Modelling the role of dairy-origin cattle for young beef production 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, Manawatu,

New Zealand

By
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MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND
GRADUATE RESEARCH SCHOOL

Note for Examiners
Explanation of COVID-19 Impacts

Thank you for taking the time to examine this thesis, which has been undertaken during the Covid-19 pandemic. The New Zealand Government's response to Covid-19 includes a system of Alert Levels which have impacted upon researchers. Our University's pandemic plan applied the Government's expectations to our research environment to ensure the health and safety of our researchers, however, research was impacted by restrictions and disruptions, as outlined below.

For a six-week period from March 26 to April 27 2020, New Zealand was placed under very strict lockdown conditions (Level 4 – Lockdown), with students and staff unable to physically access University facilities, unless they were involved in essential research related to Covid-19. All field work ceased and data collection with humans was restricted to online methods, if appropriate. The restrictions were partially lifted on April 27, but students and staff were not generally allowed back into University facilities until May 13.

Ongoing disruptions have also been encountered for some students due to uncertainties over the potential for future Covid-19-related restrictions on activities, and a Covid-19 cluster outbreak based in Auckland in New Zealand on 12 August 2020 led to the imposition of rolling Level 2 (Reduce) and Level 3 (Restrict) conditions until 23 September 2020. Auckland campus based students remained on Level 2 until 7 October 2020. This Alert Level system continues to be utilised throughout 2021.

These changing Alert Levels have meant that some research students had experimental, clinical, laboratory, field work, and/or data collection or analysis interrupted, and consequently may have had to adjust their research plans. For some students, the impacts of Covid-19 stretched far beyond the lockdown period in April/May 2020, as they may have had to significantly revise their research plans.

Overseas travel is not permitted by the University and restrictions have been placed on the New Zealand borders which are closed to non-New Zealand citizens and permanent residents. This meant that international students who were based offshore at the time of lockdown, were unable to return to New Zealand. A small number of offshore students were provided permission to return to New Zealand in early 2021. Many students have also suffered from anxiety and stress-related issues, and have had financial impacts, meaning their research progress has been significantly delayed.

This form, as completed by the supervisor and student, outlines the extent that the research has been affected by Covid-19 conditions.

Approved by DRC 10/Feb/2021
DRC 21/02/03

Please consider the factors listed below in your assessment of the work.

This statement has been prepared by the candidate's supervisor in consultation with the student and has been endorsed by the relevant Head of Academic Unit.

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ID Number: [redacted]
Supervisor Name: Emeritus Prof. Hugh Blair
Date: 14th June 2022
Thesis title: Modelling the role of dairy-origin cattle for young beef production in New Zealand

Considerations to be taken into account. Note: This statement will remain in the final copy of the thesis which will be available from the Massey University Library following the examination process. [*Enter key considerations here for the examiners. This can include but is not limited to change of scope, scale, topic, focus; limitations in relation to data collection, access to necessary literature or archival materials, laboratories, field sites; disruptions as a result of lockdown and various alert levels, medical or health considerations etc*]

Mr Addisu Hailu began his PhD studies in early 2019. The primary focus of the PhD was to use different in-silico models to investigate the use of young dairy-origin beef cattle in New Zealand. Three types of models were implemented, statistical linear models, linear programming (LP) and agent-based modelling (ABM). Implementation of these models required the collection of data directly from the industry and the extraction of suitable data from large existing databases.

ABM was initially developed using the NetLogo programming language, however, due to computational limitations the Candidate moved from Massey University, Palmerston North, to the AL Rae Research Centre for Genetics and Breeding in Hamilton. This gave the Candidate access to greater computing capacity and to staff and students to assist with learning the Julia programming language, which is a high computational programming language. Given that the Candidate had no prior knowledge or experience with ABM, Unix computing and the Julia programming language, the Covid-19 pandemic and associated lockdowns greatly affected his interaction with supervisors, staff and fellow students. The pandemic also limited his interaction with a linear programming expert, who was located in another city, who provided significant support in developing the linear programming optimization model.

The above constraints limited the Candidate's ability to create the two types of models in a timely manner. Further, it had been planned to interview industry participants to collect data to enhance the ABM. This data would have allowed for a greater depth of analysis. The absence of some key data and reduced time caused by the two national lockdowns, plus another lockdown that affected the Waikato region, reduced the quality of the final chapter of the study.

Signed, confirming this is a fair reflection of the impact of Covid-19 on this research.

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Abstract

Approximately 42% of calves produced annually in the New Zealand dairy industry are slaughtered by 2-weeks of age. This is seen as a wasted economic opportunity and has perceived welfare and ethical issues which could potentially affect both the dairy and beef trade. Young beef cattle production has been proposed to finish these calves for beef at 8 to 12-months of age. This study employed mathematical models to: 1) predict hind-leg muscle weight from young beef as an indirect indicator of saleable meat yield, 2) understand feed utilization and financial effects and 3) acceptance level of young beef cattle within the existing New Zealand beef cattle production systems. A univariate analysis using carcass weight explained 61% of variations in hind-leg muscle weight. This was improved by 6% in multivariate regression analysis using carcass weight, wither height and eye muscle area. Identifying additional traits in young beef cattle would improve the prediction accuracy and efficiency of the equations. A profit optimization model developed in this study identified selling strategies of beef cattle and sheep activities to increase farm profitability and pasture utilization on beef cattle and sheep farms. Including young beef cattle in the existing beef cattle and sheep farms increased the number of beef cattle processed per hectare, farm carcass output and pasture utilization. However, the farm earnings per hectare was lower than the optimized farm when carcasses from young beef cattle were processed under manufacturer beef price (i.e., NZ$ 4.50). Bulls (mainly Holstein-Friesian and Holstein-Frisian-Jersey cross breeds) accounted more than 50% of the total dairy-origin beef cattle processed in agent-based modelling (ABM). The uptake of Jersey breed for beef finishing was lower than 5% of the total dairy-origin beef cattle. Young beef cattle finishing under NZ$ 4.50 per kg carcass was not competitive with the traditional beef finishing systems. A 10% increase in value per kg carcass for young beef allowed them to contribute 6% of the total processed dairy-origin beef cattle. Incorporating consumers perspectives and other decision alternatives for the finisher could improve decision making on the use of young beef cattle in New Zealand.

Acknowledgments

I cannot express enough thanks to my supervisors: Emeritus Prof. Hugh Blair, Prof. Steve Morris, Prof. Dorian Garrick, Prof. Paul Kenyon and Dr. Nicola Schreurs for their valuable time, advice and friendly approach. Their doors were always opened and welcomed for any kind of questions. Their patience, positivity and leadership experience have made this study an enjoyable experience. I am deeply appreciative for the consistently prompt return of drafts, answers to my queries, and extensive editing my "*Ethio-English*".

Emeritus Prof. Hugh, I feel lucky to had you as a main supervisor. You're not a supervisor, you are a mentor, you are a leader too! Given that your leadership skill and wisdom, your deep knowledge in mathematical models and framing the objectives into practical solutions made this journey enjoyable and thoughtful. I always came into your office with faint idea and diffident, but, returned with clear and concise objectives. I wish you enjoyable retirement period "SANTA".

Prof. Steve, your motivation, encouragement and counsel on this research has been priceless. Your critical observation, enthusiasm and deep knowledge on sheep and beef production have been amazing to me. Your critical observations on the objectives and terminology usage made the PhD journey purposeful, thoughtful and clearer.

Prof. Dorian, your energy, deep knowledge on mathematical models, programming language to mentions just a few are really infectious. Your motivation, encouragement and counsel on this research have been precious. Your leadership skill on the top of your ample experience in advising domestic and international students made this journey thoughtful.

Prof. Paul, your energy, and deep knowledge on sheep and beef cattle research play a significant role in this journey. Your leadership skill on the top of your ample experience in advising domestic and international students made this journey interactive and thoughtful. My writing skills have improved with your feedback.

Dr. Nicola, your energy and deep knowledge on sheep and beef production play significant roles in this PhD journey. Your critical observations on the objectives, terminology usage made the PhD journey purposeful, thoughtful and clearer.

It's hard to name and acknowledge everyone who have helped me in this journey, Massey University staff were supportive throughout the journey, and I am really thankful for that. I would like also to extend my acknowledgment to Barrie Ridler, Tony Pleasant, and Mike Keehan for their unreserved help during linear programming and agent-based model developments. My appreciation also goes to all staff members of the AL Rae research center (ARC), Hamilton and office mates and friends at Massey University, Palmerston North for their unreserved help and encouragement.

Finally, I would like to acknowledge my family. Specially my wife, thank you for taking full responsibility of looking after our kids in my absentee.

Table of Contents

List of Tables

List of Figures

List of Video

Abbreviations

ABM: Agent-Based Model
ADG: Average Daily Gain
AIC: Akaike's Information Criterion
ANOVA: Analysis of Variance
B-8: Bulls slaughtered at 8-month old
B-10: Bulls Slaughtered at 10-month old
B-12: Bulls Slaughtered at 12-month old
B-14: Bulls Slaughtered at 14-month old
B+LNZ: Beef and Lamb New Zealand
BCBB: beef cull breeding bulls
BF: Bull Beef
BIC: Bayesian's Information Criterion
CDBB: cull dairy breeding bull
CDH: cull dairy heifers
CW: Carcass Weight
DM: Dry Matter
E2M: Enviro-Economic Model
EBITRm: Earnings Before Interest, Tax, Rent and Manager Wage
EBT: Earnings Before Tax
EMA: Eye Muscle Area
FAO: Food and Agriculture Organizations
GDBSM: Grange Dairy Beef Systems Model
GFR: Gross Farm Revenue
GHG: Greenhouse gas
GLS: Generalized Least Squares
GSL: Grazing System Ltd
H-8: Heifers Slaughtered at 8-month old
H-10: Heifers Slaughtered at 10-month old
H-12: Heifers Slaughtered at 12-month old
H-14: Heifers Slaughtered at 14-month old
Ha: Hectare
HU: Herbage Utilization (%)
Kg: Kilo Gram
LCA: Life Cycle Assessment
LM: Hind-Leg Muscle Weight

LMM: Linear Mixed Effect Model
LP: Linear Programming
LW: Live Weight
M: Million
Max: Maximum
ME: Metabolizable Energy
MIDAS: Models of an Integrated Dryland Agricultural System
Min: Minimum
MJ: Megajoules
MPI: Ministry for Primary Industry
MUDAS: Model of An Uncertain Dryland Agricultural System
N.I: North Island
No: Number
P8: Rump Fat Depth
PS: Prime Steers
R2: Rising 2 Years
R3: Rising 3 Years
RF: Rib Fat Depth
RHGT: Replacement Hoggets
RMSE: Root Mean Square Error
S-8: Steers Slaughtered at 8-month old
S-10: Steers Slaughtered at 10-month old
S-12: Steers Slaughtered at 12-month old
S-14: Steers Slaughtered at 14-month old
S-18: Steers Slaughtered at 18-months old
SR: Stocking Rate
SU: Stocking Unit
TFE: Total Farm Expenditure
VIF: Variance Inflation Factor
WH: Wither Height

Chapter I

Introduction and Thesis Objectives

Introduction

Beef production in New Zealand increasingly relies on dairy-origin cattle. The dairy industry supports beef production either directly by supplying cull heifers, cows and bulls or indirectly by providing excess calves to be finished on beef cattle and sheep farms (Schreurs et al., 2014; Berry, 2021; B+LNZ, 2022). In 2020, 73% of the beef processed in New Zealand was from dairy-origin cattle (New Zealand Statistics, 2022).

Annually, approximately 4.5 million calves are born on dairy farms (New Zealand Statistics, 2022). Of these, approximately 25% are utilized as dairy heifer replacements and 20% are reared for finishing on beef cattle and sheep farms, with the remainder commercially slaughtered within 2-weeks of age or euthanized on-farm (Andrew, 2016; B+LNZ: Economic Service, 2021). These commercially slaughtered calves are referred "bobby calves" (Cook, 2014; Andrew, 2016; B+LNZ, 2022). In 2020, New Zealand processed approximately 1.9 million bobby calves from the dairy industry (New Zealand Statistics, 2022). Transporting and slaughtering these calves is fraught with welfare and ethical issues which can be considered as a potential threat to New Zealand dairy and beef trading in the form of non-tariff barriers (Ferguson et al., 2014; Andrew, 2016; Boulton et al., 2018). Further, high prevalence detection of E.coli in bobby calves production might risk the export market (Browne et al., 2018).

If bobby calves were finished for beef, the profitability of both dairy and beef cattle and sheep farms could potentially increase, and welfare and ethical issues related to bobby calves would be alleviated. However, due to constraints (mainly grazing land), it is not possible for all excess dairy-origin calves to be finished via traditional beef production systems at 18 to 33-months of age. Therefore, alternative systems with a focus on young beef are a potential solution (Arelovich et al., 2011; Domaradzki et al., 2017; Hunt et al., 2019; Pike et al., 2019). To be successful, young beef production systems need to produce a product that has desirable meat/carcass qualities (Pike et al., 2019;

Nakitari, 2021) and have a profitability that is competitive with other land use options (Hunt et al., 2019). Under the current New Zealand beef grading system the current lower price of NZ$ 4.50 per kg for carcasses between 145.5 and 220 kg compared to NZ$ 5.65 per kg for 220.5 to 350 kg carcasses, would limit farmer uptake of young beef cattle (B+LNZ, 2022; MPI, 2022).

In New Zealand, there is no beef classification and grading system for carcasses that recognises the quality of beef from young animals. Such a system is needed if the appropriate value for the meat is to be assigned. The potential impacts of young beef production on farm profitability and feed utilization and the potential uptake of young dairy-origin beef cattle into beef cattle and sheep farms are currently unknown.

To address these matters, the current study utilized mathematical models to provide new knowledge about young beef cattle production systems in New Zealand. Mathematical models can be useful tools in gaining a better understanding of beef cattle production systems by allowing *in silico* representation of dependent and explanatory factors (Pannell et al., 1996; Thronley and France, 2007; Stygar and Makulska, 2010). This provides insight into the possible challenges and opportunities of the farm system and assists in the decision making process without the need for expensive on-farm trials (Pannell, 1996; Pannell et al., 1996; Thronley and France, 2007; Farrell et al., 2020b).

Therefore, the aims of this study were to: 1) predict saleable meat yield from young beef cattle, which could then be used to inform the young beef classification and grading system, 2) understand feed utilization and financial effects and 3) the level of acceptance of young beef cattle within the existing New Zealand beef cattle production system.

Specific objectives of the study were to:

- Develop prediction equations for hind-leg muscle weight from young beef cattle (Chapter III).
- Develop a profit optimization model for New Zealand sheep and beef cattle farms (Chapter IV).
- Optimize a young beef cattle production in terms of feed utilization and profitability on sheep and beef cattle farms (Chapter V).
- Develop an agent-based modelling to improve beef production from dairy-origin cattle (Chapter VI).
- Investigate price levers on the uptake of young beef cattle on New Zealand sheep and beef cattle farms (Chapter VII).

Chapter II

Literature Review

Global meat production

Globally, 325.7 million tonnes of meat (equivalent carcass weight) is produced (FAO, 2021). This includes poultry (132.07 million tonnes), pork (106.53 million tonnes) and beef (71.14 million tonnes) (carcass weight equivalent) as the three biggest volumes of animal meats produced (Figure 1) (FAO, 2021). Ten percent of the total meat production (33.6 million tonnes, equivalent carcass weight) was internationally traded (FAO, 2021). In 2021, the New Zealand production was 728,544 tonnes of beef and 453,580 tonnes of sheep meat (equivalent carcass weight) (New Zealand Statistics, 2022).

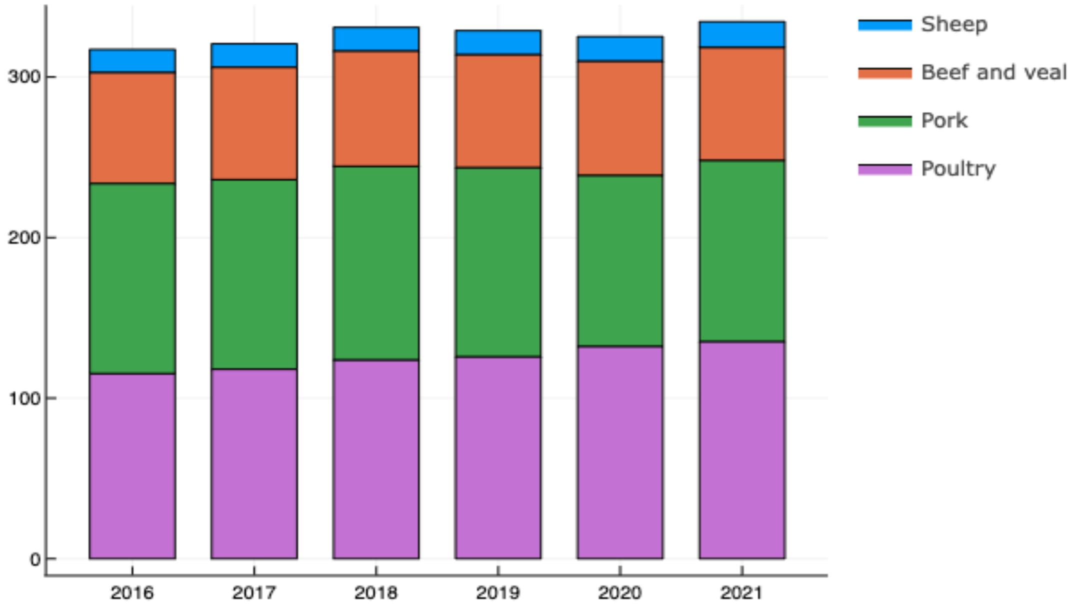

Figure 1. Worldwide meat production from 2016 to 2021, by type (in million metric tonnes).
Source: FAO (2021)

Global cattle population, beef production and trade

India (301 million) followed by Brazil (213 million) and China (103 million) have the world's largest cattle herds (B+LNZ, 2017). The New Zealand cattle population is approximately 10 million (4 million beef cattle breed and 6 million dairy cattle breed) which is less than one percent of the global cattle population (New Zealand Statistics, 2022). However, annual beef production in New Zealand accounts for 6% of globally traded beef (B+LNZ, 2017). By volume, China and USA are the first and second export destinations for New Zealand beef (B+LNZ: Economic Service, 2021).

Overview of beef production in New Zealand

Pasture provides up to 95% of livestock diets in New Zealand beef cattle and sheep production systems (Hodgson et al., 2005; Morris, 2013b; Morris and Kenyon, 2014). On beef cattle and sheep farms, cattle and sheep are complementary in both pastoral management and animal health (Morris, 2013b; Charteris et al., 2014; Morris and Kenyon, 2014) due to differing grazing patterns. This enables New Zealand to have a low-cost and economically sustainable beef production systems (Morris and Kenyon, 2014; B+LNZ, 2017) and gives a competitive advantage on the global beef market (Morris and Kenyon, 2014; B+LNZ, 2017).

New Zealand beef and sheep farm classes

There are eight defined beef cattle and sheep farm classes throughout New Zealand (Table 1) (B+LNZ, 2022). The North Island contains approximately 33% of total beef cattle and sheep farms in New Zealand (Hendy et al., 2009; B+LNZ, 2022). North Island hill country (farm class 4) has the largest number of beef cattle and sheep farm (Hendy et al., 2009; B+LNZ, 2022) whereas, South Island high country (farm class 1) has the lowest number of beef cattle and sheep farm, and the lowest stocking rate although it has the highest land area (Table 1) (Hendy et al., 2009; B+LNZ, 2022).

Table 1. The eight beef cattle and sheep farm classes of New Zealand and their estimated average land size (hectare), farm number (farm no), stocking rate (SR) and description (B+LNZ, 2022).

Classes	Class name	[1]hectare	[2]Farm no.	[1]SR	[3]Description
1	South Island high country	7,929	200	1.3	Extensive run country located at high altitude (mainly: Marlborough, Canterbury and Otago), with wool as the main source of revenue.
2	South Island hill country	1,496	620	4.4	Mainly mid micron wool sheep mostly carrying. Three quarters of the stock units wintered are sheep and one-quarter beef cattle.
3	North Island hard hill country	798	920	7.9	Steep hill country or low fertility soils. A higher proportion of stock are finished in store condition.
4	North Island hill country	429	3,055	9.5	Easier hill country or higher fertility soils than Class 3. A high proportion of sale stock sold is in forward store or prime condition.
5	North Island intensive finishing	290	1,045	9.9	Easy contour farmland with the potential for high production. A high proportion of stock is sent to slaughter and replacements are often bought in.
6	South Island finishing-breeding	394	1,820	9.5	A dominant farm class in the South Island and a more extensive type of finishing farm, also. Located mainly in Canterbury and Otago. Encompasses some irrigation units and frequently with some cash cropping
7	South Island intensive finishing	230	1,040	11.5	High producing grassland farms with some cash crop. Located mainly in Southland, South and West Otago.
8	South Island mixed cropping and finishing	427	465	8.3	Mainly on the Canterbury plains with a high proportion of the revenue being derived from grain and small seed production as well as stock finishing.

Sources: [1]B+LNZ (2022); [2]Cranston et al. (2017); [3]Hendy et al. (2009)

Stock unit and stocking rate

A stock unit is a standardized form of calculating stock numbers across different classes and age groups of animals. It converts various animal classes into a single measuring unit for estimating annual feed demand for livestock. In New Zealand, one stock unit is equivalent to the annual feed consumption of a 55 kg ewe weaning one 28 kg lamb, which is equivalent to consuming 550 kg DM per year (Trafford and Trafford, 2011).

Cattle stock unit

One mixed-age cow that rears one calf annually is equivalent to six stock units. Heifers and steers have lower feed requirements than bull and in-calf cows (Table 2).

Table 2. Per head stock unit for various classes of beef cattle.

Cattle classes	Stock unit conversion	Annual feed demand (kg DM)
MA cows	6.0	3,300
Dry MA cows	5.0	2,750
In-calf R2yr heifers	6.0	3,300
Dry R2yr heifers	5.0	2,750
R1yr heifers	4.0	2,200
Heifer calves	2.0	1,100
MA steers	5.5	3,025
R2yr steers	5.0	2,750
R1yr steers	4.0	2,200
Steers calves	2.0	1,100
MA bulls	6.0	3,300
R2yr bulls	5.5	3,025
R1yr bulls	4.5	2,475
Bull calves	2.0	1,100
Average	4.6	

Source: Trafford and Trafford (2011)

Stocking rate

Stocking rate is defined as total stock units divided to total effective land area (stock number per hectare) (Trafford and Trafford, 2011).

$$\text{Stocking rate} = \frac{\text{Stock unit (total beef cattle and sheep stock units)}}{\text{effective production land size (hectare)}}$$

Beef production systems

Heifer and steer finishing systems

Heifers and steers are the main source of prime beef finished at the ages of 20 to 30-months and produce on average 241 kg heifer and 312 kg steer carcasses (B+LNZ, 2017; MPI, 2022). Beef from heifers and steers is exported to high value and premium markets earning a higher price per kg carcass than other classes of beef (Peden, 2008). Heifers mature earlier and attain 3 mm of fat sooner than steers, so they tend to be sent for slaughter at a lighter weight (Table 3) (Barton, 1974; MPI, 2022). The average carcass weight of heifers and steers have increased by 5% and 2% respectively from 2008/09 to 2020/21 (Table 3) (New Zealand Statistics, 2022), likely explained by genetic changes in mature weight and nutritional improvements (Morris, 2013a).

Table 3. Average carcass weight (kg per head) for heifers, steers, bulls and cow for selected years since 2008/09 to 2020/21.

Years	Heifers	Steers	Bulls	Cows
2008/09[1]	232.3	306.3	301.6	200.0
2009/10[1]	234.3	312.3	306.5	203.5
2010/11[1]	234.4	306.1	289.6	203.5
2011/12[1]	245.2	316.8	309.0	205.5
2016/17[2]	241.0	313.2	305.2	199.0
2017/18[2]	240.8	311.3	300.7	198.0
2018/19[2]	241.9	312.7	299.7	200.4
2019/20[2]	242.9	311.6	299.3	202.6
2020/21[2]	243.8	309.8	300.5	202.9

Sources: [1]Morris (2013a); [2]MPI (2022)

Bull finishing system

A bull beef system is characterised by the production of meat from entire (uncastrated) male bovine cattle. Bulls have a 10-20% faster growth rate and produce greater saleable meat yield than both steers and heifers (Bailey et al., 1966; Adams et al., 1969; McNamee et al., 2015; Nogalski et al., 2017). They also display better-feed conversion efficiency (Bailey et al., 1966; Steen, 1995; Kirkland et al., 2006). However, the quality and tenderness of bull meat can be lower (Bailey et al., 1966; Martin et al., 2018). Hence, bull beef is often used for processing and grinding, earning a lower carcass value per kg than prime beef (Peden, 2008).

In New Zealand, most bull beef is derived from Holstein Friesian animals sourced from dairy farms (Morris and Kenyon, 2014; Pettigrew et al., 2017; Martin et al., 2018; Berry, 2021; van Selm et al., 2021). Bull beef production aims to achieve 270 kg carcass weight within 16 to 20-months (Morris and Kenyon, 2014) which requires an average daily gain of 1.1 kg/head/day (McRae, 2003). Bull beef production peaks during the summer (Figure 2) as farmers aim to achieve slaughter weights before the winter decline in pasture growth and availability. If feed is available and live weight targets are not met, bulls can be held on farm for a second winter (i.e., slaughter at 30-months of age to achieve 350 kg carcass weight) (Martin et al., 2018).

Cull cow

Cow beef is beef from cull cows at the end of their productive life and may be sourced from either dairy or beef production systems (Morris, 2013a). Annually, around 1,019,121 cows are processed for beef production, of that, 77% are dairy cows (Figure 2) (New Zealand Statistics, 2022).

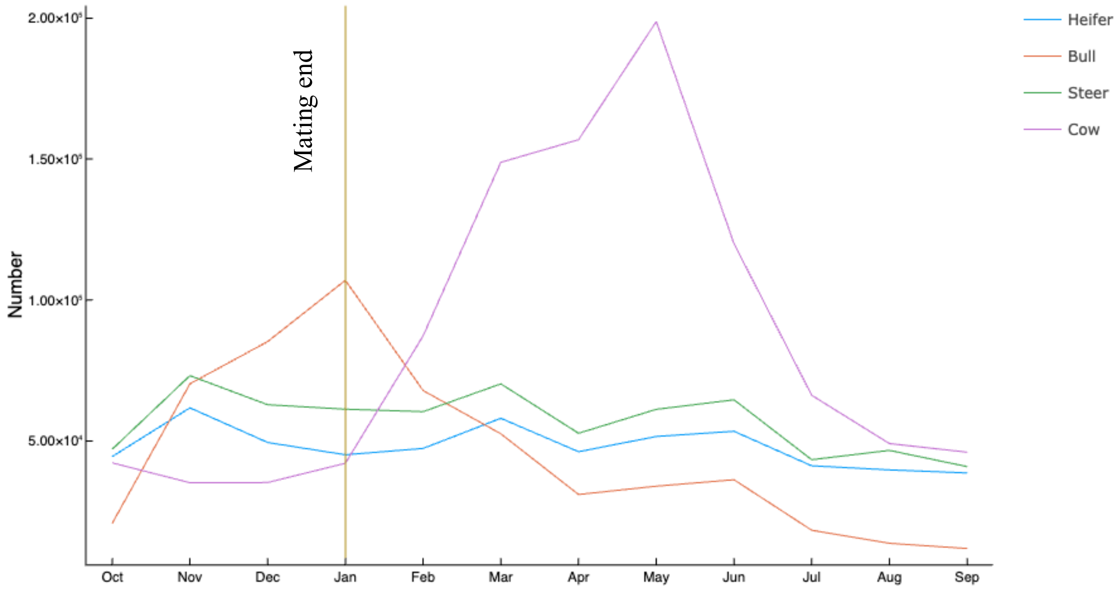

Figure 2. Annual slaughter pattern for heifers, steers, cows and bulls slaughtered each month in 2021. Source: MPI (2022)

Bobby calf production

The New Zealand dairy industry produces calves in excess to the requirement for dairy heifers replacements (New Zealand Statistics, 2022). A proportion of these calves are finished for beef on beef cattle and sheep farms with the remainder, mainly from lower genetic merit dairy cows and first calving heifers, are either commercially slaughtered as bobby calves or euthanised on dairy farm. The age at slaughter of these bobby calves is 4 to 14-days while, some companies limit the maximum age to 2-month old calves. The typical bobby calf season is 14-weeks long (Palmer et al., 2021). The bobby calf production peaks during late winter and spring following the calving period of New Zealand dairy farms (New Zealand Statistics, 2022). Since 1982, New Zealand`s bobby calf production has increased and peaked in 2014 before slightly dropping (Figure 3). This is likely explained by the increase in dairy cow numbers up to 2014 which has since decreased (Figure 3) (New Zealand Statistics, 2022).

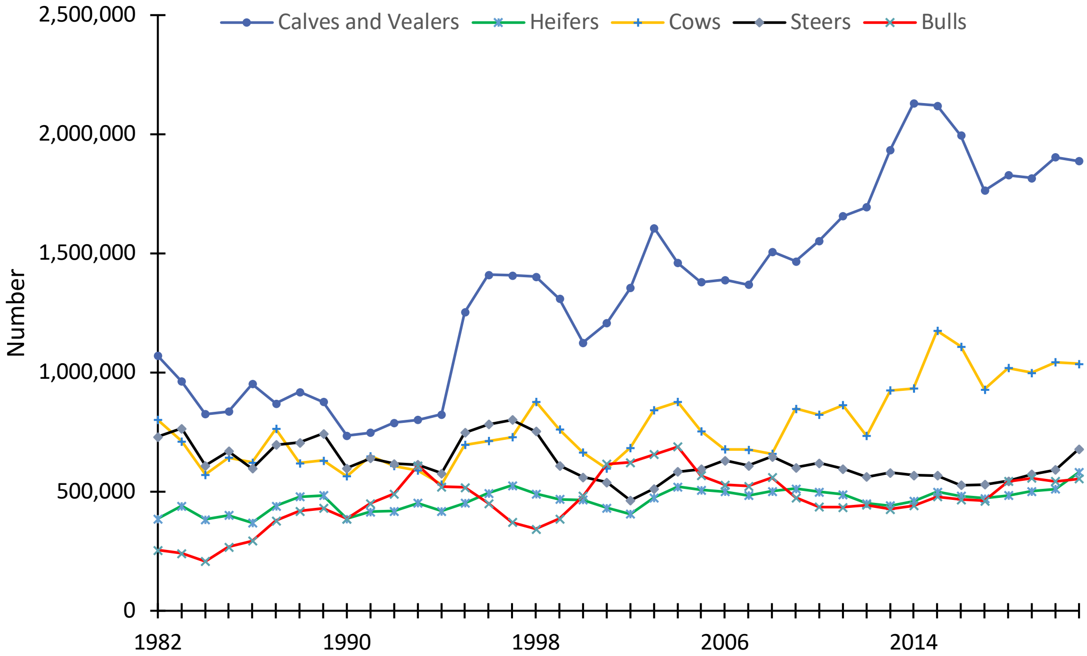

Figure 3. Trend of cattle slaughter in New Zealand by animal type, year ended September 1982 to 2021. Source: New Zealand Statistics (2022)

Commercial beef carcass classification and grading in New Zealand

Carcass classification has advantages for both farmers and consumers. It can reflect consumers choice to farmers and allows farmers to compare their products with others (Bass et al., 1977; Kirton, 1998). The classification system can therefore be used by farmers to make decisions about whether cattle are ready for slaughter. It creates a smooth, consistent, fast, transparent and reliable marketing and payment system (B+LNZ, 2022). In New Zealand, beef cattle class is based on maturity (age), gender (sex) and carcass weight (Table 4) (B+LNZ, 2022).

Table 4. New Zealand beef classification based on maturity and gender.

Classes	Definition	Carcass weight
Bobby calf	Milk feed, generally under two weeks old	<30 kg
Steer	A castrated male bovine	>145 kg
Heifer	Female cattle having no more than six permanent incisors	>145 kg
Cow	Female cattle having more than six permanent incisors	NA
Bull	Entire male bovine (with masculine characteristics)	NA

Carcasses are further classified based on fat depth and muscling (B+LNZ, 2022; MPI, 2022). Combined, the fat depth and muscling score provide an indirect indication of saleable meat yield and they are used for carcass classification and form part of the grading systems. Based on the fat thickness, heifers and steers are divided into five fat classes (A, L, P, T and F), prime cow into three (P, T and F) and bulls including young bull beef into TM and M classes (Table 5) (B+LNZ, 2022).

Table 5. New Zealand carcass classification based on sex, muscling and fat depth.

	Muscling classes			Fat depth classes		
Beef classes	1	2	3	Classes	Fat level	Fat depth (mm)
Steer/heifer	A1	A2	A3	A	Devoid	Nill
	L1	L2	L3	L	Light, patchy	under 3
	P1	P2	P3	P	Light to medium	3-10
	T1	T2	T3	T	Heavy	11-16
	F1	F2	F3	F	Excessive	17 & over
[a]Prime cow	P1	P2	P3	P	Light to medium	3-10
	T1	T2	T3	T	Heavy	11-16
	F1	F2	F3	F	Excessive	17 & over
Bull	M1	M2	M3	M	devoid to light, patchy	<3
	TM1	TM2	TM3	TM	light or medium to excessive	3 & over

[a]M cow does not have muscle classification

There are three beef muscling classes (Table 5) (B+LNZ, 2022; MPI, 2022): Muscle class 1 has a convex to super convex hindquarter profile. Muscle class 3 is characterized by lack of rump and round development and shallow loin.

Carcasses evaluated based on fat depth and muscling score are further classified by their weight for payment (Table 6) (Interest New Zealand, 2022). Historical average price for prime heifers/steers is NZ$ 5.50, NZ$ 5.25 for bulls, NZ$ 4.50 for cow beef and NZ$ 2.00 for bobby calves (Ormond et al., 2002; B+LNZ: Economic Service, 2021; Farmersweekly, 2021).

Table 6. Processor schedule price for prime P2 heifer/steer, M2 bull and P2 cow (NZ$/kg carcass weight).

Heifers/Steers (Prime P2)		Bulls (M2)		Cows (P2)	
Weight ranges (kg)	Price (NZ$)	Weight ranges (kg)	Price (NZ$)	Weight ranges (kg)	Price (NZ$)
145.5 - 195.0	4.60	145.5 - 195.00	4.40	195.0	4.15
195.5 - 220.0	5.50	195.1 - 220.0	4.95	195.5 - 220.0	4.30
220.5 - 245.0	5.80	220.1 - 245.0	5.45	220.5 - 245.0	4.30
245.5 - 270.0	5.80	245.1 - 270.0	5.50	245.5 - 270.0	4.30
270.5 - 295.0	5.80	270.1 - 295.0	5.75	270.5 - 295.0	4.30
295.5 - 320.0	5.80	295.1 - 320.0	5.75	295.5 - 320.0	4.30
320.5 - 345.0	5.80	320.1 - 345.0	5.75	321.0	4.30
345.0 - 370.0	5.80	345.5 - 445.0	5.75		
371.0 - 400.0	5.80	445.1 - 500.0	5.10		
401	5.50	500.5	4.75		

Source: https://www.interest.co.nz/; Silver Fern Farms. Visited on 9th Mar. 2022.

Challenges and opportunities of dairy farm expansion

Challenges

Despite environmental impact and competition for land from dairy farm expansion, this review only focuses on challenges related to the surplus (bobby) calf production from the dairy industry. Approximately 42% of the total calves born on dairy farms are processed as bobby calves (van Selm et al., 2021; New Zealand Statistics, 2022). Studies conducted by Boulton et al. (2018) and Palmer et al. (2021) on the welfare status of bobby calves in New Zealand beef processing premises identified that a significant number of calves in lairage are affected by faecal soiling and exhibit dehydration during transportation.

Opportunities

Supplying calves and cull cattle for traditional beef production

Approximately, four percent of the New Zealand beef cow herd are beef-dairy crossbred, such as the Hereford-Friesian-cross (B+LNZ, 2017). The dairy industry also contributes calves for beef cattle finishing system on beef cattle and sheep farm and cull cows, empty heifers and bulls for New Zealand beef production (Figure 4) (B+LNZ: Economic Service, 2021; Berry, 2021; van Selm et al., 2021; New Zealand Statistics, 2022).

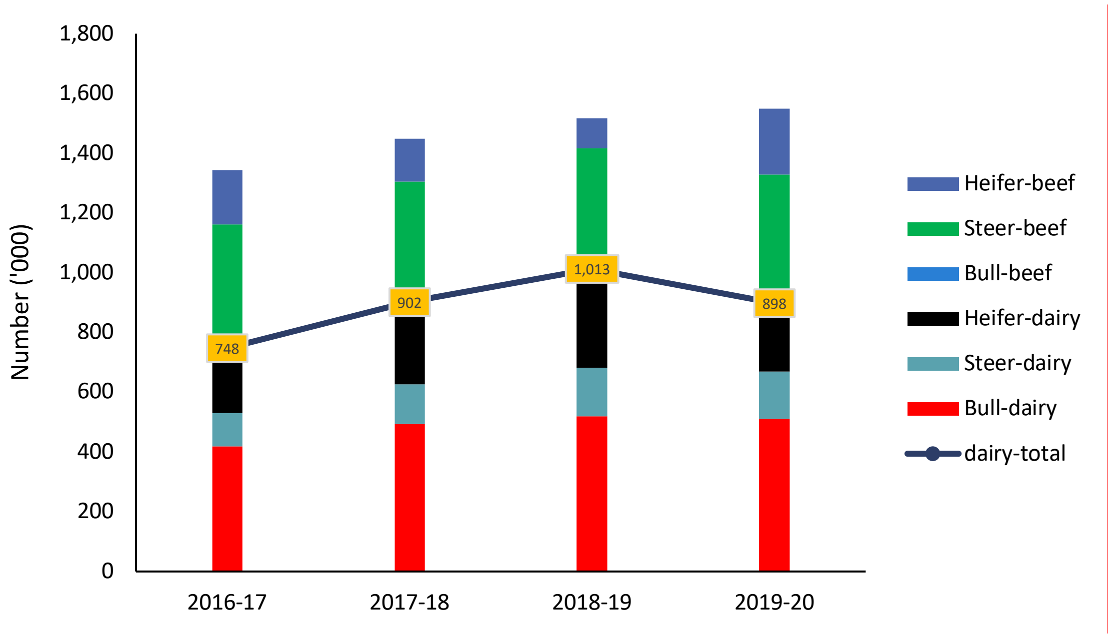

Figure 4. Number of slaughtered cattle by origin and classes since 2016/17 to 2019/20.

Source: Davison (2020)

Young beef production

If bobby calves are processed for beef production, the profit of both dairy and beef industries could increase (Cook, 2014; Andrew, 2016). However, there is not sufficient feed resources to finish them all as a traditional beef cattle at 20 to 30-months old. Young beef production, a new class of beef production system, was imagined to produce meat from young dairy-origin cattle (8 to 12-months old), is a potential solution to convert a large number of calves for beef within the given resource (Kelly and Crosson, 2010; Herron et al., 2019; Hunt et al., 2019; Pike et al., 2019; Nakitari, 2021). Young beef are produced in Europe and marketed under different descriptions, such as Jungrindfleisch (Austria, Germany), rose veal (Ireland, France), or carne de ternera (Spain) (French, 2010; Domaradzki et al., 2017), and in Argentina (Arelovich et al., 2011). Some potential advantages of young beef production are briefly discussed as follow:

Alleviate bobby calf welfare issues

Young beef production in New Zealand would finish a large number of calves for beef at the ages of 8 to 12-months (Hunt et al., 2019; Pike et al., 2019). This is a potential alternative to optimize the number of finished beef cattle and production land constraints. As the number of calves for beef production increases, bobby calves produced and related welfare issues would be decreased (Maher et al., 2021).

Improve feed conversion efficiency and feed budgeting options

Young animals have higher feed conversion efficiency and convert feed to valuable product more efficiently than older cattle (Archer et al., 1997). This would allow the finishing of a large number of young cattle for a given grazing land and feed resources (see Chapter V for detail). The finishing farmers can start with a large number of calves as they represent fewer stock units, on a per head basis, and require less feed, and then these animals could be either sold as store animal or progressively slaughtered depending on feed supply (see Chapter V for details). This expands beef finishing options starting from 8-month old cattle. This practice could improve returns for the dairy and beef industries (Cook, 2014; Andrew, 2016; Thomson, 2017).

