/10179/16378>
- Coleman LW, Back PJ, Blair HT, Lopez-Villalobos N, Hickson RE 2019. Milk production and rebreeding performance of mixed-aged dairy cows mated to Angus or Hereford bulls. *New Zealand Journal of Animal Science and Production* 79: 144-148.
- Coleman LW, Hickson RE, Schreurs NM, Martin NP, Kenyon PR, Lopez-Villalobos N, Morris ST 2016. Carcass characteristics and meat quality of Hereford sired steers born to beef-cross-dairy and Angus breeding cows. *Meat Science* 121: 403-408. DOI: 10.1016/j.meatsci.2016.07.011
- Cook A 2014. The hunt for the missing billion: NZ's dairy beef opportunity. In: Lincoln University ed. Kellogg Rural Leaders Programme. Lincoln, New Zealand.
- Country-Wide 2003 Calf rearing: Calves must be 40kg minimum at purchase. *Country-Wide*: 68
- Coyne JM, Evans RD, Berry DP 2019. Dressing percentage and the differential between live weight and carcass weight in cattle are influenced by both genetic and non-genetic factors¹. *Journal of Animal Science* 97: 1501-1512. DOI: 10.1093/jas/skz056
- Crews JDH, Pollak EJ, Weaber RL, Quaas RL, Lipsey RJ 2003. Genetic parameters for carcass traits and their live animal indicators in Simmental cattle¹. *Journal of Animal Science* 81: 1427-1433. DOI: 10.2527/2003.8161427x

- Cundiff LV, Thallman RM, van Vleck LD, Bennett GL, Morris CA 2007. Cattle breed evaluation at the US Meat Animal Research Centre and implications for commercial beef farmers. *Proceedings of New Zealand Society of Animal Production* 67: 9-17.
- Cunningham BE, Magee WT, Ritchie HD 1987. Effects of using sires selected for yearling weight and crossbreeding with beef and dairy breeds: birth and weaning traits. *Journal of Animal Science* 64: 1591-1600. DOI: 10.2527/jas1987.6461591x
- Cunningham EP 1965. The evaluation of sires from progeny test data. *Animal Science* 7: 221-231. DOI: 10.1017/S0003356100025630
- DairyNZ NZAEL: New Zealand Animal Evaluation Limited. Retrieved 19 October 2020 <https://www.dairynz.co.nz/animal/animal-evaluation/>
- Dal Zotto R, Penasa M, De Marchi M, Cassandro M, López-Villalobos N, Bittante G 2009. Use of crossbreeding with beef bulls in dairy herds: Effect on age, body weight, price, and market value of calves sold at livestock auctions. *Journal of Animal Science* 87: 3053-3059. DOI: 10.2527/jas.2008-1620
- Davison R 2020. Export cattle slaughter by beef and dairy origin. In: Morris ST ed. *Personal communication ed.* Wellington, New Zealand, Executive Director for Beef+Lamb New Zealand Economic Service & Insights.
- de Clifford RP, Hickson RE, Martín NP, Back PJ 2014. Growth rates of dairy heifers fed alternative feeds. *Proceedings of New Zealand Society of Animal Production* 74: 29-34.
- Della Rosa MM, Pavan E, Maresca S, Spetter M, Ramiro F 2019. Performance, carcass and meat quality traits of grazing cattle with different exit velocity. *Animal Production Science* 59: 1752-1761. DOI: 10.1071/an18064
- Dixon H, Thomson B, Graafhuis A 1996. Producing quality beef: Practical experience, current practice and future direction. *Proceedings of New Zealand Grassland Association* 57: 183-188.
- Dunne PG, Monahan FJ, O'Mara FP, Moloney AP 2009. Colour of bovine subcutaneous adipose tissue: A review of contributory factors, associations with carcass and meat quality and its potential utility in authentication of dietary history. *Meat Science* 81: 28-45. DOI: 10.1016/j.meatsci.2008.06.013
- Ertbjerg P, Puolanne E 2017. Muscle structure, sarcomere length and influences on meat quality: A review. *Meat Science* 132: 139-152. DOI: 10.1016/j.meatsci.2017.04.261
- Ferguson DM, Warner RD 2008. Have we underestimated the impact of pre-slaughter stress on meat quality in ruminants? *Meat Science* 80: 12-9. DOI: 10.1016/j.meatsci.2008.05.004
- Fisher M, Wild R, O'Grady K, Guigou M, Diesch T, Jamieson J, Ward L, Cross N 2017. The welfare of bobby calves sent for slaughter: a synopsis of the science literature within the context

of New Zealand's export system and the problems and gaps in it. *Proceedings of New Zealand Society of Animal Production* 77: 149-153.

García-Muñiz JG, Holmes CW, Wickham BW 1997. Growth and onset of puberty in two genetically different lines of Holstein-Friesian heifers, selected for either heavy or light body weight. *Proceedings of New Zealand Society of Animal Production* 57: 46-47.

Garrick DJ, Pollak EJ, Quaas RL, Van Vleck LD 1989. Variance heterogeneity in direct and maternal weight traits by sex and percent purebred for Simmental-Sired Calves. *Journal of Animal Science* 67: 2515-2528. DOI: 10.2527/jas1989.67102515x

Gilbert RP, Bailey DR, Shannon NH 1993. Linear body measurements of cattle before and after 20 years of selection for postweaning gain when fed two different diets². *Journal of Animal Science* 71: 1712-1720. DOI: 10.2527/1993.7171712x

Grandin T 1993. Behavioral agitation during handling of cattle is persistent over time. *Applied Animal Behaviour Science* 36: 1-9. DOI: 10.1016/0168-1591(93)90094-6

Gregory KE, Cundiff LV, Koch RM 1995. Genetic and phenotypic (co)variances for growth and carcass traits of purebred and composite populations of beef cattle. *Journal of Animal Science* 73: 1920-1926. DOI: 10.2527/1995.7371920x

Guilbert HR, Gregory PW 1952. Some Features of Growth and Development of Hereford Cattle. *Journal of Animal Science* 11: 3-16. DOI: 10.2527/jas1952.1113

Hammack SP, Gill RJ 2009. Texas Adapted Genetic Strategies for Beef Cattle X: Frame Score, Frame Size, and Weight. Retrieved 21 May 2018 <https://agrillifeextension.tamu.edu/library/ranching/texas-adapted-genetic-strategies-for-beef-cattle-x-frame-score-frame-size-and-weight/>

Hammami H, Rekik B, Gengler N 2009. Genotype by environment interaction in dairy cattle. *Biotechnology, Agronomy, Society and Environment* 13: 155-164.

Handcock RC, Hickson RE, Back PJ 2015. The use of herb mix and lucerne to increase growth rates of dairy heifers. *Proceedings of New Zealand Society of Animal Production* 75: 132-135.

Handcock RC, Lopez-Villalobos N, McNaughton LR, Back PJ, Edwards GR, Hickson RE 2018. Live weight and growth of Holstein-Friesian, Jersey and crossbred dairy heifers in New Zealand. *New Zealand Journal of Agricultural Research* 62: 173-183. DOI: 10.1080/00288233.2018.1465984

Haskell MJ, Simm G, Turner SP 2014. Genetic selection for temperament traits in dairy and beef cattle. *Frontiers in Genetics* 5: 368-386. DOI: 10.3389/fgene.2014.00368

Henderson CR 1978. Undesirable Properties of Regressed Least Squares Prediction of Breeding Values. *Journal of Dairy Science* 61: 114-120. DOI: 10.3168/jds.S0022-0302(78)83559-0

- Hickson RE, Zhang IL, McNaughton LR 2015. BRIEF COMMUNICATION: Birth weight of calves born to dairy cows in New Zealand. *Proceedings of New Zealand Society of Animal Production* 75: 257-259.
- Hickson RE, Balcomb CC, Fraser KR, Lopez-Villalobos N, Kenyon PR, Morris ST 2011. The effect of breed on the onset of puberty in heifers. *Proceedings of Association for the Advancement of Animal Breeding and Genetics* 19: 51-54.
- Hocquette JF, Gondret F, Baeza E, Medale F, Jurie C, Pethick DW 2010. Intramuscular fat content in meat-producing animals: development, genetic and nutritional control, and identification of putative markers. *Animal* 4: 303-19. DOI: 10.1017/S1751731109991091
- Holman BWB, Collins D, Kilgannon AK, Hopkins DL 2020. Using shear force, sarcomere length, particle size, collagen content, and protein solubility metrics to predict consumer acceptance of aged beef tenderness. *Journal of Texture Studies*: 1-8. DOI: 10.1111/jtxs.12523
- Holmes CW, Brookes IM, Garrick DJ, MacKenzie DDS, Parkinson TJ, Wilson GF 2007. *Milk production from pasture, principles and practices*. Palmerston North, New Zealand, Massey University. ISBN:0 473 08308 6
- Huff-Lonergan E, Lonergan SM 2005. Mechanisms of water-holding capacity of meat: The role of postmortem biochemical and structural changes. *Meat Science* 71: 194-204. DOI: 10.1016/j.meatsci.2005.04.022
- Huffman KL, Miller MF, Hoover LC, Wu CK, Brittin HC, Ramsey CB 1996. Effect of beef tenderness on consumer satisfaction with steaks consumed in the home and restaurant. *Journal of Animal Science* 74: 91-97. DOI: 10.2527/1996.74191x
- Hughes JM, Kearney G, Warner RD 2014a. Improving beef meat colour scores at carcass grading. *Animal Production Science* 54: 422-429. DOI: 10.1071/AN13454
- Hughes JM, Oiseth SK, Purslow PP, Warner RD 2014b. A structural approach to understanding the interactions between colour, water-holding capacity and tenderness. *Meat Science* 98: 520-532. DOI: 10.1016/j.meatsci.2014.05.022
- Johnston DJ, Reverter A, Ferguson DM, Thompson JM, Burrow HM 2003. Genetic and phenotypic characterisation of animal, carcass, and meat quality traits from temperate and tropically adapted beef breeds. 3. Meat quality traits. *Australian Journal of Agricultural Research* 54: 135-147. DOI: 10.1071/AR02087
- King DA, Shackelford SD, Kuehn LA, Kemp CM, Rodriguez AB, Thallman RM, Wheeler TL 2010. Contribution of genetic influences to animal-to-animal variation in myoglobin content and beef lean color stability. *Journal of Animal Science* 88: 1160-7. DOI: 10.2527/jas.2009-2544

- Kinghorn BP, Banks RG, Simm G 2015. Genetic Improvement of Beef Cattle. In: Garrick DJ, Ruvinsky A ed. The Genetics of Cattle. 2nd ed. Wallingford, United Kingdom, CAB International. Pp. 451-473. ISBN:9781780642215.
- Lawrie RA 2006a. Chapter 2 - Factors influencing the growth and development of meat animals. In: Lawrie RA ed. Lawrie's Meat Science Seventh ed. Cambridge, England, Woodhead Publishing. Pp. 15-40. ISBN:978-1-84569-159-2.
- Lawrie RA 2006b. Chapter 4 - Chemical and biochemical constitution of muscle. In: Lawrie RA ed. Lawrie's Meat Science. Seventh ed. Cambridge, England, Woodhead Publishing. Pp. 75-127. ISBN:978-1-84569-159-2.
- LIC, DairyNZ 2019. New Zealand dairy statistics 2018-19. Hamilton, New Zealand, Livestock Improvement Corporation Limited & DairyNZ Limited. ISBN:DNZ30-008. https://www.dairynz.co.nz/media/5792471/nz_dairy_statistics_2018-19_web_v2.pdf
- Litherland AJ, Woodward SJR, Stevens DR, McDougal DB, Boom CJ, Knight TL, Lambert MG 2002. Seasonal variations in pasture quality on New Zealand sheep and beef farms. Proceedings of New Zealand Society of Animal Production 62: 138-142.
- Lopez-Villalobos N, Garrick DJ 2005. Methodology for the design and enhancement of genetic improvement programs illustrated in the context of the New Zealand dairy industry. Agrociencia 9: 553-568.
- Macdonald KA, Verkerk GA, Thorrold BS, Pryce JE, Penno JW, McNaughton LR, Burton LJ, Lancaster JAS, Williamson JH, Holmes CW 2008. A Comparison of Three Strains of Holstein-Friesian Grazed on Pasture and Managed Under Different Feed Allowances. Journal of Dairy Science 91: 1693-1707. DOI: 10.3168/jds.2007-0441
- Maeda S, Grose J, Kato K, Kuchida K 2014. Comparing AUS-MEAT marbling scores using image analysis traits to estimate genetic parameters for marbling of Japanese Black cattle in Australia. Animal Production Science 54: 557-563. DOI: 10.1071/AN12368
- Mahmood S, Dixon WT, Bruce HL 2019. Cattle production practices and the incidence of dark cutting beef. Meat Science: 107873. DOI: 10.1016/j.meatsci.2019.107873
- Mateescu RG 2015. Genetics of Meat Quality. In: Garrick DJ, Ruvinsky A ed. The Genetics of Cattle. 2nd ed. Wallingford, United Kingdom, CAB International. Pp. 544-570. ISBN:9781780642215.
- McDade JL 2010. The effects of on-farm mixing of bulls on beef quality characteristics. Thesis presented in partial fulfilment of the requirements for the degree of Master of Philosophy. Massey University, Palmerston North, New Zealand. <http://hdl.handle.net/10179/2919>

- McIntyre BL, Tudor GD, Read D, Smart W, Della Bosca TJ, Speijers EJ, Orchard B 2009. Effects of growth path, sire type, calving time and sex on growth and carcass characteristics of beef cattle in the agricultural area of Western Australia. *Animal Production Science* 49: 504-514. DOI: 10.1071/ea08180
- McKiernan B 2007. Muscle scoring beef cattle. Profitable & Sustainable Primary Industries, NSW Department of Primary Industries.
- McPhee M, Walmsley B, Oddy H, Andrews T, Gudex B 2016. Enhancing BeefSpecs systems for improving market compliance of pasturefed beef in southern Australia (MLA Final Report). Meat and Livestock Australia, Sydney, Australia. B.SBP.0111. 109 p. <https://www.mla.com.au/research-and-development/search-rd-reports/final-reportdetails/Productivity-On-Farm/Enhancing-BeefSpecs-systems-for-improving-marketcompliance-of-pasturefed-beef-in-southern-Australia/3224>.
- Mcrae K, Rowe S, McEwan J 2018. BRIEF COMMUNICATION: Potential alterations in New Zealand sheep, beef cattle and deer numbers due to climate change: what can genetics offer? *New Zealand Journal of Animal Science and Production* 78: 146-150.
- Meyer K 1995. Estimates of genetic parameters for mature weight of Australian beef cows and its relationship to early growth and skeletal measures. *Livestock Production Science* 44: 125-137. DOI: 10.1016/0301-6226(95)00067-4
- Ministry for Primary Industries 2019. Livestock slaughter statistics. Retrieved 05 December 2019 (updated 22 November 2019): <http://www.mpi.govt.nz/news-and-resources/open-data-and-forecasting/agriculture>
- Ministry for Primary Industries 2020. Livestock slaughter statistics. Retrieved 11 November 2020 (updated 20 October 2020): <http://www.mpi.govt.nz/news-and-resources/open-data-and-forecasting/agriculture>
- Morgan J, Pickering F, Everitt G 1969. Some factors affecting yellow fat colour in cattle. *Proceedings of New Zealand Society of Animal Production* 29: 164-175.
- Morris CA, Baker RL, Carter AH, Cullen NG, Amyes NC, Hickey SM 1993. Evaluation of two-breed composites alongside Angus or Hereford controls for growth, reproduction, maternal, and carcass traits. *New Zealand Journal of Agricultural Research* 36: 327-340. DOI: 10.1080/00288233.1993.10417730
- Morris S 2017. Beef cattle production. In: Stafford K ed. *Livestock production in New Zealand*. Auckland, New Zealand, Massey University Press. Pp. 56-83.
- Morris S, Hickson R 2016. An overview of current and potential hill country livestock systems. In: Thom E ed. *Proceedings of Hill Country Symposium* 16: 309–316.