Increase number of animals per hectare and reduce environmental effect

Young beef cattle can be processed at a lighter weight, having a shorter feeding length than is traditionally used, which provides opportunities for efficient land utilization (Ogino et al., 2004; Roy et al., 2009) (Table 7). Casey and Holden (2006); de Vries et al. (2015); Djekic (2015); Gerber et al. (2015); Djekic and Tomasevic (2016) identified that dairy-origin beef cattle have less environmental effect than the cow-calf beef production system (Table 7). Thus, production systems for young dairy-origin cattle have the potential to reduce carbon footprint, and emissions (Ogino et al., 2004; Roy et al., 2009; B+LNZ, 2022).

Table 7. The potential environmental remediation of young dairy-origin beef cattle production.

Title	Description	Remark	Reference
Environmental impacts of the Japanese beef-fattening system with different feeding lengths as evaluated by a life-cycle assessment method	The environmental effect across different feeding lengths have compared based on LCA*	Short feeding length reduced environmental impact	Ogino et al. (2004)
Quantification of GHG emissions from sucker-beef production in Ireland	The LCA of beef-bred and dairy-originated beef production was evaluated in different scenarios	Dairy-bred beef reduced environmental impact than the suckler-beef system	Casey and Holden (2006)
Life cycle assessment of greenhouse gas emissions from beef production in western Canada: A case study	Greenhouse emission from cradle to grave were analysed between cow-calves and feedlot system	Greenhouse gas emissions are higher in cow-calf systems than feedlot finishing system	Beauchemin et al. (2010)
Comparing environmental impacts of beef production systems: A review of life cycle assessments	The LCA of beef production was compared between dairy-origin and cow-suckler based, roughage and concentrated feed type, and organic and non-organic fattening	Dairy-originated beef impact is lesser than suckler-cow based production in global warming	de Vries et al. (2015)
Life cycle environmental consequences of grass-fed and dairy beef production systems in the Northeastern United States	The study quantified global warming potential, eutrophication, acidification, fossil use, and water depletion between grass-fed intensive and confided management system of dairy-originated beef	Beef-dairy production had lower global warming-, eutrophication-, and acidification-potential than beef production	Tichenor et al. (2017)
Reducing greenhouse gas emissions of New Zealand beef through better integration of dairy and beef production	The study quantifies the GHG reduction potential of the New Zealand (NZ) beef sector when replacing beef breeding cows and their calves with dairy beef animals.	Dairy-origin beef cattle had lower emission than sucklers	van Selm et al. (2021)

[*] Life cycle assessment

Application of mathematical models in beef production

Mathematical models are a short representation of a complex phenomenon. They have the potential to play a substantial role in the understanding and representation of complex livestock production systems (Thronley and France, 2007; McPhee, 2009; Stygar and Makulska, 2010). They are crucial tools in revealing the relationship between animal feed requirement and available feed resources (Oltjen et al., 1986b; Guiroy et al., 2001; Tedeschi et al., 2004), to represent key functions of the system (McPhee, 2009), and to evaluate financial outcomes (Tedeschi et al., 2004). Mathematical models widely used to evaluate beef production systems can fall into either optimization or simulation model categories (Macal and North, 2005; Thronley and France, 2007; Stygar and Makulska, 2010) which can be either deterministic or stochastic.

Deterministic models represent the expected or average behaviour of the system (Karel, 2003). For example, when using a deterministic model, a group of bulls weighing on average 400 kg would have their feed requirement for maintenance and live weight gain assessed as 64 MJ ME/day when calculated using the equation $0.72*400^{0.75}$ (Trafford and Trafford, 2011; Brookes and Nicol, 2017). This means every individual in the group would receive the same ME MJ regardless of their live weights. Therefore, deterministic models do not allow for between animal variability (Thronley and France, 2007). When using a stochastic model where state variables are defined as probability distributions, the above group of bulls could receive 60, 61, 63, 64…or 70 ME MJ/day for maintenance and live weight gain depending on the weight of individual. This stochastic approach is more realistic than the deterministic model approach, as individuals in the group will not be the same weight and therefore would have different feed demand (Karel, 2003; Thronley and France, 2007).

Mathematical models can be also classified as static or dynamic. In a static model the output is determined by only the current input which means it does not account for the effect of time (Janssen and van Ittersum, 2007; Farrell, 2020), and the relationship is represented by an algebraic equation. This type of model can represent a system behaviour when the system is near equilibrium or where the timeframe is short such that the inputs could be considered constant (Thronley and France, 2007; Farrell, 2020). In contrast, dynamic models consider time variability and the output depends on past inputs and initial condition, and the relationship is represented as a differential equation (Janssen and van Ittersum, 2007).

Optimization models

Beef production systems are complex in nature and the benefits they provide depend on biological and management factors, and market opportunities (Tedeschi et al., 2004). An optimization model is a useful tool to assist in finding the best combination of livestock activity for given resources and to assist with strategic planning, decision-making, and understanding the system (Kingwell and Pannell, 1960; Hurley et al., 2013). A livestock production system can be optimized either using linear (Kingwell and Pannell, 1960; Stygar and Makulska, 2010; Hurley et al., 2013) or non-linear optimization models (Doole and Romera, 2013; Doole, 2015; Romera and Doole, 2015). This review focuses on the application of linear programming to beef cattle production systems.

Linear programming

Linear programming (LP) constructs and evaluates linear relationships between objective functions and constraints (McCall et al., 1999; Ferguson, 2000; Ridler et al., 2001; Anderson and Ridler, 2010) to identify the optimum combination to maximize returns or minimize production costs (Ferguson, 2000; Ridler et al., 2001; Anderson and Ridler, 2010; Stygar and Makulska, 2010). Linear programming has the capability to allocate resources used with a combination of numerous variables (Ridler et al., 2001). It is widely utilized to optimize dairy farms and beef cattle farms (Table 8) (Kingwell and Schilizzi, 1994; Pannell et al., 1996).

Table 8. Linear optimization models used on beef and dairy farms with their descriptions.

Title	Description	Reference
A linear programming model for beef cattle production	LP used to optimize beef production, breeding, and cropping with the constraints of land, labour, animal housing and crop storage	Wilton et al. (1974)
Linear programming in selection of livestock	LP used in selection index of breeds to optimize with resources, marketing, and preference constraints	Jansen and Wilton (1984)
Model of an Integrated Dryland Agri-cultural System (MIDAS)	LP optimized an integrated livestock production in Western Australia based on expected values and risk neutrality	Kingwell and Schilizzi (1994); Pannell et al. (1996)
Model of an Uncertain Dryland Agricultural System (MUDAS)	LP optimized an integrated livestock production in Western Australia by including uncertainties	Kingwell and Schilizzi (1994); Pannell et al. (1996)
Optimized dairy grazing systems in the Northeast United States and New Zealand. I. Model Description and Evaluation	LP optimized grazing length in the rotational grazing and supplement feeding strategy in USA and NZ pasture-based dairy production system	McCall et al. (1999)
Optimized dairy grazing systems in the Northeast United States and New Zealand. II. System Analysis	Per hectare gross margin profitability in USA and New Zealand dairy industries was optimized using LP	McCall and Clark (1999)
Driving innovation: Application of linear programming to improving farm systems	LP used to optimize the NZ dairy farm profitability with constraints including pasture cover	Ridler et al. (2001)
The development of a mathematical model to investigate Irish beef production systems	LP identified the optimum beef cattle production system in Ireland	Crosson et al. (2006)
Application of resource allocation optimization to provide profitable options for dairy production systems	LP used to optimize dairy farm at 100 ha of production land and 320 milking cows as optimum.	Anderson and Ridler (2010)
The effect of dairy farm intensification on farm operation, economics and risk: a marginal analysis	Examine the marginal economy from various alternative dairy production systems and identify the optimum profitability	Anderson and Ridler (2017)

Prediction equations

Prediction equations are also widely utilized to predict the value of a dependent variable based on the values of explanatory variables. It has been widely utilized to predict saleable meat yield using carcass and live ultrasound measurements as indirect indicators (Table 9) (Bass and Ackerley, 1975; Shackelford et al., 1995; May et al., 2000; Tait et al., 2005; Chen et al., 2007; Tarouco et al., 2012). Mathematically, linear prediction equation can be represented as follows:

$$Y_i = \alpha + \beta_0 X_{1i} + \beta_1 X_{2i} + \ldots + \beta_n X_{ni} + \varepsilon_i$$

Where; Y_i is a dependent variable

α: is an intercept

$\beta_0, \beta_1, \ldots, \beta n$ are the coefficients of explanatory variables

$X_{1i}, X_{2i}, \ldots X_{ni}$ are expected values of explanatory variables

ε_i: residual

Table 9. Prediction equations to indicate saleable meat yield from beef carcass.

Title	Description	Reference
A study of various beef carcass measurements in predicting carcass composition	Beef carcass composition predicted based on carcass measurements	Bass and Ackerley (1975)
Estimate of retail yield of the four major cuts in the beef carcass	Beef retail yield from four major cuts predicted using carcass linear measurements	Brungardt and Bray (1963)
Equations for estimating boneless retail cut yields from beef carcasses	Carcass measurements used to validate certain previously developed prediction equations for retail beef yields in USA beef grading system	Cross et al. (1973)
Relationships of carcass weight, conformation and carcass measurements and their use in predicting beef carcass cutability	Beef cutability predicted using carcass weight, fat depth and muscle depth measured from the carcass and conformation	Abraham et al. (1968)
Prediction of lean yield in yearling bulls using real-time ultrasound	Equations predicting 12th rib fat depth and longissimus muscle area from earlier measurements were characterized by low to moderate coefficients of determination	Bergen et al. (1996)
Using live estimates and ultrasound measurements to predict beef carcass cutability	Beef cutability predicted using live measurements and ultrasound measurements	May et al. (2000)
Use of live ultrasound, weight and linear measurements to predict carcass composition of young beef bulls	Prediction equations based on live measurements may provide more precise predictions of lean meat yield than equations derived from carcass measurements	Bergen et al. (2005)
Prediction of yield of retail cuts for native and crossbred Chinese Yellow cattle	Prediction for beef retail cut from Chinese Yellow cattle using carcass and ultrasound measurements	Chen et al. (2007)
Prediction of retail product and trimmable fat yields from the four primal cuts in beef cattle using ultrasound or carcass data	Predicting retail products based on ultrasound and carcass measurement	Tait et al. (2005)
Prediction of retail beef yield, trim fat and proportion of high-valued cuts in Nellore cattle using ultrasound live measurements	Prediction of retail and valuable cuts based on ultrasound carcass composition measurements	Tarouco et al. (2012)
Prediction of carcass composition using carcass grading traits in Hanwoo steers	Carcass measurements used to predict beef carcass composition	Lee et al. (2016)

Simulation models

Simulation models can be useful *in silico* representations of natural systems to identify production constraints and to discover alternative solutions (Cros et al., 2004). However, a simulation on its own does not identify the optimum production potential within given constraints (Ridler et al., 1987; Woodward et al., 2008; Hurley et al., 2013) and needs several iterations to identify the best alternative. For the purpose of this review, simulation models are broadly classified as empirical (descriptive), mechanistic or agent-based models.

Empirical models

An empirical simulation model is a model developed to represent the relationships among variables based on observation or experimental experience (Thronley and France, 2007). Such models are data consuming and valid only for that range of data (Oltjen et al., 1986b; France et al., 1987). The empirical relationships of nutritional and net energy requirements for beef cattle based on growth rate, frame size and condition were established by the national research centre (NRC, 1976), INRA in France (Lofgreen and Garrett, 1968; ARC, 1980; Fox and Black, 1984) are a few example of this type of model (Table 10).

Table 10. Empirical simulation models for beef cattle production and their descriptions.

Title	Description	Reference
A system for expressing net energy requirements and feed values for growing and finishing beef cattle	The rate of body growth was simulated based on average frame size and various conditions	Lofgreen and Garrett (1968); NRC (1976)
System for predicting performance of growing and finishing cattle; part 1: development of a model to describe energy and protein requirements and feed values	Empirical model developed to estimate nutrient requirements and values in feedlot cattle	Sanders and Cartwright (1979); ARC (1980)
A general cattle production systems model. I: structure of the model	Beef production was simulated for different production environments, systems and genotypes	Sanders and Cartwright (1979)
A system for predicting body composition and performance of growing cattle	Nutritional requirement for growth with adjustment for frame size, nutritional history and breed was estimated	Fox and Black (1984)

Variables in empirical equations generally lack biological meaning and generality across breed and conditions (Oltjen et al., 1986a; Oltjen et al., 1986b; Vetharaniam et al., 2001a; Vetharaniam et al., 2001b; Garcia et al., 2008). They also always fail to account for the physiological and biochemistry principles of animal growth (Oltjen et al., 1986a; Oltjen et al., 1986b; Vetharaniam et al., 2001a; Vetharaniam et al., 2001b; Thronley and France, 2007; Garcia et al., 2008) and as a consequence are often referred as "black box" methodologies. In a biological system, components needing to be expressed by the underlying physiology and biochemistry can properly be modelled using mechanistic models.

Mechanistic models

A mechanistic model is a dynamic model formulated by understanding the basic biological principles rather than the physical component of the model (Thronley and France, 2007). It can be used across breeds and conditions (Oltjen et al., 1986a; Oltjen et al., 1986b; Vetharaniam et al., 2001a; Vetharaniam et al., 2001b; Garcia et al., 2008). The first mechanistic model based on understanding the central dogma of molecular biology was developed by Baldwin and Black (1979) and Oltjen et al. (1986b) adapted it for beef cattle. Mechanistic models have been used to represent individual animal growth patterns and carcass composition (Vetharaniam et al., 2001a; Vetharaniam et al., 2001b; Tedeschi et al., 2004), and nutrient partitioning (Oltjen et al., 1986a; Oltjen et al., 1986b; Vetharaniam et al., 2001a; Vetharaniam et al., 2001b; Garcia et al., 2008). Some of mechanistic models developed for carcass composition are presented in Table 11.

Table 11. Dynamic and mechanistic models in beef cattle growth and carcass compositions.

Title	Description	Remark	Reference
Development of a dynamic model of beef cattle growth and composition	Modelled protein accretion based on molecular biology (Baldwin and Black, 1979) to represent net energy transactions and fat deposition and was used to simulate carcass composition	The model is highly sensitive for rate of protein synthesis and initial DNA	Oltjen et al. (1986b)
Evaluation of a model of beef cattle growth and composition	A dynamic model developed by Oltjen et al. (1986b) for body weight and composition of steers was evaluated based on various condition and energy intake	Cab be employed to simulate body weight and carcass composition of various breed of steers produced in different condition	Oltjen et al. (1986a)
Simulation of DNA, protein and fat accretion in growing steers	A mechanistic model of steer growth based on accretion and mobilization of DNA, protein in carcass and non-carcass and fat in general with a defined mature age	Used the central dogma of molecular biology in ad-libitum feed supply	Di Marco et al. (1989)
Mathematical modelling of metabolic regulation and growth	Based on accretion of protein and fat. Meat production was expressed qualitatively and quantitatively	Rate of conversion is constant	Danfær (1991)
A model of mammalian energetics and growth	The net protein and fat depositions were modelled based on metabolism processes	The model was validated on sheep (Vetharaniam et al., 2001b)	Vetharaniam et al. (2001a)
A mechanistic dynamic model to estimate beef cattle growth and body composition 1. Model description	Underlying expression of protein and fat accretion used for allometric expression of body weight, empty body weight and carcass yield	The model developed from weaning to maturity	Hoch and Agabriel (2004a)
A mechanistic dynamic model to estimate beef cattle growth and body composition: 2. Model evaluation	Evaluated the behavior and output of the model developed by Hoch and Agabriel (2004a). The model enabled to simulate synthesis, degradation and maintenance energies	The model output was different based on maturing rate of the animals	Hoch and Agabriel (2004b)
Simulating chemical and tissue composition of growing beef cattle: From the model to the tool	The study improved the modelling of body tissue composition accounted for allometric equation and include the model into a decision support tool	The model could represent carcass composition of steers in fed ad libitum scenario	Hoch et al. (2005)

Agent-based modelling

In a natural system there are various interlinked agents that form a complex network. The complexity of this depends on the number of factors involved and their degree of interaction (Bankes, 2002; Bonabeau, 2002; Macal and North, 2005). This leads to emergent behaviour, which is defined as a behaviour created due to interactions among factors and could not be explained by any sole factor (Bonabeau, 2002; Sajjad et al., 2016; Falco et al., 2019; Lippe et al., 2019; Mohan et al., 2019). Behaviours in a complex system cannot be easily captured by static modelling methods (Sajjad et al., 2016). Moreover, some of the behaviours such as those that are "adaptive" and "emergent" can be out of reach of many mathematical models (Bonabeau, 2002). Agent-based modelling (ABM) is one approach that can capture agent behaviours and their adaptive and emergent behaviours that are derived from their interactions (Bonabeau, 2002; Sajjad et al., 2016; Falco et al., 2019; Lippe et al., 2019; Mohan et al., 2019).

An agent is an autonomous computational individual or object with particular properties and actions and is capable of resisting, evolving, and also allows for unanticipated behaviours to emerge during interactions (Bonabeau, 2002). It could be any entity, for example, a rearer, finisher, cattle, pasture, disease, farm or environment. Agents may execute various behaviours based on the property they represent and the environment they interact (Bankes, 2002; Bonabeau, 2002; Sajjad et al., 2016; Falco et al., 2019; Lippe et al., 2019; Mohan et al., 2019; Sergeyev and Lychkina, 2019). Table 12 provides some examples of ABM (Bankes, 2002; Bonabeau, 2002; Sajjad et al., 2016; Falco et al., 2019; Lippe et al., 2019; Mohan et al., 2019; Sergeyev and Lychkina, 2019).

Table 12. Application of agent-based modelling in a complex system.

Title	Description	Reference
Agent-based modelling: Methods and techniques for simulating human systems	ABM enabled to capture behaviors in business activities, market, management and organization structure	Bonabeau (2002)
Platforms and methods for agent-based modelling	ABM captured emerging behaviors in social and economic	Gilbert and Bankes (2002)
Tutorial on agent-based modelling and simulation	ABM can produce a viable information to support decision making process	Macal and North (2005)
Social simulation: The need of data-driven agent-based modelling approach	ABM enabled to understand both microlevel and macrolevel behaviors in the complex social study	Sajjad et al. (2016)
Agent-based modelling and simulation of inter-organizational integration and coordination of supply chain participants	ABM successfully modelled cooperation, coordination and interorganizational interaction of participants of a supply chain and reconfigurable network structures of the supply chain	Sergeyev and Lychkina (2019)
Using agent-based modelling to simulate social-ecological systems across scales	ABM has become a well-established computational approach to model a complex phenomenon and the emergent behavior during interaction within socio-ecological system	Lippe et al. (2019)
Agent-based modelling to evaluate the impact of plug-in electric vehicles on distribution systems	ABM was employed to analysis the impact of electric vehicles on electric distribution system by considering charging space, time, people routine, traffic condition	Falco et al. (2019)
Agent-based modelling for migration of industrial control systems	ABM substituted migration to industrial control system to avoid cost, experts need and resource in migration of industrial control system	Mohan et al. (2019)
Developing an agent-based model to simulate the beef cattle production and transportation in Southwest Kansas	ABM simulated the beef cattle industry and the transportation industry as two independent but interconnected industries	Yang et al. (2019)
An agent-based model to simulate meat consumption behaviour of consumers in Britain	ABM provided a valid output to inform and evaluate different strategies aimed at reducing meat intake in UK based on co-workers and household network influence	Scalco et al. (2019)
An agent-based simulation model to compare different reproductive strategies in cow-calf operations: Technical performance	ABM produced a synthetic cattle population and identified the best breeding strategies in beef cattle production system	Ojeda-Rojas et al. (2021)

ABM is a computation simulation modelling which describes how agents behave depending on other agents and their environment (see Chapter VI and VII for details) (Bankes, 2002; Sajjad et al., 2016; Falco et al., 2019; Lippe et al., 2019; Mohan et al., 2019; Sergeyev and Lychkina, 2019) and allows for repetitive competitive interactions between agents (Axelrod, 1997; Epstein et al., 1998; Macal and North, 2005). ABM enables researchers to capture the adaptive and emergent nature of a complex systems resulting from agent-agent and agent-environment interactions (Macal and North, 2005). The benefits of ABM over other modelling approaches can summarized as follow:

Agent-based modeling has the capability to capture adaptive and emergent behaviour of a complex system. “Emergent behaviour” can be defined as a new phenomenon arising when agents interact which is neither of agent’s behaviour and cannot explained by any sole agent (Bonabeau, 2002; Macal and North, 2005). In repetitive competitive interactions, within and across agents and with environments, agents would evolve (change behaviour) depending on the behaviour of other agents or the environment (Axelrod, 1997; Epstein et al., 1998; Macal and North, 2005), this is called “adaptive” behaviour. Both the adaptive and emergent behaviours are cumulative outcomes of agent-agent and agent-environment interactions, and these can be better explained using ABM (Macal and North, 2005).

ABM provides a platform that the user can manipulate and manage to understand how agents interact (Bonabeau, 2002). This means ABM can simulate the natural entity of a system and can provide a full description of the system, rather than just an equation (Tisue and Wilensky, 2004; Sergeyev and Lychkina, 2019). In ABM, the modellers or users can directly control the agent’s behaviour and their environment which lets them manage how they should behave (Sajjad et al., 2016; Mohan et al., 2019). Further, ABM is a flexible type of model in allowing including of additional agents, to modify the behaviour of agents depending on the situations and can be adopted in different fields (Bonabeau, 2002; Falco et al., 2019; Mohan et al., 2019).

In conclusion, ABM is a powerful modelling tool for a complex system and has been widely utilized in social science, sociology, and economics, complexity science, system science, system dynamics, management, computer science (Table 12) (Bankes, 2002; Gilbert and Bankes, 2002; Macal and North, 2005; Sajjad et al., 2016; Falco et al., 2019; Lippe et al., 2019; Mohan et al., 2019; Sergeyev and Lychkina, 2019). However, it is computationally expensive and needs detailed programming (see Chapter VI and VII for details) which can limit its applicability across fields (Bonabeau, 2002; Gilbert and Bankes, 2002; Nardini et al., 2021).

The current study employed prediction equations to identity the main indirect indicators of saleable meat yield from young beef (Chapter III). Beef cattle and sheep farms profitability for given feed supply with or without young beef cattle production system were optimized using linear programming (Chapters IV and V). Agent-based model simulation was applied to *in silico* represent interactions between rearers, finishers and processors agents to determine breed and class type for traditional and young beef cattle finishing on beef cattle and sheep farms (Chapters VI and VII).

Chapter III

Prediction of the Hind-Leg Muscle-Weight of 8- to 12-Month Old Steers Using Carcass Weight, Wither Height and Ultrasound Carcass Measurements

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Abstract

The dissection of carcasses, collection and weighing of boneless cuts for assessing saleable meat yield is labour intensive and time demanding. An alternative is to use predictive equations to identify those variables that are associated with a saleable meat yield and could be used for carcass classification. To understand the carcass characteristics associated with saleable meat yield in 8 to 12-month old cattle, this study developed predictive equations for hind-leg muscle weight from sixty yearling steers slaughtered at 8, 10 and 12-months of age. Fat depth over the rump, rib fat depth and eye muscle area between 12th and 13th ribs measured using ultrasound and the wither height were recorded one week prior to slaughter. Hot carcass weight was obtained after commercial dressing procedures. The knuckle, topside, and silverside cuts were retrieved from chilled carcasses after 24-hours and weighed, then summed to get hind-leg muscle-weight. Univariate and multivariate prediction equations were obtained for hind-leg muscle weight using carcass weight, wither height, eye muscle area, rump and rib fat depths as independent variables. Carcass weight followed by wither height and eye muscle area were significant ($P<0.05$) univariate predictors accounting for 61.5, 51.2 and 39.9% of variation in hind-leg muscle weight across the slaughter age of groups, respectively. For multivariate analysis, 65.7% of the variation in hind-leg muscle-weight could be accounted by carcass weight, wither height and eye muscle area when using the combined data across all the slaughter age groups. The prediction ability, assessed by R^2 values, in yearling steers was lower than previous studies on older beef cattle. Identifying additional traits in yearling steers is required to improve the overall prediction ability and accuracy of saleable meat yield.

Key phrases: young beef, meat yield, linear model, yearling grading

Introduction

In 2018, global beef production reached 72.1 million tonnes (carcass weight equivalent) representing 22.5% of the total meat production (FAO, 2021). Beef production increasingly relies on calves originating from the dairy industry (Domaradzki et al., 2017; Nogalski et al., 2017) which is partly due to the expansion of dairy farms producing an accessible supply of calves (Morris, 2013a). In New Zealand, 73% of the annual beef is sourced from dairy-origin cattle (B+LNZ, 2022) and the dairy industry supplies approximately 58% of the calves required for beef finishing (van Selm et al., 2021).

Dairy-origin calves are often produced in excess to the replacement requirements of the dairy herd and are processed for veal production or petfood (Domaradzki et al., 2017; B+LNZ, 2022). In New Zealand, 1.7 million calves from the dairy industry were commercially processed at 4 to 14-days of age in 2017/18 (B+LNZ, 2022). It is considered that perceived welfare issues regarding the slaughter of calves at this young age could impose a risk for the sustainability of beef exports (Ferguson et al., 2014; Andrew, 2016). If these calves were reared for beef, they could further increase beef production (Morris, 2013a; Andrew, 2016). Dairy-origin steers managed in a beef finishing system to 24 to 36-months of age produce beef of an acceptable eating quality (Schreurs et al., 2014; Coleman et al., 2016) however, due to resource constraints (in particular grazing land), it is not manageable to finish all surplus calves from the dairy industry for beef at 20 to 36-months of age. Yearling beef is a potential solution to this issue by accelerating the cycle of beef production. Animals of a similar age are produced in Europe and marketed under different descriptions such as Jungrindfleisch (Austria, German), rose veal (Ireland),or carne de ternera (Spain) (Domaradzki et al., 2017).

Prediction of saleable meat yield is used in carcass classification systems and for the marketing of beef (Crouse et al., 1975; Lee et al., 2016). These classification systems assign value based on conformation, muscling and fat depths e.g., the EUROP system and New Zealand beef carcass classification system (Conroy et al., 2010; Tarouco et al., 2012; Bonny et al., 2016; B+LNZ, 2022). However, the carcass classification schemes for yearling cattle are undefined (Domaradzki et al., 2017) and those used for older cattle are unlikely to be applicable due to the emphasis on conformation and fat deposition which is not expressed at a yearling age in cattle (Owens et al., 1995). When assessing saleable meat yield there is a need to obtain boneless primal and subprimal cuts which is costly and require labour inputs (Cross et al., 1973; Shackelford et al., 1995; Conroy et al., 2010). The use of prediction equations avoid the need to directly assess saleable meat yield and could be used to assess potential meat yield on live animals if ultrasound measures of carcass composition were used as the predictors (Shackelford et al., 1995; Bergen et al., 2005; Tait et al., 2005; Conroy et al., 2010). The beef hindquarter can be used as a proxy of saleable meat yield for the whole carcass (Purchas et al., 2002). Identifying accurate predictors for hind-leg muscle yield in young steers could be used to develop grading systems for yearling cattle.

Carcass weight, eye muscle area, rump and rib fat depths have been used as predictors of beef saleable meat yield (Shackelford et al., 1995; May et al., 2000; Chen et al., 2007; Tarouco et al., 2012) but, lack applicability across age, breed, and sex (Oltjen et al., 1986b). Predictive models, for saleable meat yield have not yet been developed for yearling steers, hence this study was initiated to develop predictive equations for hind-leg muscle weight, used as a proxy for saleable meat yield, from 8, 10 and 12-month old steers. It was hypothesized that a combination of carcass weight, wither height, ultrasound eye muscle area, rump and rib fat depths would be suitable predictors of hind-leg muscle yield and would elucidate characteristics of importance for use in a carcass classification system for yearling cattle.

Material and methods

Sixty, 3-month old, Hereford-Kiwi cross (i.e., Holstein Friesian-Jersey crossbred) calves (103 ± 11 kg live weight) were obtained from a commercial rearer and randomly assigned into a slaughter-age group of 8, 10 and 12-months of age. The steers were managed together as one group at Massey University`s Keeble farm. They grazed herb mixes containing plantain (*Plantago lanceolata*), chicory (*Cichorium intybus*), white clover (*Trifolium repens*), and red clover (*Trifolium pratense*) with 0.5 kg meal/head for 2-months after arrival on the farm. This was followed by leafy turnip (c.v. Hunter) for a month with the remaining time up to slaughter on a perennial ryegrass-based pasture. To ensure intake was not restricted, cattle had ad-libitum forage allowance and the forage mass did not go below 1200 kg DM/ha at any time during grazing (Morris, 2013a) which allowed for a live weight gain of approximately 0.9 kg/head/day.

Live weight was recorded fortnightly and final live weight recorded on the farm, prior to transportation for slaughter. Ultrasound measurements of the carcass characteristics were collected in the week before slaughter at a site on the animal between 12th and 13th ribs for rib fat depth (RF, mm) and eye muscle area (EMA, cm^2), and on the rump for fat depth (P8, mm) (May et al., 2000; Bergen et al., 2005). Wither height was measured at the time of ultrasound measurements. Hot carcass weight was obtained after commercial dressing procedures. The dressing-out percentage was calculated as the hot carcass weight divided by the live weight obtained on-farm. Carcasses were chilled for 24 hours and knuckle, topside, and silverside cuts were retrieved. Total hind-leg muscle weight representing the major muscles surrounding the femur was calculated by summing up the weights of three cuts (i.e. topside, knuckle, and silverside). The knuckle comprising the Quadriceps femoris, the silverside (also called the outside round) comprises Biceps femoris and Semitendinosus, while the topside contains the Semimembranosus, Adductor, and Pectineus muscles (Purchas et al., 2002).

Data analysis

All analyses were conducted using the R program version 3.6.0 (R Core Team, 2016). Descriptive statistics and analysis of variance (ANOVA) for the slaughter age groups were undertaken. The association between the dependent variable, hind-leg muscle weight (LM), and the independent variables within a slaughter group and for the data from three slaughter groups as a single group were tested using Pearson correlations. The predictors of hind-leg muscle weight included: carcass weight (CW), wither height (WH), eye muscle area (EMA), rump fat depth (P8), and rib fat depth (RF) were fitted in two models (LMM: linear mixed-effects and GLS: generalized least squares) using the nlme extension (Pinheiro et al., 2018). The maximum likelihood estimation method was used in both models and the corresponding models were compared. The best-fit model was that with a lower Akaike's Information Criterion (AIC) (Supplementary Table 1). Residual errors in the final models were evaluated for influential outlier effects using Cooks distances (Walfish, 2006); normality using QQplots (Ghasemi and Zahediasl, 2012) and multicollinearity using variance inflation factor (VIF, > 10) (Alin, 2010). The multivariate analysis was carried out using forward-selection regression (Supplementary Table 2) (Bergen et al., 2005). The univariate and multivariate models were validated using goodness of fit (R^2 value) and prediction accuracy metrics including root mean square error (RMSE) (De Myttenaere et al., 2016).

Results

The 12-month old steers produced a heavier carcass ($p<0.05$), greater dressing-out percentage ($p<0.05$). The 12-month old steers also had a greater wither height, eye muscle area, rump and rib fat depths ($p<0.05$, Table 13).

Table 13. Descriptive statistics for live weight, carcass weight, dressing-out percentage, wither height, hind-leg muscle weight, eye muscle area, rump and rib fat depths measured on Hereford-Kiwi crossed steers at 8 (n = 20), 10 (n = 20) and 12-months (n = 20) months of age.

	Slaughter age (month)											
	8				10				12			
Attributes	Mean	sd.	Range		Mean	sd.	Range		Mean	sd.	Range	
Live weight (kg)	252.2^c	25.0	214.0	300.0	302.8^b	17.2	272.0	335.0	347.6^a	22.0	303.0	392.0
Carcass weight (kg)	119.0^c	12.3	97.7	141.1	145.5^b	13.0	124.7	179.1	173.9^a	11.0	148.8	193.9
Dressing-out percentage (%)	47.2^b	1.3	45.0	50.0	47.5^b	1.2	46.0	50.0	50.0^a	1.2	48.0	52.0
Wither height (cm)	108.1^c	3.0	103.0	114.0	116.6^b	4.1	108.0	124.0	119.7^a	3.1	115.0	126.0
Hind-leg muscle weight (kg)	9.0^b	0.8	7.6	10.7	11.3^a	1.1	9.2	13.5	11.2^a	1.2	8.2	13.6
Eye muscle area (cm^2)	38.2^c	3.1	34.0	45.0	41.8^b	3.7	35.0	49.0	51.2^a	4.1	46.0	62.0
Rump fat depth (mm)	1.8^b	0.8	1.0	4.0	2.1^b	0.6	1.0	3.0	2.8^a	0.9	2.0	5.0
Rib fat depth (mm)	1.1^c	0.3	1.0	2.0	1.6^b	0.5	1.0	2.0	2.1^a	0.3	2.0	3.0

^{a,b,c} Superscript within row trait indicate means are significantly different at P<0.05

Relationship between independent and dependent variables

Carcass weight had a positive correlation with hind-leg muscle weight across the slaughter groups and also within groups (correlation coefficient of 0.79 to 0.91, Table 14). Hind-leg muscle weight had a correlation with all independent variables in the 10-month old steers and in the combined data. However, the hind-leg muscle weight did not correlate with fat depths in the 8- and 12-month old steers (Table 14).

Table 14. Pearson correlation coefficient of hind-leg muscle weight (LM, kg) with carcass weight (CW, kg), wither height (WH, cm), eye muscle area (EMA, cm^2), rump (P8, mm) and rib fat depths (RF, mm) in 8 (n = 20), 10 (n= 20), and 12 (n = 20) months old steers and for combined date.

Dependent variable,	Independent variables				
LM	CW	WH	EMA	P8	RF
	Slaughter age (month)				
8	0.82***	0.01	0.75***	0.17	0.26
10	0.91***	0.55*	0.73***	0.54*	0.47*
12	0.85***	0.46*	0.34	-0.40	-0.23
[a]All ages	0.79***	0.71***	0.63***	0.26*	0.55***

*** p< 0.000; * p< 0.05, [a]Combined data from 8, 10- and 12-months old steers

Predictive equations for hind-leg muscle weight

For the data across all slaughter ages, carcass weight (CW), wither height (WH) and eye muscle area (EMA) were significant predictors of hind-leg muscle weight in yearling steers (p<0.05; Table 15). Carcass weight explained 61% of the variability in hind-leg muscle weight whereas eye muscle area explained only 40% of the variation. Their respective prediction accuracies were 0.91 and 1.14 (Table 15). The multivariate analysis indicated that 65.7% of variation in hind-leg muscle weight was explained by using carcass weight, wither height, and eye muscle area.

Table 15. Linear models for hind-leg muscle weight using carcass weight (CW, kg), wither height (WH, cm), eye muscle area (EMA, cm^2), rump fat depth (P8, mm), and rib fat depth (RF, mm) for the combined steer data and within slaughter age group.

Slaughter age group (months)	Intercept	Partial regression coefficients CW	WH	EMA	P8	RF	R2	RMSE
[a]All ages	3.83	0.05	__	__	__	__	61.5	0.91
	-9.88	__	0.18	__	__	__	51.2	1.03
	4.37	__	__	0.14	__	__	39.9	1.14
	-1.52^{NS}	0.03	0.06^{b}	__	__	__	64.2	0.88
	4.43	0.06	__	-0.06^{b}	__	__	63.5	0.89
	-0.79^{NS}	0.05	0.06^{b}	-0.06^{b}	__	__	65.7	0.86
8	2.26	0.06	__	__	__	__	68.7	0.46
	1.16	__	__	0.21	__	__	56.0	0.55
	1.19^{NS}	0.04	__	-0.07^{b}	__	__	71.3	0.44
10	-2.11^{NS}	0.09	__	__	__	__	82.8	0.44
	2.54^{NS}	__	__	0.21	__	__	52.7	0.73
	-9.23	0.08	0.07	__	__	__	88.8	0.35
	-10.30	0.09	0.08	0.01^{b}	0.18^{b}	-0.47^{b}	91.9	0.30
12	-4.80^{NS}	0.09	__	__	__	__	71.5	0.62
	-10.4^{NS}	__	0.16	__	__	__	21.4	1.03
	-8.91^{NS}	0.09	0.04	__	__	__	72.4	0.61

[a]Combined data from 8, 10, and 12-months old steers at slaughter,
[b]Independent variables were not significant in the multivariate analyses at $p< 0.05$,
R^2: Coefficient of determination,
RMSE: Root means square error,
[NS] The intercepts were not significantly different from zero at $p<0.05$.

When using the data from each slaughter-age treatment, the goodness of fitness as well as the prediction accuracies were improved compared using data from all age groups. Carcass weight explained from 68.7 to 82.8% of hind-leg muscle weight variation within the slaughter age groups (Table 15). The corresponding prediction accuracies were 0.46 and 0.44 (Table 15). Eye muscle area was a significant univariate predictor in 8 and 10-month old steers whereas wither height was significant in the 12-month old steers (Table 15). In total, 71.3, 91.9 and 72.4% of variation in hind-leg muscle weight from 8, 10- and 12-months old steers was explained using multivariate analysis (Table 15).

Discussion

This study was initiated with the main objective of developing predictive equations for hind-leg muscle weight in yearling steers to assess saleable meat yield. The dressing-out percentage from the yearling steers was lower than the 54% reported for New Zealand beef steers at 27 to 34-months of age (Morris, 2013a; Coleman et al., 2016). Martin et al. (2018) reported a higher dressing-out percentage (52.4 to 59.4%) from bulls aged between 25 to 31-months. The dressing-out percentage increases with maturation and a greater dressing-out percentage is observed when carcass weight is higher in cattle at 18 to 36-months of age (Owens et al., 1995; Schreurs et al., 2014; Coleman et al., 2016; Martin et al., 2018).

Bone is the earliest developing tissue followed by muscle and then fat (Berg and Butterfield, 1978; Owens et al., 1995). Muscle mass increases with carcass weight at a diminishing rate and then plateaus at the fattening stage (Berg and Butterfield, 1978; Owens et al., 1995). The 10 and 12-month old steers produced a heavier hind-leg muscle weight than 8-month old steers although, it was lower than 13.3 kg reported from different breeds of steers up to three years of age (Purchas et al., 2002). The eye muscle area of yearling steers was 65.5% of the size reported in Hereford sired dairy-Angus crossbred steers at 22 to 25-months of age (59.2 to 75.3 cm^2) (Coleman et al., 2016). Tarouco et al. (2012) reported 70.8 cm^2 of eye muscle area in Nellore steers at 24 to 30-months of age. Bergen et al. (2005) and Lee et al. (2016) reported an eye muscle area of 96 cm^2 in one year old bulls and Hanwoo steers at 32-months of age. The lower value of muscle weights in the yearling steers in this study is likely a direct result of the younger age and weight at slaughter.

Regardless of breed, sex, and nutrition status of an animal, fat growth is faster as animals approach maturity (Berg and Butterfield, 1978; Owens et al., 1995). The 12-

month old steers had thicker rump and rib fat depths than the young steers, but were half that reported in 22 to 25-months old Hereford sired dairy-Angus crossbred steers (Coleman et al., 2016). While Bergen et al. (2005) reported 6.0 and 5.1 mm rump and rib fat depths in one year old bulls. In the Nellore steers at age of 24 to 30-months, 9.2 rump depth and 6.4 mm rib fat depth have been reported (Tarouco et al., 2012). The reduced fat depths in this study are likely due to the growth stage of the steers and the predominately forage diet. Animals deposit more fat when fed a diet comprised of concentrates rather than pasture or forages (Owens et al., 1995).

A strong positive correlation between carcass weight and saleable meat yield was translated into prediction equations in older cattle (Epley et al., 1970; Cross et al., 1973; Crouse et al., 1975; Chen et al., 2007). For the 8 to 12-months old cattle in the current study, carcass weight explained the largest proportion of the variation in hind-leg muscle weight and the R^2 value and prediction accuracy (RMSE) were lifted up to 25.7 and 55.6% respectively within the slaughter age group compared to the combined data set. Chen et al. (2007) reported that carcass weight could explain 63 to 90% of variation in the weight of trimmed top-grade cuts from native and crossbred Chinese Yellow steers at age of 18 to 52-months. While, Epley et al. (1970), Berry et al. (1973), and Lee et al. (2016) reported 83.4 to 86.0% for the coefficient of determination of carcass weight in predicting beef prime cuts. In agreement with the current study Epley et al. (1970), Berry et al. (1973), Cross et al. (1973), Chen et al. (2007), and Lee et al. (2016) identified that carcass weight as the strongest predictor of beef meat yields.

Eye muscle area and fat depths assessed by ultrasound were more accurate (higher correlation coefficient) than the carcass measured equivalents in predicting saleable meat yield (Bergen et al., 2005; Tait et al., 2005; Tarouco et al., 2012). Amongst the ultrasound measurements, only eye muscle area was a significant predictor of hind-leg muscle weight from the yearling steers, although it controlled the least variation (40%). Similarly, Greiner et al. (2003) reported that ultrasound eye muscle area controlled 37% of variation in beef saleable meat yield from one to two years old steers. Forty-one percent of beef saleable meat yield from different age classes of Angus and Angus-crossbred bulls and steers was explained by ultrasound eye muscle area (Tait et al., 2005). Epley et al. (1970) and Crouse et al. (1975) also found that eye muscle area controlled the least variation in the prediction of beef cutability among carcass weight, rib fat thickness and kidney and pelvic fat thickness. Neither rump or rib fat depth were significant predictors of hind-leg muscle weight in yearling steers. They were also not significant predictors of weight of saleable meat from the hind-leg in Nellore steers at 24 to 30-months old (Tarouco et al., 2012). Fat measurements were closely related to the percentage of saleable meat yield than weight (Chen et al., 2007; Tarouco et al., 2012).

The coefficient of determination and accuracy of prediction equations were improved with multivariate analysis. The prediction efficiency and accuracy between models using carcass weight and wither height and carcass weight and eye muscle area, across the age groups were not different. The prediction abilities of multivariate analysis in terms of R^2 value and accuracy were improved when using data within each of the slaughter age group. Epley et al. (1970) from mixed carcasses and Lee et al. (2016) in 32-months old Hanwoo steers reported R^2 values of 88.0% and 85.9% using carcass weight and eye muscle area in predicting valuable beef cuts, respectively. According to Brungardt and Bray (1963), 82.0% of the variation in the saleable meat yield retrieved from four wholesale cuts of steers was explained using the percent of kidney fat, left side carcass weight, eye muscle area, and percent of trimmed round yield. Ninety-four percent of beef saleable meat yield from different breed steers was explained using eye muscle area, side carcass weight and trimmed round-cut as predictors (Cross et al., 1973).

Prediction equations

The goodness of fitness and accuracy of the models using data from all the slaughter age groups for hind-leg muscle weight were lower than the corresponding models for within slaughter age group. Therefore, it is recommended to use the within slaughter age prediction equations, if an accurate record of age is known when slaughtered at less than 12-months of age. However, if the carcasses are from steers of approximately one year of age, but exact age is not known, prediction equations developed across the slaughter group could be used. Furthermore, these equations could indicate saleable meat yield before slaughter by assuming a dressing-out percentage of 48%. The prediction equations developed in this study could be used for beef classification systems which produce meat from cattle of dairy-origin, finished in pasture-based production systems and are processed at an age of approximately, 8 to 12-months (Domaradzki et al., 2017).

Conclusions

Carcass weight, wither height and eye muscle area measured by ultrasound can be used to predict hind-leg muscle weight from yearling steers and maybe useful for developing a classification scheme for yearling beef-dairy carcasses. A multivariate model using carcass weight and wither height or carcass weight and eye muscle area will be pertinent for classifying carcasses from yearling beef-dairy steers. It is recommended that future research identify additional explanatory traits that would improve the overall prediction efficiency of saleable meat yield from the yearling beef-dairy steers.

Forward to chapters IV and V

The previous chapter (i.e., Chapter III) developed prediction equations to evaluate saleable meat yield from young beef cattle which could then be used to assign a fair payment system to be paid to finishers. This allowed the understanding of the drivers of saleable meat yield from young beef cattle where carcass weight was pertinent. To achieve a heavier carcass weaned calves require to be well fed up to yearling age. This could potentially affect the feed supply and demand in beef cattle and sheep farms. Therefore, Chapter IV developed a profit optimization model on beef cattle and sheep farms for the given feed sources which was then modified in Chapter V to incorporate a young beef production system to evaluate stocking rates, feed use and price scenarios on beef cattle and sheep farm profitability.

Chapter IV

Optimization of Profit for Pasture-Based Beef Cattle and Sheep Farming Using Linear Programming: Model Development and Evaluation

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Abstract

A linear programming optimization tool is useful to assist farmers with optimizing resource allocation and profitability. This study developed a linear programming profit optimization model with a silage supplement scenario. Utilizable kilograms of pasture dry matter (kg DM) of the total pasture cover was derived using minimum and maximum pasture covers and herbage utilization percentage. Daily metabolizable energy (MJ ME/head) requirements for the various activities of beef cattle and sheep were estimated and then converted to kg DM/head on a bi-monthly basis. Linear programming was employed to identify the optimum carrying capacity of beef cattle and sheep, the most profitable slaughtering ages of beef cattle, the number of prime lambs (sold to meat processing plant) and sold store lambs (sold to other farmers for finishing). Gross farm revenue (GFR) and farm earnings before tax (EBT) per hectare, and per stock unit, and total farm expenditure (TFE) were calculated and compared to the average value of Taranaki-Manawatu North Island intensive finishing sheep and beef Class 5 farms using Beef and Lamb New Zealand (B+LNZ) data. The modelled farm ran 46% more stock units (a stock unit consumed 550 kg DM/year) than the average value of Class 5 farms. At this stocking rate, 83% of the total feed supplied for each species was consumed, and pasture supplied 95% and 98% of beef cattle and sheep feed demands, respectively. More than 70% of beef cattle were finished before the second winter. This enabled the optimized system to return 53% and 188% higher GFR/ha and EBT/ha, respectively, compared to the average values for a Class 5 farm. This paper did not address risk, such as pasture growth and price fluctuations. To understand this several additional scenarios could be examined using this model. Further studies to include alternative herbages and crops for feed supply during summer and winter are required to expand the applicability of the model for different beef cattle and sheep farm systems.

Keywords: Linear programming; profit optimization; pasture utilization; sheep and beef farm; slaughter age

Introduction

The predominant beef cattle and sheep production system in New Zealand is pasture-based where pasture provides up to 95% of the diet of both beef cattle and sheep (Morris, 2013a; Morris and Kenyon, 2014) enabling New Zealand to have a low-cost and economically sustainable beef cattle and sheep production systems (Morris and Kenyon, 2014). Cattle and sheep are complementary for pasture and management of animal health (McCall, 1994; Morris, 2013a).

Pastoral beef cattle and sheep production systems are complex and are affected by many external factors (Bryant and Snow, 2008). It is neither feasible nor practical to design experiments to investigate every aspect of the potential interactions between factors (Bryant and Snow, 2008). Therefore, computer simulation can play an important role in gaining a better understanding of the beef cattle and sheep production system, and the relationships within and between factors by allowing *in silico* representation of the natural system (Cros et al., 2004; Romera et al., 2004; Crosson et al., 2006; Bryant and Snow, 2008). Computer simulation can also be used to identify production constraints and enable discovery of alternative solutions (Cros et al., 2004; Crosson et al., 2006). However, simulation on its own does not identify the optimum production potential within given constraints (Ridler et al., 1987).

Mathematical optimization models play a significant role in understanding biophysical relationships in a complex system and allow the optimization of livestock production (Waugh, 1951; Rozzi et al., 1984; McCall et al., 1999; Ridler et al., 2001; Annetts and Audsley, 2002; Romera et al., 2004; Costa and Rehman, 2005; Crosson et al., 2006; Neal et al., 2007; Notte et al., 2020). These models have the capability to identify the optimum production within defined resources, to allocate resources within combinations of numerous constraints and to suggest alternative production systems (Jansen and Wilton, 1984; Crosson et al., 2006; Anderson and Ridler, 2010).

Linear programming is defined as a deterministic optimization model (Jansen and Wilton, 1984; Rozzi et al., 1984; McCall et al., 1999; Ridler et al., 2001) and has been employed to optimize profitability of both dairy (Waugh, 1951; Dean et al., 1972; Conway and Killen, 1987; Ridler et al., 1987; McCall et al., 1999; Ridler et al., 2001; Crosson et al., 2006; Moraes et al., 2012) and beef cattle farms (Wilton et al., 1974; Rozzi et al., 1984; Nielsen et al., 2004; Costa and Rehman, 2005; Crosson et al., 2006; Rendel et al., 2013). A number of whole-farm optimization models using linear programming have been developed, including: Enviro-Economic Model (E2M) for New Zealand pasture-based dairy farms (Ridler et al., 2001; Anderson and Ridler, 2010; Ridler et al., 2010; Hurley et al., 2013; Anderson and Ridler, 2017), Models of an Integrated Dryland Agricultural System (MIDAS) and Model of an Uncertain Dryland Agricultural System (MUDAS) in Western Australia (Kingwell and Schilizzi, 1994; Pannell et al., 1996; Thamo et al., 2017), Grange Dairy Beef Systems Model (GDBSM) in Ireland and Scotland (Crosson et al., 2006; Ashfield et al., 2013; Ashfield et al., 2014; Kamilaris et al., 2020). Linear programming assumes a linear association between factors, however, some of the factors in the dairy and beef cattle industries are nonlinear. Nonlinear optimization models for New Zealand pasture-based dairy farms were developed (Doole and Romera, 2013; Doole, 2015; Romera and Doole, 2015; Romera et al., 2017). In terms of practical usage and identification of optimum outcomes for users linear programming is useful (Rozzi et al., 1984; Costa and Rehman, 2005; Crosson et al., 2006; Ashfield et al., 2013; Hurley et al., 2013; Ashfield et al., 2014; Kamilaris et al., 2020; Rendel et al., 2020). With appropriate discretization of inputs, it provides reliable outputs, the ability to plan for the optimal use of resources (Pannell, 1996; Neal et al., 2007; Ashfield et al., 2013; Hurley et al., 2013) and discern elusive enterprise interactions often missed or poorly represented in marginal analysis (Kingwell and Pannell, 1960; Hurley et al., 2013; Rendel et al., 2020).

An optimization tool that enables farmers to improve the profitability of beef cattle and sheep farming within given resources would be useful to assist with improving the best allocation of resources. FARMAX (www.farmax.co.nz) is widely employed for whole-farm simulation modelling in New Zealand, however, it does not optimize (Hurley et al., 2013). Several linear (Ridler et al., 1987; Ridler et al., 2001; Anderson and Ridler, 2010; Ridler et al., 2010; Anderson and Ridler, 2017) and nonlinear (Doole and Romera, 2013; Doole, 2015; Romera and Doole, 2015; Romera et al., 2017) profit optimization models for New Zealand pasture-based dairy farms have been developed. However, to date only a few studies based on dry matter consumption (McCall et al., 1999), or which have considered sheep production/performance only (Farrell et al., 2019; Farrell et al., 2020a; Farrell et al., 2020b) or beef cattle production/performance only (Carracelas et al., 2008) or a land-based integrated grazing farm sheep and beef production system (Rendel et al., 2020) have been applied for beef cattle and sheep, in New Zealand.

Considering the above, the current study developed a whole-farm optimization model for beef cattle and sheep based on metabolizable energy of the feed resource of various beef cattle and sheep classes. An optimization tool using linear programming would be useful for beef cattle and sheep farmers to optimize resource utilization and farm profitability and assist with strategic planning, decision-making and understanding their system (Pannell, 1996; Hurley et al., 2013; Rendel et al., 2020). It would also be beneficial for researchers, extension workers and farm advisors to suggest new solutions and optimal production systems for beef cattle and sheep farmers based on the existing resources and constraints (Pannell, 1996; Neal et al., 2007; Ashfield et al., 2013; Thamo et al., 2017).

The specific objectives of this study were to identify the maximum carrying capacity of beef cattle and sheep for a set feed resource, and to decide the profitable marketing policies and slaughtering ages of beef cattle for a Class 5 (B+LNZ: Economic Service, 2021) pasture-based, intensive finishing beef cattle and sheep farm in the North Island of New Zealand. This farm class is classed as fertile, partially cultivatable, and can support high stocking rates of livestock per hectare. It is mainly oriented for finishing, cattle directly sold to meat processing plants in comparison to the remaining seven beef cattle and sheep farm classes in New Zealand (Cranston et al., 2017; B+LNZ, 2022).

Materials and methods

Description of North Island intensive finishing sheep and beef cattle farm Class 5, Taranaki-Manawatu region

There are eight defined beef cattle and sheep farm classes in New Zealand which vary based on agro-climatic zone, farming system, stocking rate and region (Cranston et al., 2017; B+LNZ, 2022). The Taranaki-Manawatu beef cattle and sheep farming region is located on the western side of the North Island of New Zealand. It is characterized by rolling hill country and has suitable soil type and climatic conditions, which is at least partially cultivatable and has the potential for high animal production (Table 16) (Rendel et al., 2020; B+LNZ: Economic Service, 2021). The Class 5 North Island intensive finishing beef cattle and sheep farm in the Taranaki-Manawatu region was identified as a suitable farm class to implement the proposed model for the reasons of its relatively high carrying capacity per hectare (7 to 13 stock units per hectare (su/ha)) (Cranston et al., 2017; B+LNZ, 2022), the presence of large numbers of cattle relative to sheep (51:49 sheep:cattle su ratio) (B+LNZ: Economic Service, 2021) and stock policies that are mainly focused on finishing animals for sale to meat processing plants (Cranston et al., 2017; B+LNZ, 2022). Farm Class 5 is the most relevant class to base the proposed model on as it finishes a greater proportion of beef cattle than the other farm classes, which are either oriented towards sheep production, breeding or cropping (Cranston et al., 2017; B+LNZ, 2022).

A stock unit for this study was defined as the equivalent feed consumption of a 55 kg ewe weaning one 28 kg lamb, which consumes 550 kg DM/year (Trafford and Trafford, 2011; Farrell et al., 2020b). In 2018, the average number of beef cattle and sheep stock units on a Class 5 farm were 1095 sheep su and 1046 cattle su, respectively, (B+LNZ: Economic Service, 2021) which equated to 10.8 stock units (su) per hectare (B+LNZ: Economic Service, 2021). The average size of farm Class 5 in the Taranaki-Manawatu region, is 213 hectares (ha) and of that 7 ha are used for cash crop production grown between September and April, and 8 ha of new pasture is sown each year (B+LNZ: Economic Service, 2021). In this study, the land for cash crop production and new pasture grassed area was excluded from beef cattle and sheep grazing between September and April (Trafford and Trafford, 2011), however, it was considered as grazing land between May to August.

Table 16. Average production land size, total labour units, working owners, pasture fertilizer, average number of sales beef cattle and sheep and financial performance of Class 5 N.I. intensive finishing Taranaki-Manawatu sheep and beef farm in low and high quintiles and mean of 2018 (quintile analysis ranked by earnings before interest, tax, rent and manager wage (EBITRm)).

Attributes	Unit	Low quintile	High quintile	Mean
Average production land	ha	162	246	213
Total labour units	No.	1.26	1.31	1.42
Working owners	No.	0.94	0.94	0.92
Pasture fertilizer	kg/ha	297	270	260
Sales total cattle	No.	59	198	152
Sales total sheep	No.	974	1612	1483
Gross farm revenue	NZ$	178,535	476,086	308,630
Total farm expenditure	NZ$	188,546	321,281	241,853
Farm profit before tax	NZ$	-10,011	154,804	66,777

Source: B+LNZ: Economic Service (2021)

Model components and descriptions

Linear programming

A profit maximization linear programming model was developed using Microsoft excel Solver for a one-year horizon on a bi-monthly basis (Ridler et al., 1987; Fylstra et al., 1998; Crosson et al., 2006; Zgajnar and Kavcic, 2008; Rendel et al., 2013). R software version 3.6.0 (R Core Team, 2016) was employed to generate graphs of inputs and outputs of the model. Mathematical representation of linear programming can be represented as follows Jansen and Wilton (1984):

$$Z = C^T \vec{X}$$

Subject to a set of constraints

$$A\vec{X} = \vec{b}$$

$$\vec{X} \geq 0$$

Where:
Z: objective function (profit maximization),
C^T: vector of profits associated with one unit of each beef cattle and sheep activity,
$\vec{X}$: vector of activities whose levels need to be solved (number of beef cattle and sheep in each class),
A: matrix of resource coefficients that are needed by each beef cattle and sheep unit activity,
$\vec{b}$: a vector of constraints.

Model system and description

The mixed beef cattle and sheep farm model developed in this study allocated 50% of the grazing land for beef cattle activity and the remaining area for sheep production. It comprised of 19 beef cattle and sheep activities (Supplementary Table 9; Supplementary Table 11) and 163 constraints (Supplementary Table 12; Supplementary Table 13; Supplementary equation 1; Supplementary equation 2). The model consisted of a beef cattle LP interface and a sheep LP interface, each of which had input variables for each activity, objective functions and displayed the optimum number of animals in each activity of beef cattle and sheep and a dashboard to display financial performance and graphs. The number of beef cattle and sheep were determined based on the carrying capacity of total feed supply which included surplus pasture harvested as silage. Silage was supplied to cattle over 2 years of age and mature ewes at a maximum of 30% of the total feed intake to ensure that the allocated kg DM did not exceed gut fill capacity (less than 3% of live body weight), which would reduce animal intake (Trafford and Trafford, 2011). Utilized dry matter consumption was defined as the percentage of feed eaten by the beef cattle and sheep activities from the total feed supply and was estimated separately for beef cattle and sheep. A generalization of the beef cattle and sheep activities, feed demand and supply and financial performance represented in the model are presented in Figure 5.

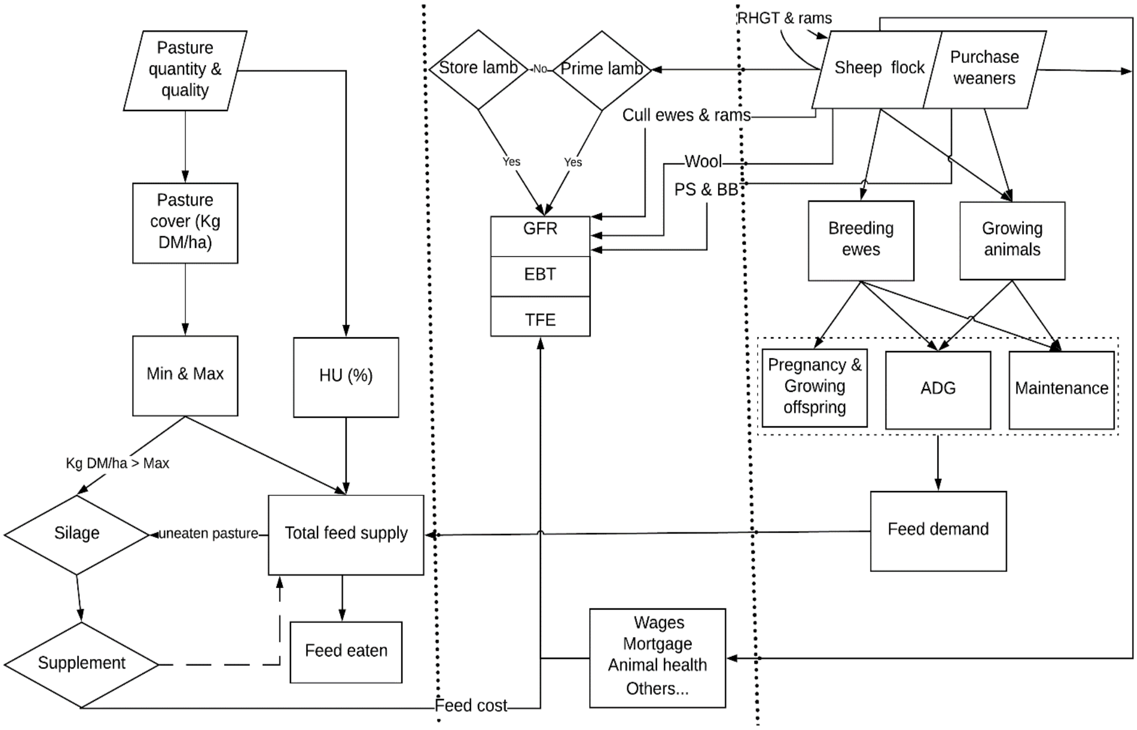

Figure 5. Model inputs (pasture quantity and quality parameters, beef cattle herd and sheep flock), total utilizable feed supply, silage and feed demand from the beef cattle and sheep activities.

The outputs of the model include prime (sold to meat processing plant) and store lambs (sold to other farmers for finishing), replacement hoggets (between 4 to 16-months of age, mated at 8-months of age), cull ewes and rams, wool, prime steers (PS) and bull beef (BB)), gross farm revenue (GFR), total farm expenditure (TFE) and farm earnings before tax (EBT). The rectangular boxes represent process of the system, activities which need decision represented by the diamond boxes and the vertical dotted lines stood to separate the three main modules of the system. Min & Max: minimum and maximum pasture cover (kg DM/ha); HU: herbage utilization (%); ADG: Average daily gain; RHGT: replacement hoggets

The model flow chart presented in Figure 5 comprises 3 modules: feed supply, feed demand and financial. Both the quantity and quality of pasture, which are functions of the minimum and maximum pasture cover limits, plus energy density and the pasture utilization percent, enabled the calculation of utilizable feed supply. In each bi-monthly period, the total herbage mass was assessed. Herbage above the maximum boundary when the utilizable pasture supply exceeded animal demand was conserved as silage, which then re-entered the system as supplementary feed when animal demand exceeded the pasture supply (see the left side of Figure 5). This study did not consider other external supplementary feed supplies. Per head feed demands for maintenance, live weight gain, plus pregnancy and lactation and growing offspring in breeding ewes and hoggets were calculated for each beef cattle and sheep activity in the feed demand module (see the right side of Figure 5). The total feed demand of beef cattle and sheep was always less than, or equal to, the feed supply (Supplementary equation 1; Supplementary equation 2). The sheep activity was a self-replacing system and thus replacement lambs re-entered the sheep flock with the remainder being sold as either prime (sold to meat processing plant) or store lambs (sold to other farmers for finishing). Prime steer beef and bull beef from the beef cattle activity and prime and store lambs, wool, mutton from the sheep activity were the revenue sources. Total farm expenditure for beef cattle and sheep rearing, including silage preparation costs and purchase of weaners in the beef cattle activity, was subtracted from the total farm gross revenue to estimate farm earnings before tax (middle of Figure 5).

Inputs of the model

Herbage supply

Daily average pasture growth rates and MJ ME/kg DM for Taranaki-Manawatu by month were obtained from B+LNZ (2022) and Brookes and Nicol (2017). The same figures within a month were used in bi-monthly periods of 14, 15 and 16 days for this study (Figure 6) which were derived as 2 x 15 days for 30-day months, 15 and 16 days for 31-day months and 2 x 14 days for February. The total average pasture cover was the sum of post-grazing pasture mass from the previous period and the net pasture growth in a given period (Figure 7). The net pasture growth was calculated by multiplying average daily pasture growth rate with the number of days in the bi-monthly period (Figure 6). This study assumed the same fertilizer rate was applied as reported in B+LNZ: Economic Service (2021), this rate was not altered to manipulate pasture growth rate. Utilizable kg DM was derived by considering the minimum and maximum pasture covers for beef cattle and sheep grazing and percent of pasture utilization (Supplementary Table 6; Supplementary Table 7) obtained from (Brookes and Nicol, 2017).

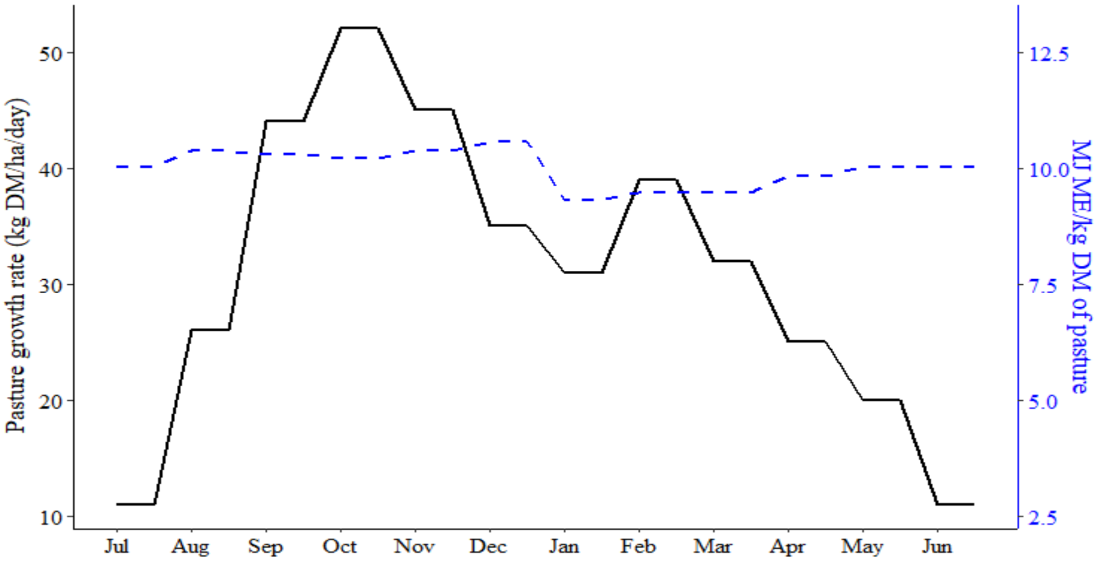

Figure 6. Bi-monthly average pasture growth rate kg DM/ha/day (left axis and black solid line) and MJ ME/kg DM of pasture (right axis and blue dashed line);

Sources: Brookes and Nicol (2017); B+LNZ (2022)

The minimum pasture cover was constrained to 1500 kg DM/ha for beef cattle grazing and 800 kg DM/ha for sheep grazing to ensure beef cattle and sheep intakes were not restricted (Matthews, 1975; Boswell and Cranshaw, 1978; Litherland et al., 2002; Trafford and Trafford, 2011; Rendel et al., 2020). The maximum pasture covers were limited to 2500 kg DM/ha for beef cattle and 1800 kg DM/ha for sheep (Figure 7) (Litherland et al., 2002; Trafford and Trafford, 2011; Rendel et al., 2020) to ensure appropriate herbage quality was maintained and animals received the required metabolizable energy from the given kg DM of pasture (Matthews, 1975; McCall, 1994). In spring when pasture cover was higher than the set maximum limits and utilizable pasture cover exceeded the animals demand, the same amount of pasture to support pasture shortage during winter was conserved as silage and used to supplement the winter feed supply (Supplementary Table 6; Supplementary Table 7) (Conway and Killen, 1987). The MJ ME/kg DM and utilization percent of harvested silage were 10.5 MJ ME/kg DM and 85%, respectively (Brookes and Nicol, 2017).

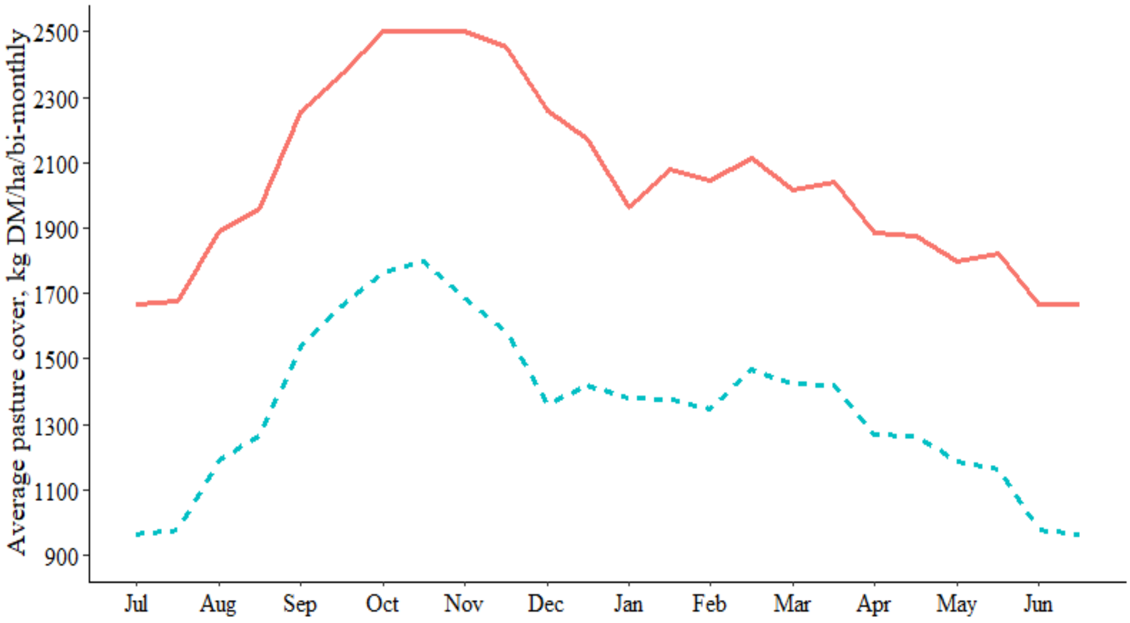

Figure 7. Bi-monthly average pasture cover (kg DM/ha/period) for beef cattle (orange solid line) and sheep (blue dashed line).

Beef cattle and sheep activities

The beef cattle activities consisted of steer and bull finishing which included rising-1yr (weaners), rising-2yrs (R2) and rising-3yrs (R3) steers, and rising-1yr (weaners) and rising-2yrs (R2) bulls (Table 17) (Morris, 2013a; B+LNZ: Economic Service, 2021). In New Zealand, suckling calves on beef farms, predominately Angus (47%), Hereford (14%) and their crosses (14%) (B+LNZ, 2017), are weaned at 6-months of age. This study purchased a range of beef cattle breed weaner steers at the age of 6-months (March), at approximately 200 kg live weight (Coleman et al., 2016; Tait et al., 2017). It was assumed that, fast-growing steers attained over 500 kg liveweight by 18-months, and slow growing steers, which had 10% less average daily live weight gain than fast growing cattle were finished before the third winter (Supplementary Figure 1).

Dairy-origin calves are weaned at 3-months of age (Muir et al., 2002; Ormond et al., 2002). While some dairy farmers rear and wean calves to on-sell to finishers, the majority sell their calves to calf rearers at 4 to 8-days of age (Muir et al., 2002; Ormond et al., 2002). Well-marked Holstein-Friesian male calves are favoured in New Zealand for bull beef finishing systems as they grow faster than other breeds and classes of beef cattle (Muir et al., 2001). Thus, this study assumed the purchase of 3-month old, uncastrated, weaner Holstein-Friesian spring-born bull calves at 100 kg live weight (Table 17) (Muir et al., 2001; McRae, 2003).

One slaughtering option before the second winter at 18-months (S-18) and two slaughtering options at the ages of 28 and 30-months (S-28 and S-30) for steers (Table 17) (Morris, 2013a; Ashfield et al., 2014) and four slaughtering options at ages of 16 (B-16), 18 (B-18), 20 (B-20) and 22 (B-22) months for bull were assumed (Table 17) (Morris, 2013a; Ashfield et al., 2014). Carcass weights for S-18 steers, bulls and, S-28 and S-30 steers were driven using dressing out percentages of 50%, 52% and 54%, respectively (Purchas and Morris, 2007; Morris, 2013a; Ashfield et al., 2014). Carcasses from steers were assumed to attain the historical average price of the P2 fat and muscle class (NZ$ 5.50/CW) and carcasses from bulls were assumed to satisfy the historical manufacture average beef price (NZ$ 5.25/CW) (Table 17) (B+LNZ: Economic Service, 2021).

Table 17. For steer and bull weaners, prime steer and bull beef: the month of purchase, stock unit/head, month of sale for slaughter, age at sale, live weight (LW), carcass weight (CW) and unit price (NZ$/unit).

Beef cattle	Months of purchase	[a]Stock unit/head	Month of sale	Age at sale	LW (kg)	CW (kg)	[b]Price (NZ$/unit)
Steer weaners	Mar	3.0	-	-	200	-	350.00
Steer beef		5.0	Feb	18	500	250	5.50
		5.5	Dec	28	578	313	
		5.5	Feb	30	590	319	
Bull weaners	Nov	2.5	-	-	100	-	450.00
Bull beef		5.5	Dec	16	450	234	5.25
		6.0	Feb	18	498	259	
		6.0	Apr	20	531	276	
		6.0	Jun	22	550	286	

[a] equivalent stock units were estimated based on amount of feed eaten using a stock unit definition of Trafford and Trafford (2011); [b] unit prices per carcass weight for sale cattle were collected from B+LNZ: Economic Service (2021) and unit prices per head for weaners purchasing were collected from Mylivestock (2020)

The sheep flock was self-replacing and included breeding ewes, rams, prime male and female lambs (i.e., sold for meat processing), store male and female lambs (i.e., sold to other farmers for finishing) and female breeding hoggets for replacement (i.e., 4 to 16-months of age), mated at 8-months of age-in April to lamb in October (Table 18) (Kenyon et al., 2014; Farrell et al., 2020a). The number of breeding ewes and rams, at a ratio of 100:1, were considered as a static population. The total number of spring-born (September) lambs was derived from the number of breeding ewes, lambing percentage (150%) and weaning percentage (80%) at 1:1 female to male ratio (Sumner et al., 2011; Tait et al., 2019). Lambs from hoggets, which accounted for 5% of the total lambs, (B+LNZ: Economic Service, 2021) were weaned in late December. From the weaned male lambs, one-third were slaughtered in late November, another one-third in March (prime lambs) and the rest, including hogget male lambs, were sold in late April as store lambs; the same number to culled rams were retained as replacement breeding rams (Table 18) (Thompson et al., 2016; Farrell et al., 2019; Farrell et al., 2020a; Farrell et al., 2020b). Similarly, 40% of weaned female lambs were finished in late November (prime lambs) and the rest were either sold store in April (store lambs) or used as replacement breeding hoggets (Figure 5) (Thompson et al., 2016; Farrell et al., 2019; Farrell et al., 2020a; Farrell et al., 2020b). The number of replacement hoggets was assumed to match ewe wastage (annual culls plus deaths equating to 30% of ewes) (Griffiths et al., 2017; Farrell et al., 2019; Farrell et al., 2020b). Ewes over five years old were culled following lamb weaning in late November (Farrell et al., 2020b) and one-third of rams were replaced each mating season.

Table 18. Prime lambs (sold for meat processing), store lambs (sold to other farmers for finishing), replacement hoggets (4 to 16-months of ages, mated at 8-months of age), cull ewes and rams (sold for meat processing), month of weaning and sale, stock unit/head, age at sale and unit price (NZ$/head).

Sheep classes	Month of weaning	Month of sale	[a]Stock unit/head	Age at sale	[b]Price (NZ$/head)
Prime lambs	Nov	Nov Mar	- 0.4	3 6	134.89
Store lambs	Nov-Dec	May	0.5	10	97.49
RHGT	Nov	-	1.1	-	-
Cull rams		Apr	1.1	Mixed age	113.92
Cull ewes		Dec	1.1	Mixed age	
Breeding ewes			1.1	Mixed age	

[a] equivalent stock units were estimated based on amount of feed eaten using a stock unit definition of Trafford and Trafford (2011); [b] Source: B+LNZ: Economic Service (2021); RHGT: replacement hoggets.

Estimation of feed demand from beef cattle and sheep

Daily metabolizable energy requirements (MJ ME) for maintenance and live weight gain in growing beef cattle (equ.1, equ. 2) and sheep, plus for pregnancy and lactation and growing offspring to weaning in breeding ewes were estimated using equations from (Brookes and Nicol, 2017) (Supplementary Tables 8, 9). To ensure that feed demand met the pasture growth curve across seasons, the rates of live weight gain of beef cattle and sheep were modified depending on the season (Boswell and Cranshaw, 1978; Morris, 2013a; Thompson et al., 2016). The total MJ ME feed demand/head/day for each beef cattle and sheep was converted into kg DM equivalence using the energy density of the feed in each period (Figure 7) (Brookes and Nicol, 2017) and then multiplied by the number of days to obtain the bi-monthly kg DM demand/head (Supplementary Tables 10, 11). The feed demand from beef cattle and sheep activities in terms of kg DM was constrained on a bi-monthly basis so that total feed demand was less than or equal to the total feed supply (utilizable pasture plus silage) (Supplementary equations 1, 2) (Ridler et al., 1987; Costa and Rehman, 2005; Farrell et al., 2020b).

$$\text{MJ ME for maintainance} = \alpha * \text{live weight}^{0.75} - - - - - - - - - \text{equ. 1}$$

$$\text{MJ ME for a kg live weight change} = (\beta + \partial * \text{ live\_weight}) * \frac{\text{ADG}}{\text{kg}} - - - - - - \text{equ. 2}$$

Where:

$$\alpha = 0.65 \text{ for heifer and steer and } 0.72 \text{ for bull}$$

$$\beta = 16 \text{ for heifer, } 15.5 \text{ for steer and } 14.915 \text{ bull}$$

$$\partial = 0.0971 \text{ for heifer, } 0.0736 \text{ for steer and } 0.0595 \text{ for bull}$$

Outputs of the model and evaluation

Steer and bull carcasses were the revenue sources of beef cattle activities. Mutton from culled ewes and rams (assumed to earn ewe carcass price), prime lambs which were sold to the meat processing plant at 3 and 6-months of age, store lambs (sold to other farmers for finishing), and wool production were the outputs of sheep activity (Figure 5; Table 17) (Farrell et al., 2019; Farrell et al., 2020a; Farrell et al., 2020b). Store lambs, prime lambs and cull ewes and rams were assumed to earn per head live weight schedule price (NZ$/head) (Figure 5; Table 18) (B+LNZ: Economic Service, 2021). An average of 4.17 kg of wool produced per ewe (kg/head/year), which was valued at NZ$ 2.10/kg wool (B+LNZ: Economic Service, 2021). Linear programming was employed to identify the most profitable steer and bull slaughtering ages, prime and store lambs and the maximum number of beef cattle and sheep that could be managed within the available feed supply.

Gross farm revenue (GFR) was defined as the total revenue earned from a one-year farm operation. It was calculated as the sum of the revenue from beef cattle and sheep activities minus total farm expenditure (TFE) to arrive at earnings before tax per farm (EBT/farm) and then their respective per hectare and per stock unit values (Farrell et al., 2020a; B+LNZ: Economic Service, 2021) were computed by dividing either by the total effective farm area (198 ha) or stock units (B+LNZ: Economic Service, 2021). For the purpose of developing the model, the per stock unit expenditure of various inputs from (B+LNZ: Economic Service, 2021) were evenly distributed across the bi-monthly periods (Supplementary Table 14). Total farm expenditure was computed by multiplying the per stock unit production cost with the number of beef cattle and sheep in each activity, their associated stock unit and the number of bi-monthly periods, plus baled silage processing costs (NZ$ 75 per large round bale) (Interest New Zealand, 2022) (https://www.interest.co.nz) and the cost of purchasing weaners for the beef cattle activity (Supplementary Table 14).

There were consultations and review with a linear programme expert Ridler et al. (2001) during the model building to ensure the model content was appropriate for the chosen farm class. Model outputs including the pasture growth curve, feed demand and supply and animal performance in response to feed supply were reviewed to ensure that they were sensible for New Zealand farming scenarios. The final outputs related to numerical and financial performance were compared with the (B+LNZ: Economic Service, 2021; B+LNZ, 2022) annual reports which were used as an evaluation benchmark.

Results

The optimized farm system carried 46% higher beef cattle and sheep stock units than that of the average value of Class 5 (Table 19). This enabled the optimized system to finish an extra 44% steers and bulls compared to that of the average value of Class 5 beef cattle and sheep farm. There were no steers slaughtered at the age of 30-months (Table 19). Similarly, a higher number of ewes (22.1%) and prime and store lambs (10.6%) were run in this study compared to the average Class 5 farm (Table 19). Unlike the average Class 5 farm, there were no store cattle and prime hoggets in the optimized system (Table 19).

Table 19. The number of weaner steers and bulls, stored (sold to other farmers for finishing) and finished steers (S-18, S-28, S-30) and bulls (B-16, B-18, B-20 and B-22) (sold for meat processing) and breeding ewes and rams, prime lambs (sold for meat processing) and store lambs (sold to other farmers for finishing) and prime and replacement hoggets (between 4 to 16-months of age, mated at 8-months of ages) and their equivalent stock units in an average Class 5 farm and optimized system.