- Morris ST 2013. Presidential Address 2012: The New Zealand beef cattle industry. Proceedings of New Zealand Society of Animal Production 73: 1-4.
- Morris ST 2019. Living Legend Address 2019: A precis of beef-cattle research over the last 45 years. Proceedings of New Zealand Society of Animal Production 79: 188-197.
- Morris ST, Smeaton D ed. 2009. Profitable Farming of Beef Cows. Hamilton, New Zealand, NZ Sheep and Beef Council, Meat and Wool New Zealand. 130 p.
- Morris ST, Kenyon PR 2014a. Intensive sheep and beef production from pasture — A New Zealand perspective of concerns, opportunities and challenges. Meat Science 98: 330-335. DOI: 10.1016/j.meatsci.2014.06.011
- Morris ST, Parker WJ, Purchas RW, McCutcheon SN 1992. Dairy crossbreeding alternatives to improve New Zealand beef production. Proceedings of New Zealand Grassland Association 54: 19-22.
- Morris ST, Chan FY, Lopez-Villalobos N, Kenyon PR, Garrick DJ, Blair HT 2014b. Growth, feed intake and maternal performance of Angus heifers from high and low feed efficiency selection lines. Animal Production Science 54: 1428-1431. DOI: 10.1071/AN14220
- Muir PD, Fugle CJ, Ormond AWA 2002. Calf rearing using a once-a-day milk feeding system: current best practice. Proceedings of New Zealand Grassland Association 64: 21-24.
- Muir PD, Wallace GJ, Dobbie PM, Bown MD 2000a. A comparison of animal performance and carcass and meat quality characteristics in Hereford, Hereford x Friesian, and Friesian steers grazed together at pasture. New Zealand Journal of Agricultural Research 43: 193-205. DOI: 10.1080/00288233.2000.9513421
- Muir PD, Nieuwenhuis G, Smith NB, Ormond AWA 2000b. A comparison of rearing systems for dairy beef calves. Proceedings of New Zealand Grassland Association 62: 9-12.
- Muir PD, Fugle CJ, Smith NB, Ormond AWA 2001. A comparison of bull beef production from Friesian type and selected Jersey type calves. Proceedings of New Zealand Grassland Association 63: 203-207.
- New Zealand AngusPure AngusPure Source & Trace. Retrieved 14 April 2020 <https://www.anguspure.co.nz/anguspure-source-trace-0>
- New Zealand Meat Classification Authority 2004. New Zealand Meat: Guide to Beef Carcass Classification. Wellington, New Zealand.
- Nicol AM, Brookes IM 2017. The metabolisable energy requirements of grazing livestock. In: Rattray PV, Brookes IM, Nicol AM ed. Pasture and supplements for grazing animals. Second ed. Cambridge, New Zealand, New Zealand Society of Animal Production. Pp. 151-172.

- Nicol D, Graser H-U, Tier B, Hammond K 1985. Breedplan: a new within-herd evaluation system for the national beef recording scheme. *Proceedings of Association for the Advancement of Animal Breeding and Genetics* 5: 151-153.
- Njisane YZ, Muchenje V 2017. Farm to abattoir conditions, animal factors and their subsequent effects on cattle behavioural responses and beef quality - A review. *Asian-Australasian Journal of Animal Sciences* 30: 755-764. DOI: 10.5713/ajas.16.0037
- Nour AYM, Thonney ML, Stouffer JR, White Jr WRC 1983. Changes in carcass weight and characteristics with increasing weight of large and small cattle. *Journal of Animal Science* 57: 1154–1165. DOI: 10.2527/jas1983.5751154x
- Nozière P, Graulet B, Lucas A, Martin B, Grolier P, Doreau M 2006. Carotenoids for ruminants: From forages to dairy products. *Animal Feed Science and Technology* 131: 418-450. DOI: 10.1016/j.anifeedsci.2006.06.018
- NSW Department of Primary Industries 2007. Frame scoring of beef cattle. Retrieved 20 October 2020 (updated 13 September 2007): <http://www.dpi.nsw.gov.au/animals-and-livestock/beef-cattle/appraisal/publications/frame-scoring>
- Nugent RA, Notter DR 1991a. Body measurements of crossbred calves sired by Simmental bulls divergently selected for progeny first-calf calving ease in relation to birth weight. *Journal of Animal Science* 69: 2422-2433. DOI: 10.2527/1991.6962422x
- Nugent RA, Notter DR, Beal WE 1991b. Body measurements of newborn calves and relationship of calf shape to sire breeding values for birth weight and calving ease. *Journal of Animal Science* 69: 2413-2421. DOI: 10.2527/1991.6962413x
- Owens FN, Dubeski P, Hanson CF 1993. Factors that alter the growth and development of ruminants. *Journal of Animal Science* 71: 3138-3150. DOI: 10.2527/1993.71113138x
- Perry D, Shorthose WR, Ferguson DM, Thompson JM 2001. Methods used in the CRC program for the determination of carcass yield and beef quality. *Australian Journal of Experimental Agriculture* 41: 953-957. DOI: 10.1071/ea00092
- Pethick D, Harper G, Oddy V 2004. Growth, development and nutritional manipulation of marbling in cattle: a review. *Australian Journal of Experimental Agriculture* 44: 705-715. DOI: 10.1071/EA02165
- Pettigrew EJ, Morris ST, Back PJ, Kenyon PR, Berry J, Donald AJ, Lane AL, Hickson RE 2017. Growth of weaned Friesian bull calves on a herb sward or with concentrate supplementation during late summer and early autumn. *New Zealand Journal of Agricultural Research* 60: 70-79. DOI: 10.1080/00288233.2016.1259641
- Ponnampalam E, Hopkins D, Bruce H, Li D, Baldi G, Bekhit A 2017. Causes and Contributing Factors to “Dark Cutting” Meat: Current Trends and Future Directions: A Review.

- Comprehensive Reviews in Food Science and Food Safety 16: 400-430. DOI: 10.1111/1541-4337.12258
- Pösö AR, Puolanne E 2005. Carbohydrate metabolism in meat animals. *Meat Science* 70: 423-434. DOI: 10.1016/j.meatsci.2004.12.017
- Puha MR, King WM, Burggraaf VT, Roberts AHC 2008. Pasture production gains from strategic winter nitrogen applications on a North Island sheep and beef hill country farm. *Proceedings of New Zealand Grassland Association* 70: 117-121.
- Purchas R 2003. Factors affecting carcass composition and beef quality. In: Smeaton D ed. *Profitable Beef Production in New Zealand*. New Zealand Beef Council Report. Wellington, New Zealand, Ministry of Primary Industries. Pp. 124-152.
- Purchas RW 1990. An assessment of the role of pH differences in determining the relative tenderness of meat from bulls and steers. *Meat Science* 27: 129-140. DOI: 10.1016/0309-1740(90)90061-A
- Purchas RW, Barton RA 1976. The tenderness of meat of several breeds of cattle raised under New Zealand pastoral conditions. *New Zealand Journal of Agricultural Research* 19: 421-428. DOI: 10.1080/00288233.1976.10420970
- Purchas RW, Aungsupakorn R 1993. Further investigations into the relationship between ultimate pH and tenderness for beef samples from bulls and steers. *Meat Science* 34: 163-178. DOI: 10.1016/0309-1740(93)90025-D
- Purchas RW, Morris ST 2007. A comparison of carcass characteristics and meat quality for Angus, Hereford x Friesian, and Jersey x Friesian steers. *Proceedings of New Zealand Society of Animal Production* 67: 18-22.
- Purchas RW, Burnham DL, Morris ST 2002. Effects of growth potential and growth path on tenderness of beef longissimus muscle from bulls and steers. *Journal of Animal Science* 80: 3211-3221. DOI: 10.2527/2002.80123211x
- Realini C, E Williams R, Pringle D, Bertrand J 2001. Gluteus medius and rump fat depth as additional live animal ultrasound measurements for predicting retail product and trimmable fat in beef carcasses. *Journal of Animal Science* 79: 1378-85. DOI: 10.2527/2001.7961378x
- Reverter A, Johnston DJ, Graser HU, Wolcott ML, Upton WH 2000. Genetic analyses of live-animal ultrasound and abattoir carcass traits in Australian Angus and Hereford cattle. *Journal of Animal Science* 78: 1786-1795. DOI: 10.2527/2000.7871786x
- Reverter A, Johnston DJ, Perry D, Goddard ME, Burrow HM 2003a. Genetic and phenotypic characterisation of animal, carcass, and meat quality traits from temperate and

- tropically adapted beef breeds. 2. Abattoir carcass traits. *Australian Journal of Agricultural Research* 54: 119-134. DOI: 10.1071/AR02086
- Reverter A, Johnston DJ, Ferguson DM, Perry D, Goddard ME, Burrow HM, Oddy VH, Thompson JM, Bindon BM 2003b. Genetic and phenotypic characterisation of animal, carcass, and meat quality traits from temperate and tropically adapted beef breeds. 4. Correlations among animal, carcass, and meat quality traits. *Australian Journal of Agricultural Research* 54: 149-158. DOI: 10.1071/AR02088
- Rios Utrera A, Van Vleck LD 2004. Heritability estimates for carcass traits of cattle: a review. *Genetics and Molecular Research* 3: 380-394.
- Robinson DL 2005. Accounting for bias in regression coefficients with example from feed efficiency. *Livestock Production Science* 95: 155-161. DOI: 10.1016/j.livprodsci.2004.12.017
- Santana ML, Eler JP, Cardoso FF, Albuquerque LG, Ferraz JBS 2013. Phenotypic plasticity of composite beef cattle performance using reaction norms model with unknown covariate. *Animal* 7: 202-210. DOI: 10.1017/S1751731112001711
- Schein MW, Fohrman MH 1955. Social dominance relationships in a herd of dairy cattle. *The British Journal of Animal Behaviour* 3: 45-55. DOI: 10.1016/S0950-5601(55)80012-3
- Schreurs NM, Hickson RE, Coleman LW, Kenyon PR, Martín NP, Morris ST 2014. BRIEF COMMUNICATION: Quality of meat from steers born to beef-cross-dairy cows and sired by Hereford bulls. *Proceedings of New Zealand Society of Animal Production* 74: 229-232.
- Shadbolt N 2007. Measuring farm profitability. In: Smeaton DC ed. *Profitable Beef Production: A Guide to Beef Production in New Zealand*. 3rd ed. Hamilton, New Zealand, New Zealand Beef Council, Meat and Wool New Zealand. Pp. 193-207.
- Su H, Golden B, Hyde L, Sanders S, Garrick D 2017. Genetic parameters for carcass and ultrasound traits in Hereford and admixed Simmental beef cattle: Accuracy of evaluating carcass traits¹. *Journal of Animal Science*. DOI: 10.2527/jas2017.1865
- Tarrant PV, Sherington J 1980. An investigation of ultimate pH in the muscles of commercial beef carcasses. *Meat Science* 4: 287-297.
- Thoney ML 2015. Genetics of Growth and Body Composition. In: Garrick DJ, Ruvinsky A ed. *The Genetics of Cattle*. 2nd ed. Wallingford, United Kingdom, CAB International. Pp. 523-543. ISBN:978-1-78064-221-5.
- Troy DJ, Kerry JP 2010. Consumer perception and the role of science in the meat industry. *Meat Science* 86: 214-26. DOI: 10.1016/j.meatsci.2010.05.009

- Valentine I, Kemp PD 2017. Pasture and supplement resources. In: Rattray PV, Brookes IM, Nicol AM ed. Pasture and supplements for grazing animals. Second ed. Cambridge, New Zealand, New Zealand Society of Animal Production. Pp. 3-12. ISBN:0473-05236-9.
- van Selm B, de Boer IJM, Ledgard SF, van Middelaar CE 2021. Reducing greenhouse gas emissions of New Zealand beef through better integration of dairy and beef production. *Agricultural Systems* 186: 102936. DOI: 10.1016/j.agsy.2020.102936
- Van Vleck LD, Hakim AF, Cundiff LV, Koch RM, Crouse JD, Boldman KG 1992. Estimated breeding values for meat characteristics of crossbred cattle with an animal model. *Journal of Animal Science* 70: 363-371. DOI: 10.2527/1992.702363x
- Verbeke W, Van Wezemael L, de Barcellos MD, Kügler JO, Hocquette J-F, Ueland Ø, Grunert KG 2010. European beef consumers' interest in a beef eating-quality guarantee: Insights from a qualitative study in four EU countries. *Appetite* 54: 289-296. DOI: 10.1016/j.appet.2009.11.013
- Walmsley BJ, McPhee MJ, Oddy VH 2014. Development of the BeefSpecs fat calculator to assist decision making to increase compliance rates with beef carcass specifications. *Animal Production Science* 54: 2003-2010. DOI: 10.1071/AN14611
- Warner RD, Greenwood PL, Pethick DW, Ferguson DM 2010. Genetic and environmental effects on meat quality. *Meat Science* 86: 171-183. DOI: 10.1016/j.meatsci.2010.04.042
- Warriss PD 1990. The handling of cattle pre-slaughter and its effects on carcass and meat quality. *Applied Animal Behaviour Science* 28: 171-186. DOI: 10.1016/0168-1591(90)90052-F
- Young OA, West J, Hart AL, van Otterdijk FFH 2004. A method for early determination of meat ultimate pH. *Meat Science* 66: 493-498. DOI: 10.1016/s0309-1740(03)00140-2

APPENDICES

Appendix 1. Estimated Breeding Values and their accuracy (in brackets) for live weight, carcass and meat quality traits, for 37 Angus and 40 Hereford sires (BREEDPLAN <http://breedplan.une.edu.au/>, April 2020).

Sire	Herdbook No	AB Code	Breed	Estimated Breeding Values						
				200d weight (kg)	400d weight (kg)	600d weight (kg)	Carcass weight (kg)	EMA [‡] (cm ²)	Rib Fat (mm)	IMF [‡] (%)
BLUE MOUNTAIN BRILLIANZ O5	210530135	715061	Angus	47 (79%)	79 (78%)	109 (79%)	62 (67%)	6.4 (63%)	-1.1 (66%)	0 (56%)
EARNSCLEUGH TUSOCK 144307	210130144307	716043	Angus	57 (92%)	98 (93%)	135 (91%)	76 (79%)	9.5 (80%)	-1.3 (82%)	1.5 (79%)
GLANWORTH WAIGROUP 1213	1215401213	714004	Angus	35 (95%)	73 (95%)	92 (95%)	42 (89%)	3.7 (88%)	1.1 (90%)	0.7 (87%)
GRAMPIANS LOTTERY K13	21150014K13	716073	Angus	38 (81%)	68 (83%)	89 (84%)	49 (70%)	3.4 (70%)	0.3 (72%)	0.8 (65%)
HEATHER DELL L72 [§]	19928015L72	Natural	Angus	36 (67%)	70 (67%)	85 (65%)	45 (58%)	0.9 (55%)	0.9 (59%)	1.2 (53%)
KAKAHU BOND 13007	13300013007	715058	Angus	49 (92%)	86 (92%)	100 (92%)	61 (78%)	1.9 (80%)	1.0 (82%)	2.7 (79%)
KAKAHU JUBILANT 13054	13300013054	715060	Angus	37 (86%)	71 (86%)	101 (88%)	46 (76%)	9.7 (72%)	0.5 (77%)	1.9 (71%)
KAKAHU JUGGLER 13059	13300013059	715103	Angus	48 (87%)	83 (88%)	106 (89%)	64 (77%)	7.9 (77%)	-2.0 (79%)	0 (74%)
LINTON 13041	20305013041	715102	Angus	42 (88%)	73 (89%)	93 (86%)	55 (78%)	7.4 (77%)	-1.8 (80%)	1.9 (76%)
MATAURI REALITY 839	14647008839	710016	Angus	41 (99%)	77 (99%)	94 (99%)	48 (97%)	4.9 (97%)	6.1 (97%)	2.8 (96%)
MATAURI RESOLUTION F030	14647010F030	712080	Angus	43 (96%)	80 (96%)	101 (96%)	51 (89%)	4.5 (89%)	4.1 (90%)	0.9 (88%)
MEADOWSLEA F540	19134010540	715105	Angus	34 (96%)	77 (96%)	89 (96%)	44 (87%)	2.7 (89%)	2.2 (90%)	1.4 (87%)
PINEBANK 1/06	119900061	708031	Angus	31 (91%)	65 (91%)	76 (90%)	28 (84%)	6.3 (83%)	3.1 (86%)	-2.1 (82%)
PUKETI REGAN 14134 [§]	21149014134	Natural	Angus	43 (65%)	81 (66%)	101 (64%)	55 (56%)	3.9 (53%)	-0.9 (59%)	0.3 (54%)
PUKETI REGAN 14123 [§]	21149014123	Natural	Angus	29 (67%)	56 (68%)	64 (66%)	34 (58%)	1.9 (55%)	0.3 (59%)	0.8 (55%)
RENNYLEA EDMUND E11 (AUS)	AUNORE11	711067	Angus	36 (99%)	67 (99%)	88 (99%)	53 (98%)	7.0 (97%)	3.5 (98%)	3.9 (97%)
RISSINGTON PROGRESSION 110178	145720110178	714046	Angus	32 (86%)	62 (86%)	70 (84%)	45 (76%)	5.1 (74%)	-0.8 (77%)	1.5 (73%)
RISSINGTON PROTEGE 110002	145720110002	712171	Angus	51 (83%)	88 (83%)	119 (82%)	59 (74%)	4.8 (72%)	-0.5 (76%)	1.7 (71%)
SEVEN HILLS 161-06	21159006161	708057	Angus	41 (91%)	82 (91%)	109 (88%)	48 (82%)	5.4 (80%)	-0.7 (80%)	1.7 (75%)
SEVEN HILLS 173-06	21159006173	715104	Angus	42 (70%)	78 (70%)	105 (70%)	42 (67%)	3.4 (66%)	-0.5 (68%)	2.1 (65%)
SHALOM WAIGROUP 101/01	10596001101	703057	Angus	23 (95%)	56 (95%)	70 (94%)	27 (86%)	5.7 (86%)	2.2 (86%)	0 (83%)
SHALOM WAIGROUP 319/07	10596007319	715088	Angus	33 (79%)	66 (77%)	85 (76%)	41 (67%)	4.5 (62%)	0.5 (64%)	1.1 (56%)
STORTH OAKS ANGUS PRIME K5	19507014K5	716058	Angus	40 (87%)	73 (87%)	91 (87%)	55 (77%)	6.9 (75%)	3.8 (79%)	4.4 (75%)
STORTH OAKS EVEREST J20	19507013J20	715038	Angus	52 (94%)	100 (93%)	133 (94%)	78 (81%)	2.1 (82%)	2.2 (84%)	2.9 (81%)
STORTH OAKS H41	19507012H41	714042	Angus	47 (92%)	89 (93%)	116 (94%)	53 (88%)	7.8 (87%)	2.1 (89%)	0.9 (86%)
STORTH OAKS J29	19507013J29	715099	Angus	43 (72%)	78 (72%)	111 (75%)	61 (65%)	6.3 (65%)	1.1 (67%)	2.8 (64%)
STORTH OAKS K134	19507014K134	716084	Angus	56 (75%)	99 (76%)	130 (76%)	80 (68%)	4.6 (67%)	0.2 (71%)	2.1 (67%)

Continue

Sire	Herdbook No	AB Code	Breed	Estimated Breeding Values						
				200d weight (kg)	400d weight (kg)	600d weight (kg)	Carcass weight (kg)	EMA [‡] (cm ²)	Rib Fat (mm)	IMF [‡] (%)
STORTH OAKS K154	19507014K154	716086	Angus	40 (90%)	78 (91%)	108 (90%)	52 (78%)	6.4 (80%)	0.7 (82%)	3.4 (78%)
TE ATARANGI KESSLERS K098 [§]	19241014K098	Natural	Angus	27 (66%)	57 (67%)	68 (66%)	37 (55%)	3.0 (56%)	0.6 (58%)	-0.3 (51%)
TE ATARANGI TURI K026 [§]	19241014K026	Natural	Angus	21 (67%)	53 (69%)	65 (67%)	18 (58%)	2.6 (58%)	2.1 (61%)	1.3 (54%)
TE ATARANGI WAI L027 [§]	19241015L027	Natural	Angus	18 (69%)	41 (70%)	49 (68%)	19 (59%)	-2.2 (60%)	1.9 (61%)	0.4 (56%)
TE MANIA UNLIMITED U3271 (AUS)	AUS0VTMU3271	702140	Angus	29 (99%)	62 (99%)	81 (99%)	26 (98%)	2.8 (98%)	0.3 (98%)	3.4 (98%)
THOMAS UP RIVER 1614 (USA)	US17091363	713089	Angus	59 (98%)	110 (98%)	132 (98%)	78 (92%)	4.3 (92%)	1.4 (92%)	1.2 (90%)
TOTARANUI 13007	12922013007	715098	Angus	49 (92%)	92 (92%)	122 (90%)	69 (80%)	3.9 (80%)	-1.0 (82%)	1.0 (78%)
TURIHAUA LIBERATION C27	17691007C27	712005	Angus	29 (93%)	68 (93%)	90 (94%)	35 (82%)	-0.3 (82%)	-0.4 (83%)	-0.3 (80%)
WAITANGI FOCUS D213	18954008D213	710091	Angus	45 (97%)	83 (97%)	97 (97%)	55 (93%)	5.9 (92%)	-0.4 (93%)	-0.5 (91%)
WOODBANK BLACKPOWER 06	15009000006	704170	Angus	36 (93%)	66 (93%)	87 (94%)	32 (84%)	5.6 (84%)	1.3 (85%)	0.3 (81%)
ARDO ACHILLES 120	0277100120	715106	Hereford	25 (96%)	47 (96%)	56 (96%)	51 (89%)	5.4 (82%)	1.0 (86%)	1.5 (89%)
ARDO BISMARCK 4256	0277144256	716017	Hereford	24 (95%)	47 (95%)	54 (95%)	51 (83%)	5.5 (74%)	1.6 (77%)	0.6 (83%)
ARDO CASPIAN 6159	0277066159	711022	Hereford	18 (95%)	33 (94%)	40 (94%)	37 (87%)	1.8 (78%)	0.9 (83%)	0.4 (85%)
ARDO EXTRACT 5298 [§]	0277155298	Natural	Hereford	25 (68%)	42 (68%)	57 (67%)	50 (58%)	2.8 (52%)	0.4 (57%)	-0.1 (55%)
ARDO FARGO 1154	0277111154	715086	Hereford	31 (96%)	52 (96%)	67 (96%)	57 (88%)	3.4 (79%)	0.7 (83%)	0.8 (87%)
BEECHWOOD DOUBTLESS	0051140527	716098	Hereford	36 (91%)	71 (92%)	93 (91%)	70 (79%)	3.0 (66%)	0.2 (67%)	-0.1 (64%)
BEECHWOOD TURK	0051100094	714037	Hereford	36 (93%)	63 (93%)	84 (94%)	66 (85%)	6.6 (74%)	1.1 (76%)	0.1 (77%)
BLUESTONE 080014	1683080014	715091	Hereford	32 (95%)	67 (95%)	90 (94%)	68 (85%)	3.9 (67%)	1.3 (76%)	0.5 (78%)
BLUESTONE 120061	1683120061	714003	Hereford	30 (88%)	48 (88%)	64 (87%)	48 (76%)	3.5 (59%)	-1.0 (68%)	-0.4 (69%)
BLUESTONE 140015	1683140015	716087	Hereford	33 (86%)	66 (87%)	91 (86%)	56 (75%)	1.4 (58%)	-1.8 (67%)	-0.8 (68%)
BLUESTONE 140027	1683140027	716088	Hereford	34 (87%)	49 (88%)	65 (88%)	53 (78%)	5.8 (66%)	-0.7 (72%)	-0.2 (73%)
BURNFOOT PLAYBOY	0735P0007	666325	Hereford	21 (95%)	32 (95%)	47 (95%)	25 (89%)	3.0 (78%)	1.3 (81%)	-0.1 (64%)
COLRAINE CODE WORD 13 139	1660130139	715101	Hereford	34 (76%)	60 (76%)	83 (76%)	54 (65%)	0.3 (52%)	0.5 (58%)	0.2 (59%)
CRAIGMORE BATON 140323 [§]	0169140323	Natural	Hereford	27 (69%)	43 (69%)	61 (68%)	47 (59%)	1.7 (52%)	1.1 (56%)	1.0 (55%)
CRAIGMORE BATON 140337 [§]	0169140337	Natural	Hereford	32 (69%)	59 (69%)	73 (68%)	52 (58%)	2.3 (52%)	1.1 (56%)	0.5 (56%)
CRAIGMORE OPIUM 10214	0169100214	716016	Hereford	30 (86%)	55 (85%)	83 (85%)	55 (74%)	3.5 (62%)	1.9 (68%)	0.5 (68%)
CRAIGMORE OPIUM 150206 [§]	0169150206	Natural	Hereford	27 (68%)	48 (68%)	64 (67%)	51 (56%)	2.5 (45%)	1.3 (50%)	1.0 (51%)
FLAGSTAFF BIG RED E8	0759090008	715073	Hereford	28 (92%)	60 (93%)	93 (94%)	65 (84%)	1.2 (77%)	-0.3 (81%)	-1.0 (83%)
FLAGSTAFF DYNAMO G6	0759110006	715084	Hereford	29 (80%)	61 (80%)	81 (80%)	59 (71%)	0.5 (66%)	0.3 (70%)	0.8 (70%)
HAUMOANA ACCENT 14032 [§]	0511140032	Natural	Hereford	27 (69%)	42 (68%)	61 (66%)	42 (55%)	1.2 (31%)	0.7 (33%)	0 (30%)