Beef cattle and sheep and classes	Class 5	Optimized system
Steers weaners	NA	100
Stored steers	5	0
S-18	4	55
S-28	43	45
S-30		0
Bull weaners	NA	100
Stored Bulls	11	0
B-16	76	7
B-18		44
B-20		36
B-22		13
Breeding ewes	901	1,100
Store lambs	251	345
Prime lambs	697	704
Prime hoggets	377	0
Replacement hoggets	NA	330
Rams	NA	11
*Stock units	2,142	3,141

*Stock unit: average throughout the year; S-18: rising-2years steers (slaughtered at the age of 18-months); S-28 and S-30: rising-3years steers (slaughtered at the ages of 28 and 30-months); B-16, B-18, B-20 and B-22: rising-2years bulls (slaughtered at the ages of 16, 18, 20 and 22-months); NA: no data reported

Figure 8 shows the feed demand and supply for beef cattle activity. The annual feed demand by the beef cattle activity was supplied predominantly by pasture (95%) and only 5% by silage. Of the total feed supply allocated to beef cattle activity, they consumed 83%.

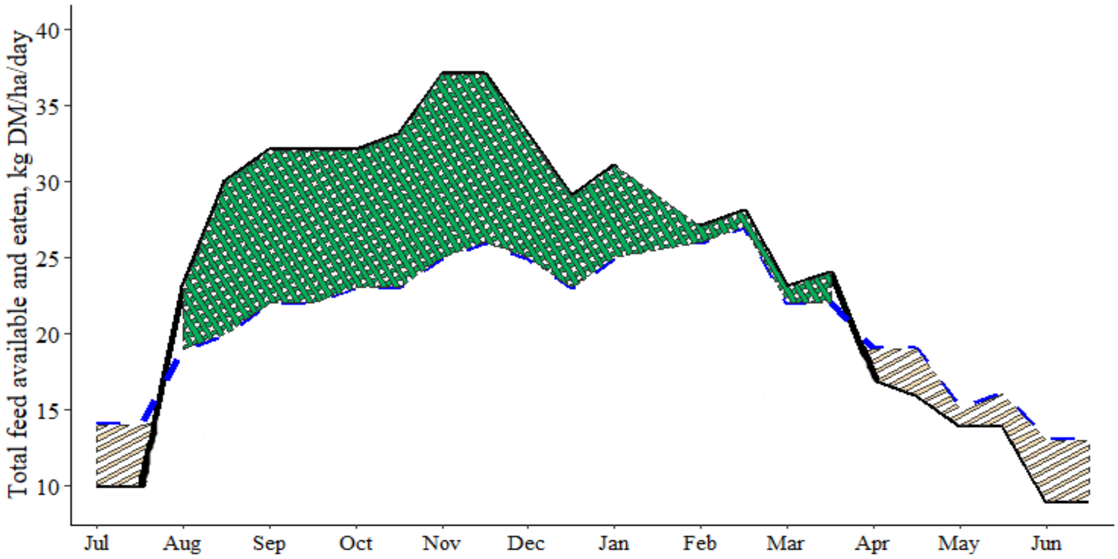

Figure 8. Utilizable pasture supplied (black line) and eaten by the beef cattle activity (blue dashed line which included silage) in the optimized farm system throughout the year. The excess herbage available (i.e., neither utilized nor processed for silage) is indicated by the green shaded area and the deficient (i.e., where cattle requirements were greater than the available pasture) which was supplemented with silage is indicated by the striped area.

The annual feed demand and supply for sheep activity of the optimized farm system is presented in Figure 9. Feed was predominantly supplied by pasture (98%) and the rest, 2% was by silage. Of the total feed supplied for sheep activity, 83% was consumed.

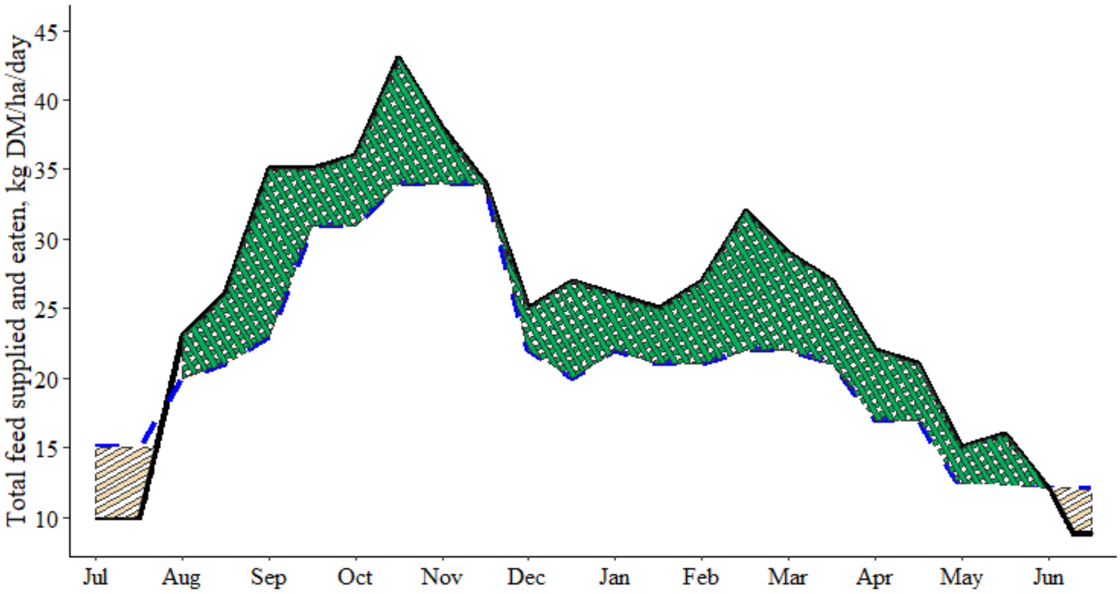

Figure 9. Utilizable pasture supplied (black line) and eaten by the sheep activity (blue dashed line which included silage) in the optimized farm system throughout the year. The excess herbage available (i.e neither utilized nor processed for silage) is indicated by the green shaded area and the deficient (i.e where sheep requirements were greater than the available pasture) which was supplemented with silage is indicated by the striped area.

The optimized farm system returned 53% and 188% higher GFR and EBT per hectare than that of the average value of Class 5 farm. Total farm expenditure was 30% higher than the industry value (Table 20).

Table 20. Total, per hectare and per stock unit values of gross farm revenue (GFR), total farm expenditure (TFE), farm earnings before tax (EBT) of beef cattle and sheep activity for an average Class 5 farm and the Optimized system.

Attributes	Unit	Class 5			Optimized System		
		GFR	TFE	EBT	GFR	TFE	EBT
Beef cattle	NZ$	-	-	-	297,700.39	207,523.49	90,176.90
Sheep	NZ$	-	-	-	175,820.19	73,789.22	102,030.97
Total	NZ$	308,630.00	241,853.00	66,777.00	473,520.57	281,312.71	192,207.86
Per hectare	NZ$/ha	1,555.20	1,218.71	336.49	2,391.52	1,420.77	970.75
Per stock unit	NZ$/SU	144.11	112.93	31.18	150.78	89.57	61.20

Discussion

Linear programming can be applied to optimize beef farm profitability (Wilton et al., 1974; Rozzi et al., 1984; McCall, 1994; Pannell, 1996; Nielsen et al., 2004; Costa and Rehman, 2005; Crosson et al., 2006; Zgajnar and Kavcic, 2008; Rendel et al., 2013; Rendel et al., 2020) and dairy farm profitability (Conway and Killen, 1987; Ridler et al., 1987; McCall et al., 1999; Ridler et al., 2001; Crosson et al., 2006). Grazing System Ltd (GSL) (Hurley et al., 2013) developed by (Ridler et al., 2001), was later modified to become Enviro-Economic Model (E2M), is a linear programming model, and has been used to optimize efficiency on pasture-based dairy farm systems in New Zealand (Ridler et al., 2001; Anderson and Ridler, 2010; Ridler et al., 2010; Hurley et al., 2013; Anderson and Ridler, 2017). The two whole-farm optimization models in Western Australia: Model of an Integrated Dryland Agricultural System (MIDAS) and Model of an Uncertain Dryland Agricultural System (MUDAS) employed linear programming (Kingwell and Pannell, 1960; Kingwell and Schilizzi, 1994; Pannell, 1996; Pannell et al., 1996; Thamo et al., 2017). Grange Dairy Beef Systems Model (GDBSM), a linear programming model, was efficient to investigate Irish beef production systems (Crosson et al., 2006; Ashfield et al., 2013; Ashfield et al., 2014). This was modified by Kamilaris et al. (2020) to optimize Scottish beef production systems. These applications indicate that linear programming can be a helpful tool to optimize a range of livestock production systems. This study built a profit maximization farm model using linear programming and identified the stocking rate, marketing policy and slaughtering age of steers and bulls for feed supplied on a Class 5 North Island intensive beef cattle and sheep finishing farm in the Taranaki-Manawatu region of New Zealand.

On a mixed beef cattle and sheep farm, the two species graze separately due to the aim of maximizing animal performance, with each species requiring different optimum pasture masses. The beef cattle and sheep farm model developed in this study allocated 50% of the grazing land for beef cattle and 50% for sheep activity. It was assumed that the two species grazed separately, but over the year, it was assumed they grazed over all areas. The profitability of a sheep enterprise was quantified by Farrell et al. (2020a); Farrell et al. (2020b) using 40% of the farm feed supply for cattle activity in a mixed beef cattle and sheep farm. Another study by McCall (1987) reported that approximately 40% of feed on mixed beef cattle and sheep farms should be allocated to beef cattle to ensure healthy complementarity of pasture management. The higher ratio of cattle relative to sheep in this study is due to the farm class type, with Class 5 farms having slightly more cattle relative to sheep (51:49 sheep:cattle) (Cranston et al., 2017; B+LNZ: Economic Service, 2021; B+LNZ, 2022). High profit from beef cattle enables this farm class to return higher GFR/ha and EBT/ha compared to hard hill and hill country beef cattle and sheep farms (Classes 3 and 4) of North Island, New Zealand (B+LNZ: Economic Service, 2021; B+LNZ, 2022).

The optimized farm finished almost twice the number of steers and 32% more bulls than an average Class 5 farm. However, when compared to the high quintile values of Class 5 farms, steer and bull numbers were, respectively, 34% and nearly 3-fold lower, (B+LNZ: Economic Service, 2021). This suggests that Class 5 farmers should increase steer, but decrease bull, numbers to optimize spring pasture utilization and profitability. Similarly, the number of ewes and lambs sold prime or store were 11% and 22% higher, respectively, than that of the average values of Class 5 farms (B+LNZ: Economic Service, 2021). These values were about 40% and 10% lower than the highest quintile values of Class 5 farms reported by the (B+LNZ: Economic Service, 2021). These differences are likely due to this study optimising sheep activity based on having a self-replacing flock, and hence all lambs were born on-farm. In contrast, North Island intensive finishing beef cattle and sheep farms typically buy replacement stock to finish for slaughter (Cranston et al., 2017; B+LNZ, 2022). The higher number of animals in the current model compared to the average values of Class 5 farms are likely due to the higher numbers of animals needed to optimize the carrying capacity, given the defined feed resource to ensure high herbage utilization rather than it being left ungrazed, which would also reduce feed quality. This could also be due to some Class 5 farmers having a beef cow herd, in this case, the average reported values are not representative of a finishing farm. Labour availability, fertilizer application, land productivity differences, and management variations are likely causes of the numerical and financial differences between the optimized system and Class 5 farm statistics.

The feed demand of beef cattle and sheep does not always fit the seasonal pasture growth curve in New Zealand (McCall, 1987; Carracelas et al., 2008). Pasture supply is high in spring and low in winter, which is a bottleneck for pasture-based beef cattle and sheep farms (Matthew et al., 1995; Carracelas et al., 2008). Supplementing winter feed supply with either crops or hay/silage to carry higher stocking rates through winter is a common practice on New Zealand beef cattle and sheep farms (Carracelas et al., 2008; Trafford and Trafford, 2011; Brookes and Nicol, 2017). In this study, 5% and 2% of total feed demand for beef cattle and sheep, respectively, were supplied by silage. This enabled the modelled farm to run more livestock in winter which improved pasture usage and reduced herbage wastage (Romera and Doole, 2015).

The conservation of excess pasture as silage is not used on all farms and therefore farmers may employ other options to control excess spring pasture. Pasture not consumed by the beef cattle or sheep nor prepared as silage in spring could alternatively be managed by increasing beef cattle and sheep numbers in the spring season (Scales and Lewis, 1971) and then either selling these animals as store or progressively finishing them as feed supply declines. Options include brought-in yearling or older cattle for finishing before summer (Walker, 1957). Other alternatives would be to increase sheep reproductive performance, for example hogget breeding (Kenyon et al., 2014), buying supplementary winter feed or growing crops to allow for greater livestock numbers in winter (Carracelas et al., 2008). These options were not evaluated in the current study, however, the model would be able to test the profitability of these alternative strategies if needed.

Heavier cattle require greater feed for maintenance and live weight gain (Trafford and Trafford, 2011; Brookes and Nicol, 2017), this meant that the model finished more than 70% of beef cattle before their second winter (rising-2yrs steers and bulls) and the remaining before their third winter. Similarly, 67% of lambs were sold prime, and the rest were sold store. This enabled the modelled Class 5 farm to earn 53% and 188% higher GFR/ha and EBT/ha than the average value of the industry data (B+LNZ: Economic Service, 2021). These values were 7% and 25% higher, respectively, compared to the industry high quintile of Class 5 farms (B+LNZ: Economic Service, 2021). The finding of McRae (2003) supported that finishing of fast-growing and younger cattle is more profitable than slow growing, older cattle. This suggests that farm Class 5 farmers would benefit from finishing a greater number of beef cattle before their second winter, which would require farmers to consider fast-growing cattle breeds or to provide alternative feeds to grow cattle faster, to improve their farm profitability.

The model developed in this study was deterministic and considered linear relationships between feed supply and demand from beef cattle and sheep activities (Rozzi et al., 1984; Costa and Rehman, 2005; Crosson et al., 2006) although it is acknowledged that pasture supply is nonlinear across the year. This is a known limitation of these types of models (Costa and Rehman, 2005). To minimise the effect of this limitation, average live weight gains of growing livestock were adjusted to fit the feed supply curve and the feed supply and demand data were discretized into bi-monthly periods (McCall, 1994; Costa and Rehman, 2005). This allowed the model to enumerate the number of cattle and to make decisions on the optimum number of animals based on the available feed supply on bi-monthly basis. It is important to realise that the production profile and financial performance of the model can be affected by slight changes in bi-monthly feed supply and unit prices of beef cattle and sheep. The current model did not investigate risk and uncertainty which could be assessed through the running of various scenarios using the model and thus comparing the outputs. Based on this farmers could determine the likelihood of positive or negative outcomes (Pannell, 1996; Hurley et al., 2013).

In the current system, the potential benefit of older cattle such as cows for controlling the pasture quality for both sheep and young cattle (McCall, 1994) was not considered. Having a herd of beef breeding cows could improve farm profitability as they can utilize low-quality pasture in winter. This would further reduce pasture wastage, but would also maintain higher quality pasture to support higher growth rates in younger cattle and lambs (McCall, 1994). The impacts of herbage quality such as protein content and the use of crops to alleviate feed shortages in summer and winter seasons were not evaluated. Hence, further studies would be required to improve this model applicability under different classes of beef cattle and sheep farms. The current profit optimization model could be extended to multi-stage linear programming to optimize land utilization, sheep:beef cattle ratio, stocking rate for different scenarios (Annetts and Audsley, 2002; Notte et al., 2020). This would enable users to include additional constraints and objective functions which were not considered in this study.

Conclusions

The optimized Class 5 farm model developed using linear programming identified the optimum number of beef cattle and sheep that could be managed within given feed resources for Class 5 New Zealand North Island intensive finishing beef cattle and sheep farms. The model could be employed by the farmers to understand pasture utilisation throughout the year and decision making for conserving excess pasture to support winter feed supply, thereby reducing pasture wastage and improving overall pasture utilization.

The modelled Class 5 farm had nearly the same numbers of beef cattle and sheep as the industry high quantile farms. The majority of beef cattle were finished before their second winter and the majority of lambs were sold prime. This enabled the modelled farm to earn comparable GFR and EBT to the top 20% of farms.

The combined outputs suggest that the model accurately represented real farm systems and therefore it would be suitable for use by beef cattle finishing farmers and could be used to model other potential production systems on this class of land. The current model could be also adapted to other farm classes in New Zealand by providing the appropriate input parameters of those systems. Further study to incorporate multiple objectives like stocking rate, sheep: beef cattle stock ratios would improve the model applicability.

Chapter V

Optimization of Profit for Pasture-Based Beef Cattle and Sheep Farming Using Linear Programming: Young Beef Cattle Production in New Zealand

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Abstract

In New Zealand, surplus dairy-origin calves not needed as replacement or for beef cattle farms requirements for finishing are commercially slaughtered within two weeks of age. This system has perceived ethical issues which can potentially negatively affect the dairy industry. Therefore, a young beef cattle production system to maximize the use of excess calves within the land size constraint is considered as an alternative to a traditional 18 to 33-months slaughtering system. The current study examined the effects of young beef cattle production with slaughter ages at 8 to 14-months on pasture utilization, farm profitability and selling policy on class 5, intensive finishing beef cattle and sheep farms in New Zealand. A linear programming model that had previously been developed for this farm class (optimized traditional beef cattle system) was modified to include a young beef cattle slaughter system and identified the carrying capacity for young and traditional beef cattle and the selling policy required to optimize pasture utilization and farm profitability. Systems with young beef cattle slaughtered at 8, 10, 12 or 14-months of age were simulated without (Scenario I) or with (Scenario II) decreasing the number of traditional beef cattle. Daily per head energy demand for maintenance and live weight change was estimated and converted to kg DM/head on a bi-monthly basis. Carcasses from young beef cattle were processed as one class under the manufacturing beef price (NZ$ 4.50). The modified young and traditional beef cattle slaughtering system maintained an extra 6% and 35% beef cattle in Scenario I and Scenario II respectively, and finished 90% and 84% of traditional beef cattle before the second winter. Pasture supplied 98% of the feed demand for the beef cattle activities and 79 to 83% of that was consumed. Mixed young and traditional beef cattle finishing scenarios returned 2% less gross farm revenue per hectare (GFR/ha). However, earnings before tax per hectare (ETB/ha) in Scenario I and Scenario II were 15 to 25% greater than that of the optimized traditional beef cattle system, respectively. Young beef cattle production increased pasture utilization and farm profitability and increased selling options for finished beef cattle. Therefore, the young beef cattle system is a viable option for farmers and will help to reduce the need to slaughter dairy-origin calves within two weeks of age.

Keywords: farm profitability; linear programming; marketing policy; pasture utilization; sheep and beef farm; young beef cattle

Introduction

New Zealand produces an average of 679,000 tonnes of beef annually (New Zealand Statistics, 2022), of which more than 80% is exported (McDermott et al., 2005; van Selm et al., 2021). This contributes to one percent of world beef production and six percent of global beef exports (Morris, 2013a; B+LNZ, 2022). Cattle for beef production can be sourced from beef breeds or can be of dairy origin (French, 2010; Morris, 2013a; Schreurs et al., 2014; Coleman et al., 2016; Martin et al., 2018; Fennell et al., 2019). Dairy-origin cattle include cull cattle at the end of their primary productive life, and heifer, steer and bull calves that are transferred to beef-finishing farms (Morris, 2013a; Nogalski et al., 2014; Coleman et al., 2016; Domaradzki et al., 2017; Nogalski et al., 2017; Fennell et al., 2019; Lynch and French, 2019; Berry, 2021). Cattle of dairy origin contribute 73% of annual beef production in New Zealand (van Selm et al., 2021; New Zealand Statistics, 2022) with more than 50% of calves for beef finishing being sourced from dairy farms (van Selm et al., 2021; New Zealand Statistics, 2022).

Approximately 4.5 million calves are born annually on New Zealand dairy farms (Andrew, 2016; New Zealand Statistics, 2022) with 25% retained as heifer and bull replacements (Cook, 2014; van Selm et al., 2021; New Zealand Statistics, 2022). Of the remainder, calves will be transferred to beef and sheep farms to be used for beef cow herd replacements or for beef production with slaughter at 18 to 33-months of age. However, the majority of the calves are slaughtered under 14-days of age directly from the dairy farm, as a means of disposal (Morris, 2013a; Andrew, 2016; Domaradzki et al., 2017). In

New Zealand, surplus calves slaughtered before 2-weeks of age are called “bobby calves” (Cook, 2014; Andrew, 2016; van Selm et al., 2021; New Zealand Statistics, 2022). In 2020, New Zealand processed 1.9 million bobby calves (New Zealand Statistics, 2022). The processing of bobby calves has potential animal welfare and ethical issues (Boulton et al., 2018) that will likely impose a risk for the market sustainability dairy cattle industry in New Zealand (Cook, 2014; Ferguson et al., 2014; Andrew, 2016; Rutherford et al., 2021).

If more bobby calves entered into beef cattle systems, ethical issues related to the bobby calf production would be reduced (Cook, 2014; Andrew, 2016; Rutherford et al., 2021) and more beef could be supplied to meet global meat demand (Ward, 1968; FAO, 2018). This might also provide financial opportunities for both beef and dairy cattle farmers (French, 2010; Cook, 2014; Andrew, 2016; Byrne et al., 2019). However, due to resource constraints in New Zealand, in particular for grazing land, it would be unmanageable to finish all surplus dairy calves for beef at the age of 18 to 33-months. Young beef production is a possible solution which can optimize land constraints and the number of animals finished for beef (French, 2010; Cook, 2014; Andrew, 2016; Byrne et al., 2019; Lynch and French, 2019).

The concept of young beef production in a New Zealand setting would utilize dairy-origin cattle slaughtered less than 14-months of age (Hunt et al., 2019; Pike et al., 2019; Addis et al., 2020). It would potentially allow a greater number of cattle to be managed in grazing systems for beef production and provide a faster rotation of animals from birth to slaughter (Kelly and Crosson, 2010; Herron et al., 2019). Young beef production also has potential to reduce the environmental footprint compared to traditional beef cattle finishing systems (Herron et al., 2019; Lynch and French, 2019). Animals of a similar age are already produced in Europe and marketed under different descriptions such as Jungrindfleisch (Austria, German), rose veal (Ireland), or carne de ternera (Spain) (Albertí et al., 2005; Domaradzki et al., 2017).

However, there is currently no study which examines the effects of young beef cattle production compared to the existing traditional beef cattle production systems in terms of feed consumption, animal productivity and farm profitability for pasture-based beef cattle finishing farms in New Zealand. Without this knowledge, farmers would not have the confidence to change to a young beef cattle system or a mix of young and traditional beef cattle on beef cattle and sheep farms.

Therefore, this study was initiated with specific objectives of examining feed demand and utilization, animal performance and farm profitability in a pasture-based production system that incorporates young beef cattle slaughtered at the ages of 8, 10, 12 or 14-months on Class 5 beef cattle and sheep farms. A profit maximization model that had previously been developed (Chapter IV) for this farm class was modified to include young beef cattle with or without decreasing traditional beef cattle within the system to identify the optimum number of young and traditional beef cattle and the marketing policies for the given feed resources to optimize feed utilization and farm profitability. The output from this new model will provide insight to farm advisors and farmers regarding to the potential use of young beef cattle finishing system under New Zealand's pasture-based farming conditions.

Material and methods

A profit maximization farm model for a Class 5 pasture-based, intensive finishing beef cattle and sheep farm in the North Island of New Zealand was developed using linear programming (Chapter IV). Detail descriptions of the model development, input and output parameters were reported in Chapter IV. Briefly, the model was developed for a one-year horizon using bi-monthly periods. This allows nonlinear pasture growth rates to be transformed into linear rates, thereby creating linear relationships between feed supply and animal demand. This also enabled live weight gains of growing livestock to be combined into bi-monthly periods. Thus, the model enabled the calculation of the number of beef cattle and sheep in bi-monthly periods based on the carrying capacity of the given feed supply and the determination of the type and number of beef cattle and sheep that should be sold at any given bi-monthly period. In the model, the sheep proportion of total farm feed intake was assumed to be constant and the sheep:beef cattle ratio was fixed (50:50 respectively), which allowed the study to focus on the beef cattle aspect of the enterprise (Chapter IV).

Total kilograms of pasture dry matter mass (kg DM) was the sum of residual post-grazing pasture and the net pasture accumulation in bi-monthly periods (Ridler et al., 1987; Litherland et al., 2002; Li et al., 2011; Brookes and Nicol, 2017). Utilizable kg DM of pasture was estimated as functions of maximum (i.e., 2500 kg DM for beef cattle and 1800 kg DM for sheep grazing) and minimum limits (i.e., 1500 kg DM for beef cattle and 800 kg DM for sheep grazing) of the total pasture mass and utilization percent (Lambert et al., 2000; Litherland et al., 2002; Brookes and Nicol, 2017). Herbage above the maximum limits, when pasture supply exceeded animal demand, was conserved as silage and utilized during winter (Lambert et al., 2000). Silage was supplied to traditional beef cattle in their second winter and mature ewes at a maximum of 30% of the total feed intake to ensure that the allocated kg DM did not exceed gut-fill capacity (Trafford and Trafford, 2011).

The current study included a range of dairy-origin young beef cattle slaughtered at 8, 10, 12 or 14-months of age on the optimized Class 5 pasture-based, intensive finishing beef cattle and sheep farm model (optimized traditional beef cattle system).

Holstein-Frisian (33.1%), Jersey (8.6%) and Holstein-Frisian-Jersey crossbreed (48.5%) are the main dairy cattle breeds in New Zealand (Coleman et al., 2017; LIC & DairyNZ, 2021). Dairy-origin calves with greater than 14/16 Holstein-Friesian are defined as Holstein-Friesian calves and calves with greater than 14/16 Jersey are defined as Jersey calves (Hickson et al., 2015; Coleman et al., 2017; Handcock et al., 2017). Holstein-Friesian bulls are favored for bull finishing systems in New Zealand; thus they were not considered in this study (Muir et al., 2001; O'Riordan and Keane, 2010; Martin et al., 2018). This study focused on uncastrated male calves born from Kiwi dams (i.e., Holstein-Friesian-Jersey crossbred) and first calving heifers for young bull beef finishing and beef breed cross dairy breed calves for young heifer and steer beef cattle finishing (Schreurs et al., 2014; Collier et al., 2015; Coleman et al., 2016; Coleman et al., 2017).

Model scenarios

Two scenarios were considered: either with or without decreasing the number of optimized traditional beef cattle. Scenario I was based on a competitive assumption where young and traditional beef cattle were mixed and competed for a limited feed resource. In this scenario, the number of weaners and slaughtering options for traditional beef cattle were maintained the same as the optimized traditional beef cattle model. This scenario examined which class(es) of young beef cattle from heifers, steers and bulls can integrate with the existing beef cattle and sheep farm system. The subsequent effect it would have on the marketing policies of traditional beef cattle, overall feed utilization efficiency and farm profitability was examined. Scenario II replaced 25% of traditional beef cattle number with young beef cattle and studied the variations on feed utilization and farm profitability. Similarly, the slaughtering options for traditional beef cattle were maintained the same as the optimized traditional beef cattle system. The number of young beef cattle and traditional beef cattle in each of the slaughtering options were optimized for farm profitability. This scenario examined the total number of young beef cattle that could be supported with feed resource consumed by 25% of traditional beef cattle and their effect on beef cattle marketing policies. Pasture utilization and farm profitability generated from the current model were compared with the optimized traditional beef cattle and sheep model (Chapter IV). In both scenarios, the proportion of sheep feed intake was maintained the same as per the base model (Chapter IV).

Young beef cattle activities

Previous studies have examined the growth performance and carcass quality of young steers slaughtered at the ages of 8, 10 and 12-months (Hunt et al., 2019; Pike et al., 2019; Addis et al., 2020) and the growth and carcass performance of young steers vs bulls slaughtered at 11-months of age from dairy-origin cattle in New Zealand (Nakitari, 2021). Young steers and bulls were shown to have the same growth rate and carcass weight (Nakitari, 2021). Thus, this study utilized live weight information for steers (Pike et al., 2019) and assumed the same live weight gains for bulls. Dairy-origin heifers were assumed to have 10% lower weaning weight and live weight gain (Albertí et al., 2005; Albertí et al., 2008; Blanco et al., 2020) compared to male calves. To utilize excess spring pasture supply, this study extended the slaughtering ages of young beef cattle to 14-months, based on live weight gain projected from 8, 10 and 12-months old young beef cattle.

Four potential slaughtering ages at 8, 10, 12 or 14-months were allowed for each class of young beef cattle. This added three constraints and 9 or 12 beef cattle activities in the existing model (Table 21). Steers slaughtered at the ages of 8, 10 and 12-months attained dressing out percentages of 47, 48 and 50% (Hunt et al., 2019; Pike et al., 2019), respectively; the same values were assumed for young heifer and bull beef cattle (Hedrick et al., 1969; Zinn et al., 1970). Similarly, young beef cattle slaughtered at the age of 14-months were given a dressing-out percentage of 50%. Carcasses from young beef cattle were processed as one carcass class (Pike et al., 2019) and based on the existing carcass weight classification system in New Zealand, those animals would earn the manufacturing schedule beef price per kg carcass weight (NZ$ 4.50/kg carcass) (Charteris et al., 1998; B+LNZ: Economic Service, 2021).

Table 21. Age, weight and daily per head feed demand for various classes of young beef cattle (kg DM/head/day).

Age (Month)	*Average Weight (kg)	Heifer				Steer				Bull			
		Slaughter Ages				Slaughter Ages				Slaughter Ages			
		H-8	H-10	H-12	H-14	S-8	S-10	S-12	S-14	B-8	B-10	B-12	B-14
3	100	3.5	3.5	3.5	3.5	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7
	115	3.8	3.8	3.8	3.8	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
4	130	3.6	3.6	3.6	3.6	3.8	3.8	3.8	3.8	3.9	3.9	3.9	3.9
	142	3.8	3.8	3.8	3.8	4.0	4.0	4.0	4.0	4.1	4.1	4.1	4.1
5	155	4.2	4.2	4.2	4.2	4.5	4.5	4.5	4.5	4.6	4.6	4.6	4.6
	164	5.5	5.5	5.5	5.5	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7
6	180	5.7	5.7	5.7	5.7	5.9	5.9	5.9	5.9	6.0	6.0	6.0	6.0
	194	5.4	5.4	5.4	5.4	5.6	5.6	5.6	5.6	5.7	5.7	5.7	5.7
7	206	6.2	6.2	6.2	6.2	6.4	6.4	6.4	6.4	6.5	6.5	6.5	6.5
	222	6.5	6.5	6.5	6.5	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8
8	237	5.9	5.9	5.9	5.9	6.2	6.2	6.2	6.2	6.3	6.3	6.3	6.3
	249	6.1	6.1	6.1	6.1	6.4	6.4	6.4	6.4	6.5	6.5	6.5	6.5
9	261		6.1	6.1	6.1		6.4	6.4	6.4		6.5	6.5	6.5
	273		6.3	6.3	6.3		6.6	6.6	6.6		6.7	6.7	6.7
10	286		4.6	4.6	4.6		5.8	5.8	5.8		6.0	6.0	6.0
	293		4.7	4.7	4.7		5.9	5.9	5.9		6.1	6.1	6.1
11	301			5.3	5.3			6.0	6.0			7.0	7.0
	308			5.4	5.4			6.1	6.1			7.1	7.1
12	316			6.7	6.7			7.6	7.6			8.4	8.4
	331			6.9	6.9			7.8	7.8			8.6	8.6
13	347				7.2				8.2				9.0
	362				7.4				7.9				8.8
14	377				7.7				8.2				9.2
	392				7.1				8.4				9.4

* The average weights are for steers/bulls (the corresponding heifers weights can be estimated as 90% of these values). H: heifers, S: steers, B: bulls, 8: young beef cattle slaughtered at 8-months of age, 10: young beef cattle slaughtered at 10-months of age, 12: young beef cattle slaughtered at 12-months of age, 14: young beef cattle slaughtered at 14-months of age.

Feed demand estimation for young beef cattle

Per head daily metabolizable energy requirements were estimated using equations from Brookes and Nicol (2017). Energy requirement for maintenance was adjusted by plus or minus 7% for pasture where MJ ME/kg DM less than or greater than 10.5, respectively (Brookes and Nicol, 2017), as per the base model (Chapter IV). Similarly, energy requirement for average daily gain was adjusted by plus or minus 10% for pasture energy density less than or higher than 11.0 MJ ME/kg DM (Brookes and Nicol, 2017), respectively. The sum of energy for maintenance and live weight change was converted into kg DM (Table 21) using the energy density of the given feed resource and multiplied by the number of days in a bi-monthly period to arrive at a per head bi-monthly kg DM requirement. On average, young beef cattle were given four stock units (a stock unit in New Zealand is defined as the annual feed requirement of a 55 kg ewe weaning one 28 kg lamb consuming 550 kg DM per year) (Trafford and Trafford, 2011; Farrell et al., 2019).

Annual sheep and beef farm expenditure for a Class 5 intensive finishing beef cattle and sheep farm from (B+LNZ: Economic Service, 2021) was used to estimate per stock unit farm expenditure as per the base model (Chapter IV). The per stock unit production costs were evenly distributed across the bi-monthly periods (Table 21). Total farm expenditure (TFE) was computed by multiplying the per stock unit expenditure with the number of young beef cattle in each slaughtering age, their associated stock units and the number of bi-monthly periods (Table 22) plus the cost of purchasing weaners at three-months age (NZ$ 450.00/head).

Table 22. Bi-monthly per stock unit expenditure for various inputs of young beef cattle production.

Production Cost Cattle	Young Cattle Slaughtered at 8-months	Young Cattle Slaughtered at 10-months	Young Cattle Slaughtered at 12-months	Young Cattle Slaughtered at 14-months
Seed	0.61	0.81	1.01	1.22
Cultivation and sowing	0.52	0.69	0.86	1.03
Feed and grazing	1.26	1.68	2.10	2.53
Weed and pest	0.67	0.90	1.12	1.35
Wages and salaries	2.69	3.59	4.48	5.38
Animal health	1.16	1.54	1.93	2.32
Fertilizer and lime	3.77	5.03	6.29	7.55
Vehicles and fuel	1.69	2.25	2.81	3.37
Electricity	0.24	0.32	0.40	0.48
Other	14.47	19.29	24.11	28.94
Sum	27.07	36.09	45.11	54.14

Per hectare carcass outputs in both scenarios and the optimized traditional beef cattle system were estimated as total carcass weight divided by the effective land size (Ashfield et al., 2014). The gross farm revenue (GFR) was estimated as the sum of revenue from beef cattle and sheep activities including young beef cattle (Chapter IV). Total farm expenditure (TFE) was subtracted from GFR to determine farm earnings before tax (EBT/farm). From that figure, gross farm revenue per hectare (GFR/ha) and per stock unit (GFR/su), earnings before tax per hectare (EBT/ha) and per stock unit (EBT/su) were derived by dividing by the effective farm area (198 ha) and total stock units, respectively (B+LNZ: Economic Service, 2021).

Results

Scenario I and Scenario II finished a total of 212 and 270 beef cattle per year which were 6% and 35% higher compared to the optimized traditional beef cattle system (Table 23). These scenarios finished 90% and 84% of the traditional beef cattle before the second winter, respectively. In Scenario I, there were no young heifer beef cattle while 67% of the young steer and bull beef cattle were finished at the age of 10-months. In Scenario II, 55% of young beef cattle were slaughtered at the age of 8-months (Table 23).

There were no steers slaughtered at 30-months of age in Scenario I as per the optimized traditional beef cattle system.

Table 23. The number of weaner steers and bulls, finished steers (S-18, S-28, S-30) and bulls (B-16, B-18, B-20 and B-22) (sold for meat processing), young heifers, steers and bulls finished at 8, 10, 12 and 14-months of age and breeding ewes and rams, prime lambs (sold for meat processing) and store lambs (sold to other farmers for finishing) and prime and replacement hoggets (between 4 to 16-months of age, mated at 8-months of age) and their equivalent stock units in the optimized beef cattle system, Scenario I and Scenario II.

Beef Cattle and Sheep Classes	Optimized Traditional Beef Cattle System †	Scenario I		Scenario II	
		8 to 12	8 to 14	8 to 12	8 to 14
Steer weaners	100	100	100	75	75
S-18	55	100	100	58	58
S-28	45			13	13
S-30				4	4
Bull weaners	100	100	100	75	75
B-16	7	10	8		
B-18	44	7	7	47	47
B-20	36	63	74	28	6
B-22	13	20	11		22
Young heifer weaners				40	40
H-8				8	
H-10				32	3
H-12					
H-14				NA	37
Young steer weaners		2	2	40	40
S-8				26	26
S-10			2	14	14
S-12		2			
S-14		NA		NA	
Young bull weaners		10	10	40	40
B-8				40	40
B-10		8	10		
B-12		2			
B-14		NA		NA	
Total beef cattle number	200	212		270	
Breeding ewes	1,100	1,100	1,100	1,100	1,100
Store lambs	345	345	345	345	345
Prime lambs	704	704	704	704	704
Replacement hoggets	330	330	330	330	330
Rams	11	11	11	11	11
Stock unit *	3,141	3,170	3,173	3,204	3,204

† Optimized traditional beef cattle system: The traditional steers and bulls optimized using linear programming developed by (Chapter IV). * Stock unit: average throughout the year; S-18: rising two-year steers (slaughtered at the age of 18-months); S-28 and S-30: rising three-year steers (slaughtered at the ages of 28 and 30-months); B-16, B-18, B-20 and B-22: rising two-year bulls (slaughtered at the ages of 16, 18, 20 and 22-months); H-8: heifers slaughtered at 8-months of age; H-10: heifers slaughtered at 10-months of age; H-12: heifers slaughtered at 12-months of age; H-14: heifers slaughtered at 14-months of age; S-8: steers slaughtered at 8-months of age; S-10: steers slaughtered at 10-months of age; S-12: steers slaughtered at 12-months of age; S-14: steers slaughtered at 14-months of age B-8: bulls slaughtered at 8-months of age; B-10: bulls slaughtered at 10-months of age; B-12: bulls slaughtered at 12-months of age; B-14: bulls slaughtered at 14-months of age; 8 to 12: young beef cattle slaughtered at the age of 8, 10 and 12-months; 8 to 14: young beef cattle slaughtered at the age of 8, 10, 12, 14-months of age; NA: no data reported.

Pasture available for beef cattle grazing in spring went up to 35 kg DM/ha/day and dropped below 10 kg DM/ha/day during the winter season. In Scenario I, pasture supplied 98% of feed requirements (Figure 10). Of the total feed available for beef cattle activities, 83% was consumed.

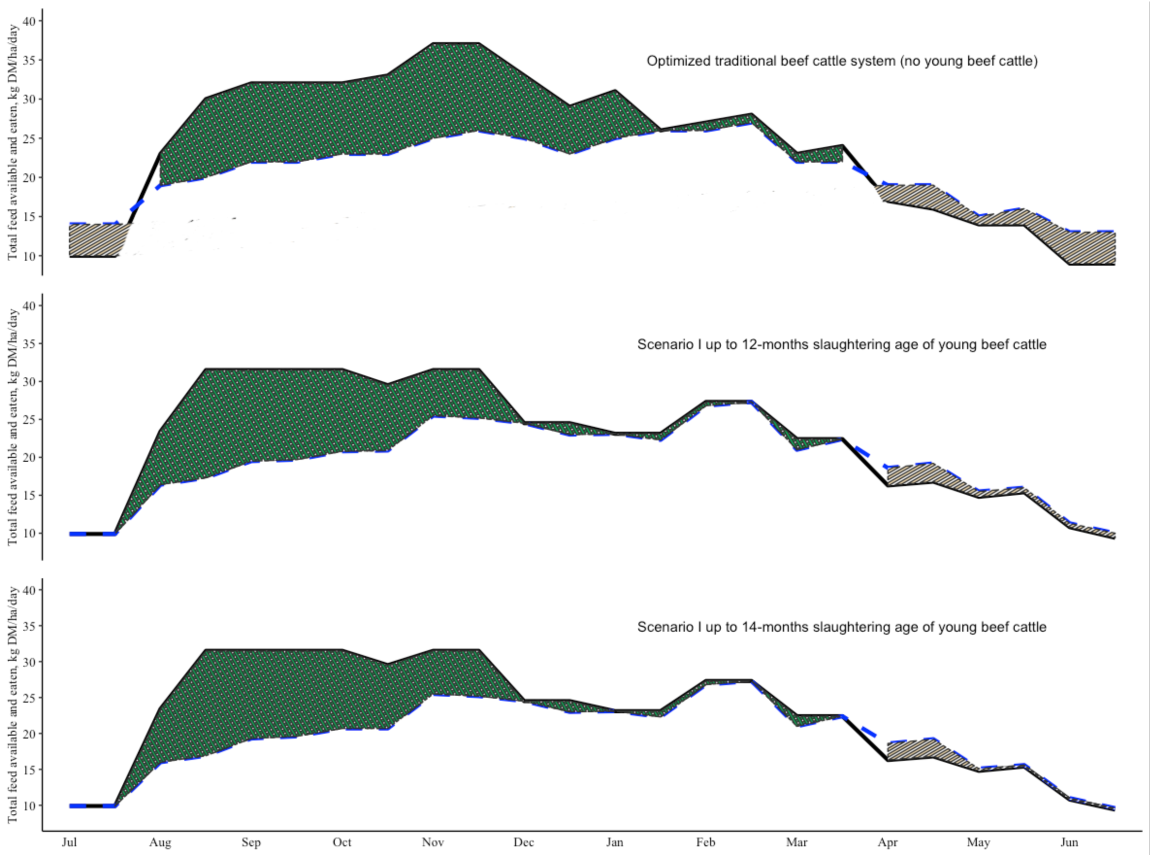

Figure 10. Utilizable pasture available (black line) and eaten by the beef cattle activity (blue dashed line which included silage) in the Optimized system and Scenario I throughout the year. The excess available herbage (i.e., neither utilized nor processed for silage) is indicated by the green shaded area and the deficient available herbage (i.e., where cattle requirements were greater than the available pasture) which was supplemented with silage as indicated by the striped area.

LP: Young beef cattle production

In Scenario II, where 25% of the traditional beef cattle were replaced with young beef cattle slaughtered at the ages of 8 to 12-months, there was a feed utilization efficiency of 79% (Figure 11). This was increased to 83% when the slaughtering age of young beef cattle extended up to 14-months of age (Figure 11). Pasture provided 98% of the feed requirements of beef cattle activity in Scenario II with the rest of feed provided by silage.

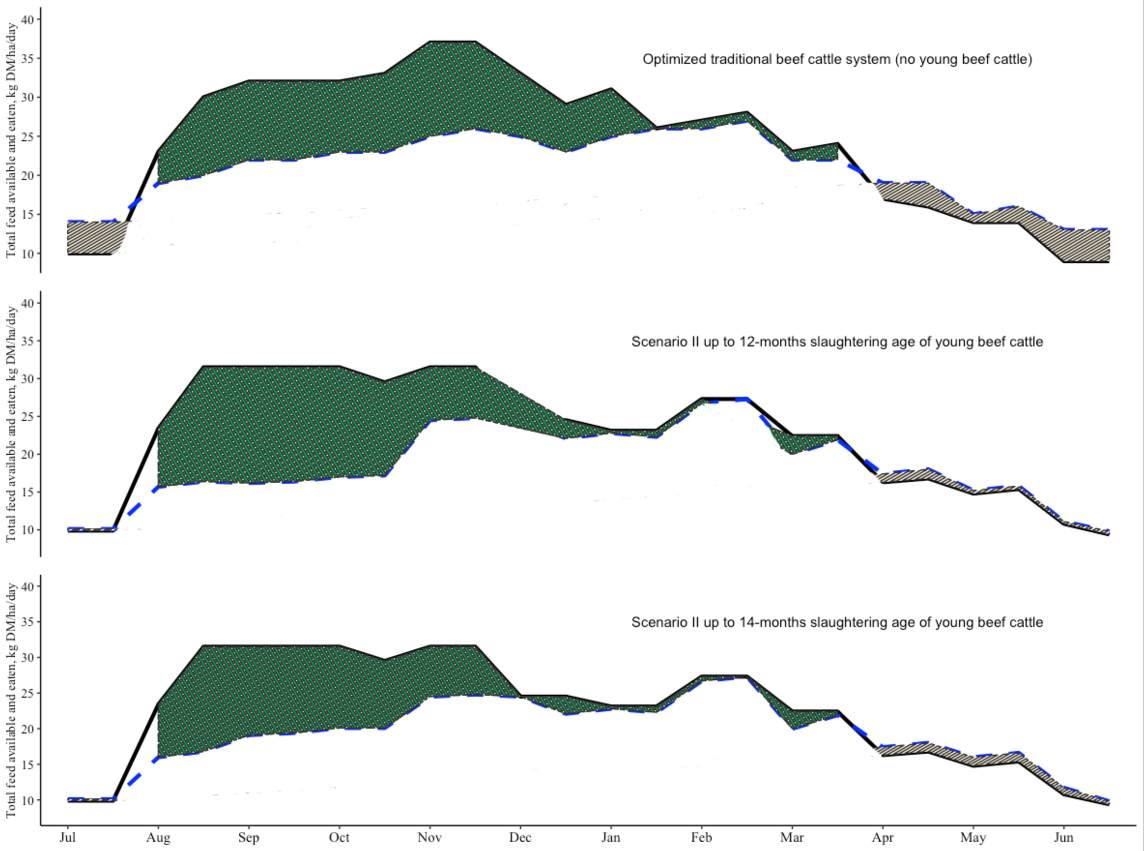

Figure 11. Utilizable pasture available (black line) and eaten by the beef cattle activity (blue dashed line which included silage) in the optimized system and Scenario II throughout the year. The excess available herbage (i.e., neither utilized nor processed for silage) is indicated by the green shaded area and the deficient of available herbage (i.e., where cattle requirements were greater than the available pasture) which was supplemented with silage is indicated by the striped area.

On average, the optimized traditional beef cattle system, Scenario I and Scenario II produced 544.19, 549.30 and 566.41 kg carcasses per hectare per year, respectively (data not shown). At these carcass outputs, Scenario I and Scenario II had 2% less GFR/ha than that of the optimized system (Table 24). However, the average EBT/ha in Scenario I and Scenario II were 15% and 25% higher than that of the optimized traditional beef cattle system (Table 24).

Table 24. Total, per hectare, and per stock unit values of the gross farm revenue (GFR), total farm expenditure (TFE), and farm earnings before tax (EBT) of beef cattle and sheep activity for the optimized system, Scenario I and Scenario II.

Systems		Beef Cattle	Sheep	Total	Total Per Hectare	Total Per Stock Unit
		NZ$	NZ$	NZ$	NZ$/ha	NZ$/SU
Optimized traditional beef system †	GFR	297,700.39	175,820.19	473,520.57	2,391.52	150.78
	TFE	207,523.49	73,789.22	281,312.71	1,420.77	89.57
	EBT	90,176.90	102,030.97	192,207.86	970.75	61.20
Scenario I (8–12)	GFR	291,321.51	175,820.19	467,141.69	2,359.30	147.36
	TFE	172,114.98	73,789.22	246,522.81	1,245.06	77.77
	EBT	119,206.52	102,030.97	220,618.88	1,114.24	69.60
Scenario I (8–14)	GFR	289,300.37	175,820.19	465,120.56	2,349.09	146.59
	TFE	169,558.23	73,789.22	243,966.06	1,232.15	76.89
	EBT	119,742.15	102,030.97	221,154.51	1,116.94	69.70
Scenario II (8–12)	GFR	283,556.54	175,820.19	459,376.73	2,320.08	143.37
	TFE	148,076.59	73,789.22	222,484.42	1,123.66	69.44
	EBT	135,479.95	102,030.97	236,892.30	1,196.43	73.93
Scenario II (8–14)	GFR	291,775.45	175,820.19	467,595.64	2,361.59	145.93
	TFE	148,044.68	73,789.22	222,452.51	1,123.49	69.43
	EBT	143,730.77	102,030.97	245,143.13	1,238.10	76.50

† Optimized traditional beef cattle system: The traditional steers and bulls identified using linear programming developed by (Chapter IV); 8 to12: young beef cattle slaughtered at the ages of 8, 10 and 12-months; 8 to 14: young beef cattle slaughtered at the ages of 8, 10, 12, 14-months of ages.

Discussion

Raising young (8 to 14-months of age) dairy-origin beef cattle is a new beef production system being considered in New Zealand and thus understanding their growth, productivity and profitability on beef cattle and sheep farms would benefit farmers and farm advisors. This study scrutinized the feed demand and pasture utilization, growth, productivity performance and farm profitability of young beef cattle slaughtered at the ages of 8, 10, 12, 14-months on Class 5 intensive finishing beef cattle and sheep farms in New Zealand. A linear programming profit optimization model which was developed for the traditional beef cattle finishing system of this farm class (Chapter IV) was modified to include a young beef cattle production system and identified the total number of young and traditional beef cattle and marketing policies for the given feed resource to maximize farm profitability and pasture utilization.

Young animals need less total feed per day for maintenance and growth (do Prado et al., 2015; Gibbs et al., 2015; Brookes and Nicol, 2017) which enabled Scenario I and Scenario II to finish 6% and 35% more beef cattle than the optimized traditional beef cattle system. This was achieved by finishing 70% to 83% young beef cattle under 10-months of ages and more than 90% (Scenario I) and 84% (Scenario II) of traditional beef cattle before the second winter. This meant that a higher number of lightweight beef cattle can be finished with the same amount of feed resource consumed by heavier beef cattle. Previous studies conducted by (McRae, 2003; Kelly and Crosson, 2010; Herron et al., 2019) also identified that the young beef cattle slaughtering system allowed higher stocking rate and greater throughput of beef cattle per hectare which increases per hectare productivity. This implies a mix of young and traditional beef cattle production system would allow farmers to run a greater number of beef cattle per hectare to increase their profitability.

The current model was developed at the farm-level where the pasture mass for beef cattle grazing had minimum and maximum limits between 1500 and 2500 kg DM/ha following the modelling rules imposed in the optimized traditional beef cattle system (Chapter IV). The beef cattle continuously grazed throughout the farm. However, paddock-based rotational grazing allows more flexible maximum and minimum pasture limits than continuous grazing (Boswell and Cranshaw, 1978; Smeal et al., 1981; Conway and Killen, 1987; Undersander et al., 2002). Thus, partitioning the whole farm into paddocks for rotational grazing would allow beef cattle grazing below 1500 kg DM/ha during winter in individual paddocks. This practice would allow feeding of a higher number of beef cattle during winter to increase spring pasture utilization.

Finishing of 1.9 million bobby calves (New Zealand Statistics, 2022) at an average age of 24-months, would require approximately 8360 million kg DM or 760,000 ha of extra land. Alternatively, these could be finished as young beef cattle, requiring 50% less kg DM of pasture for feed. Numerical and profitability outputs of Scenario II of the current study showed a pathway to a more efficient and profitable, mixed young and traditional beef cattle production system in New Zealand. Similarly, Cook (2014) reported that processing a high number of beef-cross-dairy breed calves for beef provides a pathway to a more efficient and profitable beef production system in New Zealand. This would facilitate the need to increase the proportion of selected bull semen to breed with dairy cows to modify the genetic orientation of dairy-origin cattle for beef and to make sure that fast-growing dairy-origin calves are available for young beef production (Cook, 2014; Andrew, 2016). Progeny testing evaluation of Angus and Hereford sires on improving the live weight of dairy-origin cattle by Martín et al. (2020) has shown the use of appropriate beef sires has a potential to increase live weight and growth of cattle born on dairy farms.

Older (two years old) beef cattle are a flexible stock class due to their ability to accommodate short term feed supply changes (Brookes and Nicol, 2017). The current study provided silage for beef cattle in their second winter at a maximum of 30% of the total kg DM. In both Scenarios I and II, silage supplied 2% of the total feed demand for beef cattle activity. The total pasture utilization of Scenario I and Scenario II of the current study was nearly the same as total feed utilization of the optimized traditional beef cattle system. A study conducted by Ashfield et al. (2014) identified that young beef cattle had higher pasture utilization than older cattle. This indicates that a young beef cattle production system could be an alternative to improve pasture utilization where conserving excess pasture as silage is impractical for the reasons of high processing cost or unsuitable landscape including hill and hard hill country beef cattle and sheep farms of New Zealand (Lambert et al., 2000; Gray et al., 2004; Daniell and Buckley, 2015).

Conserving the excess spring pasture as silage/hay is costly (Undersander et al., 2002) and practically difficult on the majority of beef cattle and sheep farm classes in New Zealand (Lambert et al., 2000; Carracelas et al., 2008). Spring-born 3-month old weaners coming into the beef finishing system in November of the current study increased pasture utilization. Buying earlier-born heavier weaners (for example, October weaners) would further increase spring pasture utilization, which would assist in controlling pasture quality. This would also help to make sure that animals attained the expected slaughter weight before the traditional pasture supply decline during the winter season (Gibbs et al., 2015). The current study did not consider alternative feed sources such as buying supplementary winter feed (Lambert et al., 2000; Ashfield et al., 2014), or growing winter forage, which may allow a higher number of young beef cattle to be considered (Lambert et al., 2000; Carracelas et al., 2008).

Mixed young and traditional beef cattle slaughtering systems in Scenario I and Scenario II increased carcass outputs per hectare by 1% and 4% respectively than that of the optimized beef cattle system. At these carcass outputs, each scenario returned 2% lower GFR/ha, however, 15 and 25% higher EBT/ha in Scenario I and Scenario II respectively compared to the optimized beef cattle system. Similarly, Ashfield et al. (2014) and Cook (2014) reported that young beef cattle production can improve farm profitability. Combined, this indicates that beef cattle farmers would improve their per hectare farm profitability with less production cost by rearing young and traditional beef cattle (Muir et al., 2001).

There is no carcass classification and grading system for young beef cattle in New Zealand (Chapter III) and the current study processed them as one class (Pike et al., 2019) at manufacturing beef price (NZ$ 4.50) (Charteris et al., 1998). A premium price of NZ$ 5.00 per kg carcass by targeting different markets was simulated (Hunt et al., 2019). At this price, GFR/ha in Scenario I remain unchanged, however, Scenario II returned nearly the same GFR/ha as the optimized traditional beef cattle system (data not shown). This can be explained by variations across scenarios, where Scenario II finished 90% more young beef cattle than that of Scenario I. Earnings before tax (EBT/ha) in Scenario I and Scenario II were increased by 15% and 29% compared to the optimized traditional beef cattle farm when a price of NZ$ 5.00 per kg carcass was modelled (data not shown).

Young beef cattle production enabled the supply of beef cattle staring from 8-months of age. This would allow farmers to supply beef year round when finished traditional beef cattle supply in New Zealand is scarce (Brennan, 2010; O’Riordan and Keane, 2010). This practice may also favor young beef to earn a higher price per kg carcass, by reducing competition on the beef market with traditional beef cattle carcass at the periods of year when traditional beef in short supply (O’Riordan and Keane, 2010).

Conclusions

Young beef production enabled the modelled farm to process a higher number of beef cattle per hectare and greater throughput of beef cattle from weaning to slaughter per hectare. Beef cattle farmers in New Zealand would be able to extend their beef cattle slaughtering pattern across the year and farm profitability by including young beef cattle slaughtered between 8 to 14-months of ages. This improved pasture utilization and decreased silage use. Both scenarios resulted in lower production costs, but, higher EBT compared to the optimized traditional beef cattle system. Further studies to understand the effect of young beef cattle production on sheep:cattle ratio and the complementarity of sheep and young beef cattle would be valuable.

Forward to chapters VI and VII

Chapters IV and V of this study identified pasture utilization and farm profitability of traditional and young beef cattle production systems at farm-level. However, the profitability of beef cattle enterprise and the uptake of young beef cattle cannot be solely determined by the finishing farmers. Behaviours from other agents including rearers, processors and consumers which cannot be represented by the optimization model play significant roles on the uptake of beef cattle. Thus, Chapter VI developed an agent-based modelling for traditional beef cattle finishing system using dairy-origin cattle. This was then modified in Chapter VII to included young beef cattle at different price scenarios. Both chapters utilized specific attributes of rearers, finishers and processors to select profitable beef cattle from the available dairy-origin beef cattle.

Chapter VI

Agent-Based Modelling to Improve Beef Production from Dairy cattle: Model Development and Evaluation

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Abstract

Agent-based modeling (ABM) enables an *in silico* representation of complex systems and captures agent behavior resulting from interaction with other agents and their environment. This study developed an ABM to represent a pasture-based beef cattle finishing systems in New Zealand (NZ) using attributes of the rearer, finisher, and processor, as well as specific attributes of dairy-origin beef cattle. The model was parameterized using values representing 1% of NZ dairy-origin cattle, and 10% of rearers and finishers in NZ. The cattle agent consisted of 32% Holstein-Friesian, 50% Holstein-Friesian–Jersey crossbred, and 8% Jersey, with the remainder being other breeds. Rearers and finishers repetitively and simultaneously interacted to determine the type and number of cattle populating the finishing system. Rearers brought in four-day-old spring-born calves and reared them until 60 calves (representing a full truck load) on average had a live weight of 100 kg before selling them on to finishers. Finishers mainly attained weaners from rearers, or directly from dairy farmers when weaner demand was higher than the supply from rearers. Fast-growing cattle were sent for slaughter before the second winter, and the remainder were sent before their third winter. The model finished a higher number of bulls than heifers and steers, although it was 4% lower than the industry reported value. Holstein-Friesian and Holstein-Friesian–Jersey-crossbred cattle dominated the dairy-origin beef finishing system. Jersey cattle account for less than 5% of total processed beef cattle. Further studies to include retailer and consumer perspectives and other decision alternatives for finishing farms would improve the applicability of the model for decision-making processes.

Keywords: agent-based modeling; dairy cattle; beef finishing; rearer; finisher

Introduction

New Zealand annually produces approximately 679,000 tonnes of beef carcass (New Zealand Statistics, 2022), of which 80% is exported (McDermott et al., 2005; Morris, 2013a; van Selm et al., 2021). This accounts for 6% of the global beef trade (FAO, 2021; B+LNZ, 2022). A significant proportion of New Zealand beef cattle is supplied from the dairy industry and includes calves that are surplus to the dairy sector replacement requirements (Morris, 2013a; Schreurs et al., 2014; Hickson et al., 2015; van Selm et al., 2021). From the total calves weaned for heifer, steer and bull beef finishing systems, 58% originate from the dairy sector (Davison, 2020; van Selm et al., 2021).

The number of calves originating from the dairy industry that are ultimately processed for beef production requires successful co-operation between rearers, finishers, processers and consumers (Muir et al., 2001; Muir et al., 2002; Oliver and McDermott, 2005; Andrew, 2016; van Selm et al., 2021). The interaction among and between these sectors creates a phenomenon that cannot be simply explained by any single agent (Bonabeau, 2002; Sajjad et al., 2016; Falco et al., 2019; Lippe et al., 2019; Mohan et al., 2019), nor can the collective behaviour from these complex interacting sectors be captured by static mechanisms of modelling (Sajjad et al., 2016).

Modelling systems such as agent-based modelling (ABM) are instead required to capture the behaviours of all agents and their subsequent behaviours that are derived from their interactions (Bonabeau, 2002; Sajjad et al., 2016; Falco et al., 2019; Lippe et al., 2019; Mohan et al., 2019). Agent-based modelling is a computational approach based on simulation which describes how agents behave depending on the behaviour of other agents and their environment (Bankes, 2002; Bonabeau, 2002; Sajjad et al., 2016; Falco et al., 2019; Lippe et al., 2019; Mohan et al., 2019; Sergeyev and Lychkina, 2019). In ABM, agents are autonomous but are capable of adapting and anticipating behaviours that emerge during interactions (Bonabeau, 2002). Agent-based modelling allows for repetitive and competitive interactions between agents which enables the exploration of dynamics over time (Axelrod, 1997; Epstein et al., 1998; Bonabeau, 2002; Macal and North, 2005).

To date, only a few studies have been conducted to understand the application of *in silico* ABM representation of socioeconomic and ecological impacts within a livestock production system (Schouten et al., 2014; Rasch et al., 2016). Agent-based modelling has been employed to understand beef cattle production and transportation issues in Southwest Kansas USA (Yang et al., 2019), to compare beef reproductive strategies in Brazil (Ojeda-Rojas et al., 2021), and to represent beef consumption behaviour in the United Kingdom (Scalco et al., 2019).

The current study developed an ABM to represent the New Zealand beef production chain using rearers, finishers and processors as agents and accounting for specifics of individual animals such as their breed and sex. It includes stochastic elements that can account for random variables such as date of birth, birth weight, and growth rate and calves per head prices as well as variable attributes of rearers, finishers and processors. The study defined the availability of dairy-origin beef cattle in New Zealand accounting for the expected proportions of heifer, steer and bull calves. The simulation was parameterised based on calves born in 2018 from the dairy industry (New Zealand Statistics, 2022). Among these, some of the fastest growing cattle were finished and harvested in 2019 and the remainder in 2020 (B+LNZ: Economic Service, 2021; B+LNZ, 2022). The total number of dairy-origin heifers, steers and bulls that were slaughtered were compared with values reported by Beef and Lamb New Zealand (Davison, 2020).

Material and methods

The Julia programming language

The attributes of rearers, finishers and processors to characterise dairy-origin heifers, steers and bulls finished in New Zealand were simulated using Agents.jl (Vahdati, 2019) in Julia version 1.7.1 (https://julialang.org/). Julia is a dynamic programming language designed to address the requirements of high performance numerical and scientific computing (https://julialang.org/). A simplified version of the chain of dairy-origin beef cattle production system in New Zealand and the main agents involved in the current study are presented in Figure 12.

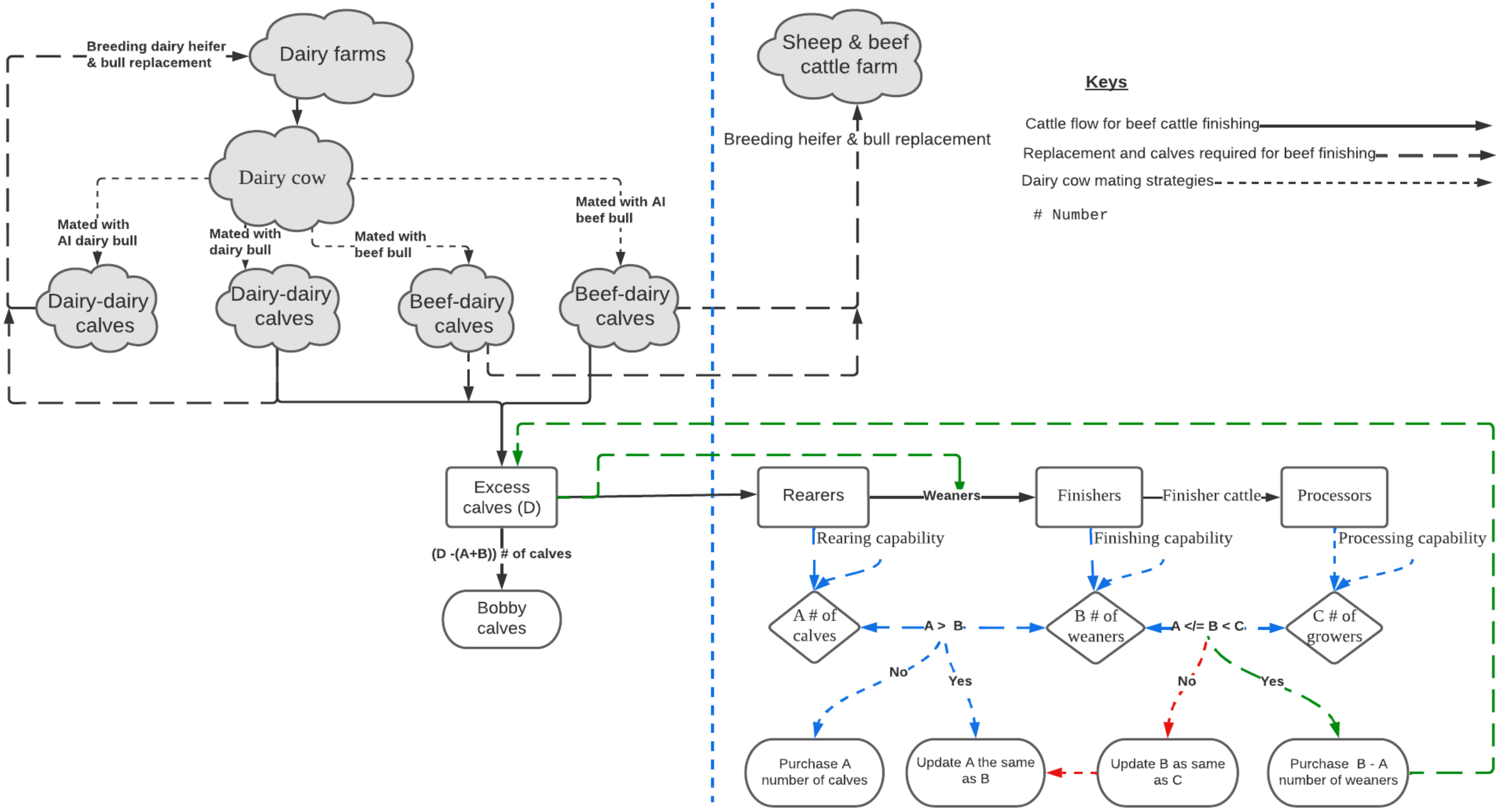

Figure 12. Agent interactions that determine the number and type of dairy-origin cattle entering the beef production chain (agents are represented by the rectangular boxes, the diamond boxes are decisions made by agents, the oval boxes are the final decisions to be executed).

The beef production chain includes a dynamic supply of dairy-origin cattle, which are respectively owned by rearers, finishers and then beef processors as agents (Figure 12). Dairy-origin cattle comprise various breeds of calves for heifers, steers and bulls finishing (LIC & DairyNZ, 2021). Rearers purchase 4-day old calves, raise them to weaning then on-sell them to finishers (Ormond et al., 2002; McRae, 2003) based on constraints determined by their calf rearing capability and the demand for weaners by finishers. If the demand for weaners was less than the rearers calf rearing capability, they decreased the number reared to meet the finisher's weaner demand (Figure 12). Finishers mainly purchased weaners from rearers, however, if the rearer weaner supply was insufficient, they sourced more weaners via a special agreement from dairy farms (i.e., this motivates dairy farmers to wean calves and on-sell to finishers). The processor agent purchased finished dairy-origin beef cattle processed from New Zealand in the range of 9,500 ± 100. This allowed finishing farmers to update their weaner intake and consequently the calf rearers to adjust their calf intake (Figure 12).

Description of agents

Dairy-origin beef cattle

In New Zealand nearly 58% of calves for heifer, steer and bull finishing are sourced from the dairy industry (Figure 13) (van Selm et al., 2021; New Zealand Statistics, 2022). Holstein-Friesian (32.5%), Jersey (8.2%) and Holstein-Friesian-Jersey crossbred (49.6%) are the main dairy cattle breeds utilized (Coleman et al., 2017; LIC & DairyNZ, 2021). Dairy-origin calves that are greater than 14/16ths Holstein-Friesian are defined as Holstein-Friesian and calves that are greater than 14/16ths Jersey are defined as Jersey calves (Hickson et al., 2015; Coleman et al., 2017; Handcock et al., 2017). Jersey calves are on-average lighter and grow slower than the other breeds (Muir et al., 2001; Muir et al., 2002; Ormond et al., 2002; Hickson et al., 2015; Coleman et al., 2017; Handcock et al., 2017; Berry et al., 2018), producing lighter carcasses, which have yellower fat than their contemporaries at slaughter (Barton et al., 1994; McNamee et al., 2015; Coleman et al., 2016; Coleman, 2016). These traits result in prejudices against the purchase of Jersey type calves and reduce their acceptance by rearers and finishers for beef finishing (Muir et al., 2001; Muir et al., 2002; Ormond et al., 2002; Andrew, 2016; Coleman et al., 2017).

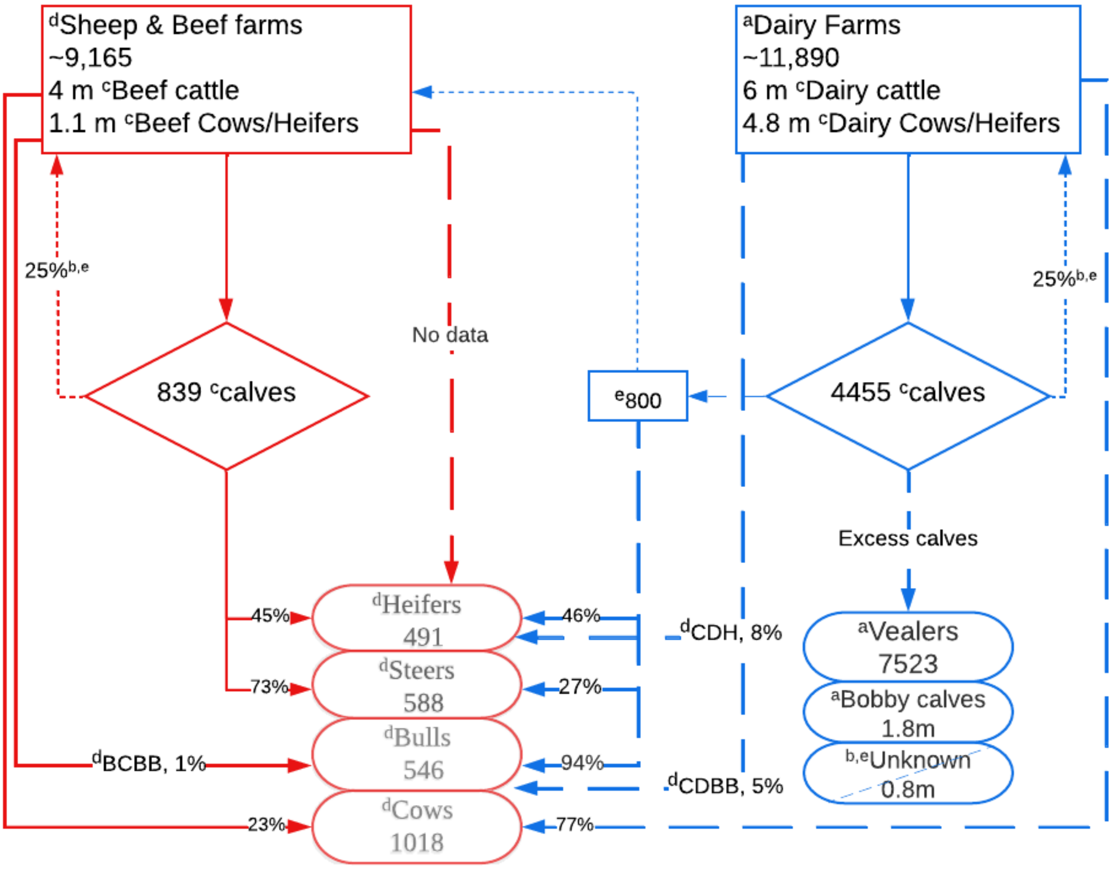

Figure 13. Sources of beef cattle in New Zealand (the red solid lines indicate beef cattle breeds and blue and red broken lines indicate dairy-origin beef cattle for finishing on beef cattle and sheep farms and blue dotted line indicate dairy-origin beef cattle for beef herd heifer replacement). BCBB: beef cull breeding bulls, CDH: cull dairy heifers; CDBB: cull dairy breeding bull; m: million and other animal, except vealers, numbers are in thousands.

Sources: a:B+LNZ (2022), b:Andrew (2016); c:New Zealand Statistics (2022), d:Davison (2020), e:van Selm et al. (2021)

Rearers

Calf rearing only requires a limited land area with housing facilities for the purpose of rearing calves to weaning (Ormond et al., 2002). Profitability is greatly affected by calf mortality, which is on average 3% (Ormond et al., 2002; Cuttance et al., 2017). In some cases, rearers are calf producers (i.e., dairy farmers) or beef cattle finishers. However, the majority of rearers purchase dairy-origin calves from 4-days old, then on-sell them to finishers as weaners at approximately 100 kg live weight (Muir et al., 2002; Ormond et al., 2002; Andrew, 2016). Rearers buy calves either directly from dairy farms or through a livestock agent (Muir et al., 2002; Oliver and McDermott, 2005). The direct calf procurement policy has some advantage of greater selectivity of calves, whereas purchasing calves via the auction system provides an opportunity to obtain a greater number of calves in a batch, although, there are risks of getting animals of unknown breed and there is a higher risk of a biosecurity breach (Muir et al., 2002).

Calf price, the availability of a secure market for selling weaners fast-growing calves are the main factors considered by rearers during calf procurement (Oliver and McDermott, 2005; Sean et al., 2019). Breed, sex, and live weight (Muir et al., 2002) have been all used to subjectively select high-quality, fast-growing calves from 4-days old. Colour of the coat, ear, nose and tongue are some of the discriminatory markers often used by rearers to identify less wanted calf-breed types, especially Jersey calves, which may be purchased at a lower price (perhaps a 50% reduced price relative to other breeds), if needed (Andrew, 2016; Coleman et al., 2017).

Finishers

There are an estimated 9,165 beef cattle and sheep farms in New Zealand with an average land area of 695 ha, supporting 6.3 stock units per hectare (su/ha) (B+LNZ:

Economic Service, 2021). On sheep and beef farms, cattle on average account for 40% of total stock units (i.e., feed consumed) (B+LNZ: Economic Service, 2021). Finishers can also be calf producers and/or rearers, however, the majority of them buy dairy-origin weaners from rearers and finish them as heifer, steer or bull beef, perhaps alongside beef cattle bred on their farm (Oliver and McDermott, 2005). Beef cattle finishing can include cattle with beef-breed and dairy-breed origins (Morris, 2013a; van Selm et al., 2021). There can be a preference for dairy-origin cattle by finishers, as they mature earlier and provide a more flexible marketing policy compared to beef-breed cattle (Oliver and McDermott, 2005; Andrew, 2016). Dairy-origin cattle contributed 60% and 50% of the total cattle processed for beef in 2019 and 2020 (van Selm et al., 2021), respectively.

The most important factors considered by finishers when purchasing beef cattle are high potential growth rate and saleable meat yield, early maturing, payment security for finished cattle (i.e., certainty to sell finished cattle) and the likely selling price (Oliver and McDermott, 2005; Andrew, 2016). Having a secured binding agreement with either rearers and/or processors and having a long-term relationship with rearers for sourcing weaners, are considered of less importance by finishers (Oliver and McDermott, 2005).

Processors

There are 60 commercial meat processing plants, excluding homekill butchers, throughout New Zealand (MPI, 2022). Of these more than half of them process both cattle and sheep whereas the others process either cattle or sheep, but not both (MPI, 2022). These plants primarily slaughter animals (excluding poultry), bone-out carcasses, and freeze or chill meat products (Ibisworld, 2021). New Zealand processed approximately 331,000 heifers, 161,000 steers and 520,000 bulls with dairy origins in 2019. In 2020 these corresponding numbers were 228,000, 159,000 and 511,000 (Davison, 2020).

Each class of finished beef cattle received different weekly published schedule prices based on carcass weight, age, conformation, muscling and fat depth (B+LNZ, 2022). Lighter heifers, steers and bulls received lower price per kg carcass weight than their counterpart premium heifers and steers (B+LNZ, 2022). The schedule payment system varied across seasons where cattle slaughtered in winter received low prices compared to other seasons. This creates a misalignment between finishers and processors (Cook, 2014; Andrew, 2016) as finishers kill a large number of their cattle in winter following the decline of feed supply (Davison, 2020). Processors are reluctant to have long term binding agreements with finishers nor to have value-based payment (Oliver and McDermott, 2005; Andrew, 2016).

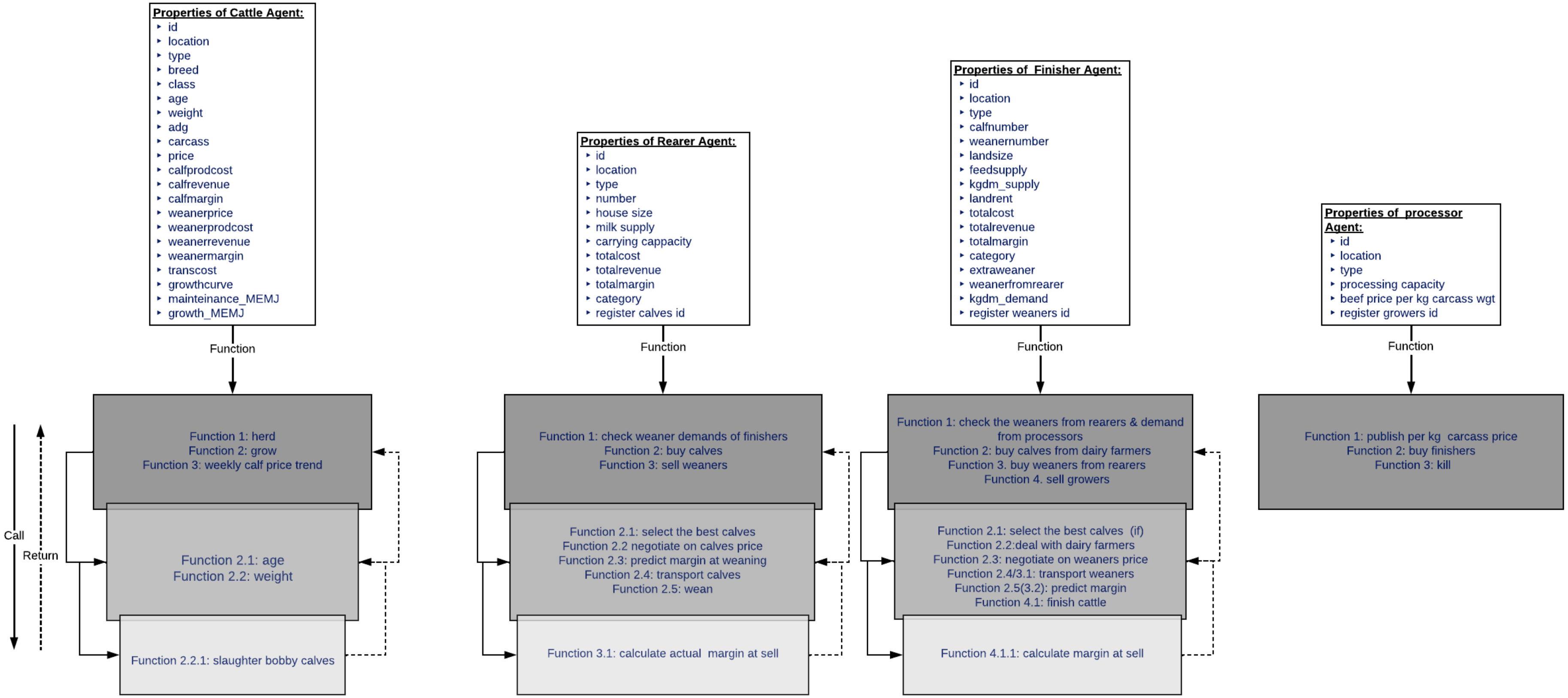

Figure 14. Properties and functions of cattle, rearers, finishers and processors agents in the chain of New Zealand's dairy-origin beef cattle production.

Figure 14 summarizes the main properties of cattle, and activities of agents representing rearers, finishers and processors as modelled in the current study and detailed in the following section.

Model parameterization

Cattle

The model was parameterised with 45,000 spring-born (July to September) dairy-origin calves (Hickson et al., 2015; Coleman et al., 2017; Handcock et al., 2017; LIC & DairyNZ, 2021) at 1:1 female to male ratio for computation (van Selm et al., 2021). Dam breed proportions were parametrized based on the breed proportions of herd-tested first calving dairy heifers over the last five years. The breed proportions were Holstein-Friesian (32%), Holstein-Friesian-Jersey cross (50%), Jersey (8%) and other (10%) (Hickson et al., 2015; Coleman et al., 2017; Handcock et al., 2017; LIC & DairyNZ, 2021). The "other" category was assigned the same properties as the Jersey breed, due to insufficient information, but could be modified in the future as new information becomes available. In each breed, 80% of the calves produced to these dams were from a dairy breed and the remaining 20% were a beef-dairy crossbred (Burggraaf, 2016). Within each dairy breed, 25% of the total female calves were excluded as they became dairy herd replacements (van Selm et al., 2021). For male calves, 50% were processed as steers and the remainder processed as bulls, except for the Holstein-Friesian breed where all male calves were finished as bull beef (Muir et al., 2001; Ormond et al., 2002; Martin et al., 2018).