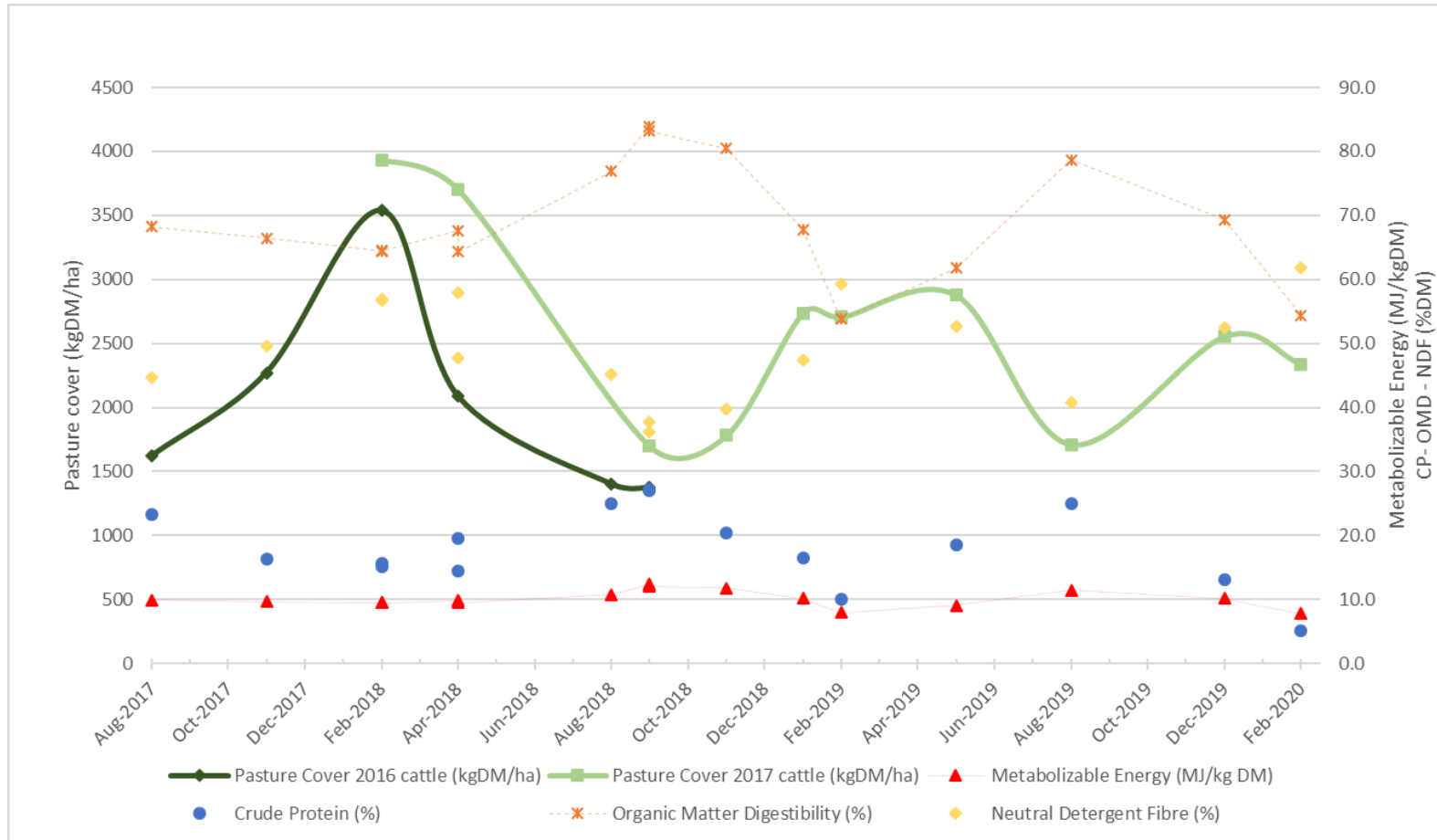
Continue

Sire	Herdbook No	AB Code	Breed	Estimated Breeding Values						
				200d weight (kg)	400d weight (kg)	600d weight (kg)	Carcass weight (kg)	EMA [‡] (cm ²)	Rib Fat (mm)	IMF [‡] (%)
KAIRAUMATI COAL FACE 1482	1483140082	715092	Hereford	34 (77%)	57 (77%)	75 (74%)	52 (62%)	3.5 (54%)	0.6 (56%)	0.1 (51%)
KOANUI BEDFORD 4081	0216144081	715108	Hereford	28 (69%)	43 (69%)	63 (69%)	42 (58%)	0.4 (50%)	-0.3 (52%)	0.2 (50%)
KOANUI BRITON 2044	0216122044	716097	Hereford	36 (92%)	72 (92%)	104 (93%)	72 (82%)	1.5 (69%)	1.5 (70%)	1.3 (67%)
KOANUI ROCKET 0219	0216000219	703131	Hereford	29 (99%)	53 (99%)	73 (99%)	55 (98%)	1.9 (96%)	1.2 (97%)	0.1 (97%)
KOANUI UNANIMOUS 0408	0216100408	715093	Hereford	38 (96%)	79 (96%)	105 (96%)	80 (89%)	3.8 (81%)	0.9 (83%)	0.2 (84%)
LIMEHILLS AWESOME X117	0677020117	715107	Hereford	21 (93%)	48 (92%)	64 (92%)	43 (84%)	1.8 (74%)	1.4 (78%)	1.8 (76%)
LIMEHILLS STAMPER 20719	0677120719	715082	Hereford	46 (94%)	76 (94%)	100 (94%)	72 (84%)	6.2 (76%)	1.4 (79%)	0.4 (83%)
MAHUTA KIMO 4029 [§]	0828144029	Natural	Hereford	27 (69%)	49 (68%)	65 (68%)	50 (58%)	1.4 (51%)	0.3 (53%)	-0.3 (49%)
MARANUI HICK 11-62	0659110062	715095	Hereford	23 (94%)	41 (93%)	54 (89%)	38 (76%)	2.1 (50%)	2.7 (54%)	0.9 (39%)
MATAPOURI KOA 09 99	0251090099	715094	Hereford	21 (95%)	31 (95%)	44 (92%)	29 (81%)	2.6 (56%)	0.8 (62%)	0.4 (52%)
OKAWA MARSHALL 0109	0617100109	715089	Hereford	33 (93%)	65 (93%)	94 (94%)	65 (85%)	1.2 (77%)	0.5 (81%)	0.6 (84%)
ORARI GORGE MISCHIEF 120083	0400120083	716044	Hereford	36 (94%)	66 (94%)	89 (94%)	63 (84%)	3.5 (75%)	2.1 (79%)	1.2 (84%)
OTAPAWA SPARK 3060	0347033060	705090	Hereford	48 (98%)	79 (98%)	114 (98%)	84 (96%)	4.1 (93%)	1.9 (95%)	2.0 (95%)
OTENGI WISCO 23	0816040023	715090	Hereford	19 (79%)	39 (78%)	62 (79%)	33 (67%)	1.9 (52%)	1.0 (54%)	0.7 (38%)
PLATFORM QUEBEC	0813Q0344	666931	Hereford	20 (97%)	36 (97%)	46 (97%)	26 (94%)	0.8 (83%)	0.7 (86%)	-0.2 (82%)
RIVERTON BALTIC 09 183	0091090183	715087	Hereford	32 (96%)	55 (96%)	72 (96%)	59 (89%)	1.8 (80%)	0.2 (85%)	-0.1 (87%)
TE TAUMATA DELUXE 12520	0308120520	714043	Hereford	42 (91%)	66 (92%)	88 (93%)	71 (80%)	6.3 (66%)	0 (69%)	0.1 (67%)
WESTHOLM KOALA K13	0421090013	715085	Hereford	30 (87%)	59 (84%)	82 (83%)	54 (70%)	2.5 (54%)	-0.2 (57%)	-0.9 (49%)
WIRRUNA DAFFY D1 (AUS)	AUWNAD1	710087	Hereford	21 (98%)	35 (98%)	35 (98%)	44 (95%)	8.0 (92%)	1.4 (92%)	0.4 (94%)
WIRRUNA ECHUCA E99 (AUS)	AUWNAE99	712049	Hereford	38 (97%)	55 (97%)	75 (98%)	50 (94%)	2.4 (90%)	2.1 (90%)	1.3 (93%)
Angus	EBV Mean			39±10	75±14	96±21	49±16	4.6±2.5	0.9±1.8	1.3±1.4
	EBV Range			18 to 59	41 to 110	49 to 135	18 to 80	-2.2 to 9.7	-2 to 6.1	-2.1 to 4.4
	Accuracy Range			65% to 99%	66% to 99%	64% to 99%	55% to 98%	53% to 98%	58% to 98%	51% to 98%
	Percentile Bands			1 st to 100 th	1 st to 100 th	5 th to 100 th	1 st to 100 th	1 st to 100 th	0 th to 99 th	0 th to 100 th
Hereford	EBV Mean			30±7	54±13	73±19	53±14	2.9±1.9	0.8±0.9	0.4±0.7
	EBV Range			18 to 48	31 to 79	35 to 114	25 to 84	0.3 to 8	-1.8 to 2.7	-1 to 2
	Accuracy Range			68% to 99%	68% to 99%	66% to 99%	55% to 98%	31% to 96%	33% to 97%	30% to 97%
	Percentile Bands			1 st to 99 th	1 st to 99 th	0 th to 100 th	0 th to 100 th	0 th to 100 th	0 th to 100 th	1 st to 100 th

[§] Sires used via natural mating on 15-month-old heifers. [‡] EMA: Eye Muscle Area, IMF: Intramuscular Fat. Percentile Bands: fit of EBV within the percentile bands for 2018 born calves for each breed, where 0th is the top value and 100th is the bottom value for the trait.

Appendix 2. Pooled pasture mass cover, metabolizable energy, crude protein, neutral detergent fibre and organic matter digestibility from August 2017 to February 2020, for grazing cattle born in 2016 and 2017 at Limestone Downs.

Month	Pasture cover 2016 cattle (kgDM/ha)	Pasture cover 2017 cattle (kgDM/ha)	Metabolizable Energy (MJ/kg DM)	Crude Protein (%)	Neutral Detergent Fibre (%)	Organic Matter Digestibility (%)
Aug-2017	1619		9.9	23.2	44.7	68.2
Nov-2017	2271		9.7	16.4	49.7	66.4
Feb-2018	3540		9.5	15.6	56.7	64.5
Feb-2018		3931	9.4	15.1	56.9	64.4
Apr-2018	2087		9.9	19.5	47.7	67.6
Apr-2018		3701	9.4	14.5	57.9	64.3
Aug-2018	1398		10.8	25.0	45.2	76.9
Sep-2018	1376		12.3	27.2	36.2	84.0
Sep-2018		1698	12.0	26.9	37.7	83.2
Nov-2018		1780	11.8	20.5	39.8	80.4
Jan-2019		2735	10.2	16.4	47.4	67.8
Feb-2019		2706	7.9	10.0	59.2	53.8
May-2019		2875	9.1	18.5	52.7	61.7
Aug-2019		1711	11.4	25.0	40.8	78.7
Dec-2019		2553	10.2	13.1	52.5	69.3
Feb-2020		2339	7.8	5.1	61.7	54.4



Pooled pasture mass cover, metabolizable energy, crude protein (CP), organic matter digestibility (OMD) and neutral detergent fibre (NDF) from August 2017 to February 2020, for grazing cattle born in 2016 and 2017 at Limestone Downs.

Appendix 3. Least-squares means (\pm SE) of the progeny groups for live weight (LWT) and individual ranking (in brackets) at 131, 200, 400, 600 and 800 days of age, for 34 Angus and 39 Hereford sires. Number of progeny (n), mean (\pm SD) of the least-squares means of the progeny groups, coefficient of variation (CV) and *P-value* for the effect of sire are presented at the end of the table.

Sire	Breed	n 131d	LWT 131d	n 200d	LWT 200d	n 400d	LWT 400d	n 600d	LWT 600d	n 800d	LWT 800d
A1	Angus	19	115.1 \pm 3.4 (58)	19	158.5 \pm 3.8 (40)	19	280.3 \pm 6.3 (46)	19	420.8 \pm 9.1 (50)	18	503.3 \pm 11.6 (35)
A2	Angus	8	117.0 \pm 4.3 (48)	8	153.6 \pm 5.1 (62)	7	277.0 \pm 8.7 (57)	7	407.3 \pm 12.0 (68)	6	489.6 \pm 16.1 (61)
A3	Angus	14	117.1 \pm 3.7 (47)	14	158.0 \pm 4.2 (42)	14	284.0 \pm 7.0 (40)	14	418.6 \pm 9.9 (56)	9	493.9 \pm 14.2 (54)
A4	Angus	17	116.9 \pm 3.5 (49)	17	160.1 \pm 3.9 (36)	17	279.9 \pm 6.5 (49)	16	426.8 \pm 9.4 (38)	15	498.4 \pm 12.1 (43)
A5	Angus	9	125.7 \pm 4.2 (04)	9	165.2 \pm 4.9 (08)	9	299.9 \pm 8.0 (03)	9	434.1 \pm 11.1 (19)	5	519.8 \pm 17.2 (12)
A6	Angus	14	118.0 \pm 3.7 (41)	14	156.9 \pm 4.2 (46)	13	286.9 \pm 7.1 (27)	11	419.8 \pm 10.5 (52)	10	486.4 \pm 13.7 (66)
A7	Angus	13	118.8 \pm 3.7 (35)	13	153.7 \pm 4.3 (60)	13	279.2 \pm 7.0 (52)	13	408.9 \pm 10.0 (67)	13	488.7 \pm 12.7 (63)
A8	Angus	17	121.8 \pm 3.6 (17)	17	157.8 \pm 4.0 (44)	16	290.7 \pm 6.7 (17)	15	428.4 \pm 9.7 (31)	10	512.2 \pm 13.8 (22)
A9	Angus	20	119.1 \pm 3.4 (33)	19	155.7 \pm 3.9 (53)	19	288.4 \pm 6.4 (21)	18	428.3 \pm 9.3 (32)	13	508.1 \pm 12.8 (29)
A10	Angus	19	119.1 \pm 3.4 (32)	19	153.9 \pm 3.8 (59)	17	276.5 \pm 6.5 (59)	17	419.7 \pm 9.3 (53)	16	492.6 \pm 11.9 (56)
A11	Angus	12	118.6 \pm 3.9 (37)	12	168.1 \pm 4.4 (05)	12	295.6 \pm 7.3 (11)	12	442.3 \pm 10.3 (11)	9	508.9 \pm 14.2 (24)
A12	Angus	14	124.0 \pm 3.7 (05)	14	159.8 \pm 4.2 (39)	14	289.2 \pm 7.0 (20)	13	430.9 \pm 10.1 (26)	13	506.4 \pm 12.8 (30)
A13	Angus	20	114.5 \pm 3.4 (63)	20	155.8 \pm 3.7 (52)	19	286.0 \pm 6.3 (33)	18	421.4 \pm 9.2 (49)	15	484.2 \pm 12.2 (68)
A14	Angus	12	123.0 \pm 3.8 (10)	11	165.0 \pm 4.5 (09)	11	291.8 \pm 7.4 (14)	10	448.5 \pm 10.7 (04)	10	525.8 \pm 13.6 (06)
A15	Angus	11	115.8 \pm 4.0 (54)	10	161.4 \pm 4.7 (26)	10	279.4 \pm 7.7 (51)	10	416.7 \pm 10.8 (58)	7	476.6 \pm 15.3 (71)
A16	Angus	20	117.9 \pm 3.4 (42)	20	160.3 \pm 3.8 (33)	20	285.2 \pm 6.3 (35)	20	430.8 \pm 9.0 (28)	17	514.4 \pm 11.9 (21)
A17	Angus	15	122.6 \pm 3.6 (12)	15	164.3 \pm 4.1 (11)	14	286.1 \pm 6.9 (32)	14	417.8 \pm 9.8 (57)	13	508.3 \pm 12.6 (27)
A19	Angus	19	122.0 \pm 3.4 (15)	18	161.6 \pm 3.9 (25)	16	279.9 \pm 6.6 (49)	16	426.1 \pm 9.4 (39)	15	495.6 \pm 12.2 (51)
A20	Angus	12	120.4 \pm 3.8 (23)	12	165.2 \pm 4.3 (07)	12	286.4 \pm 7.2 (30)	12	436.2 \pm 10.1 (16)	11	502.7 \pm 13.2 (37)
A21	Angus	15	120.5 \pm 3.6 (22)	14	156.5 \pm 4.1 (49)	14	286.7 \pm 6.9 (29)	14	427.0 \pm 9.7 (36)	11	503.5 \pm 13.2 (34)
A22	Angus	13	118.3 \pm 3.7 (40)	13	155.2 \pm 4.2 (55)	13	274.3 \pm 7.0 (62)	12	423.0 \pm 10.1 (44)	10	508.3 \pm 13.5 (26)
A23	Angus	21	116.0 \pm 3.4 (53)	20	154.7 \pm 3.8 (57)	19	277.9 \pm 6.3 (55)	18	420.6 \pm 9.2 (51)	17	495.5 \pm 11.9 (52)
A24	Angus	11	115.7 \pm 4.0 (55)	10	149.2 \pm 4.7 (71)	10	269.4 \pm 7.7 (70)	10	410.9 \pm 10.8 (64)	8	487.8 \pm 14.7 (64)
A25	Angus	13	117.7 \pm 3.7 (43)	13	147.6 \pm 4.2 (73)	13	274.6 \pm 7.0 (61)	12	409.3 \pm 10.1 (66)	11	485.8 \pm 13.2 (67)
A27	Angus	14	122.7 \pm 3.7 (11)	13	162.0 \pm 4.3 (22)	13	296.0 \pm 7.1 (09)	13	438.1 \pm 10.1 (14)	12	519.6 \pm 13.1 (13)
A28	Angus	12	114.7 \pm 3.9 (62)	12	150.8 \pm 4.4 (69)	12	271.4 \pm 7.3 (67)	11	403.6 \pm 10.5 (71)	10	498.4 \pm 13.7 (44)
A29	Angus	16	111.5 \pm 3.6 (72)	16	148.0 \pm 4.1 (72)	15	271.7 \pm 6.9 (66)	15	401.2 \pm 9.7 (73)	14	490.7 \pm 12.6 (59)

Continue

Sire	Breed	n 131d	LWT 131d	n 200d	LWT 200d	n 400d	LWT 400d	n 600d	LWT 600d	n 800d	LWT 800d
A30	Angus	11	120.0±4.0 (26)	11	160.0±4.5 (37)	10	296.1±7.7 (08)	9	464.5±11.1 (01)	9	539.9±14.1 (02)
A31	Angus	15	121.0±3.7 (19)	15	163.9±4.1 (13)	15	290.2±6.8 (19)	13	431.3±10.0 (25)	13	514.8±12.7 (19)
A32 [§]	Angus	11	120.8±4.7 (20)	11	173.9±5.2 (01)	11	314.9±8.7 (01)	9	457.5±13.8 (02)	6	524.9±20.0 (08)
A33 [§]	Angus	16	116.4±4.4 (52)	16	170.4±4.8 (03)	16	310.0±8.1 (02)	16	454.2±12.5 (03)	13	527.7±17.1 (04)
A35 [§]	Angus	31	112.4±4.1 (70)	30	163.8±4.3 (14)	30	287.8±7.3 (23)	27	427.5±11.8 (35)	21	495.8±16.2 (50)
A36 [§]	Angus	24	123.9±4.2 (06)	24	161.6±4.4 (24)	24	285.0±7.5 (36)	24	432.2±11.1 (22)	24	497.1±13.6 (48)
A37 [§]	Angus	21	126.3±4.2 (03)	21	160.6±4.5 (31)	21	268.0±7.6 (71)	21	412.0±11.3 (62)	21	454.5±13.8 (73)
H1	Hereford	14	114.8±3.7 (60)	14	152.2±4.1 (66)	14	277.1±6.8 (56)	14	409.9±9.7 (65)	13	499.9±12.6 (39)
H2	Hereford	13	115.1±3.8 (57)	13	151.5±4.3 (67)	13	269.7±7.1 (69)	13	407.0±10.1 (69)	13	492.7±12.8 (55)
H3	Hereford	26	121.7±3.2 (18)	25	163.0±3.5 (17)	25	293.1±5.9 (12)	25	435.2±8.6 (17)	24	531.3±11.0 (03)
H4	Hereford	23	121.9±3.3 (16)	23	156.3±3.6 (51)	23	287.5±6.1 (24)	22	430.1±8.9 (29)	19	516.9±11.7 (17)
H5	Hereford	18	115.5±3.5 (56)	17	153.5±4.0 (63)	17	272.8±6.6 (64)	16	412.5±9.6 (61)	13	482.7±12.9 (69)
H6	Hereford	14	113.5±3.7 (67)	14	150.0±4.2 (70)	14	264.4±7.0 (73)	13	404.1±10.1 (70)	13	489.4±12.8 (62)
H7	Hereford	13	120.0±3.7 (26)	13	160.9±4.3 (28)	12	291.1±7.2 (16)	11	437.7±10.4 (15)	9	508.5±14.0 (25)
H8	Hereford	12	115.0±3.9 (59)	12	154.1±4.4 (58)	12	281.2±7.3 (42)	12	411.1±10.3 (63)	8	482.2±14.8 (70)
H9	Hereford	20	117.6±3.4 (44)	20	156.7±3.7 (47)	19	284.5±6.3 (39)	19	424.3±9.1 (42)	18	497.9±11.7 (45)
H10	Hereford	11	119.4±4.0 (30)	11	152.8±4.6 (64)	11	278.9±7.5 (53)	11	426.9±10.5 (37)	11	518.5±13.4 (15)
H11	Hereford	11	119.9±4.0 (28)	11	162.2±4.5 (20)	11	295.6±7.5 (10)	11	447.2±10.5 (07)	8	518.3±14.8 (16)
H12	Hereford	17	123.6±3.5 (08)	17	162.0±3.9 (21)	17	280.7±6.5 (44)	17	428.1±9.3 (33)	15	492.3±12.2 (57)
H13	Hereford	18	118.5±3.5 (39)	18	154.9±3.9 (56)	18	284.9±6.5 (37)	16	421.5±9.6 (47)	16	506.2±12.1 (31)
H14	Hereford	19	118.6±3.4 (38)	19	160.2±3.8 (34)	19	283.3±6.3 (41)	19	427.9±9.1 (34)	17	499.7±11.8 (41)
H15	Hereford	13	119.6±3.8 (29)	13	152.6±4.3 (65)	13	280.0±7.1 (48)	12	422.9±10.3 (45)	9	496.7±14.2 (49)
H16	Hereford	16	118.8±3.5 (36)	15	163.3±4.0 (15)	15	284.7±6.7 (38)	15	433.5±9.6 (20)	15	510.9±12.1 (23)
H17	Hereford	7	126.7±4.5 (02)	7	157.8±5.3 (43)	7	292.6±8.6 (13)	7	422.5±11.9 (46)	6	519.5±16.0 (14)
H18	Hereford	6	111.9±4.8 (71)	6	160.7±5.7 (30)	6	280.5±9.2 (45)	6	433.1±12.7 (21)	5	499.8±17.3 (40)
H19	Hereford	19	119.3±3.4 (31)	19	160.2±3.8 (35)	19	287.3±6.3 (26)	19	429.7±9.1 (30)	17	502.9±11.8 (36)
H20	Hereford	12	122.1±3.9 (14)	12	163.2±4.4 (16)	12	286.3±7.3 (31)	11	419.5±10.5 (54)	8	497.5±14.7 (46)
H21	Hereford	15	118.9±3.7 (34)	15	164.5±4.1 (10)	15	298.0±6.9 (04)	14	447.1±9.9 (08)	9	525.1±14.2 (07)
H22	Hereford	11	117.2±4.0 (46)	11	157.5±4.5 (45)	11	275.4±7.5 (60)	11	415.1±10.5 (60)	9	490.6±14.2 (60)
H23	Hereford	6	114.4±4.8 (64)	6	162.2±5.7 (19)	6	286.9±9.3 (28)	6	431.9±12.7 (23)	6	508.1±16.2 (28)
H24	Hereford	15	116.6±3.7 (50)	15	158.1±4.2 (41)	15	285.3±6.9 (34)	15	431.8±9.8 (24)	14	514.5±12.7 (20)

Continue

Sire	Breed	n 131d	LWT 131d	n 200d	LWT 200d	n 400d	LWT 400d	n 600d	LWT 600d	n 800d	LWT 800d
H25	Hereford	14	116.4±3.7 (51)	14	160.8±4.2 (29)	14	280.7±7.0 (43)	13	421.4±10.1 (48)	11	494.5±13.5 (53)
H26	Hereford	13	123.1±3.8 (09)	13	172.5±4.3 (02)	13	297.0±7.1 (06)	13	448.0±10.1 (05)	11	526.6±13.4 (05)
H27	Hereford	11	120.8±4.0 (21)	11	169.0±4.6 (04)	11	297.3±7.6 (05)	11	444.3±10.6 (10)	9	523.0±14.4 (09)
H28	Hereford	15	113.8±3.7 (66)	15	151.1±4.1 (68)	14	274.2±7.0 (63)	14	415.7±9.9 (59)	13	504.4±12.8 (33)
H29	Hereford	11	113.4±4.0 (68)	11	155.3±4.6 (54)	11	267.7±7.5 (72)	11	402.4±10.5 (72)	10	471.4±13.7 (72)
H30	Hereford	10	120.0±4.1 (25)	10	156.5±4.7 (50)	10	271.9±7.7 (65)	10	424.3±10.8 (43)	10	487.3±13.7 (65)
H31	Hereford	18	114.8±3.5 (60)	18	153.6±3.9 (61)	18	276.7±6.5 (58)	18	425.1±9.4 (40)	17	502.6±12.0 (38)
H32	Hereford	10	114.3±4.1 (65)	10	162.3±4.7 (18)	10	280.1±7.7 (47)	10	418.9±10.8 (55)	10	498.7±13.7 (42)
H33	Hereford	9	120.2±4.2 (24)	9	161.7±4.9 (23)	9	287.9±8.0 (22)	9	430.8±11.1 (27)	9	520.0±14.1 (10)
H34	Hereford	12	122.4±3.9 (13)	12	161.0±4.4 (27)	12	290.4±7.3 (18)	11	440.2±10.5 (12)	11	544.8±13.4 (01)
H36 [§]	Hereford	21	113.3±4.2 (69)	20	164.0±4.6 (12)	19	296.4±7.8 (07)	18	446.2±11.6 (09)	14	520.0±15.8 (11)
H37 [§]	Hereford	29	110.6±4.1 (73)	28	156.5±4.3 (48)	28	287.4±7.3 (25)	27	438.8±11.0 (13)	23	516.6±14.8 (18)
H38 [§]	Hereford	5	117.3±5.7 (45)	5	160.5±6.5 (32)	5	291.7±10.8 (15)	5	447.9±15.1 (06)	4	505.7±20.9 (32)
H39 [§]	Hereford	39	123.7±4.0 (07)	38	160.0±4.1 (38)	37	271.3±7.1 (68)	37	424.8±10.6 (41)	36	491.4±13.0 (58)
H40 [§]	Hereford	6	129.7±5.6 (01)	6	165.9±6.4 (06)	6	278.3±10.5 (54)	5	434.8±15.6 (18)	5	497.4±19.5 (47)
Total n		1101		1086		1069		1035		913	
Mean			118.6±3.9		159.1±5.5		284.2±9.6		427.0±13.5		503.6±15.9
CV			3%		3%		3%		3%		3%
Sire effect P-value			0.002		<0.001		<0.001		<0.001		<0.001

[§] Sires used via natural mating on 15-month-old heifers.

Appendix 4. Least-squares means (\pm SE) of the progeny groups for weight traits at slaughter (age, live weight, carcass weight and dressing-out) and individual ranking (in brackets) for 34 Angus and 39 Hereford sires. Weight traits were adjusted by age deviation of the progeny within contemporary group. Number of progeny (n), mean (\pm SD) of the least-squares means of the progeny groups, coefficient of variation (CV), *P-value* for the effect of sire and *P-value* for the effect of age are presented at the end of the table.

Sire	Breed	n [†]	Age (days)	Live weight (kg)	Carcass weight (kg)	Dressing-out (%)
A1	Angus	19	861.3 \pm 11.0	570.2 \pm 16.8 (30)	274.6 \pm 8.5 (42)	48.2 \pm 0.4 (66)
A2	Angus	7	843.0 \pm 18.1	553.0 \pm 19.7 (55)	270.9 \pm 10.1 (52)	49.1 \pm 0.5 (23)
A3	Angus	14	823.1 \pm 12.8	559.6 \pm 17.6 (46)	273.7 \pm 9.0 (45)	48.9 \pm 0.4 (32)
A4	Angus	16	871.5 \pm 12.0	565.0 \pm 17.1 (40)	272.1 \pm 8.7 (50)	48.2 \pm 0.4 (67)
A5	Angus	9	808.3 \pm 16.0	572.7 \pm 18.8 (26)	285.0 \pm 9.6 (16)	49.8 \pm 0.5 (07)
A6	Angus	11	841.9 \pm 14.4	558.3 \pm 18.2 (50)	275.7 \pm 9.4 (40)	49.4 \pm 0.5 (15)
A7	Angus	13	879.0 \pm 13.3	546.8 \pm 17.6 (64)	266.0 \pm 9.0 (67)	48.6 \pm 0.4 (53)
A8	Angus	15	827.8 \pm 12.4	569.8 \pm 17.4 (31)	279.3 \pm 9.0 (30)	48.9 \pm 0.4 (37)
A9	Angus	18	815.2 \pm 11.3	557.9 \pm 17.1 (51)	277.2 \pm 8.7 (34)	49.4 \pm 0.4 (17)
A10	Angus	17	859.4 \pm 11.6	561.3 \pm 17.0 (45)	270.4 \pm 8.6 (54)	48.1 \pm 0.4 (68)
A11	Angus	12	832.2 \pm 13.8	589.7 \pm 18.0 (10)	287.0 \pm 9.2 (11)	48.6 \pm 0.5 (52)
A12	Angus	13	872.4 \pm 13.3	565.6 \pm 17.8 (38)	272.3 \pm 9.1 (49)	48.2 \pm 0.5 (65)
A13	Angus	18	855.3 \pm 11.3	553.1 \pm 16.9 (54)	268.0 \pm 8.6 (61)	48.5 \pm 0.4 (57)
A14	Angus	10	888.0 \pm 15.2	603.0 \pm 18.4 (02)	294.6 \pm 9.4 (03)	48.8 \pm 0.5 (40)
A15	Angus	9	830.2 \pm 16.0	545.0 \pm 18.8 (67)	263.9 \pm 9.6 (70)	48.4 \pm 0.5 (59)
A16	Angus	20	845.3 \pm 10.7	577.4 \pm 16.8 (21)	281.7 \pm 8.5 (27)	48.8 \pm 0.4 (42)
A17	Angus	14	854.9 \pm 12.8	564.2 \pm 17.5 (41)	283.6 \pm 8.9 (22)	50.3 \pm 0.4 (01)
A19	Angus	14	863.5 \pm 12.8	550.7 \pm 17.5 (60)	270.6 \pm 8.9 (53)	49.2 \pm 0.4 (20)
A20	Angus	12	863.0 \pm 13.8	577.0 \pm 17.8 (22)	281.0 \pm 9.1 (28)	48.8 \pm 0.5 (46)
A21	Angus	14	835.1 \pm 12.8	565.5 \pm 17.4 (39)	276.9 \pm 8.9 (37)	49.0 \pm 0.4 (31)
A22	Angus	11	851.2 \pm 14.4	571.5 \pm 18.0 (27)	273.4 \pm 9.2 (48)	47.8 \pm 0.5 (71)
A23	Angus	18	859.4 \pm 11.3	559.3 \pm 17.0 (47)	271.5 \pm 8.6 (51)	48.6 \pm 0.4 (55)
A24	Angus	10	853.3 \pm 15.2	562.2 \pm 18.5 (43)	273.9 \pm 9.5 (44)	48.7 \pm 0.5 (50)
A25	Angus	12	852.3 \pm 13.8	545.1 \pm 17.8 (66)	264.2 \pm 9.1 (69)	48.5 \pm 0.5 (56)
A27	Angus	12	883.2 \pm 13.8	575.8 \pm 18.0 (24)	278.0 \pm 9.2 (33)	48.4 \pm 0.5 (60)
A28	Angus	10	868.8 \pm 15.2	552.5 \pm 18.5 (56)	273.6 \pm 9.5 (46)	49.6 \pm 0.5 (11)
A29	Angus	15	870.1 \pm 12.4	534.4 \pm 17.5 (73)	257.8 \pm 8.9 (73)	48.2 \pm 0.4 (64)
A30	Angus	9	888.9 \pm 16.0	616.5 \pm 18.8 (01)	304.2 \pm 9.9 (01)	49.0 \pm 0.5 (29)
A31	Angus	12	874.1 \pm 13.8	579.9 \pm 17.9 (17)	283.7 \pm 9.2 (21)	48.9 \pm 0.5 (33)
A32 [§]	Angus	9	804.1 \pm 16.0	566.2 \pm 25.9 (37)	283.4 \pm 13.1 (24)	50.2 \pm 0.6 (02)
A33 [§]	Angus	16	845.4 \pm 12.0	579.2 \pm 24.6 (18)	288.9 \pm 12.4 (06)	49.9 \pm 0.5 (04)
A35 [§]	Angus	27	834.6 \pm 9.2	535.2 \pm 24.1 (72)	265.7 \pm 12.1 (68)	49.7 \pm 0.5 (09)
A36 [§]	Angus	24	880.9 \pm 9.8	597.8 \pm 22.3 (04)	293.1 \pm 11.2 (04)	48.8 \pm 0.5 (41)
A37 [§]	Angus	21	896.3 \pm 10.5	547.3 \pm 22.4 (63)	268.7 \pm 11.2 (58)	49.0 \pm 0.5 (26)
H1	Hereford	14	854.0 \pm 12.8	548.2 \pm 17.4 (61)	268.2 \pm 8.9 (60)	48.9 \pm 0.4 (35)
H2	Hereford	13	870.2 \pm 13.3	551.5 \pm 17.8 (59)	269.7 \pm 9.1 (55)	48.9 \pm 0.5 (34)
H3	Hereford	25	862.0 \pm 9.6	586.6 \pm 16.4 (13)	287.3 \pm 8.3 (10)	49.0 \pm 0.4 (28)
H4	Hereford	22	857.3 \pm 10.2	577.8 \pm 16.6 (20)	284.0 \pm 8.4 (20)	49.1 \pm 0.4 (21)
H5	Hereford	14	842.5 \pm 12.8	540.0 \pm 17.6 (70)	266.8 \pm 9.1 (66)	49.9 \pm 0.5 (05)
H6	Hereford	13	874.7 \pm 13.3	544.4 \pm 17.8 (68)	260.8 \pm 9.1 (72)	47.9 \pm 0.5 (69)
H7	Hereford	11	852.6 \pm 14.4	576.5 \pm 18.0 (23)	284.8 \pm 9.2 (17)	49.4 \pm 0.5 (16)
H8	Hereford	12	810.6 \pm 13.8	540.3 \pm 18.0 (69)	267.2 \pm 9.2 (63)	49.6 \pm 0.5 (10)
H9	Hereford	19	863.0 \pm 11.0	557.5 \pm 16.8 (52)	276.3 \pm 8.5 (39)	49.6 \pm 0.4 (12)
H10	Hereford	11	864.0 \pm 14.4	584.6 \pm 18.2 (14)	285.3 \pm 9.3 (15)	48.8 \pm 0.5 (43)
H11	Hereford	11	839.8 \pm 14.4	587.1 \pm 18.2 (11)	287.7 \pm 9.5 (08)	49.0 \pm 0.5 (27)