The distribution of date of birth was based on the within-herd calving distribution from herd-tested dairy farms throughout New Zealand in 2019. A linearly transformed Poisson distribution function (Poisson et al., 1981) was used to provide a location parameter that along with the within-herd calving distribution locate the reconstructed national distribution of date of birth over the three-month Spring calving period. Average birth weight, slaughter weight, age at slaughter, prices per calf and per kg carcass for dairy-origin beef cattle were parameterized using data collected from various studies (Table 25). Birth weight and per head calf price were distributed with ± 2 kg and ± NZ$ 5 standard deviations (Hickson et al., 2015; Mylivestock, 2020), respectively. A multivariate normal distribution function and Cholesky factorization (Huang et al., 2013) was employed to simulate positively correlated birth weight, average growth rate, and price of calf (Coleman et al., 2021). Average birth weights for bull and steer calves were the same, however, bulls grew faster than steers (Table 25). A Richards growth equation comprising four parameters (Richards, 1959) was employed to model the growth curves of the various beef cattle breeds (Supplementary Figure 3) (Ormond et al., 2002; Handcock et al., 2017; de Sousa et al., 2021).

Table 25. Birth weight, final slaughter weight, slaughter age, per head calves and per kg live weight weaners prices of various classes of dairy-origin beef cattle.

Attributes	Holstein-Friesian			Holstein-Friesian–Jersey			[a] Jersey			Reference
	Heifer	Steer	Bull	Heifer	Steer	Bull	Heifer	Steer	Bull	
* Birth weight, kg	36.1	38.2	38.2	31.7	33.9	33.9	27.6	29.8	29.8	Hickson et al. (2015)
Minimum weight at slaughter (kg)	500	-	550	500	580	550	500	580	550	Perry et al. (1993); Hopkins and Roberts (1995); Schreurs et al. (2014); Coleman et al. (2016); Robert (2019); Martín et al. (2020); Coleman et al. (2022)
Adjusted average age at slaughter (d)	610	-	600	679[+]	896	805	700[+]	920	880[+]	Coleman et al. (2016); Lynch and French (2019); Robert (2019); Martín et al. (2020)
Calf price/head (NZD)	90	-	110	80	100	100	70	90	90	Mylivestock (2020); Interest New Zealand (2022)
Weaner price/kg live weight (NZD)	3.70	-	4.50	3.60	3.70	4.00	3.00	3.20	3.20	Mylivestock (2020); Interest New Zealand (2022)
	Beef–Holstein-Friesian cross			Beef-Holstein-Friesian–Jersey cross			Beef–Jersey cross			
* Birth weight, kg	38.3	40.2	40.2	37[+]	39[+]	39[+]	35[+]	37[+]	37[+]	Coleman et al. (2021); Coleman et al. (2022)
Minimum weight at slaughter	500	580	550	500	580	550	500	580	550	Perry et al. (1993); Hopkins and Roberts (1995); Schreurs et al. (2014); Coleman et al. (2016); Robert (2019); Martín et al. (2020); Coleman et al. (2022)
Adjusted average age at slaughter (d)	561	663	625	579[+]	689	640	600[+]	750[+]	703[+]	Muir et al. (2001); Coleman et al. (2016)
Calf price/head	95	120	120	90	110	110	75	95	95	Mylivestock (2020); Interest New Zealand (2022)
Weaner price/kg live weight	3.90	4.00	4.70	3.60	3.70	4.00	3.00	3.20	3.20	Mylivestock (2020); Interest New Zealand (2022)

* Male calves' birth weight was 2.2 kg heavier (Hickson et al., 2015); [+] estimated based on the value of other classes and breeds; [a] includes "other breed" category; heifers, steers and bulls carcass weights were estimated as 50, 54, and 52 % of live weight, respectively (Perry et al., 1993; Hopkins and Roberts, 1995; Muir and Thomson, 2008).

Early born calves earn higher per head prices compared to later born calves (Ormond et al., 2002), therefore the per head calf price dropped 5% per week from the previous price for unselected calves and late born calves (Mylivestock, 2020). In this process, if the calf price dropped lower than the bobby calf price (i.e., NZ$ 2 per kg live weight) (Farmersweekly, 2021), the unsold calves were slaughtered at 16-days of age (Cook, 2014; Andrew, 2016; van Selm et al., 2021; MPI, 2022; New Zealand Statistics, 2022).

Rearers

There is no information about the number of rearers in New Zealand. The current study assumed the number of rearers to be 10% the number of dairy farmers (i.e., 11,890). This reduces computational effort compared to a greater number of rearers but does not compromise the heterogeneity of rearers (Bullen and Brack, 2014). Rearing capacity followed one of three Poisson distributions with 10% rearers having mean capacity of 100 calves, 80% rearers having mean capacity of 500 calves and 10% rearers having mean capacity of 1000 calves (Ormond et al., 2002; Bullen and Brack, 2014). Rearers bought-in spring-born (July to September) calves at 4-day olds in a four day interval and then sold these calves to finishers at an average weaning weight of 100 kg (Muir et al., 2002; Ormond et al., 2002; Oliver and McDermott, 2005; Thomson, 2017). If the rearers weaning capability was greater than the number needed by finishers, they subsequently adjusted the numbers reared to ensure a secured market to sell weaners (Figure 12). In contrast, when there was high weaner demand by the finishers, rearers bought additional calves up to their maximum rearing capacity to then on-sell to finishers.

For the purpose of this study, it was assumed that during calf procurement, rearers had no geographic limitations, indicating they could access all available calves and evaluate their attributes to predict weaning weight, time to weaning, production and transport costs and returns at weaning. From the given selling price of a calf, rearers started price negotiation by offering a 10 ± 2% lower purchasing price (normally distributed). This behaviour should really be attributed to dairy farmers, however, to reduce the complexity of the agents and computation time, cattle agents had this attribute on behalf of their dairy farm owners. The sellers reduced their selling price and rearers increased their purchasing price by 0.1% of their previous amount until they reached an equilibrium point. The calf price did not reduce if the number of calves available for sale was lower than the demand. During price negotiation, if the calf price dropped to be lower than the bobby calf price, the calves were processed to slaughter as bobby calves rather than being reared, along with other calves that were light and slow-growing (Cook, 2014; Andrew, 2016; New Zealand Statistics, 2022).

Once the price equilibrium point was achieved, calf rearers predicted the per head production cost, revenue and margin of calves for a 100 day weaning period (i.e., reported average age to wean dairy-origin calves) (Muir et al., 2001; Muir et al., 2002; Ormond et al., 2002). Calves with a higher margin, which were fast-growing, heavier calves and closer to rearers, were picked and transported to rearing facility (Oliver and McDermott, 2005; Hickson et al., 2015; Sean et al., 2019). The calf transportation cost was estimated as the distance of a calf from the rearer times NZ$ 2 per km (Ormond et al., 2002). Calves were weaned and sold when the average weight of 60 calves (assumed a full truck carrying capacity) attained 100 kg live weight. Then, actual production cost, revenue and margin of weaners at sale weights were calculated which was different from the predicted value as some fast-growing calves attained the target weaning weight before 100 days and slow-growing calves might take longer than 100 days to achieve the target average weaning weight. The calf rearing cost to 3-months (Ormond et al., 2002) including labour and feed was evenly distributed per day to estimate a rearing cost at weaning. Calf revenue was calculated as a function of live weight and price per kg live weight (Mylivestock, 2020) (Table 25). A calf margin was estimated as the difference between the costs for calf purchase, production and transport and the revenue from calf sale (B+LNZ: Economic Service, 2021). The study assumed poissonly distributed 3% calf death rate. The enterprise expenditure, revenue and margin were estimated as the sum of these values from weaners plus purchasing cost and production cost of the 3% dead calves.

Finishers

To reduce computational effort, only 10% of 9,165 finishers were included in the ABM (Bullen and Brack, 2014). They were split into small, medium, large holder finishers at 20:60:20 ratio (Oliver and McDermott, 2005) and had one of the three poissonly distributed farm areas with means of 100, 500 or 1000 hectares (B+LNZ: Economic Service, 2021), respectively. Monthly average pasture growth rate, utilization percent, megajoules metabolizable energy per kilo gram dry matter were collected from Brookes and Nicol (2017) and B+LNZ (2022) The total average pasture mass was the sum of the post-grazing pasture mass from the previous day and the net pasture growth in a given period which was limited between 1500 kg DM and 2500 kg DM minimum and maximum pasture covers. This was multiplied by utilization percent (i.e., 70 to 90%) to estimate the available utilizable kg DM which was available for cattle activities. Detail descriptions feed supply and pasture cover calculation can be found in Chapter IV. Of that, 20% was allocated to the dairy-origin cattle and the remaining to beef cattle and sheep bred on the beef cattle and sheep farm which was used to determine the total carrying capability of a finisher.

Finishers mainly purchased weaners from rearers, with the remainder from dairy farms when the weaner demand was higher than the supply from rearers (Andrew, 2016). The finishers sold them when 30 cattle per finisher (i.e., a full truck carrying capacity) attained targeted slaughter weight. Heifers, bulls and steers were finished from 480, 500, 550 kg live weight respectively (O'Riordan and Keane, 2010; Schreurs et al., 2014; Collier et al., 2015; Coleman et al., 2016; Martín et al., 2020) when the total feed demand of cattle was greater than the consumable feed supply (Chapters IV and V). However, slaughtering weights were extended to minimum of 500, 550, and 580 kg respectively when there was sufficient consumable feed supply. At these slaughter weights, fast-growing cattle were finished before their second winter (R2-cattle) and the remaining before their third winter (R3-cattle) (Chapters IV and V). Carcass weight was assumed to be 50, 52 or 54% of final slaughter weight for heifers, bulls or steers, respectively (Perry et al., 1993; Hopkins and Roberts, 1995; Nijdam et al., 2012).

Processors

The beef processing sector was represented by a single agent, which bought finished 9,500 ± 100 dairy-origin cattle and set a historical average price per kg carcass weight given to finishers. Beef heifers and steers were given the historical average price of NZ$ 5.50 per kg carcass weight price, or NZ$ 5.25 for bull beef (B+LNZ: Economic Service, 2021).

Model outputs and evaluation

This model is stochastic such that the number of slaughtered cattle, breed and class type and other attributes of cattle such as date of birth, birth weight and growth rate follow various random distributions. These affect the behaviour of the agents and the supply chain as a whole, thus to quantify the uncertainty and robustness of the model and determine minimum simulation runs, variance stability which was expressed as coefficient of variation (CV) across a set of 10, 20, 30, and 40 simulation runs (Lorscheid et al., 2012; Lee et al., 2015). The minimum number of simulation runs was fixed when the absolute difference of two consecutive sample sets became lower than the fixed value (Supplementary Table 17) (i.e., 0.005 confidence interval) (Lorscheid et al., 2012; Lee et al., 2015). Further a total of 100,000 bootstrap replicates were carried out to estimate mean and variance of each class of dairy-origin beef cattle using Bootstrap.jl (https://github.com/juliangehring/Bootstrap.jl). These figures then were compared to mean and variance of ABM simulation at 95% confidence level (Supplementary Table 18). Slaughtered number of dairy-origin heifers, steers and bulls from this study were then compared to the actual numbers of heifers, steers and bulls finished in 2019 and 2020 as part of the model validation to make sure that the results were sensible in the context of the New Zealand beef production industry (Davison, 2020).

Results

One hundred ABM simulation runs were performed representing 1% of New Zealand's total number of dairy-origin calves, and 10% of the rearers and finishers. Supplementary Video 1 captures the interactions of rearers, finishers and processor to represent the movement of cattle from birth to slaughter, using 100 cattle, 20 finishers, 20 rearers and a processor. Briefly, calves (red triangles) were purchased and moved to rearing facilities by rearers (black diamonds) and then reared to attain a targeted weaning weight before being on-sold to finishers. Unselected calves were processed as bobby calves at the age of 16-days. Finishers, represented by blue circles purchased weaners from the rearers to finish cattle to a target weight at which they were sold to processors (yellow squares) (Supplementary Video 1).

The average number of traditional dairy-origin heifer, steer and bull beef cattle processed across the 100 runs is presented in Table 26. The profit motive of the agents in the ABM resulted in a slight discrepancy in the sex ratio of animals that were reared and finished compared to the industry statistics. The number of steers processed in this study was 8% higher than the value reported by B+LNZ in 2020 (Table 26). In contrast, the current study processed 8% and 4% lower numbers of dairy-origin heifers and bulls compared to in the values reported by B+LNZ in 2020 (Table 26). On average, bulls accounted 53%, heifer 28%, and steer 19% of the total number of processed dairy-origin beef cattle (Table 26).

Table 26. Mean and standard deviation (sd), final slaughter weight of traditional dairy-origin heifer, steer and bull beef cattle in the ABM and actual reported B+LNZ numbers (the number represented 1% of dairy-origin beef cattle processed in NZ based on the average of 2019 and 2020 processing statistics).

Class of beef cattle	B+LNZ industry data		Mean ± sd of the 100 runs of ABM	
	[a]Number, n	[b]Slaughter weight, kg	Number, n	[c]Slaughter weight, kg
Heifer	2,800	484	2,562 ± 186	480/500
Steer	1,600	579	1,744 ± 217	550/580
Bull	5,160	576	4,952 ± 318	500/550
Total	9,560	-	9,257	-

[a]1% of dairy-origin beef cattle processed in New Zealand, [b] Estimated from carcass weight reported by B+LNZ (2022); MPI (2022) using 0.5%, 0.54% and 0.52% dressing-out percentage for heifer, steer and bull beef, respectively; [c]two minimum slaughter weights were allocated for fast-growing or slow-growing beef cattle in each class.

The average number of traditional dairy-origin heifers, steers and bulls finished across 100 runs of ABM is presented in Figure 15. Across the runs, the total number of bulls remained lower than the average reported value (red lines), however, steers and heifers number were above the mean till 10th run before reduced for heifers (black and blue lines) (Figure 15).

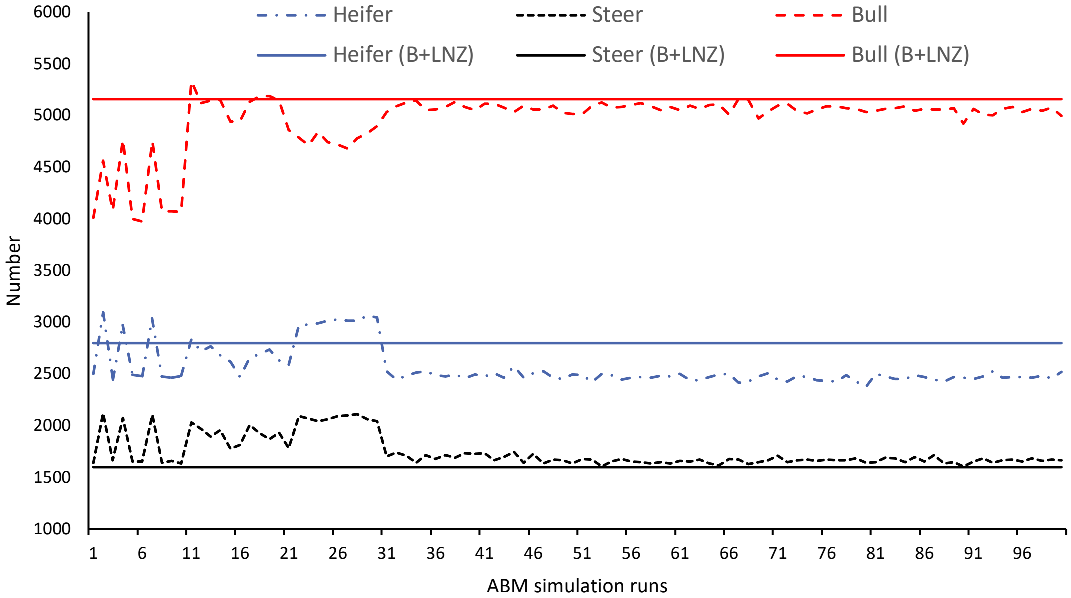

Figure 15. The total number of traditional dairy-origin heifer (blue dash dotted line), steer (black dotted line) and bull (red dashed line) process in the ABM across 100 runs. The solid lines in each class of beef cattle represented the actual B+LNZ average values.

Figure 16 summarizes the number of dairy-origin cattle (i.e., sum of beef-dairy and dairy-dairy calves) in the respective dam breed type that were finished for beef production in the ABM model simulations. Holstein-Friesian and Holstein-Friesian-Jersey-cross bulls accounted for approximately 49% of the total finished beef cattle (Figure 16). The Jersey breed contributed less than 5% of total dairy-origin beef breed cattle processed in ABM study (Figure 16).

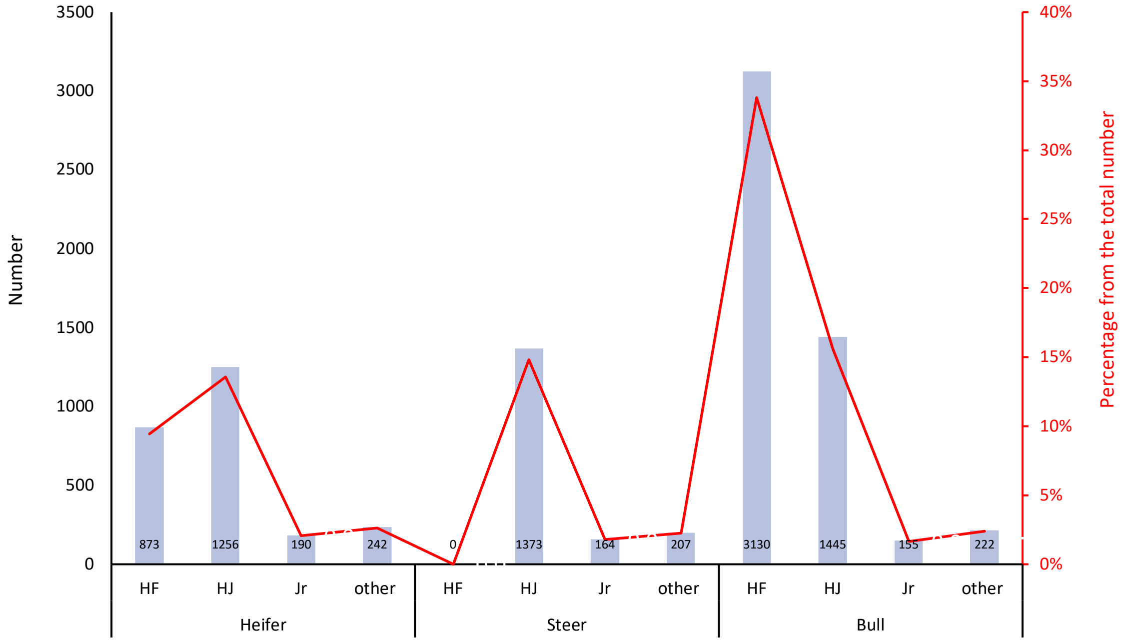

Figure 16. The average number of traditional finished heifer, steer and bull across dam breed types in the Agent Based Model (HF: Holstein-Friesian; HJ: Holstein-Friesian-Jersey cross and Jr: Jersey cattle).

Discussion

Agent-based modelling (ABM) can be utilized in silico to represent complex systems (Schouten et al., 2014; Rasch et al., 2016; Lippe et al., 2019; Scalco et al., 2019; Yang et al., 2019). It has been employed to represent beef cattle production and transportation issues in southwest Kansas, USA (Yang et al., 2019), to compare beef reproductive strategies in Brazil (Ojeda-Rojas et al., 2021), and to represent meat consumption behavior in the United Kingdom (Scalco et al., 2019). This study developed an ABM to represent the movement of dairy-origin beef cattle in New Zealand from birth to slaughter using the attributes of rearers, finishers and processor agents and specific attributes of dairy-origin beef cattle. This enabled agents to interact and select cattle with potentially higher return for finishing on beef cattle and sheep farms (Epstein et al., 1998; Bonabeau, 2002; Macal and North, 2005).

Bulls grow 10-20% faster than other gender classes of cattle (Nogalski et al., 2017; Blanco et al., 2020). This increases the demand for bull beef finishing system on beef cattle and sheep farms, as they are likely to be more profitable per kg of dry matter consumed basis (Oliver and McDermott, 2005; Martin et al., 2018). The ABM showed that bull beef cattle accounted for more than 50% of the total dairy-origin beef cattle processed. However, this figure was 4% lower than the 1% of actual number reported by Davison (2020). The variation might be explained bull beef received lower per kg carcass price compared to steers and heifers (B+LNZ, 2022).

Holstein-Friesian and Holstein-Friesian-Jersey-cross breed cattle are preferred for dairy-origin bull finishing systems as they grow faster and likely attain the targeted slaughter weight earlier than Jersey breed (Ormond et al., 2002; Martin et al., 2018). Therefore, their dominance in the industry data and the ABM was not unexpected. In contrast, Jersey breed type cattle accounted less than 5% of the total dairy-origin finished beef cattle in the model. This is likely explained by their lighter live weight and slower grow rate than the other breeds (Muir et al., 2001; Muir et al., 2002; Ormond et al., 2002; Hickson et al., 2015; Coleman et al., 2017; Handcock et al., 2017; Berry et al., 2018). This suggests that aspects of the industry may need an appropriate breeding strategy, to improve their growth rates and thus increase the acceptance of these cattle for beef finishing (Martín et al., 2020; Coleman et al., 2021; Coleman et al., 2022) or find other alternatives which are less driven by liveweight and growth rate, such as Asian markets, where lighter carcasses are the norm.

In New Zealand Jersey bulls could be preferred to sire first calving heifers in the dairy industry (i.e., 2-years old heifer) to reduce calving difficulty (Coleman et al., 2021; Coleman et al., 2022). However, calves from these mating are not used for dairy herd replacement nor preferred for beef finishing on sheep and beef farms as they grow slower and do not achieve heavy carcasses (Ormond et al., 2002; Hickson et al., 2014; Hickson et al., 2015; Coleman, 2016; Thompson et al., 2018; Muir et al., 2020). Another option instead of Jersey bulls is using selected beef sires that have the potential to improve the growth rate of beef-dairy cattle for beef finishing (Martín et al., 2020; Coleman et al., 2022). Coleman et al. (2022) identified that Angus and Hereford bulls with low birthweight and high direct calving ease estimated breeding values can be used to produce calves of greater value than Jersey-sired calves with only a small increase of assistance at calving in first calving heifers. Using these beef breed bulls to improve the value of non-replacement Jersey calves from Jersey cows and first calving heifers would increase the value of Jersey type calves and their acceptance for beef finishing system on beef cattle and sheep farms (Martín et al., 2020; Coleman et al., 2022).

A four parameter equation was employed to simulate the growth curves of the various breeds in this study (Richards, 1959). Live weight change was based solely on the growth stage of the animal and did not consider the variability in feed supply across seasons. It is important to acknowledge this limitation of the growth simulation equation in this study as body growth at some stages may actually be limited by feed supply reducing the growth rates simulated in the ABM. Likewise, the effects of compensatory growth when feed supply is abundant were not incorporated. It would be possible to modify the model simulating growth to account for the feed supply (Handcock et al., 2017). Modifying the growth curve equation to account for the dynamics of feed supply could improve the efficiency of the model and would allow finishers to consider alternative selling strategies. This would allow farmers to consider if to sell their cattle when they do not have sufficient feed during winter while the others might be in a situation to carry-over cattle through to the third winter by allowing either no change in live weight or weight loss during the winter period which could be gained by compensatory growth in spring (Scales and Lewis, 1971; Morris, 2013b).

Conclusions

The agent-based model represented the pasture-based beef production systems in New Zealand and allowed various autonomous agents to interact among themselves in determining breed and class type for dairy-origin beef cattle finishing. The model finished higher number of bulls than heifers and steers. Regarding breed types, Holstein-Friesian and Holstein-Friesian-Jersey-cross breed cattle dominated the dairy-origin beef production system. Further studies to include retailer and consumer perspective and other decision alternatives for finishing farms would improve the applicability of the model to support decision making process.

Chapter VII

Agent-Based Modelling to Improve Supply Chain of Dairy-Origin for Young Beef Cattle Production

Introduction

Dairy-origin calves significantly contribute to beef finishing systems (Berry, 2021; van Selm et al., 2021; MPI, 2022; New Zealand Statistics, 2022), accounting for more than 58% of the beef cattle finished annually on beef cattle and sheep farms in New Zealand (Davison, 2020; van Selm et al., 2021). In New Zealand approximately 20% of calves born on dairy farms are a beef-dairy crossbred which are subsequently finished for beef on beef cattle and sheep farms (Burggraaf, 2016). Early-born and heavier beef-dairy cross calves are preferred for prime heifer or steer finishing as they grow faster and attain a better conformation than their dairy counterparts (Hickson et al., 2015; Twomey et al., 2020). Well-marked Holstein-Friesian bull calves are favoured in New Zealand for bull-beef finishing systems (Morris and Kenyon, 2014; Bown et al., 2016; Pettigrew et al., 2017; Martin et al., 2018; Muir et al., 2020).

Dairy-origin calves which are not required for dairy heifer replacement nor beef finishing (especially Jersey) or calves from cows not suitable for breeding replacements, first calving heifers and late calving cows have traditionally been disposed of as bobby calves (Cook, 2014; Palmer et al., 2021). This practice is considered a wasted opportunity as these animals could be used for beef production (Cook, 2014; Palmer et al., 2021) and the practice has perceived ethical issues (Cook, 2014; Andrew, 2016; Boulton et al., 2018; Palmer et al., 2021) and food contamination risk (Browne et al., 2018) that may affect market sustainability for both the dairy and beef cattle industries in New Zealand (Cook, 2014; Ferguson et al., 2014; Andrew, 2016). To address these matters, systems of young beef cattle production have been proposed to increase the number of dairy-origin cattle finished for beef while working with a fixed quantity of grazing land, in New Zealand (Hunt et al., 2019; Pike et al., 2019; Nakitari, 2021).

For this study, Agent Based Modelling (ABM) was applied in a New Zealand context to represent young beef cattle production systems that would finish dairy-origin calves for beef before their first winter (i.e., 8 to 12-months of old). The use of ABM would highlight challenges and opportunities of implementing a young beef cattle production system. The study modelled unselected dairy-origin calves identified in chapter VI for beef production slaughtered at 8, 10 or 12-months with the current weaner cattle and manufacturer beef price and their 10% premiums (i.e., 10% per kg live weight for weaner cattle and per kg carcass weight for finishing cattle). It was hypothesised that a 10% increase in price would increase their chance of being selected as young beef cattle, enabling a greater number of dairy-origin beef cattle to be finished for a given feed supply.

Materials and methods

The interactions between rearers, finishers and processors for weaning and finishing dairy-origin beef cattle on New Zealand beef cattle and sheep farms were modelled using "Agents.jl" of Julia (Vahdati, 2019) (Chapter VI). Briefly, from Chapter VI, the number of calves of various breeds of spring-born dairy-origin cattle available on a daily basis followed a Poisson distribution (Poisson et al., 1981) to provide a location parameter along with the within-herd calving distribution. This distributed the date of birth for all calves from the national herd to a three-month, Spring, calving period. Calves with a likely higher marginal return due to being heavier and faster growing (i.e., Holstein-Friesians and Holstein-Friesian-Jersey crossbreds) were finished via the existing beef finishing systems on beef cattle and sheep farms (i.e., traditional dairy-origin beef cattle) and the remainder were processed as bobby calves.

Rearer, finisher and processor agents, simultaneously and repetitively, interacted with each other to determine the number and type of dairy-origin cattle finished for beef to ensure a reliable market across agents. Rearers brought-in heavier and likely faster-growing potential 4-day old calves and weaned them before on-selling to a finisher. If the rearing capability of the rearers (i.e., the number of calves they could successfully rear) was higher than weaner demand by finishers, they adjusted their rearing capability to be the same as weaner demand by finishers. Finishers primarily bought weaners from rearers, however, if the weaner supply from rearers was insufficient relative to their finishing capability, they sourced more weaners directly from dairy farms. This encouraged dairy farmers to rear more calves along with replacement heifer calves (Nor et al., 2015).

Young dairy-origin beef cattle finishing systems modelled with and without premuim prices

The current model was parameterised with a total of 45,000 spring-born calves (i.e., 1% of the total calves) for computation, the same as the base model for traditional dairy-origin beef cattle finishing systems (chapter VI). Unselected calves, which were comparatively slower-growing and lighter calves from chapter VI, were modelled to determine whether they could be finished at the ages of 8, 10, or 12-months for young beef. This would allow finishers to start with a higher number of beef cattle including traditional and young beef cattle and then progressively finishing animals starting from 8-months of age to ensure feed demand equalled feed supply as it declined over the winter period. Slaughter started in May with those young beef cattle that were heavier and finished in August.

Energy requirements for maintenance and live weight gain for traditional and young beef cattle were estimated using values from Brookes and Nicol (2017) and

Trafford and Trafford (2011). Carcass weight from the 8 and 10-month old beef cattle were estimated as 0.48 times the live weight, increasing to 0.5 times the live weight for 12-month old beef cattle (Chapter III, Hunt et al., 2019; Pike et al., 2019; Nakitari, 2021). Young beef was valued at manufacturing beef price of NZ$ 4.50 per kg carcass weight (B+LNZ: Economic Service, 2021). At this price the ABM simulation was limited to five runs as the result did not change from the previous model (i.e., without young beef cattle). In addition, a total of 25 further ABM simulations were run at 10% higher price per kg live weight for weaners and a 10% higher value for per kg carcass weight of young beef to examine the effect of an increased value on the uptake of young beef cattle.

Results

Processing young beef cattle at NZ$ 4.50 per kg carcass value did not make the finishing competitive with traditional heifer, steer and bull beef finishing systems. This meant the utilisation of young cattle did not improve on the result in chapter VI (Figure 17). Calves born from Holstein-Friesian dams (i.e., sum of beef breed sired and dairy breed sired calves) accounted for 29% total harvested cattle. However, calves from Jersey cows (i.e., sum of beef breed sired and dairy breed sired calves) contributed less than 5% of total traditional dairy-origin beef breed cattle processed in this study (Figure 17). Across breed and sex type, the number of young beef cattle were zero (Figure 17).

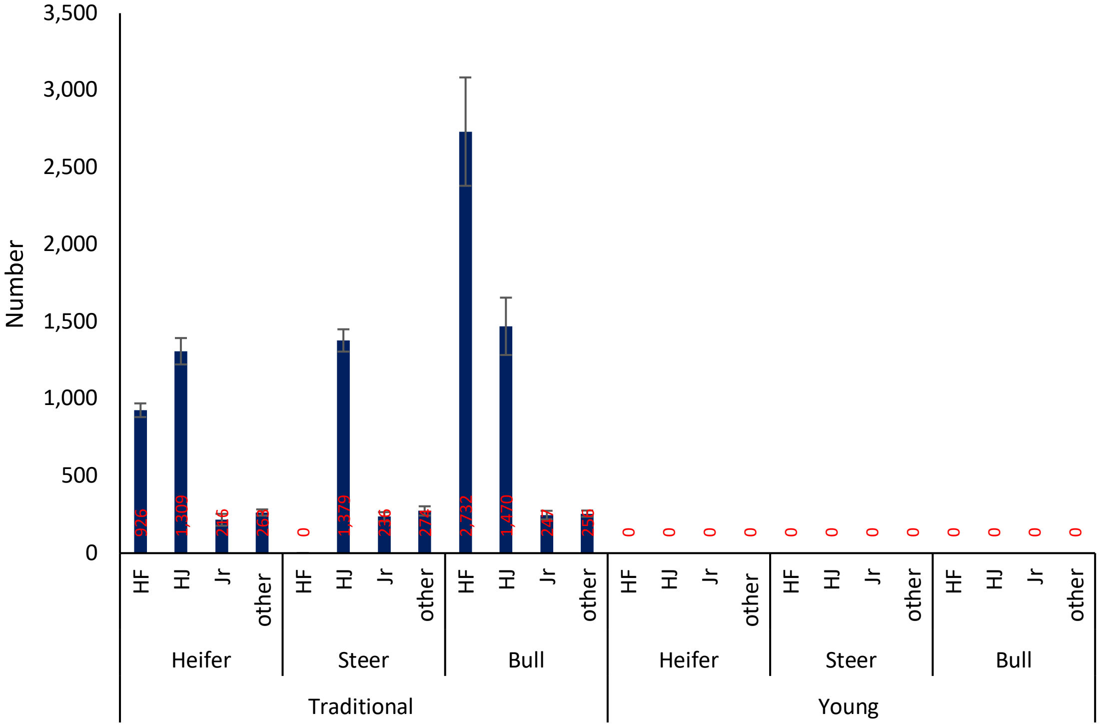

Figure 17. Mean and standard devaition of dairy-origin cattle processed for beef across dam-breed type (out of 45,000) when carcasses from young beef cattle sold at NZ$ 4.50 per kg (HF: Holstein-Friesian; HJ: Holstein-Friesian-Jersey cross, Jr: Jersey breed cattle and other: other dairy breed cattle).

Increasing the weaner selling price by 10% per kg live weight and the carcass price by 10% to NZ$ 4.95 improved the value proposition and this increased the total number of dairy-origin beef cattle processed in this study by 6% compared to traditional beef cattle finishing (i.e, without young beef cattle) (Figure 18). There was also a further increase in the contribution of Friesian bulls used for traditional beef finishing, however, decreased heifers processed for traditional heifer beef (Figure 18). Heifers from "Other" dairy breeds followed by Jersey and Holstein-Friesian-Jersey crossbred dominated the young beef cattle production. In contrast, the contribution of Holstein-Frisian for young beef finishing was much lower compared to the contribution of other breeds for young beef finishing (Figure 18).

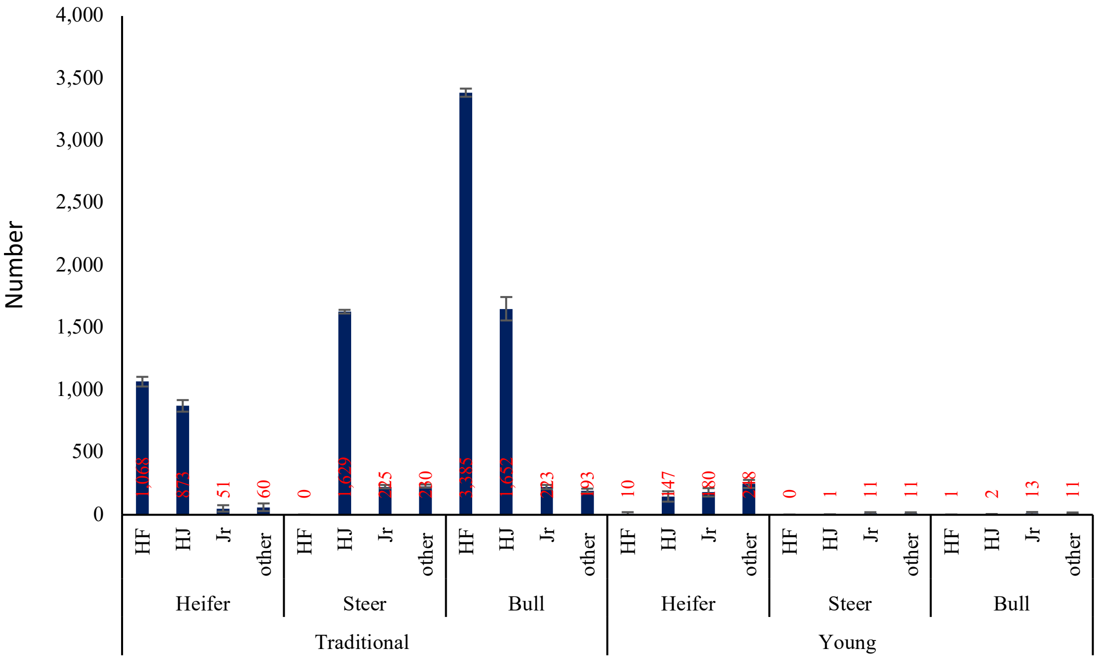

Figure 18. Mean and standard deviation of diary-origin traditional and young beef cattle across breed type (out of 45,000) when carcasses from young beef cattle sold at NZ$ 4.95 per kg (HF: Holstein-Friesian; HJ: Holstein-Friesian-Jersey cross, Jr: Jersey cattle and other: other dairy breed cattle)..

Out of the 45,000 dairy-origin calves in the ABM, 9,570 were finished as traditional beef cattle, with the remainder being available for young beef finishing. Young heifers contributed approximately 94% of total beef cattle processed for young beef production at NZ$ 4.95 per kg carcass price (Table 27). Jersey and other breeds accounted for 76% of the total young beef cattle (Table 27).

Table 27. Total number traditional beef cattle (i.e., finished 20 to 30-months old) and young beef cattle sold at NZ$ 4.95 per kg carcass (i.e., finished at 8, 10 or 12-months old) processed per sex and dam breed out of 45,000 modelled calves across 25 ABM simulation runs.

	Heifer				Steer				Bull			
	HF	HJ	Jr	other	HF	HJ	Jr	other	HF	HJ	Jr	other
Traditional beef cattle	1,068	864	55	58	-	1,632	229	236	3,397	1,618	221	192
Young beef cattle	10	147	180	248	-	0	11	11	1	2	13	11

HF: Holstein-Friesian; HJ: Holstein-Friesian-Jersey cross, Jr: Jersey cattle and others: other dairy breed cattle

Discussion

Young beef cattle production (8 to 12-months) is a potential new class of beef production system being considered in New Zealand. It is aimed at finishing as many calves for beef as possible, to reduce bobby calf numbers. Understanding the level of acceptance of these systems on existing beef cattle and sheep production systems and the main constraints associated to their use, would allow farmers and processors to make informed decisions regarding the utility of this system. The current study simulated dairy-origin heifer, steer and bull beef cattle slaughtered at either 8, 10 or 12-months of age to the ABM model developed in chapter VI, based on the historical average weaner and manufacture beef prices and at a 10% premium on both prices.

Young beef cattle are slaughtered at lighter weight and so the carcass would be categorised into the manufacturing price of NZ$ 4.50 per kg carcass weight category based on the existing carcass weight payment system in New Zealand (B+LNZ, 2022; MPI, 2022). At this price and with the existing 4-day old calf purchasing cost, the margin return from young beef would be lower compared to the traditional beef cattle (Hunt et al. (2019). This would not allow the young beef cattle production systems to be competitive with the traditional beef cattle systems, with the ABM indicating that no calves would enter the young beef system.

Increasing the price per kg live weight for weaners and per kg carcass weight for young beef by 10% (to NZ$ 4.95 for carcasses from young beef cattle) resulted in young beef cattle contributing 6% of the total dairy-origin beef cattle processed in the current study (out of the 45,000 calves simulated). This relatively low percentage indicates that young beef cattle would need a price premium of more than 10% to increase their chance of being utilized in beef production by a significant amount on beef cattle and sheep farms, thereby harnessing the beef production opportunity they offer. Hunt et al. (2019)

identified that young steers slaughtered at 8 to 12-months would require more than NZ$ 6.00 to break-even with traditional bull finishing system. This suggests higher prices are required to encourage farmers to increase the uptake of male calves which are the majority of bobby calves (Palmer et al., 2021; B+LNZ, 2022). If either social pressure or government regulation leads to a ban on the bobby calf trade in New Zealand and the young beef premium remains low, dairy farmers might have to lower their calf sale price expectations to prevent wastage of these calves. Further simulations with higher price scenarios are required to understand beef value which is needed to increase the uptake of young beef cattle production systems.

Heifer beef cattle are processed at lighter weights compared to their male counterparts (Berg and Butterfield, 1978; B+LNZ: Economic Service, 2021). These lighter weights enable a higher number of heifers to be farmed per hectare compared to other beef cattle classes, for the given feed supply, as they consume less dry matter (kg DM) per animal to achieve target weights (Chapter V, Trafford and Trafford, 2011; Brookes and Nicol, 2017). This would allow young heifers to contribute more than 90% of the total young beef cattle processed in the current study. This could be also due to young heifers being sold at lower per calf price which might have allowed them to return higher margin compared to the other sex classes of young beef cattle.

Young beef is more tender due to being finished at an earlier age than beef from traditional beef cattle (Pike et al., 2019) which might allow for premiums over either traditional beef (i.e., heifer or steer beef) or processing beef (i.e., bull beef). Selling valuable cuts at a higher price would lift the value of the whole carcass, would also increase the profitability of young beef cattle production (Garmyn et al., 2018; Monteils and Sibra, 2019; Mandolesi et al., 2020) and make the system more attractive for farmers.