Continue

Sire	Breed	n [†]	Age (days)	Live weight (kg)	Carcass weight (kg)	Dressing-out (%)
H12	Hereford	16	858.2±12.0	556.4±17.2 (53)	274.2±8.7 (43)	49.3±0.4 (18)
H13	Hereford	16	873.2±12.0	567.6±17.3 (34)	275.2±8.9 (41)	48.4±0.4 (58)
H14	Hereford	19	848.1±11.0	562.3±16.8 (42)	273.6±8.5 (47)	48.6±0.4 (51)
H15	Hereford	11	818.2±14.4	552.0±18.2 (58)	268.8±9.3 (57)	48.8±0.5 (45)
H16	Hereford	15	873.2±12.4	575.0±17.3 (25)	283.2±8.8 (25)	49.2±0.4 (19)
H17	Hereford	6	840.5±19.6	591.1±20.3 (08)	280.4±10.5 (29)	47.4±0.6 (73)
H18	Hereford	6	829.0±19.6	568.7±20.4 (32)	278.9±10.6 (32)	49.1±0.6 (25)
H19	Hereford	19	856.8±11.0	567.5±16.8 (35)	276.7±8.5 (38)	48.8±0.4 (39)
H20	Hereford	11	821.4±14.4	545.9±18.2 (65)	268.6±9.5 (59)	48.7±0.5 (48)
H21	Hereford	14	824.7±12.8	592.7±17.6 (07)	286.6±9.0 (13)	48.3±0.4 (63)
H22	Hereford	10	844.5±15.2	552.2±18.5 (57)	266.9±9.7 (65)	48.3±0.5 (61)
H23	Hereford	6	848.8±19.6	582.2±20.5 (16)	283.4±10.6 (23)	48.7±0.6 (49)
H24	Hereford	15	864.2±12.4	578.7±17.5 (19)	277.0±9.0 (36)	47.7±0.4 (72)
H25	Hereford	13	845.5±13.3	559.0±17.8 (48)	267.0±9.3 (64)	48.8±0.5 (47)
H26	Hereford	13	846.5±13.3	594.7±17.8 (06)	290.7±9.2 (05)	48.8±0.5 (38)
H27	Hereford	10	873.0±15.2	596.7±18.6 (05)	288.0±9.5 (07)	48.3±0.5 (62)
H28	Hereford	14	868.9±12.8	558.7±17.6 (49)	267.2±9.0 (62)	47.9±0.4 (70)
H29	Hereford	10	883.4±15.2	536.1±18.5 (71)	261.7±9.5 (71)	48.8±0.5 (44)
H30	Hereford	10	874.9±15.2	547.9±18.5 (62)	269.5±9.5 (56)	49.1±0.5 (22)
H31	Hereford	17	871.8±11.6	567.7±17.2 (33)	284.3±8.7 (19)	50.1±0.4 (03)
H32	Hereford	9	873.9±16.0	566.3±18.8 (36)	277.0±9.7 (35)	48.9±0.5 (36)
H33	Hereford	9	865.2±16.0	590.5±18.8 (09)	286.8±9.7 (12)	48.6±0.5 (54)
H34	Hereford	11	855.4±14.4	599.3±18.2 (03)	295.8±9.3 (02)	49.4±0.5 (14)
H36 [§]	Hereford	18	831.0±11.3	570.8±22.7 (29)	282.0±11.4 (26)	49.4±0.5 (13)
H37 [§]	Hereford	26	847.0±9.4	571.1±22.2 (28)	284.7±11.1 (18)	49.9±0.5 (06)
H38 [§]	Hereford	5	828.8±21.4	562.0±25.9 (44)	279.1±13.3 (31)	49.7±0.7 (08)
H39 [§]	Hereford	35	887.2±8.1	586.7±21.9 (12)	287.7±11.0 (09)	49.0±0.5 (30)
H40 [§]	Hereford	5	907.2±21.4	583.5±26.5 (15)	286.2±13.6 (14)	49.1±0.7 (24)
Total n		1015				
Mean			854.6±21.8	567.2±17.9	277.3±9.3	48.9±0.6
CV			3%	3%	3%	1%
Sire effect P-value			<0.001	<0.001	<0.001	<0.001
Age effect P-value			-	0.479	0.988	0.049

[§] Sires used via natural mating on 15-month-old heifers. [†] Carcass weight and dressing-out for: A6 n= 10, A8 n= 14, A9 n= 17, A30 n= 8, A35 n= 26, A36 n= 23, H5 n= 13, H11 n= 10, H13 n= 15, H20 n= 10, H22 n= 9, H24 n= 14, H25 n= 11, H26 n= 12.

Appendix 5. Least-squares means (\pm SE) of the progeny groups for carcass traits (carcass length, eye muscle area (EMA), rib fat depth and marble score) and individual ranking (in brackets) for 34 Angus and 39 Hereford sires. Carcass traits were adjusted by carcass weight. Number of progeny (n), mean (\pm SD) of the least-squares means of the progeny groups, coefficient of variation (CV), *P-value* for the effect of sire and *P-value* for the effect of carcass weight are presented at the end of the table.

Sire	Breed	n [†] carcass	Carcass length (cm)	EMA (cm ²)	Rib fat depth (mm)	n score	Marble score
A1	Angus	19	240.8 \pm 2.2 (29)	69.8 \pm 2.0 (62)	7.1 \pm 0.7 (41)	17	1.54 \pm 0.19 (02)
A2	Angus	7	238.3 \pm 2.6 (60)	74.4 \pm 3.4 (31)	9.0 \pm 1.2 (11)	6	0.75 \pm 0.31 (48)
A3	Angus	14	239.1 \pm 2.3 (56)	76.2 \pm 2.3 (17)	6.2 \pm 0.8 (63)	12	0.73 \pm 0.23 (52)
A4	Angus	16	240.3 \pm 2.2 (35)	75.8 \pm 2.2 (22)	6.4 \pm 0.8 (61)	14	0.98 \pm 0.21 (30)
A5	Angus	9	240.2 \pm 2.5 (37)	77.3 \pm 2.8 (11)	8.2 \pm 1.0 (20)	8	0.86 \pm 0.27 (39)
A6	Angus	10	237.3 \pm 2.4 (66)	72.6 \pm 2.6 (43)	7.0 \pm 0.9 (44)	8	1.45 \pm 0.27 (06)
A7	Angus	13	236.0 \pm 2.3 (70)	74.6 \pm 2.3 (30)	9.0 \pm 0.8 (12)	10	1.04 \pm 0.24 (24)
A8	Angus	14	238.4 \pm 2.3 (58)	73.6 \pm 2.3 (38)	6.8 \pm 0.8 (48)	10	1.35 \pm 0.25 (08)
A9	Angus	17	238.3 \pm 2.3 (61)	76.2 \pm 2.1 (18)	6.4 \pm 0.8 (59)	15	1.03 \pm 0.21 (26)
A10	Angus	17	242.3 \pm 2.2 (17)	69.7 \pm 2.1 (64)	8.3 \pm 0.7 (18)	15	0.73 \pm 0.20 (54)
A11	Angus	12	239.6 \pm 2.4 (48)	72.1 \pm 2.4 (49)	7.4 \pm 0.9 (33)	11	1.49 \pm 0.24 (04)
A12	Angus	13	239.4 \pm 2.3 (52)	67.1 \pm 2.4 (71)	7.7 \pm 0.8 (30)	13	0.57 \pm 0.22 (63)
A13	Angus	18	239.7 \pm 2.2 (45)	77.0 \pm 2.0 (12)	7.0 \pm 0.7 (46)	17	1.13 \pm 0.19 (20)
A14	Angus	10	244.0 \pm 2.4 (04)	71.3 \pm 2.6 (56)	7.7 \pm 0.9 (29)	9	1.16 \pm 0.26 (17)
A15	Angus	9	238.6 \pm 2.5 (57)	78.1 \pm 2.8 (07)	7.9 \pm 1.0 (26)	7	1.39 \pm 0.29 (07)
A16	Angus	20	240.3 \pm 2.2 (36)	72.2 \pm 1.9 (47)	8.7 \pm 0.7 (15)	19	1.48 \pm 0.18 (05)
A17	Angus	14	238.0 \pm 2.3 (63)	72.1 \pm 2.3 (50)	6.7 \pm 0.8 (49)	14	0.67 \pm 0.21 (57)
A19	Angus	14	239.5 \pm 2.3 (49)	76.4 \pm 2.3 (15)	5.0 \pm 0.8 (69)	12	0.62 \pm 0.22 (59)
A20	Angus	12	240.1 \pm 2.3 (43)	75.7 \pm 2.4 (23)	6.4 \pm 0.8 (60)	11	0.90 \pm 0.23 (36)
A21	Angus	14	237.2 \pm 2.3 (67)	75.1 \pm 2.2 (25)	6.6 \pm 0.8 (55)	13	1.06 \pm 0.22 (23)
A22	Angus	11	241.4 \pm 2.4 (24)	66.8 \pm 2.5 (72)	8.7 \pm 0.9 (14)	9	1.34 \pm 0.26 (09)
A23	Angus	18	241.7 \pm 2.2 (22)	75.1 \pm 2.0 (26)	6.2 \pm 0.7 (64)	17	1.09 \pm 0.19 (22)
A24	Angus	10	242.6 \pm 2.4 (13)	76.1 \pm 2.7 (19)	4.8 \pm 0.9 (72)	7	1.27 \pm 0.29 (12)
A25	Angus	12	240.6 \pm 2.3 (31)	74.8 \pm 2.4 (28)	6.6 \pm 0.8 (57)	10	0.56 \pm 0.24 (65)
A27	Angus	12	240.3 \pm 2.4 (34)	74.8 \pm 2.5 (29)	8.2 \pm 0.9 (23)	12	1.27 \pm 0.23 (13)
A28	Angus	10	237.2 \pm 2.4 (68)	78.9 \pm 2.6 (05)	9.1 \pm 0.9 (07)	10	1.53 \pm 0.25 (03)
A29	Angus	15	238.0 \pm 2.3 (62)	69.6 \pm 2.2 (65)	6.7 \pm 0.8 (51)	15	0.73 \pm 0.21 (51)
A30	Angus	8	240.0 \pm 2.5 (44)	74.1 \pm 2.9 (35)	5.0 \pm 1.0 (68)	8	0.70 \pm 0.27 (55)
A31	Angus	12	237.9 \pm 2.4 (64)	71.7 \pm 2.4 (52)	6.6 \pm 0.9 (53)	12	1.15 \pm 0.23 (18)
A32 [§]	Angus	9	234.6 \pm 3.4 (72)	80.5 \pm 2.9 (02)	8.0 \pm 1.0 (24)	8	0.54 \pm 0.29 (67)
A33 [§]	Angus	16	235.8 \pm 3.2 (71)	79.3 \pm 2.3 (03)	6.5 \pm 0.8 (58)	13	0.90 \pm 0.23 (34)
A35 [§]	Angus	26	234.5 \pm 3.2 (73)	73.9 \pm 1.9 (37)	8.2 \pm 0.7 (19)	21	1.03 \pm 0.20 (27)
A36 [§]	Angus	23	240.5 \pm 2.9 (33)	74.4 \pm 2.0 (32)	8.2 \pm 0.7 (21)	23	1.14 \pm 0.18 (19)
A37 [§]	Angus	21	239.6 \pm 2.9 (47)	71.0 \pm 2.0 (58)	9.3 \pm 0.7 (05)	21	0.73 \pm 0.18 (52)
H1	Hereford	14	242.6 \pm 2.3 (14)	70.7 \pm 2.2 (60)	7.4 \pm 0.8 (34)	13	0.57 \pm 0.22 (62)
H2	Hereford	13	242.3 \pm 2.3 (18)	67.2 \pm 2.4 (70)	10.3 \pm 0.8 (02)	13	0.56 \pm 0.22 (66)
H3	Hereford	25	240.2 \pm 2.2 (37)	71.8 \pm 1.8 (51)	8.6 \pm 0.6 (16)	23	0.77 \pm 0.17 (45)
H4	Hereford	22	239.5 \pm 2.2 (50)	73.5 \pm 1.9 (39)	9.2 \pm 0.7 (06)	21	0.92 \pm 0.18 (33)
H5	Hereford	13	240.7 \pm 2.3 (30)	78.9 \pm 2.4 (06)	7.3 \pm 0.8 (36)	9	0.87 \pm 0.26 (38)
H6	Hereford	13	242.9 \pm 2.3 (12)	67.9 \pm 2.4 (68)	7.6 \pm 0.8 (32)	13	1.19 \pm 0.22 (16)
H7	Hereford	11	240.1 \pm 2.4 (42)	68.9 \pm 2.6 (66)	7.1 \pm 0.9 (40)	10	0.85 \pm 0.24 (41)
H8	Hereford	12	240.8 \pm 2.4 (28)	79.2 \pm 2.5 (04)	7.1 \pm 0.9 (42)	10	1.01 \pm 0.25 (28)
H9	Hereford	19	241.8 \pm 2.2 (20)	74.9 \pm 2.0 (27)	6.7 \pm 0.7 (52)	17	0.37 \pm 0.19 (70)
H10	Hereford	11	239.2 \pm 2.4 (54)	72.2 \pm 2.5 (48)	6.3 \pm 0.9 (62)	11	1.28 \pm 0.24 (11)
H11	Hereford	10	243.1 \pm 2.4 (09)	71.4 \pm 2.7 (55)	8.5 \pm 0.9 (17)	8	0.74 \pm 0.27 (49)
H12	Hereford	16	240.2 \pm 2.2 (40)	76.9 \pm 2.1 (13)	6.2 \pm 0.7 (65)	15	0.44 \pm 0.20 (69)

Continue

Sire	Breed	n [†] carcass	Carcass length (cm)	EMA (cm ²)	Rib fat depth (mm)	n score	Marble score
H13	Hereford	15	243.2±2.3 (07)	68.1±2.2 (67)	7.9±0.8 (27)	14	0.81±0.21 (42)
H14	Hereford	19	239.4±2.2 (51)	74.4±2.0 (33)	7.4±0.7 (35)	17	0.59±0.19 (60)
H15	Hereford	11	239.7±2.4 (46)	72.4±2.5 (44)	6.6±0.9 (56)	9	0.35±0.26 (71)
H16	Hereford	15	240.1±2.3 (41)	77.5±2.2 (10)	6.6±0.8 (54)	14	0.76±0.21 (47)
H17	Hereford	6	243.4±2.6 (05)	71.6±3.3 (53)	7.7±1.2 (31)	4	0.64±0.38 (58)
H18	Hereford	6	241.7±2.7 (21)	72.8±3.4 (42)	9.1±1.2 (08)	5	0.85±0.34 (40)
H19	Hereford	19	240.8±2.2 (27)	75.9±2.0 (20)	6.7±0.7 (50)	17	0.77±0.19 (46)
H20	Hereford	10	239.2±2.4 (55)	78.0±2.7 (08)	9.8±0.9 (03)	9	0.70±0.26 (56)
H21	Hereford	14	241.3±2.3 (25)	75.9±2.3 (21)	6.9±0.8 (47)	13	0.57±0.22 (64)
H22	Hereford	9	243.0±2.5 (11)	70.1±2.8 (61)	8.2±1.0 (22)	7	1.21±0.29 (15)
H23	Hereford	6	240.2±2.7 (39)	73.9±3.4 (36)	11.3±1.2 (01)	5	1.04±0.34 (25)
H24	Hereford	14	242.5±2.3 (15)	74.2±2.3 (34)	7.2±0.8 (38)	11	1.58±0.24 (01)
H25	Hereford	11	237.0±2.4 (69)	76.8±2.5 (14)	8.0±0.9 (25)	9	1.30±0.26 (10)
H26	Hereford	12	241.5±2.4 (23)	82.9±2.5 (01)	5.3±0.9 (66)	10	0.27±0.25 (72)
H27	Hereford	10	245.2±2.4 (01)	69.8±2.7 (63)	7.1±0.9 (39)	8	0.81±0.28 (43)
H28	Hereford	14	242.1±2.3 (19)	72.3±2.3 (45)	9.0±0.8 (10)	14	0.48±0.21 (68)
H29	Hereford	10	239.2±2.4 (53)	67.5±2.7 (69)	8.8±0.9 (13)	10	0.90±0.25 (35)
H30	Hereford	10	244.8±2.4 (02)	71.5±2.7 (54)	4.9±0.9 (70)	10	0.99±0.25 (29)
H31	Hereford	17	241.0±2.3 (26)	71.1±2.1 (57)	5.2±0.7 (67)	17	0.97±0.20 (32)
H32	Hereford	9	240.5±2.5 (32)	73.1±2.8 (40)	7.0±1.0 (45)	9	1.13±0.26 (21)
H33	Hereford	9	242.4±2.5 (16)	72.3±2.8 (46)	9.0±1.0 (09)	9	0.74±0.26 (50)
H34	Hereford	11	243.1±2.4 (08)	73.1±2.6 (41)	9.5±0.9 (04)	11	0.80±0.24 (44)
H36 [§]	Hereford	18	237.6±3.0 (65)	75.4±2.2 (24)	7.0±0.8 (43)	15	0.90±0.22 (37)
H37 [§]	Hereford	26	238.4±2.9 (59)	76.4±1.9 (16)	7.3±0.7 (37)	21	0.58±0.19 (61)
H38 [§]	Hereford	5	243.1±3.4 (09)	77.8±3.7 (09)	4.9±1.3 (71)	4	1.27±0.38 (14)
H39 [§]	Hereford	35	243.2±2.9 (06)	71.0±1.7 (59)	7.8±0.6 (28)	35	0.97±0.15 (31)
H40 [§]	Hereford	5	244.1±3.5 (03)	65.5±3.8 (73)	4.3±1.3 (73)	5	0.21±0.35 (73)
Total n		1000				902	
Mean			240.3±2.3	73.6±3.5	7.4±1.4		0.91±0.32
CV			1%	5%	19%		35%
Sire effect P-value			<0.001	<0.001	<0.001		<0.001
Carcass weight effect P-value			<0.001	<0.001	0.002		0.122

[§] Sires used via natural mating on 15-month-old heifers. [†] Carcass length for: H24 n= 13; Eye Muscle Area (EMA) and Rib fat depth for: A2 n= 6, A4 n= 15, A33 n= 15, H7 n= 10, H37 n= 25; Rib fat depth for: A9 n= 16.