Dairy-origin beef cattle produce 29% less greenhouse gas emissions (GHG) compared to cow-calf beef production system per kg carcass (van Selm et al., 2021). This is due to them being a product of cow which provides milk for sale and a calf for beef production for the same amount of dry matter consumed. Further, at a younger age (less than 12-months of age), growth is faster and there is less fat in the gain compared to older cattle (Berg and Butterfield, 1978), which would make younger cattle more efficient in terms of feed converting to saleable product. Chapter V identified that young beef cattle increased gross per farm carcass output for a given feed supply, which meant they produced lower GHG emissions per kg carcass. This implies young dairy-origin beef cattle production should be considered as a mitigation strategy to reduce GHG emission from livestock production (Molano et al., 2006). Finishing dairy-origin cattle for beef at a young age would have also less impact on the soil compared to heavier animals in wet seasons (Richard and Gemma, 2019; van Selm et al., 2021). These positive environmental impacts might allow young beef to attract a higher per kg carcass value driven by consumer demand which would potentially increase the uptake of young beef cattle systems. Identifying markets that would pay extra for ethical and welfare friendly beef and/or reducing calf selling price at 4-day old would also allow young beef to earn higher value per kg live/carcass weight (Krystallis et al., 2006; Xue et al., 2010).

Conclusions

Processing young beef cattle at NZ$ 4.50 per kg carcass did not allow the system to be competitive with a traditional beef finishing system. At a price premium of 10% there was only a 6% uptake of, primarily, young heifer beef animals. This indicates that to substantially increase the young beef cattle number in young beef cattle production systems a greater price premium is needed. The marginal return for young beef cattle could also be increased by reducing costs. Further studies including meat quality, retailer and consumer perspectives, potential price premiums and other levers would allow the model to represent different scenarios and better identify potential ways of processing higher numbers of young beef cattle on beef cattle and sheep farms.

Chapter VIII

Overall Discussion and Conclusion

Introduction

New Zealand has less than 1% percent of the world cattle population, however, it contributes 6% percent of global beef trade (New Zealand Statistics, 2022). The animals may be either beef or dairy cattle breeds, or their crosses and includes cull cattle or calves grown out for heifer, steer or bull finishing on pasture-based sheep and beef farms (Berry, 2021; van Selm et al., 2021; MPI, 2022; New Zealand Statistics, 2022). In 2020, approximately 20% of the total calves born in the dairy industry were finished on beef cattle and sheep farms (van Selm et al., 2021).

Nearly 42% of the total calves born in the New Zealand dairy industry were commercially slaughtered within 14-days of age (van Selm et al., 2021; New Zealand Statistics, 2022). This practice is seen as a wasted opportunity to produce animals for beef production (Cook, 2014; Palmer et al., 2021; Rutherford et al., 2021) and has perceived ethical issues (Cook, 2014; Andrew, 2016) which might negatively affect both dairy and beef exports (Cook, 2014; Ferguson et al., 2014; Andrew, 2016; Rutherford et al., 2021). Due to limited availability of land area for finishing it would be impossible to take all of these calves to slaughter at 20 to 33-months without reducing the supply of dry matter to some other classes of stock. Young beef cattle production was proposed as a potential solution to finish these calves for beef before their first winter at ages of 8 to 12-months and reduce total feed demand compared with finishing at heavier weight (Hunt et al., 2019; Pike et al., 2019; Nakitari, 2021). This would allow the processing of a greater number of beef cattle with the available limited feed resource, and reduce the number of bobby calves and the potential welfare issues related to bobby calf production (Palmer et al., 2021; Rutherford et al., 2021).

Young beef cattle processed at 8 to 12-months of age is a new class of beef cattle production for New Zealand considered as an alternative system for surplus dairy-origin calves (Hunt et al., 2019; Pike et al., 2019; Nakitari, 2021). As a new class of beef cattle, there is a need to consider how young beef cattle would be integrated into New Zealand sheep and beef farming systems including the signals to the farmer regarding carcass value given that their carcasses would not fit into current schemes which are orientated to rewarding meat yield per animal. Therefore, this study employed mathematical models to 1) predict saleable meat yield from young beef cattle, which could then be used to inform a classification and grading system for young cattle, 2) understand feed utilization and financial effects of implementing young beef finishing on beef cattle and sheep farms and 3) the extent of young beef cattle integration under different pricing scenarios within the existing New Zealand beef cattle production systems.

Major findings of the study

Prediction equations for hind-leg muscle weight

The weight of muscle from the hind-leg is indirectly used to represent saleable meat yield of carcasses. Prediction equations using measures of carcass composition can then be used to evaluate meat yield from the hind-leg (Conroy et al., 2010; Tarouco et al., 2012; Craigie et al., 2013; Bonny et al., 2016; Mendizabal et al., 2021). This can then be used as an indirect indicator of whole saleable meat yield for carcass classification and grading systems (Conroy et al., 2010; Tarouco et al., 2012; Bonny et al., 2016). Prediction equations developed for older beef cattle have poor predictability for the classification and grading of carcasses from young beef cattle, as their conformation, muscling and fat depth are less developed compared to older beef cattle (Bergen et al., 1996; Bergen et al., 1997; Bergen et al., 2005).

Chapter III developed prediction equations for hind-leg muscle weight for indirect estimation of saleable meat yield from young dairy-origin steers slaughtered at the ages of 8, 10 or 12-months. The equations were developed using carcass weight, wither height, eye muscle area, rib and back fat thickness as predictors. Carcass weight was the strongest predictor of hind-leg muscle weight, explaining 61% of the variation. Including wither height and eye muscle area in a multivariate regression analysis improved the coefficient of determination by 6%. This study emphasised that measures of fat are ineffective for assessing the value of young beef due to them being a lean carcass and that the goal for producers is to have a well grown animal up to 12-months of age to achieve a higher carcass weight before the feed supply significantly decline in winter.

A profit optimization model for class 5 intensive finishing sheep and beef cattle farms and implementation of a young beef cattle system

Linear programming has been utilized to optimize various livestock production systems (Kingwell and Pannell, 1960; Pannell, 1996; Pannell et al., 1996; Ridler et al., 2001; Hurley et al., 2013). Chapter IV developed a profit maximization model using linear programming for class 5 intensive finishing beef cattle and sheep farms in New Zealand based on the metabolizable energy requirements of various classes of beef cattle and sheep. This enabled estimation of the total number of beef cattle and sheep, and selling strategies of lambs and finished beef cattle to be identified for given feed supply. Then, the model was modified in chapter V to include young heifer, steer and bull beef cattle slaughtered at either 8, 10, 12 or 14-months of age. Introducing young beef cattle into the production system increased the number of finished beef cattle and carcass output per farm. It also increased pasture utilization and decreased silage use. This study indicated that New Zealand beef cattle and sheep farmers and the industry as whole would be able to extend their beef cattle slaughtering pattern by including young beef cattle in their portfolio of livestock.

ABM representation of dairy-origin beef cattle production in New Zealand

ABM is a computational model able to capture emergent and adaptive behaviours of agents resulted from agent-agent and/or agent-environment interactions in complex systems (Schouten et al., 2014; Rasch et al., 2016; Lippe et al., 2019; Scalco et al., 2019; Yang et al., 2019). Chapter VI represented dairy-origin cattle within a traditional beef cattle production chain using the specific attributes of rearer, finisher and processor. This enabled them to interact and determine the number and type of cattle for beef cattle finishing on beef cattle and sheep farms. The ABM finished a higher number of bulls (i.e., more than 50% of the total dairy-origin beef cattle) compared to the other gender classes of dairy-origin beef cattle as they grew faster and attained the targeted slaughter weight earlier than steers or heifers which allowed them to return higher profit per kg dry matter basis (Ormond et al., 2002; Bown et al., 2016). Holstein-Friesian and Holstein-Friesian-Jersey-cross cattle (i.e., sum of beef-dairy and dairy-dairy calves) contributed more than 85% of total processed dairy-origin beef cattle in the model while the Jersey breed contributed less than 5% of the total beef produced. These values broadly aligned with the that of observed in the traditional beef industry (Davison, 2020).

Price levers on the uptake of young beef cattle in New Zealand beef production systems

Chapter VII of this study simulated young dairy-origin beef cattle slaughtered at the ages of 8, 10, and 12-months and valued the carcasses at NZ$ 4.50 and NZ$ 4.95 per kg to understand the lever of price on incorporating a young beef cattle into New Zealand beef cattle finishing systems. Young beef cattle were not competitive with the traditional beef finishing system under the manufacturer per kg carcass price (i.e., no calves enter the system at NZ$ 4.50 per kg carcass price). However, increasing the per kg price to NZ$ 4.95 allowed young beef cattle to contribute approximately 6% of the total dairy-origin finished beef cattle. This is a low value and suggests that premiums would need to be greater than this if aim is to increase the uptake of the system.

Limitations and recommendations of the study

The multivariate analysis of carcass weight, wither height and eye muscle area explained only 65% hind-leg muscle weight variation from young steer beef in chapter III. This might limit its applicability as a classification and grading tool of carcasses from young beef cattle by meat processing companies as not all of the variation could be explained. The data was also limited by the small number of animals utilized. Thus, identification of other novel traits in young cattle including more animals and carcasses from young heifers and bulls of other breeds to improve the prediction efficiency are considered for further research. This should then be validated to determine its suitability for use.

The profit optimization linear programming models developed in the current study assumed linear relationships between dependent and explanatory variables although most of the variables in grazing beef production system including pasture and animal growth curves are non-linear (Romera et al., 2004; Doole and Romera, 2013; Romera and Doole, 2015). The model also allocated 50% of the total feed supply for beef cattle activities and the remaining 50% was allocated for the sheep enterprise as per average for class 5 beef cattle and sheep farms. However, in a beef cattle and sheep mixed farm the sheep:cattle ratio and rotation of beef cattle and sheep for grazing could be also optimized using a multi-stage linear optimization model to allow for different allocations of feed to sheep and cattle (Notte et al., 2020). This might influence the results found and therefore conclusions made.

Further, the optimization models utilized historical average prices for various beef cattle and sheep classes. However, beef and sheep carcass prices vary reflecting the market demand and exchange rate (MLA, 2021; B+LNZ, 2022). For instance, both the optimization studies purchased steer weaners for traditional beef finishing at NZ$ 350.00 per head. However, that price was low compared to the current steer weaners price at seven-months of age. Therefore, farm profitability in chapters IV and V was re-estimated using a current price of NZ$ 700.00 and earning before tax (EBT) per hectare was 11 to 22% lower than the reported values in chapters IV and V (Supplementary Table 15; Supplementary Table 16). Considering the dynamics of beef and sheep carcass prices and the incorporation of other classes of beef cattle could expand the applicability and enable the model to be used for other beef production systems.

In real farm situations, when feed demand from the animals becomes higher than the supply especially during winter, finishers could employ various alternatives including but not limited to selling cattle store, leasing grazing land, growing crops for winter feed supply and/or using hay or silage as supplements. Future studies including these alternatives for finishers would be required to explore every possible alternatives in both LP and ABM studies.

In the ABM studies beef retailer and consumer perspectives were not included. Consumers perspectives associated with meat quality (meat colour, tenderness, juiciness, flavour) and extrinsic characteristics (brand, price, labelling, package and outlet) (Bello Acebrón and Calvo Dopico, 2000; Bredahl, 2004; Banović et al., 2009; Strydom et al., 2019) are important factors that determine breed and class of beef cattle required for beef production (Scalco et al., 2019; Foraker et al., 2022). Considering these parameters in future studies might affect the proportion of dairy-origin beef cattle processed in the current studies. Beef cattle enterprise profitability including the cost of 3% calf death rate in the ABM studies, which will be included in manuscript(s), is not analysed due time limitation as some of the ABM simulations were limited to 500 steps (i.e., days) to generate more ABM outputs within limited time.

Implications of the study

Implications for farmers

The prediction equations developed in this research work could be used by farmers to evaluate saleable meat yield from young beef cattle and thereby make a decision on selling of them. This would require them to estimate carcass weight from live weight as 0.48 dressing-out percentage for 8 and 10-months young beef cattle and 0.5 dressing-out percentage for 12-months young beef cattle (Bergen et al., 1996; Bergen et al., 2005; Conroy et al., 2010; Scognamiglio, 2010; Tarouco et al., 2012; Lee et al., 2016). The prediction equations developed in the current study could be easily customized and used in other countries, particularly where pasture-based young beef is predominant.

Bio-economic simulation and farm management tools including FARMAX (www.farmax.co.nz) have been widely utilized to understand beef cattle and sheep production systems in New Zealand (Farrell et al., 2019; Farrell et al., 2021). Therefore, incorporating this profit optimization model with the exiting optimization (Farrell et al., 2019; Farrell et al., 2021) or bio-economic simulation models on beef cattle and sheep farm could support farmers in their decision making processes to determine the optimum carrying capacity, selling strategies and ratio of stock classes to increase farm profitability in relation to young beef cattle production system. Furthermore, the optimization models developed in the current study would allow various simulation and farm management tools to incorporate the profile of young beef cattle in their system.

Implications for beef and dairy industries

Carcass weight, muscle conformation and fat depth are used for carcass classification and grading in the New Zealand beef processing industry (Purchas et al., 2002; B+LNZ, 2022; MPI, 2022). Prediction equations developed for traditional beef cattle are insufficient to predict saleable meat yield from young beef as the carcasses are lean, so fat depths become irrelevant and unlikely to be useful in a carcass classification scheme for these young cattle. Further, 8 to 12-month old cattle do not reach the minimum carcass weight threshold for the New Zealand beef classification system. Therefore, the prediction equations developed in the current study could be utilized by the processing industry to indirectly evaluate saleable meat yield from young beef cattle and to classify and grade carcasses. This would then assist in assigning prices to create a fair payment system.

The agent-based model enabled representation of the cumulative behaviour of the rearer, finisher and processor utilising dairy-origin cattle for beef and identified the competition level of young beef cattle under two price scenarios. The model could be utilized by the dairy industry to understand the dairy-origin calf supply for beef cattle finishing and ensure the industry is supplying the required type of cattle for beef finishing, to make early decision on type of calves which are not required for beef finishing and identify price premiums needed to ensure a high uptake. It could also be used by the beef cattle industry to understand the supply chain system of dairy-origin beef cattle and their main challenges, thereby allowing them to suggest alternatives within the industry. Therefore, the model can be used at a national level to identify the challenges in young beef production in New Zealand and to support decision-making about the use of young beef production in New Zealand.

Conclusions

The prediction equations developed in this study identified that carcass weight was pertinent to classify and grade carcasses from young beef cattle. Using solely carcass weight or in combination with other traits would help to assign appropriate per kg carcass price to allow young beef cattle to earn higher value. Including young beef cattle in the existing beef cattle and sheep production system increased the number of beef cattle processed and carcass output per hectare. It also allowed the beef cattle selling policy to be more flexible. However, selling young beef at NZ$ 4.50 per kg carcass price reduced farm revenue (Chapter V) compared to the optimized system for traditional beef cattle finishing system. This price scenario also did not allow young beef cattle to compete with traditional heifer, steer and bull beef finishing cattle in the ABM study (Chapter VII). At price of 10% premium per kg carcass there is only a small uptake and thus to increase the uptake, the premium will need to be higher or the purchasing cost of 4-day-old calf lower.

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Appendices

Appendices-A: Supplementary materials for chapter III

Supplementary Table 1. Comparisons between corresponding generalised linear model (gls) and linear mixed model (lme).

ANOVA	Models	Df	AIC	BIC	logLik	Test	L.ratio	p-value
Model1.gls	1	3	161.88	168.11	-77.94			
Model1.lme	2	4	163.88	172.18	-77.94	1 vs 2	0	1
Model2.gls	1	4	160.27	168.58	-76.13			
Model2.lme	2	5	162.27	172.65	-76.13	1 vs 2	5.684342e-14	1
Model3.gls	1	4	161.32	169.64	-76.66			
Model3.lme	2	5	163.32	173.71	-76.66	1 vs 2	0	1
Model4.gls	1	5	159.76	170.15	-74.88			
Model4.lme	2	6	161.76	174.23	-74.88	1 vs 2	2.842171e-14	1
Model5.gls	1	6	161.54	174.01	-74.77	1 vs 2	2.842171e-14	1
Model5.lme	2	7	163.54	178.08	-74.77			
Model6.gls	1	7	162.92	177.46	-74.46			
Model6.lme	2	8	164.92	181.54	-74.46	1 vs 2	8.526513e-14	1

Df: degree of freedom
AIC: Akaike`s Information Criteria
BIC: Baysian Information Criteria

As shown in Supplementary Table 1, the corresponding models between gls and lme were not significantly different. However, the gls models had lower AIC and BIC. Thus, gls functions were selected for further analysis.

Supplementary Table 2. All age steers within generalized linear models comparison.

ANOVA	Models	Df	AIC	BIC	logLik	Test	L.ratio	p-value
Model1.gls	1	3	161.87	168.11	-77.94			
Model2.gls	2	4	160.27	168.58	-76.13	1 vs 2	3.61	0.05
model3.gls	3	4	161.32	169.64	-76.66	-	-	-
Model4.gls	4	5	159.76	170.15	-74.88	3 vs 4	3.56	0.06
model5.gls	5	6	161.54	174.01	-74.77	4 vs 5	0.22	0.64
model6.gls	6	7	162.92	177.46	-74.46	5 vs 6	0.62	0.43

Model 1: FMW ~ CWT
Model 2: FMW ~ CWT + wither
Model 3: FMW ~ CWT + ema
Model 4: FMW ~ CWT + ema + wither
Model 5: FMW ~ CWT + ema + wither + rib
Model 6: FMW ~ CWT + ema + wither + rib + p8

From the above model comparisons, the gls functions which are model2.gls and model4.gls showed significant improvement from the previous models when extra variables were added but model5 and model 6 did not significantly improve the model.

Appendices-B: Supplementary materials for chapter IV and V

Supplementary Table 3. Pasture growth rates around New Zealand (Kg DM/ha/day).

		Months											
REGION	SITE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Northland	Dargaville	60	61	49	43	33	24	24	30	48	57	63	75
	South Kaipara	31	30	30	36	27	17	18	29	35	52	50	44
Waikato	Hamilton	18	19	21	23	15	9	10	30	48	53	48	45
	Central Plateau Wairakei (Flat)	20	14	13	8	11	4	4	6	18	30	35	32
	Wairakei (Hill)	35	17	25	18	15	7	6	10	29	45	40	52
Taranaki	Waimate West	38	25	31	30	22	11	12	19	33	45	45	44
	Stratford	38	30	34	30	16	8	7	15	23	42	42	43
Gisborne	Manutuke	29	28	32	29	25	18	17	33	45	50	41	38
	Waerenga o Kuri (Hill)	53	38	38	33	21	11	7	16	25	41	51	52
Hawkes Bay	Hastings	9	12	16	15	23	10	10	23	30	40	15	15
Manawatu	Flock House	17	18	16	13	15	13	5	9	20	26	30	22
	Marton	31	39	32	25	20	11	11	26	44	52	45	35
Wairarapa	Masterton	15	12	23	18	28	16	16	38	55	65	70	35
Nelson	Motueka	18	10	28	30	15	13	17	25	55	55	52	35
Canterbury	Winchmore (irrigated)	49	43	35	22	10	5	5	12	30	41	40	47
	Winchmore (dryland)	13	13	14	17	8	5	4	10	29	40	30	19
Westland	Westport	52	41	31	26	10	10	10	11	17	30	52	53
	Hokitika	31	33	33	21	12	7	3	6	22	32	51	32
	Reefton	36	35	34	23	10	6	4	11	32	51	51	34
	Central Otago Arrowtown (irrigated)	55	51	43	28	8	0	0	0	12	30	60	55
	Poolburn (dryland)	12	7	7	6	3	0	0	0	12	22	20	12
Otago	Owaka	31	28	18	16	12	9	8	10	28	49	56	50
	Stirling	54	50	35	28	14	6	6	8	25	53	48	51
	Taieri Plain (Invermay)	42	33	30	21	8	5	5	12	35	55	50	46
	Dunedin Hill (Invermay)	36	32	25	16	9	5	5	9	25	45	47	44
	Windsor	24	16	18	15	8	2	1	8	19	44	34	27
Southland	Palmerston	28	20	23	14	9	2	2	10	22	50	55	40
	Mona Bush	58	58	49	30	13	7	5	8	30	55	70	68
	Woodlands	56	46	42	26	15	7	7	10	25	50	60	52

[a]Source: B+LNZ (2022)

Supplementary Table 4. Input-output relationship of sheep and beef production and constraints.

Period/ attribute	BREWE	STMLAMB	FINMLAMB	STFLAMB	TRDHGT	REPHGT	RAM	HERCALF	R1HERJAN	R1HERMAR	R2FFEB	demand	direction	Limit
JulyIFD	22.11		16.75		16.55	18.95	25.03		65.41	65.41	224.8	29075.58	<=	29403
JulyIIFD	24.69		18.06		17.85	20.48	26.77		70.39	70.39	230.57	31439.41	<=	31363.2
AugIFD	29.63		16.53		16.34	21.52	24.29		62.73	62.73	215.57	31494.98	<=	69498
AugIIFD	32.89		17.82		17.61	23.89	25.91		67.51	67.51	221.11	34292.25	<=	74131.2
SepIFD	21.21		17.84		17.64	23.5	24.5		94.66	94.66	314.23	36157.15	<=	98010
SepIIFD	25.47		18.04		17.85	24.38	24.5		97.55	97.55	321.13	37031.63	<=	98010
OctIFD	28.3		19.2		19.01	25.49	24.72		101.34	101.34	330.98	39100.34	<=	115830
OctIIFD	35.99		20.72		20.52	35.49	26.45		111.17	111.17	344.82	42114.42	<=	123552
NovIFD	42.8		18.53		18.34	27.81	24.44	50.92	156.26	156.26	440.85	46249.83	<=	93445.44
NovIIFD	45.95		18.72		18.54	31.26	24.52	54.25	162.39	162.39	454.22	52422.3	<=	93373
DecIFD	48.24	13.48	32.15	13.48	163.23	35.49	24.17	56.5	165.47	165.47	459.22	70832.81	<=	72572.97
DecIIFD	15.1	14.62	34.81	14.62	187.79	38.39	24	63.65	182.77	182.77	487.49	77653.53	<=	77397.32
JanIFD	16.22	15.85	15.85	15.85	216.13	43.23	25.43	74.85	202.83	202.83	565.48	61972.39	<=	64190.78
JanIIFD	17.3	17.18	17.18	17.18	248.59	16.75	27.13	83.58	223.18	223.18	598.87	68064.86	<=	68454.96
FebIFD	18.9	14.98	14.98	14.98	188.29	14.6	16.82	75.13	75.13	197.79	564	59490.57	<=	75416.47
FebIIFD	20.38	16.28	16.28	16.28	217.96	16.73	18.02	83.64	83.64	217.67	596.31	65274.53	<=	80791.24
MarIFD	18.36	16.52	16.52	16.52	221.16	16.98	18.02	86.96	86.96	223.79	223.79	63934.38	<=	66247.97
MarIIFD	19.66	18.79	18.79	18.79	267.11	19.31	19.3	96.27	96.27	245.19	245.19	70934.86	<=	70653.77
AprIFD	15.75		17.32	0	16.41	17.7	17.49	90.32	90.32	90.32	90.32	30247.25	<=	51693.89
AprIIFD	15.82		17.66		16.63	17.99	17.49	93.44	93.44	93.44	93.44	30955.68	<=	51685.31
MayIFD	11.49		17.67		16.55	17.92	17.17	64.08	64.08	64.08	64.08	26521.34	<=	41336.48
MayIIFD	12.12		19.21		17.88	19.39	18.18	68.98	68.98	68.98	68.98	28746.26	<=	44086.91
JunIFD	15.31		18.36		16.17	18.45	16.9	65.29	65.29	65.29	65.29	19610.81	<=	25889.2
JunIIFD	15.37		18.69		16.36	18.7	16.97	65.88	65.88	65.88	65.88	19541.25	<=	25890.51
MLAMB	-0.5	1	1.03									713.4	<=	713.4
FLAMB	-0.5			1	1.03	1.03						713.4	<=	713
EWEREP	0.25					-1								
EWECULL	-0.19													
Minewe	1													
HERCALF								1	1.05	1.05	1.05	74	<=	74
BEEFH1									196			0		
BEEFH2										221	241	15559.66		
BEEFS1												0		
BEEFS2												22587.19		
BULLS1												20314.7		
BULLS2												2004.79		

Supplementary Table 5. Class 5 N.I. Intensive Finishing - Taranaki -Manawatu Farm profit before tax.

Inputs	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	Provisional 2018-19	Forecast 2019-20
Revenue Per Hectare										
Wool	107.49	109.72	82.73	106.29	103.54	120.93	62.78	48.67	51.01	52.02
Sheep	494.67	676.89	534.91	556.87	616.78	544.15	573.66	620.81	746.46	683.84
Cattle	255.70	278.88	327.51	320.36	431.19	343.85	605.85	655.06	567.17	618.18
Dairy Grazing	113.44	129.77	59.60	70.88	72.35	67.05	39.49	37.72	34.34	37.37
Deer + Velvet	26.54	32.52	32.28	25.67	22.56	31.15	29.35			
Cash Crop	58.79	40.75	74.67	64.54	56.96	74.89	126.67	104.27	111.11	98.99
Other	39.66	53.16	42.51	45.92	44.89	38.81	49.06	92.21	83.84	82.83
Total Gross Revenue	1096.28	1321.68	1154.22	1190.52	1348.25	1220.83	1486.86	1558.74	1593.94	1573.23
Expenditure Per Hectare										
Wages	49.36	51.48	45.21	50.89	64.55	81.35	102.29	116.42	118.75	121.13
Animal Health	45.70	47.75	46.84	48.05	48.76	51.02	57.38	50.04	49.23	52.22
Weed & Pest Control	22.23	21.49	22.58	23.61	29.46	28.99	21.62	29.06	29.35	29.65
Shearing Expenses	40.91	47.81	47.06	45.91	46.29	49.08	41.07	35.63	38.10	36.73
Fertiliser	129.40	157.66	127.56	122.78	107.35	97.24	88.52	156.88	160.61	166.36
Lime	3.16	10.87	9.78	8.71	13.10	8.60	3.67	6.40	9.39	13.74
Seeds	20.66	18.67	20.31	20.02	26.46	26.66	26.70	26.30	26.56	27.09
Vehicle Expenses	43.41	39.87	38.56	33.08	36.08	40.85	44.23	42.39	43.24	44.11
Fuel	26.78	28.71	27.62	33.71	24.84	21.75	25.57	30.52	33.57	38.61
Electricity	9.70	11.20	9.32	8.36	8.04	9.37	9.65	10.27	10.47	10.68
Feed & Grazing	72.82	69.72	68.80	72.71	78.19	76.77	71.36	54.57	55.66	56.78
Irrigation Charges										
Cultivation & Sowing	30.92	17.83	19.53	27.74	30.33	39.58	35.50	22.26	22.48	22.71
Cash Crop Expenses	8.73	5.18	8.09	3.99	4.90	6.46	7.71	14.86	15.01	15.16
Repairs & Maintenance	94.77	92.75	74.26	72.39	83.17	94.05	80.31	98.18	100.15	101.00
Cartage	14.30	14.93	17.06	15.98	20.00	17.26	31.22	26.84	27.37	27.92
Administration Expenses	42.18	45.40	51.84	52.14	48.72	47.70	54.68	54.22	54.76	55.31
Total Working Expenses	655.03	681.33	634.42	640.07	670.23	696.73	701.46	774.85	794.71	819.20
Insurance	17.80	16.26	19.50	19.43	20.91	24.15	24.60	30.03	30.93	31.86
ACC Levies	11.95	12.12	11.83	9.63	7.53	10.67	8.63	9.25	9.34	9.44
Rates	46.75	48.62	51.01	51.60	54.44	58.96	63.19	68.44	70.49	71.20
Managerial Salaries	13.85	15.17								
Interest	74.96	81.48	95.96	109.10	127.08	129.33	201.37	208.09	205.70	190.50
Rent	22.89	21.63	20.68	17.43	18.14	19.95	36.31	41.95	42.37	42.80
Total Standing Charges	188.20	195.29	198.98	207.18	228.11	243.07	334.10	357.76	358.84	345.79
Total Cash Expenditure	843.23	876.62	833.40	847.26	898.34	939.79	1035.56	1132.61	1153.56	1164.99
Depreciation	70.93	62.28	58.58	51.38	57.48	62.90	95.39	88.87	93.43	95.88
Total Farm Expenditure	914.16	938.90	891.98	898.64	955.82	1002.69	1130.95	1221.48	1246.97	1261.11
Farm Profit before Tax	182.12	382.78	262.24	291.89	392.43	218.14	355.91	337.26	346.97	312.12

Supplementary Table 6. Land size (ha), number of days, pasture growth rate/ha/day, post-grazing and pre-grazing pasture masses (kg DM), percent of pasture utilization (%), utilizable kg dry matter of pasture (kg DM), metabolizable energy density per kg DM (MJ ME/kg DM), excess pasture for silage preparation (Silage), silage utilization percent (%) and MJ ME/kg DM of silage throughout the year for beef cattle activity.

Attributes	Jul		Aug		Sep		Oct		Nov		Dec		Jan		Feb		Mar		Apr		May		Jun	
Land size (ha)	106.5	106.5	106.5	106.5	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	106.5	106.5	106.5	106.5
Number of days	15	16	16	15	15	15	16	15	15	15	16	15	15	16	15	14	16	15	15	15	16	15	15	15
[a]Pasture growth rate/ha/day	11	11	26	26	44	44	52	52	45	45	35	35	31	31	39	39	32	32	25	25	20	20	11	11
Post-grazing (kg DM)	1500	1500	1500	1577	1625	1647	1645	1632	1664	1685	1677	1613	1601	1588	1500	1518	1521	1528	1523	1500	1500	1500	1500	1500
[b]Pre-grazing (kg DM/ha/bi-monthly)	1665	1676	1916	1967	2285	2307	2425	2464	2339	2360	2202	2173	2066	2084	2085	2064	2033	2008	1898	1875	1820	1800	1665	1665
[c]Utilization percent (%)	90	90	90	90	75	75	75	75	70	70	70	70	70	70	70	70	70	70	70	70	70	70	80	80
Utilizable pasture (Kg DM/ha/bi-monthly)	149	158	374	390	473	473	473	533	550	553	450	417	332	422	435	410	378	358	278	263	224	210	132	132
[c]MJ ME/kg DM	11.0	11.0	11.4	11.4	11.3	11.3	11.2	11.2	11.4	11.4	11.6	11.6	10.2	10.2	10.4	10.4	10.4	10.4	10.8	10.8	11.0	11.0	11.0	11.0
Silage (kg DM/ha)	0	0	0	0	97	139	255	211	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
[d]Silage utilization percentage (%)	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85
Utilizable silage (kg DM/ha)	0	0	0	0	82	118	217	179	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
[e]Silage MJ ME/kg DM	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5

Sources: [a] B+LNZ (2022); [b] pre-grazing pasture values are presented after the equivalent amount of pasture for silage production was taken out; [c] Brookes and Nicol (2017); [d]Assumed; MJ ME/kg DM: metabolizable energy density per kg dry matter of pasture; land size for cash crop production and new pasture grassed area (15 ha) was considered as grazing land between May to August, however, excluded from beef cattle and sheep grazing between September and April (Trafford and Trafford, 2011).

Supplementary Table 7. Land size (ha), number of days, pasture growth rate/ha/day, post-grazing and pre-grazing pasture masses (kg DM), percent of pasture utilization (%), utilizable kg dry matter of pasture (kg DM), metabolizable energy density per kg DM (MJ ME/kg DM), excess pasture for silage preparation (prepared silage), silage utilization percent (%) and MJ ME/kg DM of silage throughout the year for sheep activity.

Attributes	Jul		Aug		Sep		Oct		Nov		Dec		Jan		Feb		Mar		Apr		May		Jun	
Land size (ha)	106.5	106.5	106.5	106.5	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	106.5	106.5	106.5	106.5
Number of days	15	16	16	15	15	15	16	15	15	15	15	16	16	15	14	15	16	15	15	15	16	15	15	15
[a]Pasture growth rate/ha/day	11	11	26	26	44	44	52	52	45	45	35	35	31	31	39	39	32	32	25	25	20	20	11	11
Post-grazing (kg DM/ha)	800	800	800	851	880	977	863	881	940	863	803	845	896	869	800	892	939	907	897	876	860	861	859	800
[b]Pre-grazing (kg DM/ha/bi-monthly)	965	976	1216	1241	1540	1637	1695	1661	1615	1538	1363	1370	1392	1334	1385	1438	1451	1387	1272	1251	1180	1161	1024	965
[c]Pasture utilization percentage (%)	90	90	90	90	75	75	75	75	70	70	70	70	70	70	70	70	70	70	70	70	70	70	80	80
Utilizable pasture (kg DM/bi-monthly)	149	158	374	396	525	525	578	646	571	516	394	399	416	378	410	449	454	405	316	295	241	237	167	132
[c]MJ ME/kg DM	11.0	11.0	11.4	11.4	11.3	11.3	11.2	11.2	11.4	11.4	11.6	11.6	10.2	10.2	10.4	10.4	10.4	10.4	10.8	10.8	11.0	11.0	11.0	11.0
Silage (kg DM/ha)	0	0	0	0	40	137	125	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
[d]Silage utilization percentage (%)	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85	85
Utilizable silage (kg DM/ha)	0	0	0	0	34	116	106	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
[c]Silage MJ ME/kg DM	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5

Sources: [a] B+LNZ (2022); [b] pre-grazing pasture values are presented after the equivalent amount of pasture for silage production was taken out; [c] Brookes and Nicol (2017); [d]Assumed; MJ ME/kg DM: metabolizable energy density per kg dry matter of pasture; land size for cash crop production and new pasture grassed area (15 ha) was considered as grazing land between May to August, however, excluded from beef cattle and sheep grazing between September and April (Trafford and Trafford, 2011).

Supplementary Table 8. Daily per head feed demand for various classes of steers and beef bulls (kg DM/head/day).

Periods	Weaner steers	R2 steers	R2S-rep	R3 steers	Weaner bulls	R2 bulls
Jul		5.3	4.7	7.2		6.7
		5.4	4.8	7.2		6.8
Aug		7.5	6.7	9.0		8.7
		7.8	7.0	9.1		9.0
Sep		8.2	7.3	9.4		9.5
		8.5	7.6	9.5		9.3
Oct		8.9	7.9	9.7		9.7
		8.6	8.2	9.9		10.0
Nov		8.8	7.8	7.4	3.4	9.6
		9.1	8.0	7.4	3.6	9.8
Dec		9.2	8.1	7.3	3.7	9.3
		9.5	8.3	7.3	4.0	9.5
Jan		9.7	9.0	8.1	5.0	11.1
		9.9	9.2	8.1	5.2	11.3
Feb		9.7	9.2	8.0	5.8	11.3
		9.9	9.3	8.0	6.1	11.4
Mar	5.2		9.5	8.0	6.7	10.7
	5.3		9.7	8.0	7.0	10.8
Apr	5.3		7.9		6.1	10.4
	5.1		8.0		6.3	10.5
May	5.0		7.9		6.3	10.3
	5.2		7.9		6.5	10.4
Jun	4.3		7.6		5.2	9.8
	4.4		7.6		5.3	9.8

R2 steers: rising-2yr steers finished before the second winter; R2S-rep: rising-2yr steers for replacement of R3 steers; R3 steers: rising-3yr steers finished before the third winter; R2 bulls: rising-2yr bull finished before the second winter

Supplementary Table 9. Bi-monthly per head feed demand for different slaughtered age steers and beef bulls (kg DM/head/bi-monthly).

Periods	STRWNR	S-18	RS2-rep	S-28	S-30	BULWNR	B-16	B-18	B-20	B-22
Jul		80.0	70.6	107.6	107.6		100.6	100.6	100.6	100.6
		87.0	76.2	115.4	115.4		109.3	109.3	109.3	109.3
Aug		119.5	107.8	143.7	143.7		138.8	138.8	138.8	138.8
		117.3	117.3	137.0	137.0		135.7	135.7	135.7	135.7
Sep		123.2	109.9	140.3	140.3		142.1	142.1	142.1	142.1
		128.1	113.7	142.5	142.5		139.1	139.1	139.1	139.1
Oct		134.1	118.5	145.9	145.9		145.3	145.3	145.3	145.3
		138.1	130.5	157.9	157.9		160.1	160.1	160.1	160.1
Nov		131.9	116.4	110.7	110.7	50.4	143.5	147.2	147.2	147.2
		136.3	119.8	111.1	111.1	53.8	147.2	147.2	147.2	147.2
Dec		138.2	121.1	109.5	109.5	56.2	139.1	139.1	139.1	139.1
		151.9	132.7		117.3	63.3	151.2	151.2	151.2	151.2
Jan		146.1	134.7		121.7	74.6		166.3	166.3	166.3
		158.8	146.4		130.1	83.3		180.4	180.4	180.4
Feb		145.8	137.3		119.9	87.6		168.9	168.9	168.9
		138.3	130.5		128.3	85.9		160.2	160.2	160.2
Mar	82.7		151.6			106.7			170.7	170.7
	79.9		144.8			105.3			161.9	161.9
Apr	79.1		118.9			92.1			155.5	155.5
	76.8		120.0			94.9			157.1	157.1
May	80.6		125.7			100.7				165.1
	77.3		118.9			97.4				156.4
Jun	65.1		113.7			78.5				146.6
	65.6		114.5			79.2				147.5

STRWNR: weaner steers; BULWNR: weaner bulls; S-18: rising-2yr steer slaughtered at 18-months of age; R2S-rep: R2-replacement steers for R3 steers; S-28 and S-30: rising-3yr steer slaughtered at the ages of 28 and 31-momths; B-16, B-18, B-20 and B-22: rising-2yr bull slaughtered at the ages of 16, 18, 20 and 22-months.

Supplementary Table 10. Per head feed demand on a daily basis for sheep flock (kg DM/head/day).

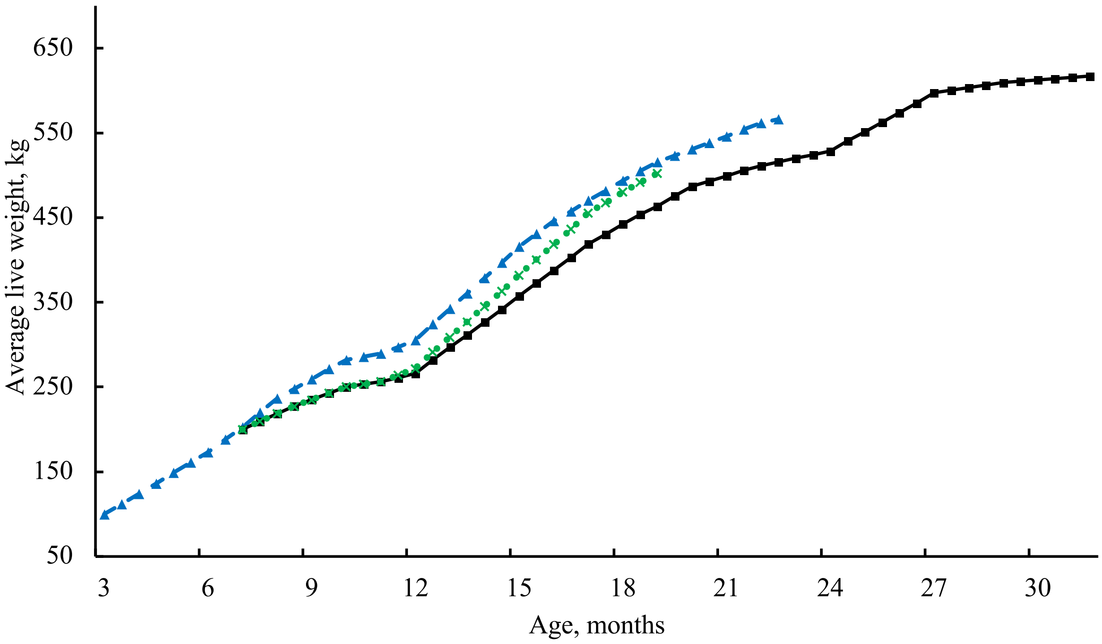
Periods	Breeding ewes	Cull ewes	Prime lambs	Store lambs	Replacement hogget	Rams
Jul	1.1	1.1			1.1	1.2
	1.1	1.1			1.1	1.2
Aug	1.5	1.5			1.6	1.4
	1.5	1.5			1.6	1.4
Sep	1.5	1.5			1.9	1.4
	2.2	2.2			1.9	1.4
Oct	2.2	2.2			1.9	1.3
	2.3	2.3			2.5	1.3
Nov	2.4	2.4			2.2	1.3
	2.6	2.6			1.7	1.2
Dec	1.0		1.0	0.8	1.8	1.0
	1.0		1.0	0.8	2.0	1.0
Jan	1.3		1.2	0.9	1.5	1.5
	1.3		1.2	0.9	1.4	1.5
Feb	1.3		1.2	0.9	1.4	1.4
	1.3		1.2	0.9	1.4	1.4
Mar	1.3		1.3	0.9	1.4	1.5
	1.4		1.3	0.9	1.3	1.5
Apr	1.2			0.9	1.2	1.2
	1.2			0.9	1.3	1.2
May	1.1				1.3	1.2
	1.1				1.3	1.2
Jun	1.1				1.3	1.1
	1.1				1.3	1.1

Prime lambs are lambs sold for meat processing plant, store lambs are lambs sold to other farmers for finishing and replacement hoggets (RHGT) are lambs between 5 to 16-months of age.

Supplementary Table 11. Per head feed demand on bi-monthly basis for sheep flock (kg DM/ha/bi-monthly).

Periods	Breeding ewes	Cull ewes	*Prime lambs (Nov)	Prime lambs (Mar)	Store lambs	RHGT	Rams
July	16.3	16.3				15.8	17.4
	17.5	17.5				17.0	18.6
Aug	23.6	23.6				25.3	22.1
	23.1	23.1				24.7	20.8
Sep	22.8	22.8				28.2	21.2
	32.7	32.7				29.2	21.3
Oct	35.3	35.3				30.8	21.4
	34.1	34.1				37.6	20.1
Nov	35.9	35.9				32.3	19.9
	38.4	38.4				25.7	17.6
Dec	15.3			12.1	12.1	28.1	16.3
	14.5			13.9	11.5	30.5	15.2
Jan	21.2			13.2	14.1	23.7	23.3
	19.9			13.1	13.4	20.7	21.9
Feb	19.6			12.4	13.3	20.7	21.5
	18.4			18.9	12.5	19.6	20.0
Mar	21.5			18.1	14.5	22.8	23.8
	20.3			17.7	13.7	19.1	22.4
Apr	17.6				13.4	18.7	18.4
	17.6				13.5	19.0	18.4
May	17.0					20.1	19.2
	16.0					19.1	18.0
Jun	16.6					19.4	16.0
	16.7					19.6	15.8

*male and female prime lambs; Prime lambs are lambs sold for meat processing plant, store lambs are lambs sold to other farmers for finishing and replacement hoggets (RHGT) are lambs between 4 to 16-months of age, mated at the age of 8-months



Supplementary Figure 1. Live weight of bulls (dashed blue line), fast-growing steers (green round dot) and slow-growing steers (solid black line).

Supplementary Table 12. Bi-monthly constraints of beef cattle and sheep numbers.

Activity	Constraint	Upper limit
Steer weaners	=	Steer weaners
S-18	≤	Weaner steers
R2-repl steers	=	S-28 + S-30
S-28	≤	Weaner steers – S-18
S-30	≤	Weaner steers – S-18 – S-28
Bull weaners	=	Bull weaners
B-16	≤	Weaners bulls
B-18	≤	Weaners bulls – B-16
B-20	≤	Weaners bulls – B-16 – B-18
B-22	≤	Weaners bulls – B-16 – B-18 – B-20
Breeding ewe	=	(Breeding ewes – cull ewes) + RHGT
Rams	=	(Rams – cull rams) + RepR
RHGT	=	Cull ewes
Cull ewes	=	0.3 * breeding ewes
Prime female lambs	≤	Female lambs
Store female lambs	≤	Female lambs – prime female lambs
*Prime male lambs	≤	Male lambs
Store male lambs	≤	Male lambs – prime male lambs

* prime male lambs were processed in November and March which meant it had two activities

Supplementary equation 1. Total feed demand and feed supply constraints for beef cattle activity

1. $\sum_{i=0}^{10}(number\ of\ cattle\ in\ activityi * feed\ demand/headi/bi - monthly) \leq feed\ supply - -Jul\ I$

2. $\sum_{i=0}^{10}(number\ of\ cattle\ in\ activityi * feed\ demand/headi/bi - monthly) \leq feed\ supply - -Jul\ II$

3. $\sum_{i=0}^{10}(number\ of\ cattle\ in\ activityi * feed\ demand/headi/bi - monthly) \leq feed\ supply - -Aug\ I$

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24. $\sum_{i=0}^{10}(number\ of\ cattle\ in\ activityi * feed\ demand/headi/bi - monthly) \leq feed\ supply - -Jun\ II$

Where; i = 1, 2, 3…10

1 = steer weaner; 2 = steers slaughtered at 18-months; 3 = R2-replacement steers; 4 =steers slaughtered at 28-months; 5 = steers slaughtered at 30-months; 6 = bull weaners; 7 = bulls slaughtered at the ages of 16-monhs; 8= bulls slaughtered at the ages of 18-monhs; 9= bulls slaughtered at the ages of 20-monhs and 10 = bulls slaughtered at the ages of 22-monhs.

Supplementary equation 2. Total feed demand and feed supply constraints for sheep activity

1. $\sum_{i=0}^{6}(number\ of\ sheep\ in\ activityi * feed\ demand/headi/bi - monthly) \leq feed\ supply - - Jul\ I$

2 . $\sum_{i=0}^{6}(number\ of\ sheep\ in\ activityi * feed\ demand/headi/bi - monthly) \leq feed\ supply - - Jul\ II$

3. $\sum_{i=0}^{6}(number\ of\ sheep\ in\ activityi * feed\ demand/headi/bi - monthly) \leq feed\ supply - - Aug\ I$

.

.

.

24. $\sum_{i=0}^{6}(number\ of\ sheep\ in\ activtyi * feed\ demand/headi/bi - monthly) \leq feed\ supply - - Jun\ II$

Where; i = 1, 2, 3… 6

1= breeding ewes; 2= cull ewes; 3= prime lambs; 4= store lambs; 5=replacement hoggets; 6=rams

These equations can be represented in general as:

Total feed demand $\leq Total\ feed\ supply$

Supplementary Table 13. The bi-monthly minimum and maximum pasture mass constraints.

For sheep grazing	For cattle grazing
JulIMin ≥ 800	1. JulIMin ≥ 1500
JulIMax ≤ 1500	2. JulIMax ≤ 2500
JulIIMin ≥ 800	3. JulIIMin ≥ 1500
.	.
.	.
.	.
48. JunIIMax ≤ 1500	48. JunIIMax ≤ 2500

Supplementary Table 14. Costs of buying weaners for the beef cattle activity and the bi-monthly costs of various inputs per stock unit for beef cattle and sheep activities.

Production cost	Weaner steers	S-18	R2-rep	S-28	S-30	Weaner bulls	B-16	B-18	B-20	B-22	BREWE	Ram	RGHT	Cull ewe	Prime lambs, Mar	Store lambs
Weaner purchases	700.00					450.00					-	-	-	-	-	-
Seed	0.41	1.22	1.62	2.18	2.43	0.81	1.42	1.62	1.82	2.03	1.22	1.22	1.22	0.56	0.41	0.51
Cultivation and sowing	0.34	1.03	1.37	1.85	2.06	0.69	1.20	1.37	1.55	1.72	1.03	1.03	1.03	0.47	0.34	0.43
Feed and grazing	0.84	2.53	3.37	5.05	5.05	1.68	2.95	3.37	3.79	4.21	2.53	2.53	2.53	1.16	0.84	1.05
Weed and pest	0.45	1.35	1.79	2.41	2.69	0.90	1.57	1.79	2.02	2.24	1.35	1.35	1.35	0.62	0.45	0.56
Wages and salaries	1.79	5.38	7.17	9.64	10.76	3.59	6.28	7.17	8.07	8.97	5.38	5.38	5.38	2.47	1.79	2.24
Animal health	0.77	2.32	3.09	4.15	4.63	1.54	2.70	3.09	3.47	3.86	2.32	2.32	2.32	1.06	0.77	0.96
Shearing	-	-	-	-	-	-	-	-	-	-	3.29	3.29	3.29	1.51	1.10	1.37
Fertilizer and lime	2.52	7.55	10.06	13.52	15.09	5.03	8.80	10.06	11.32	12.58	7.55	7.55	7.55	3.46	2.52	3.14
Vehicles and fuel	1.12	3.37	4.49	6.04	6.74	2.25	3.93	4.49	5.06	5.62	3.37	3.37	3.37	1.54	1.12	1.40
Electricity	0.16	0.48	0.63	0.85	0.95	0.32	0.55	0.63	0.71	0.79	0.48	0.48	0.48	0.22	0.16	0.20
Others	9.65	28.94	38.58	51.84	57.87	19.29	33.76	38.58	43.40	48.23	28.94	28.94	28.94	13.26	9.65	12.06
Total	18.05	54.14	72.18	97.52	108.27	36.09	63.16	72.18	81.20	90.23	57.43	28.49	28.49	13.06	9.50	11.87

[a] Prime lambs are lambs sold to the meat processing plant, store lambs are lambs sold to other farmers for finishing and replacement hoggets (RHGT) are lambs between 4 to 16-months of age, mated at 8-months of ages; S-18: rising-2yrs steers (slaughtered at the age of 18-months); R2-rep: two years old replacement steer; S-28 and S-30: rising-3yrs steers (slaughtered at the ages of 28 and 30-months); B-16, B-18, B-20 and B-22: rising-2yrs bulls (slaughtered at the ages of 16, 18, 20 and 22-months).

Source: B+LNZ: Economic Service (2019

Supplementary Table 15. Total, per hectare and per stock unit values of gross farm revenue (GFR), total farm expenditure (TFE), farm earnings before tax (EBT) of beef cattle and sheep activity for an average Class 5 farm and the Optimized system.

Attributes	Unit	Class 5			Optimized system		
		GFR	TFE	EBT	GFR	TFE	EBT
Beef cattle	NZ$	-	-	-	297,700.39	242,523.49	55,176.90
Sheep	NZ$	-	-	-	175,820.19	73,789.22	102,030.97
Total	NZ$	308,630.00	241,853.00	66,777.00	473,520.57	316,312.71	157,207.86
Per hectare	NZ$/ha	1,555.20	1,218.71	336.49	2,391.52	1,597.54	793.98
Per stock unit	NZ$/SU	144.11	112.93	31.18	150.78	100.70	50.05

Supplementary Table 16. Total, per hectare, and per stock unit values of the gross farm revenue (GFR), total farm expenditure (TFE), and farm earnings before tax (EBT) of beef cattle and sheep activity for the optimized system, Scenario I and Scenario II.

Systems		Beef Cattle (NZ$)	Sheep (NZ$)	Total (NZ$)	Total Per Hectare (NZ$/ha)	Total Per Stock Unit (NZ$/SU)
Optimized traditional beef system †	GFR	297,700.39	175,820.19	473,520.58	2,391.52	150.75
	TFE	242,523.49	73,789.22	316,312.71	1,597.54	100.70
	EBT	55,176.90	102,030.97	157,207.87	793.98	50.05
Scenario I (8–12)	GFR	291,321.51	175,820.19	467,141.70	2,359.30	147.36
	TFE	207,114.98	73,789.22	280,904.20	1,418.71	88.61
	EBT	84,206.53	102,030.97	186,237.50	940.59	58.75
Scenario I (8–14)	GFR	289,300.37	175,820.19	465,120.56	2,349.09	146.59
	TFE	195,808.23	73,789.22	269,597.45	1,361.60	84.97
	EBT	93,492.14	102,030.97	195,523.11	987.49	61.62
Scenario II (8–12)	GFR	283,556.54	175,820.19	459,376.73	2,320.08	143.38
	TFE	174,326.59	73,789.22	248,115.81	1,253.11	77.44
	EBT	109,229.95	102,030.97	211,260.92	1,066.97	65.94
Scenario II (8–14)	GFR	291,775.45	175,820.19	467,595.64	2,361.59	145.94
	TFE	174,294.68	73,789.22	248,083.90	1,252.95	77.43
	EBT	117,480.77	102,030.97	219,511.74	1,108.65	68.51

† Optimized traditional beef cattle system: The traditional steers and bulls identified using linear programming developed by (Chapter IV); 8 to12: young beef cattle slaughtered at the ages of 8, 10 and 12-months; 8 to 14: young beef cattle slaughtered at the ages of 8, 10, 12, 14-months of ages.

Appendices-C: Supplementary materials for chapter VI and VII

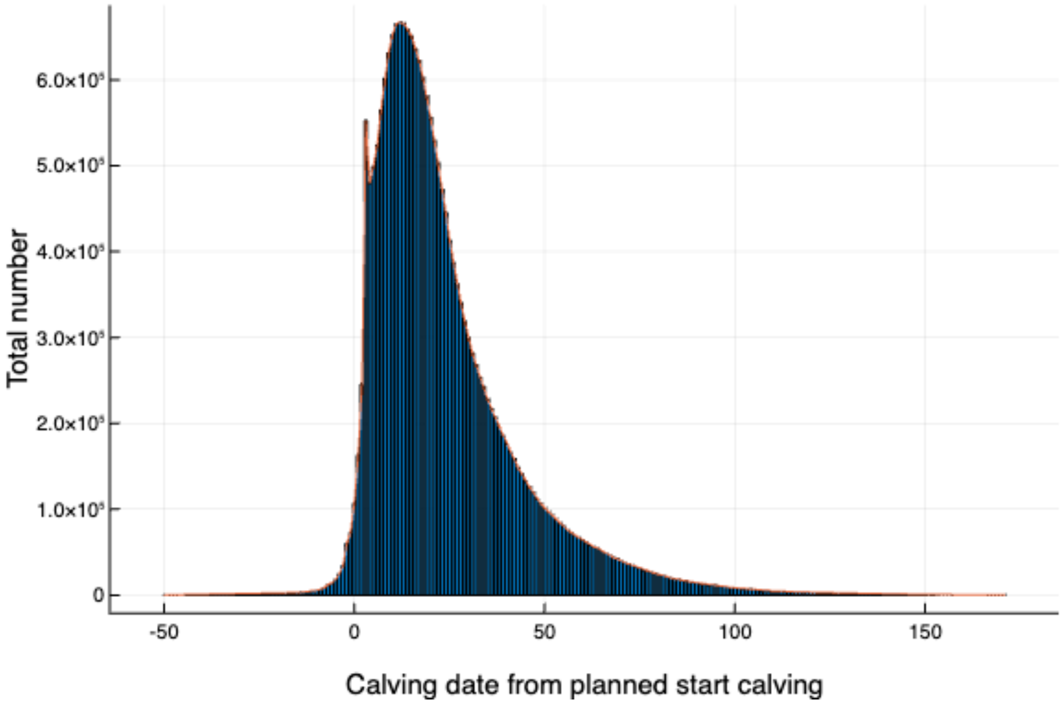
Supplementary Table 17. Variance stability analysis.

Set	Sample size (ABM simulation runs)	Coefficient of variation
Sample set 1	10	0.105
Sample set 2	20	0.026
Sample set 3	30	0.006
Sample set 4	40	0.005

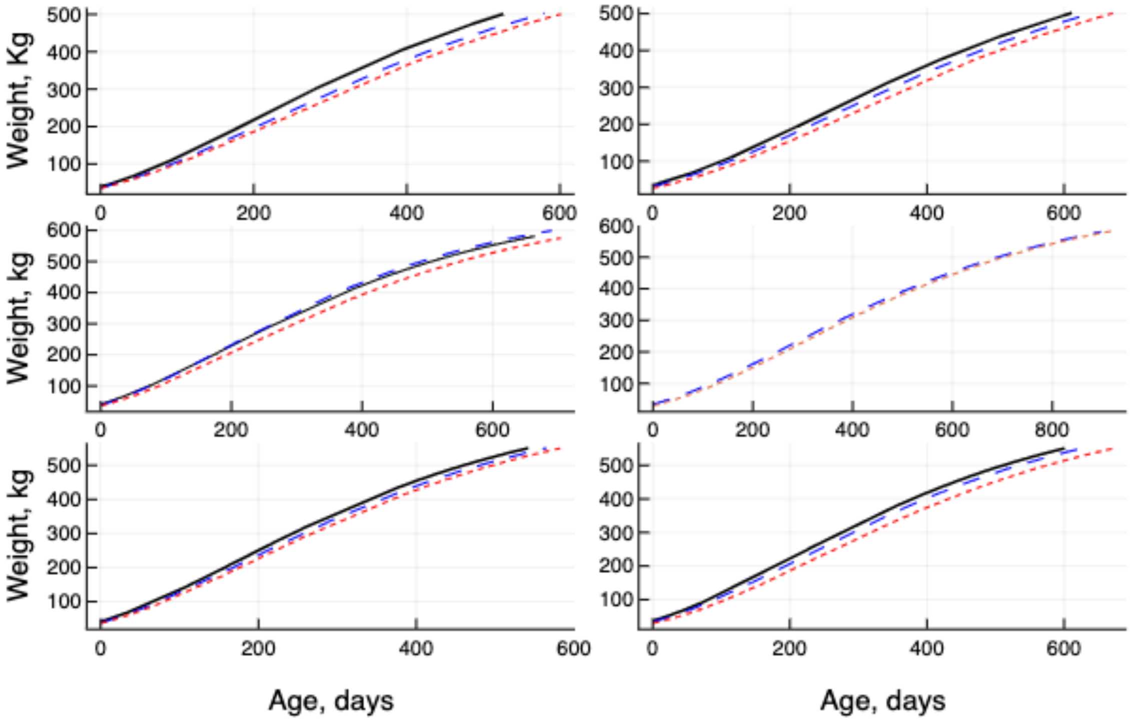
As shown in Supplementary Table 17, the difference in coefficient of variation between the 2nd set of the sample and 3rd set of sample was less than 0.002. Comparing this figure with 0.005 fixed value (*epsilon*), 20 ABM simulation run are sufficient.

Supplementary Table 18. Bootstrap analysis at 95% confidence interval.

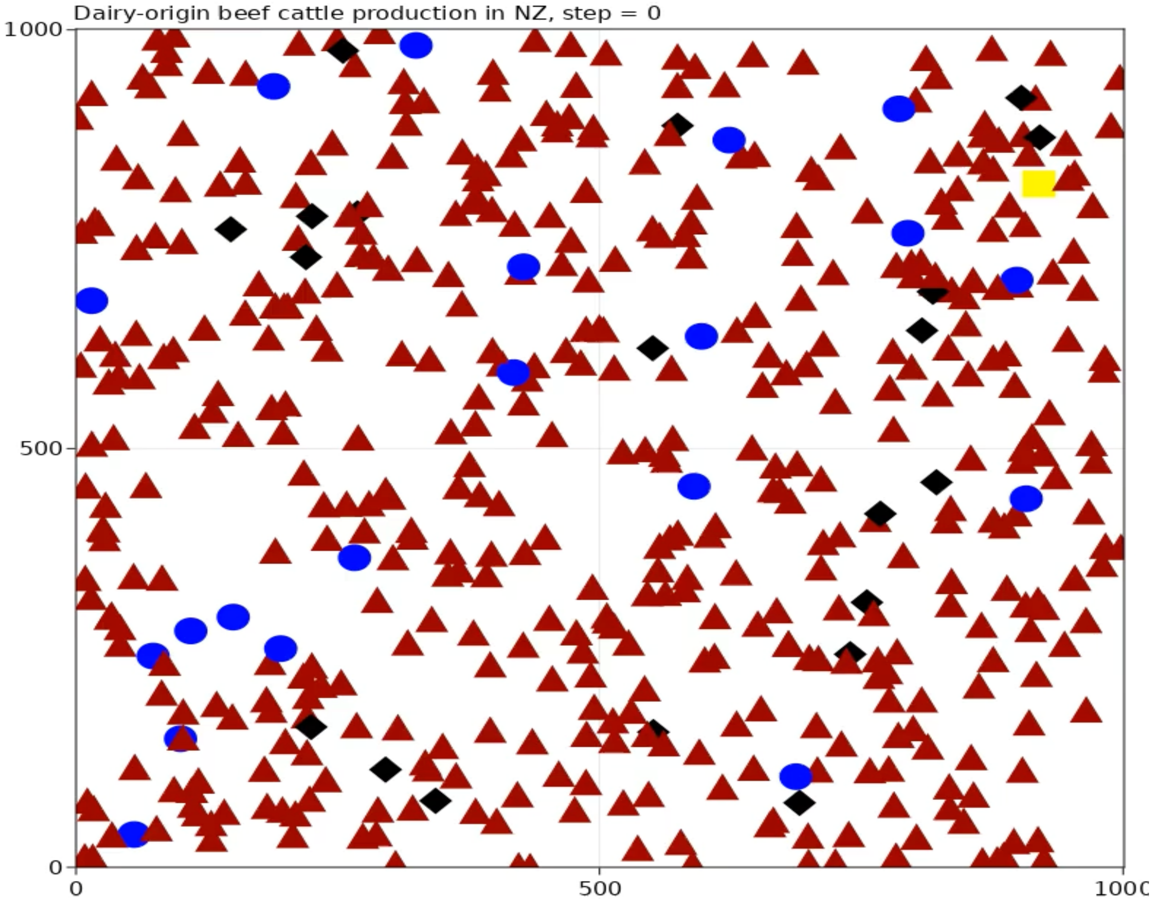
	Sample mean (from ABM simulation)			
	n	Heifer	Steer	Bull
Mean	100	2563	1747	4968
Std	100	222	184	344
100000 bootstraps (at 95%, normal method)				
	n	Heifer	Steer	Bull
Mean	100	2563	1747	4968
Std	100	191	159	277
		95% confidence level		
		Heifer	Steer	Bull
Lower		2526	1716	4914
Mean		2563	1747	4968
Upper		2600	1778	5022



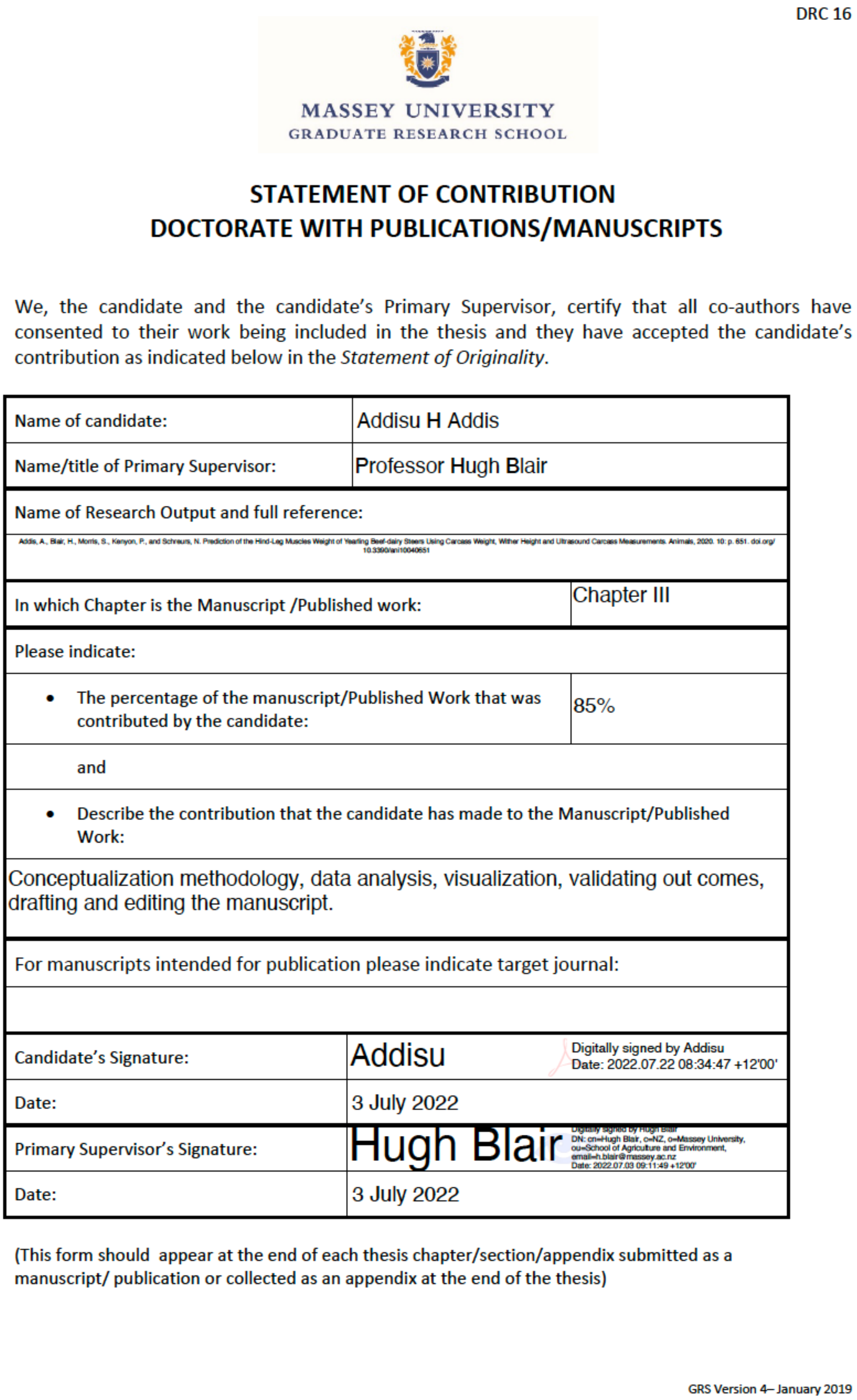
Supplementary Figure 2. Calving distribution from planned start calving in first calving heifers throughout New Zealand.



Supplementary Figure 3. Growth curve of dairy-originated cattle in New Zealand simulated using the Richards four parameter equation. The left side of the graph represented for beef-dairy cattle and the right side dairy-dairy cattle. In both columns, heifers, steers and bulls from top to bottom (black solid line stood Holstein-Frisian origin, dotted red line for Jersey origin and the blue dashed line for their crosses.



Supplementary Video 1. A simplified ABM in New Zealand dairy-origin beef production (red triangles black diamonds, blue circulars and yellow squares represent cattle, rearers, finishers and processors agents respectively).



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STATEMENT OF CONTRIBUTION
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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:	Addisu H Addis
Name/title of Primary Supervisor:	Professor Hugh Blair
Name of Research Output and full reference:	
Addis, A., Blair, H., Morris, S., Kenyon, P., and Schreurs, N. Prediction of the Hind-Leg Muscles Weight of Yearling Beef-dairy Steers Using Carcass Weight, Wither Height and Ultrasound Carcass Measurements. Animals, 2020. 10: p. 651. doi.org/10.3390/ani10040651	
In which Chapter is the Manuscript /Published work:	Chapter III
Please indicate:	
• The percentage of the manuscript/Published Work that was contributed by the candidate:	85%
and	
• Describe the contribution that the candidate has made to the Manuscript/Published Work:	
Conceptualization methodology, data analysis, visualization, validating out comes, drafting and editing the manuscript.	
For manuscripts intended for publication please indicate target journal:	
Candidate's Signature:	Addisu Digitally signed by Addisu Date: 2022.07.22 08:34:47 +12'00'
Date:	3 July 2022
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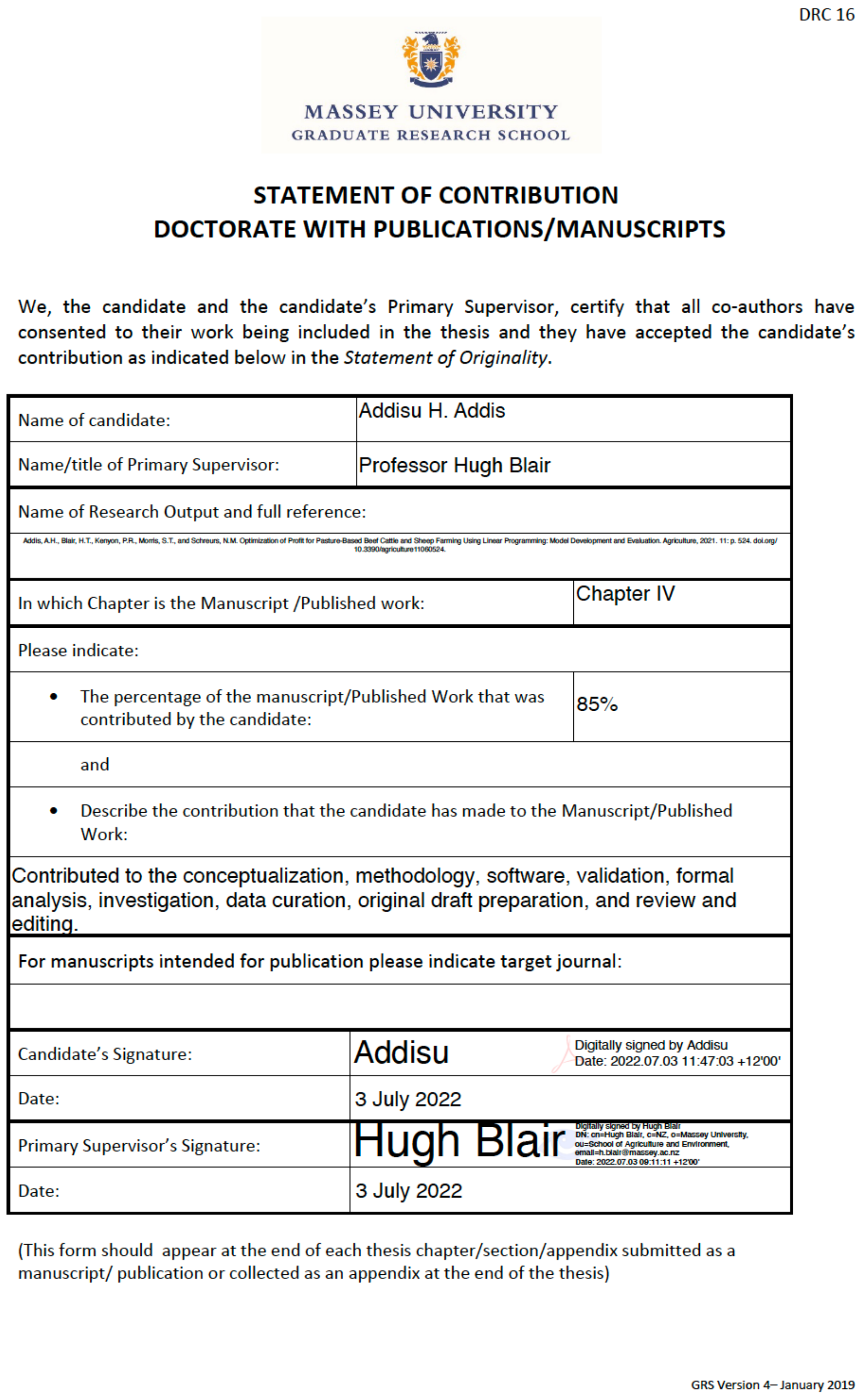

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Name/title of Primary Supervisor:	Professor Hugh Blair
Name of Research Output and full reference:	
Addis, A.H., Blair, H.T., Kenyon, P.R., Morris, S.T., and Schreurs, N.M. Optimization of Profit for Pasture-Based Beef Cattle and Sheep Farming Using Linear Programming: Model Development and Evaluation. Agriculture, 2021. 11: p. 524. doi.org/10.3390/agriculture11060524.	
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• Describe the contribution that the candidate has made to the Manuscript/Published Work:	
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For manuscripts intended for publication please indicate target journal:	
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Date:	3 July 2022
Primary Supervisor's Signature:	Hugh Blair Digitally signed by Hugh Blair DN: cn=Hugh Blair, c=NZ, o=Massey University, ou=School of Agriculture and Environment, email=h.blair@massey.ac.nz Date: 2022.07.03 09:11:11 +12'00'
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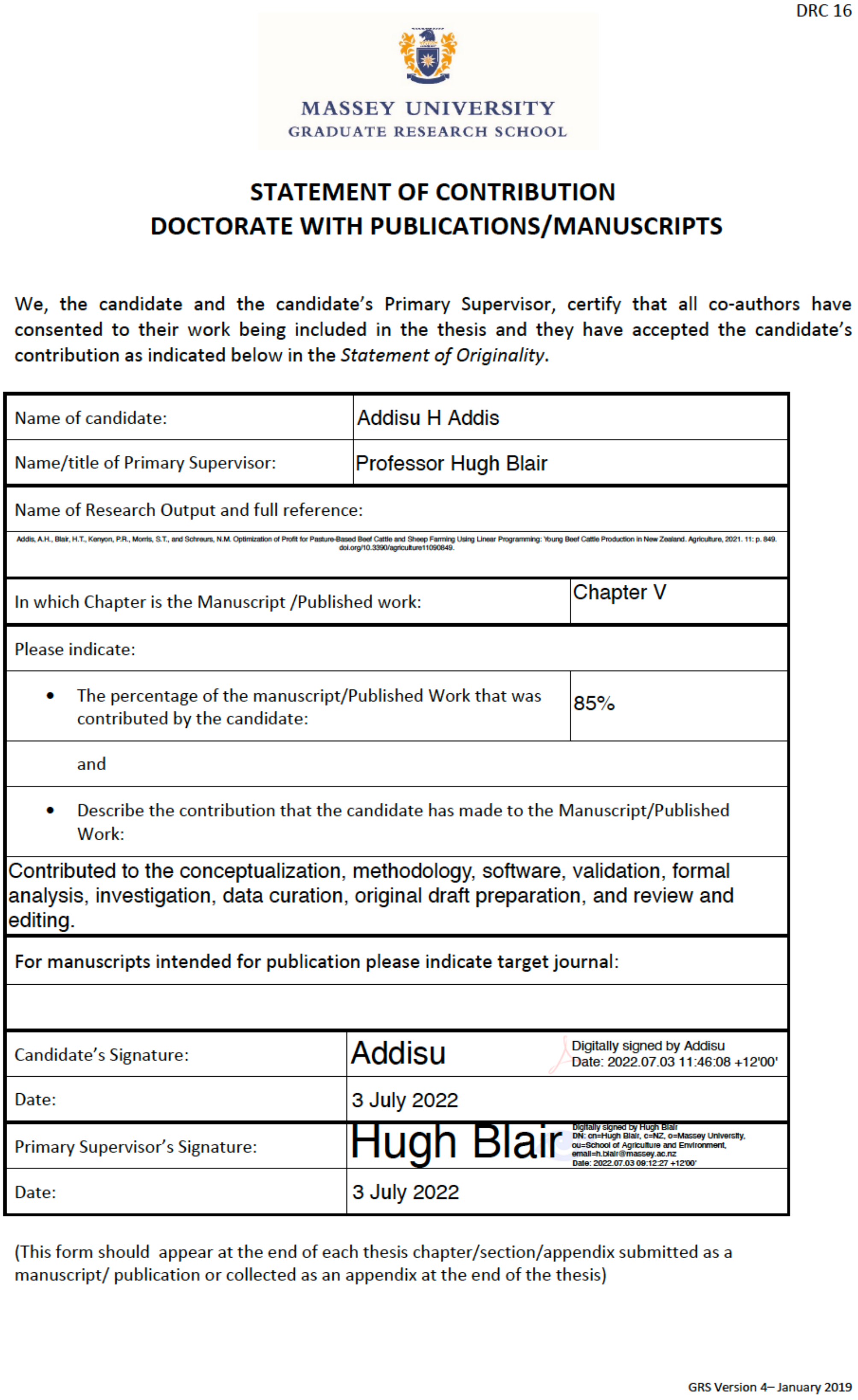

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In which Chapter is the Manuscript /Published work:	Chapter V
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• The percentage of the manuscript/Published Work that was contributed by the candidate:	85%
and	
• Describe the contribution that the candidate has made to the Manuscript/Published Work:	
Contributed to the conceptualization, methodology, software, validation, formal analysis, investigation, data curation, original draft preparation, and review and editing.	
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Candidate's Signature:	Addisu Digitally signed by Addisu Date: 2022.07.03 11:46:08 +12'00'
Date:	3 July 2022
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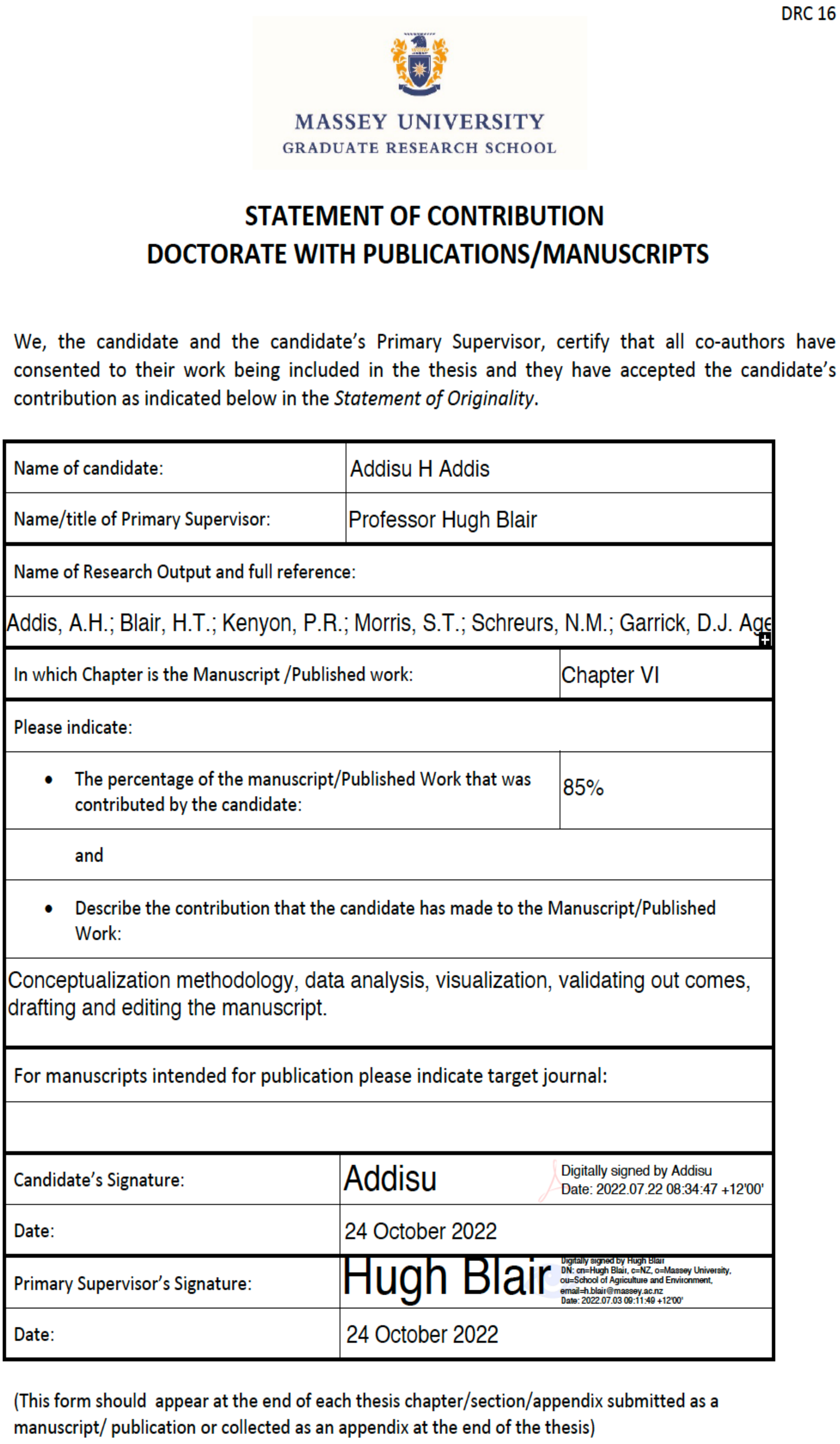

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STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

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:	Addisu H Addis
Name/title of Primary Supervisor:	Professor Hugh Blair
Name of Research Output and full reference:	
Addis, A.H.; Blair, H.T.; Kenyon, P.R.; Morris, S.T.; Schreurs, N.M.; Garrick, D.J. Age	
In which Chapter is the Manuscript /Published work:	Chapter VI
Please indicate:	
• The percentage of the manuscript/Published Work that was contributed by the candidate:	85%
and	
• Describe the contribution that the candidate has made to the Manuscript/Published Work:	
Conceptualization methodology, data analysis, visualization, validating out comes, drafting and editing the manuscript.	
For manuscripts intended for publication please indicate target journal:	
Candidate's Signature:	Addisu Digitally signed by Addisu Date: 2022.07.22 08:34:47 +12'00'
Date:	24 October 2022
Primary Supervisor's Signature:	Hugh Blair Digitally signed by Hugh Blair DN: cn=Hugh Blair, c=NZ, o=Massey University, ou=School of Agriculture and Environment, email=h.blair@massey.ac.nz Date: 2022.07.03 09:11:49 +12'00'
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