Appendix 6. Least-squares means (\pm SE) of the progeny groups for meat quality traits (fat colour score, meat colour score and ultimate pH) and individual ranking (in brackets) for 34 Angus and 39 Hereford sires. Number of progeny (n), mean (\pm SD) of the least-squares means of the progeny groups, coefficient of variation (CV) and *P-value* for the effect of sire are presented at the end of the table.

Sire	Breed	n score	Fat colour Score	Meat colour Score	n pH	Ultimate pH
A1	Angus	17	2.85 \pm 0.18 (13)	2.94 \pm 0.14 (22)	19	5.66 \pm 0.04 (20)
A2	Angus	6	2.68 \pm 0.28 (04)	3.20 \pm 0.23 (65)	7	5.62 \pm 0.05 (05)
A3	Angus	12	3.02 \pm 0.21 (38)	2.81 \pm 0.17 (11)	14	5.62 \pm 0.04 (04)
A4	Angus	14	3.29 \pm 0.20 (63)	3.15 \pm 0.16 (60)	16	5.65 \pm 0.04 (15)
A5	Angus	8	3.16 \pm 0.25 (54)	2.94 \pm 0.20 (24)	9	5.67 \pm 0.05 (28)
A6	Angus	8	3.44 \pm 0.25 (69)	3.57 \pm 0.20 (73)	11	5.79 \pm 0.05 (65)
A7	Angus	10	3.26 \pm 0.23 (62)	2.94 \pm 0.18 (26)	6	5.66 \pm 0.06 (24)
A8	Angus	11	3.32 \pm 0.22 (65)	2.88 \pm 0.18 (17)	13	5.66 \pm 0.04 (17)
A9	Angus	16	3.12 \pm 0.19 (50)	2.89 \pm 0.15 (18)	14	5.66 \pm 0.04 (19)
A10	Angus	15	3.11 \pm 0.19 (48)	2.93 \pm 0.15 (21)	16	5.76 \pm 0.04 (62)
A11	Angus	11	3.18 \pm 0.22 (56)	3.31 \pm 0.18 (70)	12	5.71 \pm 0.05 (48)
A12	Angus	13	2.79 \pm 0.21 (11)	3.09 \pm 0.16 (50)	13	5.71 \pm 0.04 (53)
A13	Angus	17	3.23 \pm 0.19 (60)	3.04 \pm 0.14 (42)	18	5.70 \pm 0.04 (47)
A14	Angus	9	3.14 \pm 0.23 (52)	2.98 \pm 0.19 (34)	6	5.64 \pm 0.06 (12)
A15	Angus	7	3.59 \pm 0.26 (72)	3.34 \pm 0.22 (71)	9	5.64 \pm 0.05 (10)
A16	Angus	19	3.05 \pm 0.18 (39)	3.06 \pm 0.14 (44)	18	5.69 \pm 0.04 (42)
A17	Angus	14	3.07 \pm 0.20 (40)	2.99 \pm 0.16 (36)	11	5.69 \pm 0.05 (41)
A19	Angus	12	2.60 \pm 0.21 (03)	3.09 \pm 0.17 (49)	7	5.71 \pm 0.05 (49)
A20	Angus	11	2.70 \pm 0.22 (06)	2.77 \pm 0.17 (09)	6	5.66 \pm 0.06 (17)
A21	Angus	13	2.87 \pm 0.20 (16)	2.95 \pm 0.16 (28)	14	5.68 \pm 0.04 (35)
A22	Angus	9	3.00 \pm 0.23 (32)	3.23 \pm 0.19 (68)	6	5.68 \pm 0.06 (34)
A23	Angus	17	2.92 \pm 0.19 (17)	3.03 \pm 0.14 (41)	18	5.70 \pm 0.04 (45)
A24	Angus	7	3.00 \pm 0.26 (31)	3.30 \pm 0.22 (69)	-	
A25	Angus	10	2.94 \pm 0.22 (20)	2.94 \pm 0.18 (25)	4	5.69 \pm 0.07 (38)
A27	Angus	12	2.92 \pm 0.21 (18)	3.10 \pm 0.17 (52)	12	5.67 \pm 0.05 (33)
A28	Angus	10	2.93 \pm 0.23 (19)	3.07 \pm 0.18 (46)	10	5.69 \pm 0.05 (37)
A29	Angus	15	2.86 \pm 0.20 (14)	3.01 \pm 0.15 (40)	15	5.66 \pm 0.04 (16)
A30	Angus	9	3.13 \pm 0.24 (51)	3.04 \pm 0.19 (43)	9	5.69 \pm 0.05 (40)
A31	Angus	12	2.98 \pm 0.21 (25)	2.96 \pm 0.17 (31)	12	5.66 \pm 0.05 (21)
A32 [§]	Angus	8	3.22 \pm 0.29 (59)	3.23 \pm 0.22 (67)	-	
A33 [§]	Angus	13	3.15 \pm 0.25 (53)	3.08 \pm 0.18 (48)	-	
A35 [§]	Angus	22	3.07 \pm 0.22 (41)	2.82 \pm 0.15 (12)	13	5.72 \pm 0.05 (55)
A36 [§]	Angus	24	3.08 \pm 0.19 (44)	3.12 \pm 0.13 (54)	24	5.57 \pm 0.05 (01)
A37 [§]	Angus	21	3.09 \pm 0.20 (45)	3.13 \pm 0.14 (55)	21	5.64 \pm 0.05 (11)
H1	Hereford	13	2.95 \pm 0.20 (22)	2.95 \pm 0.16 (30)	14	5.71 \pm 0.04 (51)
H2	Hereford	13	3.19 \pm 0.21 (58)	2.87 \pm 0.16 (15)	13	5.63 \pm 0.04 (07)
H3	Hereford	23	3.26 \pm 0.17 (61)	2.96 \pm 0.13 (32)	25	5.71 \pm 0.04 (52)
H4	Hereford	21	3.30 \pm 0.17 (64)	3.11 \pm 0.13 (53)	22	5.69 \pm 0.04 (39)
H5	Hereford	10	3.43 \pm 0.23 (68)	3.54 \pm 0.18 (72)	13	5.75 \pm 0.04 (61)
H6	Hereford	13	3.12 \pm 0.21 (49)	3.00 \pm 0.16 (38)	13	5.74 \pm 0.04 (59)
H7	Hereford	10	2.57 \pm 0.22 (02)	2.88 \pm 0.18 (16)	4	5.63 \pm 0.07 (08)
H8	Hereford	10	2.86 \pm 0.23 (15)	2.77 \pm 0.19 (08)	11	5.62 \pm 0.05 (06)
H9	Hereford	17	2.98 \pm 0.19 (24)	2.94 \pm 0.14 (27)	19	5.66 \pm 0.04 (25)
H10	Hereford	11	3.02 \pm 0.22 (37)	2.86 \pm 0.18 (14)	11	5.67 \pm 0.05 (26)
H11	Hereford	9	2.79 \pm 0.24 (10)	2.75 \pm 0.19 (06)	10	5.67 \pm 0.05 (31)
H12	Hereford	15	2.83 \pm 0.19 (12)	3.15 \pm 0.15 (58)	16	5.70 \pm 0.04 (46)
H13	Hereford	15	3.07 \pm 0.20 (42)	2.90 \pm 0.15 (19)	15	5.72 \pm 0.04 (54)

Continue

Sire	Breed	n score	Fat colour Score	Meat colour Score	n pH	Ultimate pH
H14	Hereford	17	3.07±0.18 (43)	3.14±0.14 (57)	19	5.75±0.04 (60)
H15	Hereford	9	2.70±0.24 (05)	2.69±0.19 (04)	11	5.66±0.05 (23)
H16	Hereford	14	3.01±0.20 (35)	2.95±0.16 (29)	15	5.65±0.04 (14)
H17	Hereford	4	2.48±0.33 (01)	3.23±0.28 (66)	2	5.78±0.09 (63)
H18	Hereford	5	3.18±0.30 (57)	3.08±0.25 (47)	-	
H19	Hereford	17	2.99±0.19 (28)	2.84±0.14 (13)	18	5.69±0.04 (36)
H20	Hereford	9	2.73±0.24 (08)	2.97±0.19 (33)	10	5.64±0.05 (13)
H21	Hereford	13	2.99±0.21 (29)	2.77±0.16 (10)	14	5.67±0.04 (32)
H22	Hereford	8	3.00±0.25 (33)	3.15±0.20 (59)	10	5.72±0.05 (56)
H23	Hereford	5	3.94±0.30 (73)	3.16±0.25 (61)	-	
H24	Hereford	11	3.37±0.22 (66)	2.99±0.18 (35)	12	5.73±0.05 (57)
H25	Hereford	11	3.16±0.22 (55)	2.63±0.18 (01)	12	5.63±0.05 (09)
H26	Hereford	11	2.76±0.22 (09)	2.65±0.18 (02)	13	5.73±0.04 (58)
H27	Hereford	8	2.98±0.25 (27)	2.94±0.21 (23)	-	
H28	Hereford	14	3.01±0.20 (34)	3.14±0.16 (56)	14	5.67±0.04 (29)
H29	Hereford	10	2.99±0.23 (30)	3.18±0.18 (62)	10	5.67±0.05 (30)
H30	Hereford	10	3.02±0.23 (36)	2.91±0.18 (20)	10	5.71±0.05 (50)
H31	Hereford	17	3.10±0.19 (46)	3.10±0.15 (51)	17	5.69±0.04 (43)
H32	Hereford	9	3.11±0.24 (47)	2.68±0.19 (03)	9	5.67±0.05 (27)
H33	Hereford	9	3.54±0.24 (71)	3.19±0.19 (64)	9	5.70±0.05 (44)
H34	Hereford	11	2.96±0.22 (23)	3.00±0.18 (37)	11	5.66±0.05 (21)
H36 [§]	Hereford	15	3.38±0.23 (67)	2.76±0.16 (07)	15	5.80±0.05 (66)
H37 [§]	Hereford	21	2.98±0.21 (26)	2.74±0.14 (05)	15	5.78±0.05 (64)
H38 [§]	Hereford	4	3.52±0.35 (70)	3.01±0.29 (39)	-	
H39 [§]	Hereford	35	2.94±0.18 (21)	3.19±0.12 (63)	35	5.60±0.04 (02)
H40 [§]	Hereford	5	2.71±0.33 (07)	3.07±0.26 (45)	5	5.61±0.07 (03)
Total n		914			855	
Mean			3.05±0.25	3.01±0.19		5.68±0.05
CV			8%	6%		1%
Sire effect P-value			0.058	0.212		0.089

[§] Sires used via natural mating on 15-month-old heifers.

Appendix 7. Least-squares means (\pm SE) of the progeny groups for meat quality traits measured on meat samples in the laboratory (fat lightness L*, redness a* and yellowness b*, meat lightness L*, redness a* and yellowness b*, shear force, thaw loss and cook loss), for 15 Angus and 18 Hereford sires. Meat colour L*, a* and b*, shear force, thaw and cook loss were adjusted by ultimate pH. Number of progeny (n), mean (\pm SD) of the least-squares means of the progeny groups, coefficient of variation (CV), *P-value* for the effect of sire and *P-value* for the effect of ultimate pH are presented at the end of the table.

Sire	Breed	n [†]	Fat colour L*	Fat colour a*	Fat colour b*	Meat colour L*	Meat colour a*	Meat colour b*	Shear force peak (kgF)	Thaw loss (%)	Cook loss (%)
A1	Angus	11	65.84 \pm 1.24	5.61 \pm 0.87	12.38 \pm 0.72	38.68 \pm 0.90	17.93 \pm 0.55	7.95 \pm 0.51	4.12 \pm 0.23	0.74 \pm 0.14	24.34 \pm 0.74
A2	Angus	7	63.30 \pm 1.44	7.62 \pm 0.99	12.03 \pm 0.86	37.94 \pm 1.03	17.76 \pm 0.64	7.70 \pm 0.55	4.22 \pm 0.29	0.99 \pm 0.16	26.00 \pm 0.83
A3	Angus	14	63.79 \pm 1.16	6.41 \pm 0.82	14.87 \pm 0.66	36.92 \pm 0.85	17.14 \pm 0.51	6.97 \pm 0.49	4.71 \pm 0.21	1.09 \pm 0.13	25.76 \pm 0.70
A4	Angus	9	64.26 \pm 1.32	6.46 \pm 0.92	12.25 \pm 0.78	36.65 \pm 0.95	17.50 \pm 0.59	6.88 \pm 0.53	4.70 \pm 0.26	0.61 \pm 0.15	25.09 \pm 0.77
A5	Angus	9	65.47 \pm 1.32	5.58 \pm 0.92	13.43 \pm 0.78	37.14 \pm 0.95	18.38 \pm 0.59	8.02 \pm 0.53	4.99 \pm 0.26	1.05 \pm 0.15	25.22 \pm 0.77
A6	Angus	11	65.28 \pm 1.24	5.42 \pm 0.87	13.91 \pm 0.72	36.59 \pm 0.91	16.50 \pm 0.55	6.92 \pm 0.51	4.75 \pm 0.23	0.86 \pm 0.14	24.91 \pm 0.74
A8	Angus	13	64.99 \pm 1.18	5.71 \pm 0.83	13.47 \pm 0.68	37.70 \pm 0.86	17.96 \pm 0.52	7.75 \pm 0.50	4.51 \pm 0.22	0.85 \pm 0.13	25.20 \pm 0.72
A9	Angus	14	64.16 \pm 1.15	4.78 \pm 0.82	14.44 \pm 0.66	36.52 \pm 0.85	17.65 \pm 0.51	7.52 \pm 0.49	4.16 \pm 0.21	0.84 \pm 0.13	24.77 \pm 0.70
A10	Angus	8	66.97 \pm 1.38	6.87 \pm 0.96	13.20 \pm 0.82	39.45 \pm 1.00	17.69 \pm 0.62	7.45 \pm 0.54	4.32 \pm 0.27	0.84 \pm 0.16	26.23 \pm 0.81
A11	Angus	12	64.63 \pm 1.21	4.94 \pm 0.85	12.45 \pm 0.70	37.33 \pm 0.88	18.55 \pm 0.53	8.07 \pm 0.50	4.57 \pm 0.22	0.92 \pm 0.13	24.13 \pm 0.72
A13	Angus	5	65.57 \pm 1.63	7.34 \pm 1.12	12.78 \pm 0.99	38.41 \pm 1.15	18.19 \pm 0.73	7.62 \pm 0.60	3.96 \pm 0.34	0.99 \pm 0.19	26.79 \pm 0.92
A15	Angus	9	64.89 \pm 1.32	5.43 \pm 0.92	14.31 \pm 0.78	36.89 \pm 0.95	16.72 \pm 0.59	6.74 \pm 0.53	4.67 \pm 0.26	0.90 \pm 0.15	25.40 \pm 0.77
A16	Angus	12	64.06 \pm 1.21	5.58 \pm 0.85	16.00 \pm 0.70	36.46 \pm 0.88	18.26 \pm 0.54	7.65 \pm 0.50	3.92 \pm 0.22	0.87 \pm 0.13	23.50 \pm 0.72
A21	Angus	8	62.29 \pm 1.38	6.26 \pm 0.96	13.88 \pm 0.82	37.43 \pm 0.99	18.16 \pm 0.61	7.66 \pm 0.54	4.51 \pm 0.27	0.71 \pm 0.15	24.79 \pm 0.80
A23	Angus	4	61.98 \pm 1.78	8.78 \pm 1.22	15.01 \pm 1.09	37.20 \pm 1.25	19.30 \pm 0.80	8.31 \pm 0.64	3.68 \pm 0.38	0.90 \pm 0.21	26.15 \pm 0.99
H1	Hereford	6	65.09 \pm 1.51	7.83 \pm 1.05	13.90 \pm 0.91	35.60 \pm 1.08	17.73 \pm 0.68	7.10 \pm 0.57	4.29 \pm 0.31	1.12 \pm 0.17	27.28 \pm 0.86
H3	Hereford	11	64.04 \pm 1.24	5.51 \pm 0.87	13.79 \pm 0.72	37.24 \pm 0.90	18.30 \pm 0.55	7.76 \pm 0.51	4.50 \pm 0.23	0.82 \pm 0.14	24.63 \pm 0.74
H4	Hereford	5	64.52 \pm 1.63	6.57 \pm 1.12	13.51 \pm 0.99	37.04 \pm 1.16	16.25 \pm 0.73	7.10 \pm 0.60	4.69 \pm 0.34	1.11 \pm 0.19	25.44 \pm 0.92
H5	Hereford	13	63.36 \pm 1.18	5.09 \pm 0.83	16.15 \pm 0.68	36.35 \pm 0.86	16.84 \pm 0.52	6.72 \pm 0.50	4.30 \pm 0.22	0.94 \pm 0.13	25.41 \pm 0.71
H8	Hereford	11	63.20 \pm 1.24	7.52 \pm 0.87	12.80 \pm 0.72	37.13 \pm 0.90	16.15 \pm 0.55	6.49 \pm 0.51	5.09 \pm 0.23	0.99 \pm 0.14	25.62 \pm 0.74
H9	Hereford	6	64.60 \pm 1.52	5.65 \pm 1.05	14.35 \pm 0.92	36.32 \pm 1.08	18.13 \pm 0.68	7.55 \pm 0.57	4.79 \pm 0.31	1.07 \pm 0.17	26.47 \pm 0.87
H11	Hereford	10	64.07 \pm 1.28	6.09 \pm 0.89	14.26 \pm 0.75	37.32 \pm 0.92	17.00 \pm 0.57	6.65 \pm 0.52	4.20 \pm 0.24	0.98 \pm 0.14	27.74 \pm 0.75
H12	Hereford	6	64.01 \pm 1.52	5.84 \pm 1.05	13.99 \pm 0.92	37.44 \pm 1.08	17.14 \pm 0.68	6.97 \pm 0.57	5.07 \pm 0.31	1.09 \pm 0.17	27.53 \pm 0.86
H14	Hereford	11	65.56 \pm 1.24	5.73 \pm 0.87	13.20 \pm 0.72	37.64 \pm 0.90	17.56 \pm 0.55	7.38 \pm 0.51	4.79 \pm 0.23	1.05 \pm 0.15	25.34 \pm 0.74
H15	Hereford	11	63.48 \pm 1.24	5.77 \pm 0.87	14.14 \pm 0.72	36.67 \pm 0.90	17.22 \pm 0.55	7.30 \pm 0.51	5.02 \pm 0.23	1.14 \pm 0.14	26.05 \pm 0.73
H16	Hereford	7	62.41 \pm 1.44	6.94 \pm 1.00	12.19 \pm 0.86	36.08 \pm 1.03	17.65 \pm 0.64	7.17 \pm 0.55	4.92 \pm 0.29	1.01 \pm 0.16	26.24 \pm 0.83

Continue

Sire	Breed	n [†]	Fat colour L*	Fat colour a*	Fat colour b*	Meat colour L*	Meat colour a*	Meat colour b*	Shear force peak (kgF)	Thaw loss (%)	Cook loss (%)
H19	Hereford	12	65.14±1.21	5.55±0.85	13.74±0.70	37.94±0.88	17.20±0.53	7.21±0.50	4.73±0.22	0.94±0.13	26.33±0.72
H20	Hereford	10	64.16±1.27	5.45±0.89	14.44±0.75	36.85±0.92	17.05±0.57	6.91±0.52	4.60±0.24	0.99±0.15	25.10±0.75
H21	Hereford	14	65.40±1.16	6.01±0.82	13.61±0.66	36.24±0.85	17.83±0.51	7.18±0.49	4.84±0.21	0.67±0.13	26.53±0.70
H22	Hereford	10	62.90±1.27	6.59±0.89	13.32±0.75	37.07±0.92	16.88±0.57	6.96±0.52	4.82±0.24	0.82±0.14	24.94±0.75
H24	Hereford	12	63.71±1.21	6.44±0.85	14.70±0.70	37.74±0.88	17.53±0.54	7.39±0.50	4.34±0.22	0.73±0.13	24.90±0.72
H25	Hereford	12	61.22±1.21	6.11±0.85	13.82±0.70	37.42±0.88	17.49±0.53	7.29±0.50	4.83±0.22	0.76±0.14	25.70±0.72
H26	Hereford	13	65.06±1.18	6.97±0.83	12.48±0.68	37.58±0.86	17.19±0.52	6.93±0.50	4.94±0.21	1.08±0.13	26.65±0.71
Total n		326									
Mean			64.22±1.23	6.19±0.9	13.72±1.01	37.18±0.78	17.54±0.69	7.31±0.45	4.56±0.36	0.92±0.14	25.64±0.97
CV			2%	15%	7%	2%	4%	6%	8%	15%	4%
Sire effect P-value			0.159	0.072	<0.001	0.342	0.019	0.016	0.008	0.322	<0.001
Ultimate pH effect P-value			-	-	-	0.001	<0.001	<0.001	0.038	0.017	<0.001

[†] Thaw loss for: A1 n= 10, A3 n= 12, A4 n= 8, A6 n= 9, A9 n= 13, H14 n= 9, H20 n= 8, H21 n= 12, H25 n= 11; Cook loss for: A8 n= 12.

STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Natalia P. Martin
Name/title of Primary Supervisor:	Assoc. Professor Rebecca Hickson
In which chapter is the manuscript /published work:	3
Please select one of the following three options:	
<input checked="" type="radio"/> The manuscript/published work is published or in press <ul style="list-style-type: none"> Please provide the full reference of the Research Output: Martin N, Schreurs N, Morris S, López-Villalobos N, McDade J, Hickson R 2020. Sire effects on post-weaning growth of beef-cross-dairy cattle: a case study in New Zealand. <i>Animals</i> 10. DOI: 10.3390/ani10122313 	
<input type="radio"/> The manuscript is currently under review for publication – please indicate: <ul style="list-style-type: none"> The name of the journal: [Redacted] The percentage of the manuscript/published work that was contributed by the candidate: [Redacted] Describe the contribution that the candidate has made to the manuscript/published work: [Redacted] 	
<input type="radio"/> It is intended that the manuscript will be published, but it has not yet been submitted to a journal	
Candidate's Signature:	Natalia Martin <small>Digitally signed by Natalia Martin Date: 2021.01.14 11:17:46 +13'00'</small>
Date:	14-Jan-2021
Primary Supervisor's Signature:	Rebecca Hickson <small>Digitally signed by Rebecca Hickson Date: 2021.01.14 11:25:40 +13'00'</small>
Date:	14-Jan-2021

This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/ publication or collected as an appendix at the end of the thesis.



GRADUATE
RESEARCH
SCHOOL

STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Natalia P. Martin
Name/title of Primary Supervisor:	Assoc. Professor Rebecca Hickson
In which chapter is the manuscript /published work:	3
Please select one of the following three options:	
<input checked="" type="radio"/> The manuscript/published work is published or in press <ul style="list-style-type: none"> • Please provide the full reference of the Research Output: Martín NP, Schreurs NM, Morris ST, McDade JL, Coleman LW, Hickson RE (2018). Live weight of beef-cross-dairy calves during the first year of life. Proceedings of the World Congress on Genetics Applied to Livestock Production 11 (Electronic Poster Session - Biology - Growth and Development). Auckland. New Zealand. Pp697. 	
<input type="radio"/> The manuscript is currently under review for publication – please indicate: <ul style="list-style-type: none"> • The name of the journal: <div style="background-color: #e6f2ff; height: 20px; width: 100%;"></div> • The percentage of the manuscript/published work that was contributed by the candidate: <div style="background-color: #e6f2ff; width: 50px; height: 15px; display: inline-block;"></div> • Describe the contribution that the candidate has made to the manuscript/published work: <div style="background-color: #e6f2ff; height: 40px; width: 100%;"></div> 	
<input type="radio"/> It is intended that the manuscript will be published, but it has not yet been submitted to a journal	
Candidate's Signature:	Natalia Martin <small>Digitally signed by Natalia Martin Date: 2021.01.14 11:20:56 +13'00'</small>
Date:	14-Jan-2021
Primary Supervisor's Signature:	Rebecca Hickson <small>Digitally signed by Rebecca Hickson Date: 2021.01.14 11:27:10 +13'00'</small>
Date:	14-Jan-2021

This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/ publication or collected as an appendix at the end of the thesis.

STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Natalia P. Martín
Name/title of Primary Supervisor:	Assoc. Professor Rebecca Hickson
In which chapter is the manuscript /published work:	4
Please select one of the following three options:	
<input checked="" type="radio"/> The manuscript/published work is published or in press <ul style="list-style-type: none"> • Please provide the full reference of the Research Output: Martín NP, Schreurs NM, Morris ST, López-Villalobos N, McDade JL, Hickson RE (2021). Sire effects on carcass of beef-cross-dairy cattle: a case study in New Zealand. <i>Animals</i> 11: 636-648. DOI:10.3390/ani11030636. 	
<input type="radio"/> The manuscript is currently under review for publication – please indicate: <ul style="list-style-type: none"> • The name of the journal: _____ • The percentage of the manuscript/published work that was contributed by the candidate: _____ • Describe the contribution that the candidate has made to the manuscript/published work: _____ 	
<input type="radio"/> It is intended that the manuscript will be published, but it has not yet been submitted to a journal	
Candidate's Signature:	Natalia Martín <small>Digitally signed by Natalia Martín Date: 2021.07.26 11:27:36 +1200</small>
Date:	26-Jul-2021
Primary Supervisor's Signature:	Rebecca Hickson <small>Digitally signed by Rebecca Hickson DN: cn=Rebecca Hickson, o=Massey University, ou=Massey University, email=hickson@massey.ac.nz Date: 2021.07.27 17:02:16 +1200</small>
Date:	27-Jul-2021

This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/publication or collected as an appendix at the end of the thesis.

STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Natalia P. Martin
Name/title of Primary Supervisor:	Assoc. Professor Rebecca Hickson
In which chapter is the manuscript /published work:	4
Please select one of the following three options:	
<input type="radio"/> The manuscript/published work is published or in press <ul style="list-style-type: none"> Please provide the full reference of the Research Output: 	
<input checked="" type="radio"/> The manuscript is currently under review for publication – please indicate: <ul style="list-style-type: none"> The name of the journal: Meat Science The percentage of the manuscript/published work that was contributed by the candidate: 90.00 Describe the contribution that the candidate has made to the manuscript/published work: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing - original draft, Writing - review & editing 	
<input type="radio"/> It is intended that the manuscript will be published, but it has not yet been submitted to a journal	
Candidate's Signature:	Natalia Martin <small>Digitally signed by Natalia Martin Date: 2021.07.26 11:37:36 +1200</small>
Date:	26-Jul-2021
Primary Supervisor's Signature:	Rebecca Hickson <small>Digitally signed by Rebecca Hickson, o=NIZ, ou=Massey University, cn=Rebecca.Hickson@massey.ac.nz Date: 2021.07.27 11:07:36 +1200</small>
Date:	27-Jul-2021

This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/publication or collected as an appendix at the end of the thesis.

STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Natalia P. Martín
Name/title of Primary Supervisor:	Assoc. Professor Rebecca Hickson
In which chapter is the manuscript /published work:	5
Please select one of the following three options:	
<input type="radio"/> The manuscript/published work is published or in press <ul style="list-style-type: none"> • Please provide the full reference of the Research Output: 	
<input checked="" type="radio"/> The manuscript is currently under review for publication – please indicate: <ul style="list-style-type: none"> • The name of the journal: Frontiers in Genetics- Livestock Genomics • The percentage of the manuscript/published work that was contributed by the candidate: 85.00 • Describe the contribution that the candidate has made to the manuscript/published work: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing - original draft, Writing - review & editing 	
<input type="radio"/> It is intended that the manuscript will be published, but it has not yet been submitted to a journal	
Candidate's Signature:	Natalia Martin <small>Digitally signed by Natalia Martin Date: 2021.07.26 11:37:36 +1200</small>
Date:	26-Jul-2021
Primary Supervisor's Signature:	Rebecca Hickson <small>Digitally signed by Rebecca Hickson DN: cn=Rebecca Hickson, o=Massey University, email=hickson@massey.ac.nz Date: 2021.07.27 17:05:56 +1200</small>
Date:	27-Jul-2021

This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/publication or collected as an appendix at the end of the thesis.



GRADUATE
RESEARCH
SCHOOL

STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Natalia P. Martín
Name/title of Primary Supervisor:	Assoc. Professor Rebecca Hickson
In which chapter is the manuscript /published work:	6
Please select one of the following three options:	
<input type="radio"/> The manuscript/published work is published or in press <ul style="list-style-type: none"> Please provide the full reference of the Research Output: 	
<input checked="" type="radio"/> The manuscript is currently under review for publication – please indicate: <ul style="list-style-type: none"> The name of the journal: New Zealand Journal of Animal Science and Production The percentage of the manuscript/published work that was contributed by the candidate: 90.00 Describe the contribution that the candidate has made to the manuscript/published work: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing - original draft, Writing - review & editing 	
<input type="radio"/> It is intended that the manuscript will be published, but it has not yet been submitted to a journal	
Candidate's Signature:	Natalia Martín <small>Digitally signed by Natalia Martín Date: 2021.07.26 11:37:36 +1200</small>
Date:	26-Jul-2021
Primary Supervisor's Signature:	Rebecca Hickson <small>Digitally signed by Rebecca Hickson DN: cn=Rebecca Hickson, o=Massey University, email=R.Hickson@massey.ac.nz Date: 2021.07.27 11:08:53 +1200</small>
Date:	27-Jul-2021

This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/publication or collected as an appendix at the end of the thesis.